Hierarchical Modeling of Energy Systems

Edited by
Nikolai I. Voropai
Valery A. Stennikov

ELSEVIER

HIERARCHICAL MODELING OF ENERGY SYSTEMS

This page intentionally left blank

HIERARCHICAL MODELING OF ENERGY SYSTEMS

Edited by

Nikolai I. Voropai[†]
Melentiev Energy Systems Institute
Siberian Branch of the Russian Academy of Sciences
Irkutsk, Russia

Valery A. Stennikov
Melentiev Energy Systems Institute
Siberian Branch of the Russian Academy of Sciences
Irkutsk, Russia

ELSEVIER

[†]Deceased.

Elsevier
Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

ISBN: 978-0-443-13917-8

For information on all Elsevier publications
visit our website at https://www.elsevier.com/books-and-journals

Acquisitions Editor: Peter Adamson
Editorial Project Manager: Teddy A. Lewis
Production Project Manager: Anitha Sivaraj
Cover Designer: Vicky Esser Pearson

Typeset by VTeX

Dedication

This book is dedicated to my colleague and friend Nikolai Voropai, who passed away on February 28, 2022 before the book was published. He was the principal initiator of this book as an outstanding expert in energy systems. N.I. Voropai always took an active part in scientific and social life, his proposals and opinions were always substantial, useful, and unselfish. His personal qualities – sincerity, humanity, patience combined with determination, wisdom, and intelligence – are the qualities of a true scientist.

Professor, Academician of Russian Academy of Sciences
Valery Stennikov

This page intentionally left blank

Contents

†Deceased.

3. Hierarchical modeling in expansion planning of electric power systems

N.I. Voropai, S.V. Podkovalnikov, V.V. Trufanov, V.V. Khanaev, P.S. Drachev, G.I. Sheveleva, V.V. Selifanov, O.V. Khamisov, and K.V. Suslov

4. Hierarchical modeling principles for operation and control of electric power systems

N.I. Voropai, A.V. Domyshev, D.N. Efimov, I.N. Kolosok, E.S. Korkina, V.G. Kurbatsky, A.B. Osak, D.A. Panasetsky, N.V. Tomin, V.A. Shakirov, D.N. Sidorov, A.N. Kozlov, and E.V. Popova

5. Hierarchical modeling for development of pipeline energy systems, coal supply systems, and integrated energy systems

V.A. Stennikov, E.A. Barakhtenko, N.I. Voropai, T.V. Dzyubina, O.A. Edeleva, N.I. Ilkevich, Zh.V. Kalinina, A.D. Sokolov, D.V. Sokolov, L.N. Takaishvily, and O.N. Voitov

List of figures

This page intentionally left blank

Contributors

A.V. Alexeev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

E.A. Barakhtenko Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.V. Domyshev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

P.S. Drachev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

T.V. Dzyubina Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

O.A. Edeleva Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

D.N. Efimov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

N.O. Epishkin Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

O.A. Grebneva Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

N.I. Ilkevich Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

I.Yu. Ivanova Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Zh.V. Kalinina Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

O.V. Khamisov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

V.V. Khanaev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.M. Kler Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

I.N. Kolosok Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Yu.D. Kononov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

E.S. Korkina Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.G. Korneev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.N. Kozlov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

D.S. Krupenev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

V.G. Kurbatsky Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.V. Lagerev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.V. Lutsenko Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.Yu. Marinchenko Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.G. Massel Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

L.V. Massel Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.S. Mednikov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

E.E. Mednikova Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.V. Mikheev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

R.I. Muzychuk Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

N.N. Novitsky Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.B. Osak Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

D.A. Panasetsky Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.V. Penkovsky Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

S.V. Podkovalnikov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

S.P. Popov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

E.V. Popova Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

I.V. Postnikov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Yu.M. Potanina Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

N.I. Pyatkova Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

B.G. Saneev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

V.V. Selifanov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

S.M. Senderov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

V.A. Shakirov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Z.I. Shalaginova Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

G.I. Sheveleva Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

D.N. Sidorov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

A.D. Sokolov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

D.V. Sokolov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

V.A. Stennikov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

E.L. Stepanova Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

K.V. Suslov Irkutsk National Research Technical University, Irkutsk, Russia

L.N. Takaishvily Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

V.V. Tokarev Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

N.V. Tomin Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

V.V. Trufanov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

E.A. Tyurina Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

O.N. Voitov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

N.I. Voropai[†] Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

P.V. Zharkov Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

The book was translated into English by Svetlana Steklova

[†]Deceased.

This page intentionally left blank

Biography

Nikolai Voropai (1943–2022)

N.I. Voropai was a renowned expert in the field of energy systems research. He was an author, and co-author of more than 700 published research contributions. He identified and investigated the fundamental features of complex extended electric power systems. This allowed explaining multiple phenomena and processes, such as system accidents, based on clear physical representations and developing theoretical foundations for the analysis and synthesis of structurally heterogeneous power interconnections. These achievements laid off the methodological backbone of research efforts by a school of thought that still leads its field to this day. He successfully supervised over 20 PhD students.

Professor, President of Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Corresponding Member of Russian Academy of Sciences, Russia

Valery Stennikov (1954–)

V.A. Stennikov is a leading expert in the field of heat and power systems, the developer of the methodology for modeling, calculating, optimizing pipeline systems in the energy sector, managing their development and operation, and district heating systems. His work significantly increases the level of validity and effectiveness of decision making on the development and reconstruction of energy systems, and their management and control. He is an author, and co-author of more than 600 published research contributions.

Professor, Director of Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Academician of Russian Academy of Sciences, Russia

This page intentionally left blank

Preface

The modern design of the energy industry has strong vertical (within the boundaries of the energy sector) and horizontal (relative to the systems) links, which define for them different hierarchical levels in the territorial context: the country, the economic district, settlements, energy consumers. The combination of territorial-and-technological and temporal aspects of energy systems management leads to the complexity and multidimensionality of the hierarchical system, a comprehensive study of which allows one to overcome the problems of information discrepancy and methodological inconsistency along with computational costs, to align and link the decisions made at different temporal, territorial, and organizational levels. The hierarchical approach developed at the MESI of SB RAS to model the object of a study and solve the problems of optimal management of operation and development of systems and the energy sector as a whole, as well as information and organizational structures, serves as the basis for overcoming the difficulties arising in this process.

The book presents the methodology of hierarchical modeling of energy systems in their relation to the energy sector, which takes into account the patterns of their previous development and nascent future changes. As a formal apparatus in the implementation of procedures for hierarchical modeling of complex systems, we cover a wide range of mathematical methods and approaches used in accordance with the type of systems, the level of their consideration, and the problems to be solved. We make extensive use of the idea of multilevel programming, which reasonably enough takes into account the current trends of changes in technological and organizational management of the energy sector.

We outline formalized technologies of aggregation and disaggregation in accordance with the levels of the hierarchy of models of energy systems, as well as methods of decomposition of the problems to be solved. Multi-agent systems, modern methods and models of machine learning in combination with classical computational methods, as well as other methods, including heuristic methods of optimization and management of the energy industry are a promising approach to the implementation of hierarchical intelligent control over operating conditions of energy systems with effective distribution of functions between the levels of the hierarchy of the control architecture being created. They are versatile enough, enable modeling energy systems of any complexity, scale, and capacity, take into account their diversity and provide a solution for the optimal management of energy supply in the context of divergent interests of the entities of market relations.

At the same time, the modern energy industry under the influence of newly emerged drivers of technological development is undergoing a radical transformation of individual systems and their relationships within the energy sector, thus forming a new organizational, technological, and regulatory structure. A key factor of the energy transition is the ever-increasing impact of digitalization and computerization of economic and social sectors. This factor, together with a fundamental shift in the paradigm of the development and operation of the energy sector as client-oriented infrastructure systems, dramatically raises the standards of the reliability of energy supply to consumers and the quality of energy resources supplied to them. The fundamentally new quality in the use of innovative energy technologies and systems manifests itself as a result of their integration with information, cybernetic infrastructures, and the transformation into intelligent cyber-physical energy metasystems.

New properties of the systems are enhanced due to the increasingly active behavior on the part of consumers who control on themselves their own energy consumption in interaction with energy systems with respect to automatic self-adaptation to internal and external influences. Along with the technological and functional integration of intelligent energy systems among themselves, their technical and economic ties within the energy sector are strengthening. Emerging cyber-physical energy systems as critical infrastructures of utmost importance are subject to appropriate requirements to ensure the necessary level of survivability and energy security of the country and its regions. Meeting the above requirements should guarantee the operability of intelligent energy systems in critical and extreme situations. The consequence of this may be (expected) fundamental changes in the structure and properties of future systems, which will require the adjustment of the general methodological approach, rethinking of well-established and formulation of new problems of managing the development and operation of future energy systems as integrated into a single comprehensive methodology with fundamentally new content. Its core tenets should cover an objective structure of problems, theoretical principles, models, and methods for solving them as applied to both individual energy systems and the energy sector as a whole.

The most important task should be to check the performance of the energy metasystems that are integrated at the technological, organizational, and informational levels and being developed within the framework of the energy sector. In the new methodology, an integral component should be the basic principles of formalization of interaction between the levels of development and operation of intelligent integrated energy systems and their interrelationships within the energy sector.

The methodology for optimal strategizing of the energy sector and energy systems will retain the fundamental commitments of the scenario approach and will be based on the theory of energy systems analysis, but the "packing" of this approach changes significantly, considering the radical transformation of the energy sector. Moreover, the actual configuration of the management of energy systems and the energy sector as a whole appears to be an even more complex hierarchical structure than it is presented in the book in broad strokes because one often has to solve not a single management problem but rather an array of interrelated ones in the process of planning, design, organizational and operational management at each technological, territorial, and temporal level. The analysis, formalization, and solution to these, as well as new problems arising in the context of the formation of future energy systems, their mutual alignment and harmonization within the ideology of the hierarchical approach, are the subject of further research.

Editors

Nikolai Voropai
Valery Stennikov

February 2022

This page intentionally left blank

CHAPTER

1

Methodological framework for hierarchical modeling of energy systems

N.I. Voropai[†], *V.A. Stennikov*, *S.M. Senderov*, *B.G. Saneev*, *N.N. Novitsky*, *O.V. Khamisov*, *L.V. Massel*, *A.G. Massel*, *and A.V. Mikheev*

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abbreviations

DPG – dual projected gradient
DSA – dual subgradient ascent
EPS – electric power system
FACTS – flexible AC transmission systems
IEEE – Institute of Electrical and Electronic Engineers
M2M – Machine-to-Machine
SB RAS – Siberian Branch of the Russian Academy of Sciences
SSTD – Strategy of Scientific and Technological Development

1.1 Energy systems as objects of hierarchical modeling

General remarks. By the middle of the 21st century, we should expect drastic changes in the appearance of the energy sector. These changes are related not only to the processes that are intrinsic to the energy sector (intensive development of energy technologies, a quantum shift in the scale of adoption of intelligent information and communication technologies and means of control of energy facilities and systems) but also to a

[†]Deceased.

Hierarchical Modeling of Energy Systems
https://doi.org/10.1016/B978-0-44-313917-8.00010-9

fundamental change in the paradigm of development and operation of energy systems as client-oriented infrastructure systems that provide reliable and efficient services to industries and the community. The energy infrastructure systems are primarily those of electric power, heating, and gas supply systems with developed transportation and distribution network infrastructure. In a sense, the infrastructure also includes oil and petroleum product supply systems, although the latter do not have developed distribution networks. Infrastructure systems also include water supply systems.

The patterns of changes in the conditions of development and operation of energy systems lead to the following substantial transformations in the structure of systems and their operation modes.

The scale of the energy systems and the expansion of the areas they serve keeps growing.

The development of urban agglomerations around large cities continues due to the establishment of public and business administration centers located therein, the concentration of high-tech production facilities, financial resources, the creatives, and the research and educational cluster. At the same time, the trend towards the de-urbanization of urban settlements continues, including the removal of industrial production facilities from urban areas and the development of activities of individual low-rise residential buildings construction. Furthermore, the prestige and standard of living in medium- and small-sized towns will continue to increase. All of the above will lead to a growing dispersal of energy consumption across the territory in the process of deep electrification and gasification of the industrial and residential sectors to ensure the growth in the quality of life and workforce productivity [1–4].

The trend towards decentralization of energy supply is also developing on the energy generation side as a result of the increased adoption of distributed generation sources connected to distribution power and heat network hubs. This trend is due to the emergence of new highly efficient energy production technologies that enable energy supply systems to be flexible in their adjustment to the uncertainty of the demand for energy. Energy sources that make use of renewable energy resources also contribute to distributed generation.

New highly efficient technologies are increasingly being adopted for large energy sources as well. In fact, the mix of the generation capacity of future energy supply systems should include relatively large generation sources to supply energy to large energy-intensive consumers and a rather high share of distributed generation. In what follows, we will consider in more detail the features of future energy systems and the challenges they face.

Innovations-driven electric power systems of the future. The widespread adoption of distributed generation units in electric power systems

(EPSs) is responsible for the emergence of several distinctive features. Many small generating units that make use of gas turbine technologies operate at higher frequencies than the utility frequency and are connected to the system via rectifier-inverter units. Wind turbines have a similar connection while having the distinctly stochastic nature of the generated power. As a result, the frequency characteristics of generation in electric power systems change significantly, and the frequency control effect of generation diminishes. Distributed generation units have small rotor inertia if compared to conventional high-capacity generators and also possess simplified control systems, which is responsible for the challenges to be faced when ensuring the stability of power energy systems.

Connection of distributed generation units to the distribution grid drastically changes its properties, leading to stability issues, underpinning the need for significant development and fundamental reconstruction of power-system protection systems at this level [2,4].

Due to the trends in the development and location of electric power generation and consumption, the electrical network will also change significantly in the future. Taking into account new technologies in converters based on power electronics, cost reduction, reliability improvement, and high controllability of DC power transmissions, they will enjoy undergoing substantial development in the electrical transmission network. At the same time, the widespread adoption of devices that form flexible AC transmission systems (FACTS) on the basis of power electronics will radically increase the controllability of the AC transmission grid [5]. New technologies, including the use of FACTS devices, will significantly improve the reliability and controllability of the distribution grid.

The growth of electricity consumption in the context of scattered generating sources and consumers across a given territory leads to an increase in the density of transmission and distribution networks. In general, with the above factors taken into account, future electric power systems will increasingly acquire the functions and properties of infrastructure systems (think "the Energy Internet"), which will be able to provide the consumer with electricity in the required location, having the necessary quality and reliability of electric power supply and being available at an affordable price.

There is a tendency for the share of new electrical receivers with new load characteristics to grow. These receivers include all electrical installations powered through modern power supplies, that is rectifiers/stabilizers and rectifiers/inverters. They are the variable speed drive, all computer, office, and household appliances with pulse power supplies, LED lighting, etc. Their distinctive feature is the constant amount of the consumed active power immune to a wide range of changes in the voltage of the electrical network (some receivers ensure the same load even when the voltage level drops up to 30% of the rated voltage). While conventional consumers reduce their consumption when the supply voltage decreases, thus ensuring voltage-regulating effect of the load, new consumers increase the current consumption when the supply voltage decreases, while maintaining the same active power. When taking into account losses in the power distribution network, this leads to an increase in the active and reactive power of the load. Accordingly, with the growth of the total share of new electrical receivers, the voltage-regulating effect of the load in the electric power system will decrease.

The situation is aggravated by the widespread use of modern on-load tap changers (OLTCs) of transformers, including those used in the distribution electrical network, which results in relatively stable voltage levels on the consumers' buses and the compliance with regulatory requirements, but in case of an emergency in the transmission and distribution electrical networks instead of reducing the voltage on the consumers' buses (and, as a consequence, reducing the active and reactive load), there is a constant load, an increase in losses within the grid, and a significant growth of reactive power consumption from the electrical network.

Another issue is that an increasing number of receivers are keeping their power consumption constant when the frequency is changed. Such receivers include not only the new consumers mentioned above, but also most of the heating elements used for electric heating. This reduces both the total power and the total share of the load directly connected to the AC network (without frequency converters), which would ensure a frequency-regulating effect of the load for the entire electric power system.

Another important new factor for future electric power systems is the emergence of active consumers who independently manage their own electricity consumption, depending on the price terms as set in the retail electricity market, by transferring electricity consumption by some receivers from time intervals with high electricity prices to time intervals with low prices. Such load management independent of the dispatch schedule as practiced by active consumers challenges the control of the electric power system operation modes due to the uncertainty of power consumption by active consumers. Therefore, the interaction between the electric power system and consumers with respect to their joint control of the system's operation modes using the controlling capabilities of consumers sounds promising.

A significant change in the properties of future electric power systems will occur as a result of the ubiquitous spread of electric power storage systems, the technologies of which by now have already been adopted in the industrial sector [6]. It is telling that system-wide electric power storage has high-efficiency and high-speed control systems based on power electronics that can contribute to the controllability of electric power systems. A large share of electric power storage is expected to be based on electric vehicles, that, when used on a mass scale, will significantly change the appearance and operation modes of future electric power systems.

Taking into account the indicated tendencies of the growing adoption of electric receivers and electric power storage systems supplied with direct current through converter elements, one can expect the transition to the establishment of electric power supplying DC distribution grids with shared AC to DC converter units placed at feeder substations [7,8].

The above new load characteristics of consumers, storage, and generation of future electric power systems will significantly alter the properties and controllability of the systems. The existing principles of the control over operation modes of conventional electric power systems are based on the use of the voltage and frequency regulating effects of the load and frequency characteristics of generation. Due to these effects, modern electric power systems have intrinsic self-stability, while control systems intervene when the operation mode parameters go beyond certain limits. Due to changes in the properties of future electric power systems, their intrinsic self-stability is essentially being challenged and, as a result, the traditional principles of control over the electric power systems operation modes will require substantial modification and development.

Almost all countries around the world have declared the concept of the intelligent power system (Smart Grid) as their national policy for the technological development of the electric power industry of the future. This concept is based on the integration of several innovative strands at all links of the chain ranging from electricity generation to consumption, namely [9]:

- Innovative technologies and installations for the generation, storage, transmission, distribution, and consumption of electricity;
- Highly efficient means and technologies for measuring, collecting, processing, storing, transmitting, and presenting (visualizing) information;
- Advanced information and computer technologies, including the Internet;
- Highly efficient methods of monitoring and control based on modern approaches backed by the control theory;
- Active consumers.

At the same time, full-fledged digitalization of all stages of the information and control subsystem will be carried out, ranging from measuring the current values of the operation mode parameters to the implementation of control actions.

The development of future electric power systems on the technological basis of the intelligent power system will make it possible to offset the above potentially negative tendencies in altering the properties of the electric power system in many respects. At the same time, new challenges are already emerging and will become more acute in the future in terms of the need to strengthen the coordination of the control over the operation modes of electric power systems at various levels, improve control efficiency, and ensure the reliability of the system of control over the operation modes of the electric power system itself. The issues of information security and cybersecurity in the monitoring and control of electric power systems are becoming particularly critical [10,11].

Innovative technological transformations of future heat supply systems. Key conditions that define the development of heat supply at the present stage and in the oncoming future are the following [12]:

- Increased requirements for indoor comfort and heat supply quality aimed at expanding the range of services, including heating, cooling, ventilation, air conditioning, and hot water supply;
- Structural transformations in the economy, growth of the level of availability of amenities in the housing sector, changes in the territorial location of industrial production facilities and their transition to in-house energy sources will have a significant impact on the structure and demand for heat, as well as on the make-up of generating capacity;
- Energy-saving, adoption of energy-efficient technologies in production, changes in the structure of industrial production, use of heat-saving structures of buildings, the introduction of systems of metering and controlling of heat supply and consumption contribute to a substantial reduction in the heat intensity of industrial products and total heat consumption in general;
- Decrease in the density of housing development, its expansion mostly within unoccupied areas, the emergence of the market of efficient heat-generating equipment of small capacity make the role of decentralized (distributed) systems more prominent;
- Growth of the cost of electricity, higher prices of fuel and its transportation, more expensive equipment and materials, and, as a result, higher heat tariffs all contribute to the adoption of energy-saving measures in the processes of production, transportation, and consumption of heat and also increase the share of secondary and renewable energy resources;
- Structural changes in the energy sector that increase the use of gas for heat supply as a result of gasification of regions contribute to the development of distributed, highly efficient, and competitive gas-fired heat sources;
- Increased requirements for reliability and safety of heat supply and the need to comply with them in the context of contractual relations lead to increased costs in the heat network, which reduces the economic performance of large heat sources, limits the scopes of heat supply, and increases the number of sources required;
- The increased community commitment of the population with regard to environmental issues will also support the trend of unbundling of systems and facilitate their technological improvement;

- Changes in the investment policy, lack of large public investments in heat supply, lack of interest on the part of private investors in financing the construction of heat supply facilities and, effectively, the transition of heating companies to self-financing with limited subsidies from local budgets, creation and strengthening of a competitive environment in all sectors of the economy, development of a free market for technologies and equipment significantly weaken the position occupied by centralized heat supply and lead to a shift in the investment activity towards distributed generation, but do not deprive the former of its leading role;
- The diversity of ownership forms in the heat supply sector and the inevitable change in the relationship between the parties with the predominance of economic interests, rule out the measures of forcing consumers into using certain types of heating without providing economic incentives and encouraging them to behave actively.

The above conditions lead to the following changes:

1. decreased competitiveness of large centralized heat supply systems and reduction of per unit heat source capacities;
2. wider adoption of small distributed heat generation;
3. consumer interest in energy saving;
4. fuller use of secondary energy resources and the production waste suitable for obtaining thermal energy;
5. increase in the use of renewable heat sources;
6. interest in making genuinely optimal decisions on heat supply development.

The task of managing the development and operation of heat supply systems will be to adapt in a timely manner and respond properly to changes in heat demand and other external challenges.

The new trends emerging in the heat supply industry will determine the technological transformation of heating systems. On the one hand, this is becoming strongly sought-after, but on the other hand, it is ensured by the emerging market of available innovative technologies and equipment.

Availability of mini- and micro-sources of heat, having heat consumption systems equipped with smart meters, automatic regulation and control provide the necessary conditions for active consumer behavior. Such a consumer will have a significant impact on the technology of the operation of heat supply systems and will facilitate the transition from qualitative to quantitative regulation and differentiated control.

Technical re-equipment of heat supply systems is underway and is being developed in three main directions: changes in the structure of systems, systemic and technological changes, technical measures for the re-equipment of systems.

The main directions for changing the structure of heat systems are as follows:

a) Orientation towards hierarchical principles of the system design with separation of ring backbone and dead-end distribution networks by control nodes;

b) Adoption of generally independent connection configurations for consumers and closed hot water supply systems;

c) Separation of heat sources, heat networks, and heat consuming installations into independent loops by means of heat exchangers, automation and control devices;

d) Creation of an automated control system for technological processes of production, transport, and consumption of thermal energy.

Systemic and technological transformations are focused on new technologies of operation of heat supplying systems:

- Joint operation of heat sources, which actually fulfills the main purpose of large heat supply systems and ensures efficient supply of heat to consumers;
- Hybrid quantitative and qualitative as well as quantitative-only control of heat output and consumption, which contributes to the organization of joint operation of sources and ensuring that the amount of heat supplied and the demand for it match in real-time;
- Relatively low temperatures of the heat transfer fluid, providing ample opportunities for involvement in joint operation for unified heat networks on the part of heat sources of different types and capacities, such as boiler plants, cogeneration plants, sources that run on secondary energy resources and other non-conventional sources of heat; in addition, it makes it possible to use new materials in heating and will ensure the extension of the service life of the equipment;
- Reduced pressure of the heat transfer fluid due to the fact that in the independent circuits of heat and power system elements it is necessary to provide only for heat transfer fluid circulation, while leakage of such a fluid reduces and working life of equipment extends.

Technical re-equipment of the systems includes a set of measures that are mandatory for the pursuit of the above-mentioned directions. Such measures include the following:

- Application of the system of on-line monitoring, control, and diagnostics of the condition of equipment and heat pipelines in heat networks, use of ball, disk, and other shut-off and control valves that are motor-operated and remotely controlled;
- Introduction of automation, controlling, metering, and measuring systems and creation of an automated dispatcher control system on their basis;
- Wide-scale digitalization of all stages of operation of the information and control subsystem from measuring the parameters of the heating system operating mode to the implementation of control actions;

- Wide-scale application of the automated heat points with plate heat exchangers and monitoring and control systems for sources, heat networks, and heat inputs of consumers.

A promising technological platform for the heat-supply of the future, that is to be in line with the above-mentioned changes in the principles of design and structure of heat supply systems, is the creation of an intelligent heat supply system that will unify, at a brand-new technological level, sources, networks, and consumers into a single automated system [13]. This will provide it with the necessary flexibility and adaptability to changing operating conditions, increase efficiency, reliability, and quality of heat supply, facilitate a decrease in heat losses, and smooth out the unevenness of heat consumption curves, etc. Availability of an opportunity to monitor and control in real-time the operation modes of all the participants of the process of generation, transmission, and consumption of heat, and to automatically respond to changes in various parameters in the heat supply system would allow for interactive ("here and now") behavior of consumers in the heating market. This will ensure bilateral and mutually coordinated interaction between the consumer and the heat and power system.

Innovative trends in gas supply systems. The scale and complexity of gas supply systems continue to grow. The distance separating gas fields from the points of its consumption, the aspiration to diversify transport corridors and increase the possibility of adjusting the flow lead to an increase in the total length and growing complexity of the configuration of trunk gas pipeline systems. Active gasification of regions, further urbanization of the country, the "overgrowth" of cities with townhouse villages and suburban settlements with a high degree of availability of amenities lead to the need for the development of centralized gas supply systems and gas distribution networks, and the broadening of the area covered by them.

The product range of hardware components used in the gas supply system is being improved and expanded:

- Pipelines made of new materials, including polymeric ones;
- New materials and technologies for heat- and waterproofing, mitigation of corrosion processes and the build-up of deposits on internal surfaces of pipes, etc.;
- Energy-efficient, compact, and low-noise compressor equipment with high efficiency in a wide range of capacities;
- Reliable and quality shut-off and control valves.

Possibilities of monitoring and identification of the inefficient use of gas, in turn, reinvigorate the processes of mass adoption of more efficient and higher quality gas dispenser valves, gas-consuming devices, and automatic means of control at the points of consumption. Increasingly active consumer behavior leads to a significantly more elaborate processes of the gas supply system operation, strengthened non-stationarity of gas supply system operation modes, and increased probability of the operation modes that are either beyond-design or even non-standard.

This in turn serves as an incentive for the following:

- Introduction of new highly adaptable energy-saving compressor and power equipment with the adjustable speed of rotation in the gas supply system;
- Wider application of control and local automation means at the main facilities, automatic controllers of pressure, flow rate, etc. in gas transportation and gas distribution networks;
- Deployment of large-scale telemetry and fiscal metering systems to monitor consumption patterns and processes;
- Application of differentiated tariffs for consumers per day.

Worldwide and in Russia alike, the gas industry is following in the footsteps of the electric power industry in its upgrading of networks, utilities, metering devices, creating a variety of pilot projects, and all these actions are ultimately aimed at the deployment of remote data collection using the M2M (Machine-to-Machine) technology.

As early as 2020, Europe could become one of the largest regional markets for M2M devices, reaching the level of 13.5 million installed devices. According to the projection published by Pike Research [14], the total number of M2M-based monitoring devices installed in the gas industry across the globe will grow rapidly over the next few years, rising from 8.5 million in 2009 to 36.3 million by 2016. The M2M technology involves equipping gas metering units with telemetry systems. The equipment, as a rule, includes fiscal metering complexes of gas metering units and a cabinet to automate the telemetry system. The main task of the system of gas distribution facilities telemetry is to control process parameters: inlet and outlet gas pressure, pressure drops in filters, shut-off valves, etc. Alarm generation should be carried out with minimum delays in order to continuously monitor the condition of the facility and respond promptly in case of any malfunctions. According to some estimates, the telemetry system will allow controlling about 80% of the supplied natural gas. Data transmission is possible via one of the four communication channels: GSM (Global System for Mobile communication), a dedicated physical line, a switched telephone line, or a radio channel. GSM is used most often because of its unquestionable advantages: the cost and speed of deployment while maintaining acceptable values of quality metrics.

Today there is an urgent need to create so-called intelligent gas distribution networks on a digital basis. Here, the intelligent system is understood as such a system of transmission and distribution of gas flows that combines conventional components and the state-of-the-art technologies, integrated control and monitoring tools as well as information technologies and means of communication that ensure higher efficiency of the gas distribution network and gas supply resources management.

Integral parts of this gas network are as follows:

– Automation and control (intelligent metering systems: gas meters and electronic control devices);
– Network communication infrastructure (process, instrument, and local networks);
– A dedicated case-based center that makes use of artificial intelligence methods.

Building an intelligent network involves the installation of intelligent metering stations that enable creating a primary information field.

The main module influencing gas supply modes of the region is the subsystem of control over the operation of metering stations of gas distribution stations. This subsystem enables one to see the status of the main parameters of the gas distribution station, such as gas pressure at the outlet, the hourly gas flow rate, the gas flow rate as accumulated over a given contractual day, and gas flow rate for the previous day with the transfer of relevant data to a dedicated case-based center in the periodic automatic polling mode.

The next, as per the order of the process of gas transportation in the gas distribution system, is the subsystem of control over gas control units of the enterprise. This subsystem is built on the basis of a software and hardware system that allows online monitoring of the following parameters of gas control units via radio communication channels:

– Inlet and outlet gas pressure;
– Temperature inside the gas control unit room;
– Level of gas content in the gas control units' process rooms and those of consumers within the gas control units' service area.

Thus, the use of intelligent support apparatus or smart technologies in the gas industry is directly related to gas distribution networks, is close to the consumer and allows on-line redistribution of gas flows in the gas distribution network, thus optimizing (to the necessary and possible extent) the gas flows through its branches.

General trends in the development and operation of future energy systems.

The innovative trends in electric power, heat supply, and gas supply systems outlined above in many respects hold true for water supply systems, and oil supply systems as well when it comes to the process and transportation infrastructure. Generalizing these trends enables us to formulate a number of statements that apply equally to all of these systems.

1. Increase in the scale of the energy systems in expansion of the areas served by them.

2. Increasingly complex structure of energy systems due to increased diversity of energy elements in a wide range of technologies and capacities, including distributed generation, and increased complexity of the network infrastructure configuration.

3. Strengthening of interaction and interdependence of different energy systems within the energy sector, especially so in the event of emergencies, and thereby aggravation of energy security problems in the country and its regions.

4. Wide use of innovative technologies in production, transport, distribution, and consumption of energy resources and types of final energy.

5. The active nature of consumer behavior in terms of managing their own energy consumption at the pace that matches that of the process, while using time-differentiated prices for consumed energy resources.

6. Wide use of information and communication technologies for measuring the state of energy systems, transmission, processing, and visualization of current information for monitoring and control of operation modes.

7. Active use of the ideology of intelligent energy systems as a technological platform for future energy systems.

8. Significant change in the properties of future intelligent energy systems as objects of monitoring of their condition and control over their operation modes.

9. Setting the stage for the development of integrated intelligent energy systems as unified technological complexes with a shared control system due not only to conventional integration factors at the level of energy production (e.g., that of combined heat and power plants that generate electricity and heat when using gas as their fuel), but also due to the availability of alternative technologies for the use of different types of energy for the same purpose on the consumer side (e.g., heat that comes either from a district heating system or an electric heater) [15].

The listed general tendencies of development and operation of future energy systems predetermine the directions of their research.

The current state of the research in the field of smart energy systems. Over the past 10–15 years, experts have been actively discussing and developing the agenda of creating intelligent electric power systems, that is Smart Grids [16–20]. Under the auspices of international organizations, international conferences are held annually on the issues of intelligent electric power systems. For example, the Institute of Electrical and Electronic Engineers (IEEE) annually holds dedicated international conferences titled "Innovative Smart Grid Technologies" in Europe, Asia, Africa, North and South America. The subject of intelligent technologies and intelligent electric power systems is also covered to a significant extent by the general electric power conferences held by the IEEE, that is IEEE PES General Meeting, IEEE Power Tech, IEEE Power Con, and the like. Intelligent technologies and the issue of adding intelligent capabilities to the control of electric power facilities and electric power systems are actively discussed at international conferences, congresses, symposiums, seminars held by the International Federation of Automatic Control (IFAC), as well as at the International Conference on Large Electric Systems (CIGRE), International Conference on Electricity Distribution, and by a few other international associations and organizations. The top-of-the-agenda challenges of intelligent technologies are also dealt with at international conferences held in Russia and CIS countries in Russian, such as "Contemporary directions in the development of the systems of power-system protection", "Electric power engineering as seen by the youth", "Methodological issues of research on reliability of large energy systems", and a number of others.

The strong interest in the ideology of intelligent electric power systems as a technological platform for the power industry of the future has well-justified grounds. In many countries, this is due to several major factors: the expected widespread use of highly fluctuating renewable energy sources, the additional demand for electricity due to the gradual transition to electric vehicles, and the development of information technologies that enable one to create game-changing highly efficient monitoring and control systems of the electric power system. At the same time, approaches and priorities vary from country to country due to the different profiles of the electric power industry and electric power systems, and differences in preferences.

In Europe, the United States, and a host of other countries, the focus is on the electric power distribution system and consumer activity [16,17]. In China, emphasis is placed on the high-voltage transmission system in terms of equipping it with high-precision PMU-based systems of synchronized vector measurements, modern systems of collection, transmission, processing, and presentation of information that serve as the backbone for the creation of large-scale systems of monitoring (WAMS) and control (WACS) of the operation modes of electric power systems [21,22]. In Russia, the concept of the active and adaptive electrical network is being developed, which refers, first of all, to the transmission electrical network, but also to distribution electrical networks [18,19]. The active and adaptive network, being a counterpart to Smart Grid, assumes a wide use of modern systems of metering, collection, processing, transmission, and visualization of data, active elements that change the topology of the network and influence the generation and consumers, real-time control systems that allow responding adequately to the changing situation in the electric power system, systems of real-time monitoring and forecasting of the state of the electric power system.

In 2010–2012, at the initiative and with the support of the Federal Grid Company of the Unified Energy System (FGC UES), the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, the Institute of Control Sciences, RAS, and the Scientific and Technical Center of the FGC UES, with the participation of a number of organizations and experts, developed the Conceptual framework for the intelligent electric power system of Russia with the active and adaptive electrical network [23]. On the basis of this conceptual framework, the above organizations have developed and systematized theoretical foundations, methods, and models of control of intelligent power systems [24]. In 2008–2011, within the framework of the 7th framework program of cooperation between the European Union and Russia in the field of energy under the State Contract of the Ministry of Education and Science under the coordination of the Melentiev Energy Systems Institute, SB RAS, and with the participation of the Trapeznikov Institute of Control Sciences, RAS, and a number of other organizations, the project "Knowledge-based coordination of operational and emergency control of interconnected power systems of the European Union and Russia" was implemented [25]. These fundamental studies have served as a methodological basis for the development of research in Russia into the field of intelligent technologies and intelligent electric power systems.

In 2011–2013, Irkutsk National Research Technical University backed by the methodological support provided by the Melentiev Energy Systems Institute, SB RAS, implemented the project titled "The Intelligent Energy System for the Efficient Electric Power Industry of the Future", supported by the grant of the Ministry of Education and Science of the Russian Federation in accordance with the Resolution of the Government of the Russian Federation dated April 9, 2010, No. 220 "On Measures for Recruiting Leading Researchers for Russian Institutions of Higher Professional Education". The visiting scholar was Prof. Dr. Z.A. Styczynski, Otto von Gerike University of Magdeburg, Germany. The letter of intent was signed between Irkutsk National Research Technical University, Otto von Gericke University, Melentiev Energy Systems Institute SB RAS, Fraunhofer Institute (Magdeburg), Irkutskenergo JSC, and Siemens, and an advanced research infrastructure within the framework of the project was established. On the basis of this infrastructure, the studies planned for the project were carried out.

The Smart Grid ideology is beginning to be adopted in gas supply systems [26–28]. The main line of research and its findings focus on gas distribution networks and more specifically on intelligent metering, processing, and presentation of up-to-date information to the consumer. This field is pioneered by Japan. Relevant work is being done in European countries, although the attitude to this problem is rather cautious [28]. In Russia, the process of using the Smart Grid ideology is still in its infancy [29,30].

Heating systems have significant methodological, technological, and information potential to take advantage of the adoption of the Smart Grid ideology. This is facilitated by the successfully developing market of affordable modern technologies for adding intelligent capabilities, systems of control and metering of heat energy, telecommunications, and data support, small generation based on non-conventional and renewable energy sources, etc. They ensure the active behavior of consumers, handling of the storage and their own production of the thermal energy to create the most comfortable conditions indoors. A large-scale pilot project "Combined Efficient Large Scale Integrated Urban Systems" (CELSIUS) for the development of intelligent electricity, heat, and cooling systems is being implemented in five major European cities: Gothenburg, Genoa, Cologne, London, and Rotterdam [31]. The greatest progress has been made in Gothenburg, where not only new technologies for energy production but also integrated transport technologies in the form of a single structure for simultaneous transmission of electric power, heat, and gas are employed. The first projects that deal with building intelligent heating systems are being implemented in a number of other European cities, such as Marstal and Copenhagen (Denmark) [32–34] Bietigheim-Bissingen and Crailsheim (Germany) [31], Malmö (Sweden) [35], Delft and Heerlen (Netherlands) [35,36], etc. These projects are carried out on the basis of the existing systems with the inclusion of renewable energy sources, heat storages, and the involvement of consumers in the active management of their heat consumption, taking into account their individual characteristics and requirements.

Methodological developments in the research published on the subject of intelligent heat supply systems abroad are primarily related to the definition of their properties, the shaping of the technological concept of the intelligent heating system (smart thermal grids) [37,38], a general mathematical description of such systems that take into account the storage and alternative production of thermal energy on the consumer side [39,40]. The mathematical model for optimal control of the system operation that ensures reconciling energy balances at the minimum cost of heat generation is proposed [40], the problem of optimizing the system operation modes given the minimum fuel consumption for heat generation was stated and solved [41,42]. The problems of real-time forecasting of the demand for heat and its distribution among sources, including renewable ones, were stated [43]. The main feature of these projects is that they focus on the application to systems with a high degree of automation of process flow. However, they do not cover the entire range of new challenges that arise. In Russia, the issue of "smart thermal grids" has made it only to the stage of discussion. Having said that, the technological backbone has been prepared for its implementation, and there is scientific and methodological progress made with respect to managing development and operation. These are the studies on solving the problems of optimal distribution of heat loads between heat sources [44], on the ideology, principles of design, and control of operation modes [45]. They can lay the methodological foundation for intelligent heating systems.

On the basis of the analysis of problems of design and operation of pipeline systems of heat, water, oil, and gas supply, as well as current trends of innovative development of energy systems the problem statements of construction and control of intelligent pipeline systems were proposed at the Melentiev Energy Systems Institute SB RAS [13]. New content was elucidated for the problems of analysis and synthesis of hydraulic circuits, which serve as the theoretical basis of intelligent pipeline systems. Methods were developed to quantify the controllability and identifiability of these systems.

In connection with the mainstreaming of research within the framework of the concept of Smart Grid, studies were carried out on the subject of analysis of integrated energy supply systems, taking into account the activity of consumers in the management of their own energy supply, the use of energy storage devices, modern information and communication technologies, etc. [45,46]. Furthermore, specific applications to the various integrated energy supply systems are discussed: those of electricity and heat; electricity, water, and gas; electricity and gas; electricity, heat, and cold; etc.

In the European Union countries, the issues of equipping residential and public buildings with smart meters are being studied. The European Commission has formulated the task of standardization of smart meters of electricity, gas, heat, water (Mandate M/4416, 2009) [27,28]. The smart metering system is considered a key link in the implementation of integrated intelligent energy supply systems. In connection with the standardization of smart meters and the active use by consumers of their own micro-sources of energy (solar photovoltaic panels and collectors, microturbines, micro-storage of electricity and heat, etc.), as well as alternative devices that record energy use, there is ongoing work on the creation and operation of micro-energy systems at the level of consumers [45,46].

Development problems of energy systems digitalization in Russia. The digitalization is a key factor of design and development of smart energy systems in Russia [47]. The digital energy industry in Russia is built and developed within the framework of and taking into account the “Strategy of Scientific and Technological Development (SSTD) of the Russian Federation” [48], which defines as one of the big challenges “...the transition to environmentally friendly and resource-saving energy, ...forming new sources, means of transportation and storage of energy...”, Program “Digital Economy of the Russian Federation”, and “EnergyNet Roadmap”. There are also substantial industry-specific programs, for example, the state information system of the energy sector is being implemented under the Federal Law No. 382-FZ of December 3, 2011. The Ministry of Energy launches the program “Digital Transformation of the Electric Power Industry of Russia”.

Presidential Decree No. 204 of May 7, 2018 "On National Goals and Strategic Development Objectives of the Russian Federation to 2024" sets the goal of "...transforming priority sectors of the economy and social services, including...the energy infrastructure, through the introduction of digital technology and platform solutions" by "...implementing intelligent systems of control of power grid facilities on digital technology."

In the SSTD, the most significant challenges in terms of scientific and technological development of the Russian Federation include the exhaustion of Russia's economic growth opportunities based on extensive exploitation of raw material resources, against the background of forming the digital economy and the emergence of a limited group of leading countries possessing new production technologies and focusing on the use of renewable resources. The creation of technologies is happening more and more on a digital basis, so the digital transformation for Russia is both a challenge and "a window" into great opportunities.

Already at the present time, and to an even greater extent in future energy systems, the physical (power) and information and communication subsystems are becoming comparable in complexity and responsibility in terms of the increasing requirements of consumers to the reliability of their energy supply and the quality of energy supplied to them, which are objectively determined by the computerization and digitalization of process flows of consumers. Meeting these significantly increased demands, in turn, is only possible through the digitalization of energy systems. This means the use of digital technologies and devices at all stages of operation of information and communication subsystems, from measuring parameters and state variables by digital meters, through digital transmission and processing of this information to the implementation of control actions by digital actuators. Given the active adoption of modern information technology and artificial intelligence methods, energy systems are becoming intelligent cyber-physical systems.

The objective need for digitalization of energy systems is also increasing due to their increasing complexity and decreasing self-adaptation and self-stability, which is most characteristic of the Electric Power Systems – see above. This requires a significant increase in the efficiency of EPS operation mode control by processing large amounts of data and reducing the intervals of generating control actions, which can be rationally organized on the basis of digitalization of the control process [4].

According to available estimates, digitalization of energy systems has a wide range of advantages, such as reducing the running and capital costs of system reconstruction and development, reducing maintenance and repair costs, and increasing the service life of equipment, improving personnel productivity, and a number of others. Digitalization of energy systems will significantly improve the efficiency of decisions making and the quality of systems operation, the reliability of energy supply to consumers, and the quality of energy resources supplied to them.

The above analysis of the state of research in this subject area attests to the availability of elaborate developments in building and studying intelligent energy systems. At the same time, the quality of the findings that apply to individual directions and various energy systems varies. In addition, the state of development in Russia appears to be inadequate if compared to the practices adopted in the other countries. All this requires revitalizing and incorporating basic research into the problems of intelligent energy systems and ways of solving them.

The complexity of energy systems, their interaction and interdependence, the complexity of substantiating the development of these systems as stand-alone systems and as part of the energy sector as well as integrated energy systems, the complexity of the processes that take place in energy systems - all this predetermines the relevance of the application of hierarchical modeling to substantiating the development and management of the operation of energy systems [49,50].

1.2 General methodological approaches to hierarchical modeling of complex systems

Introductory remarks. By the second half of the 20th century, academics and decision makers alike faced the need to handle complex large-scale systems of various nature in the process of researching them, and most importantly when substantiating their development and the way the operation of such systems is controlled. Naturally, this situation did not arise out of the blue, but, metaphorically speaking, was “ripening” at a steady pace as man-made systems were developing and growing in complexity along with our becoming aware of the need to treat the real world we live in from the systems viewpoint. At the same time, defining tenets and the very structure of the theory of large systems were articulated, based on the fundamental principle that states that any theory that claims to study complex systems should do so by operating the models, the structure of which reflects this complexity [51–53]. Treating energy systems as complex large systems was typical of this period with respect to the energy sector problems as well [54–58].

It is self-explanatory that the solution to the majority of problems of substantiating the development and operation control when dealing with large systems if undertaken in the “head-on” fashion proves to be the source of substantial methodological challenges owing to bulkiness and immensity of multi-variance and uncertainty of external conditions, the availability of multiple decision criteria, etc. which are all prerequisites for using such models. Herein we omit from our consideration some problems that can be handled reasonably well by means of relatively simple models of a given system. The complexity of solving problems on the basis of using complex models makes us decompose the initial problem into its sub-problems, or, in general, into a hierarchy of sub-problems, for the description of which the hierarchy of corresponding models is required. The hierarchy of sub-problems corresponds to the hierarchical organizational structure, each of the elements of which implements its own solution, obtained as a result of solving the corresponding sub-problem.

Consequently, the hierarchical approach is determined not by the complex system under study, the hierarchical structure of which, as a rule, does not manifest itself clearly, but by the hierarchy of sub-problems to be solved and models employed for this purpose. In other words, the hierarchical representation of a given large system follows from the hierarchy of the sub-problems to be solved as stated by the decision maker. It needs no further clarification that the hierarchy of research sub-problems is to a certain extent subjective.

In what follows this study presents a concise overview of general methodological approaches to hierarchical modeling of complex systems. Let us start from generalization for energy systems.

Main hierarchical aspects in energy system research. The above considerations regarding the application of the hierarchical approach to the study of large systems are also fully characteristic of energy systems [54–58]. The main provisions of hierarchical representations as applied to energy systems are systematically described in [56] and constitute an important aspect of system studies in energy as a scientific field and consist of the following.

Complex objects are studied as a hierarchically constructed unity of open systems, and solutions within this unity must take into account their influence on adjacent elements and links. At the same time, treating this complex object as a hierarchically constructed unity of open systems:

a) corresponds to reality and allows us to organize ideas about the complex set of vertical and horizontal, external and internal relations of the systems under study;

b) allows us qualitatively and often quantitatively elucidate the essence of the integrity of the system in question, meaning the unity of the whole, combined with the existence of this whole set of parts, each of which, in turn, can represent a hierarchical system with its inherent set of properties;

c) forces us to study a given whole in its development and to find causality in this development;

d) emphasizes the importance of a special study of the properties of the whole (system) and its components (subsystems), carried out under incomplete information, which predetermine, thus, the lack of certainty of decisions made;

e) characterizes the importance of studying the external relations of the system, which largely determine the direction of development of the system under study.

In [56], attention is drawn to the difficulties of modeling complex energy systems with the necessary level of detail due to their scale. Therefore, any description of a large energy system will be aggregated or simplified as a model. In other words, any description of a large system in the form of its model is always only an approximation. In this context, it is decomposition methods that usually prove rewarding. However, these methods can perform well only if the system is partitioned along weak or relatively weak links. Another group of useful methods is based on aggregation, which refers to the replacement of a group of variables by a single one (aggregate) and an aggregated study of only the most significant links of the system and related constraints.

The key provisions of the hierarchical approach to the study of large energy systems, as stated in [56], will be used to some extent to form a generalized methodology of hierarchical modeling of complex energy systems.

Overview of general methodological approaches. In general, we are dealing with three hierarchies: the hierarchy of the object of the study: a large system represented by the corresponding hierarchy of models; the hierarchy of problems and solutions based on the former; the hierarchy of the organizational structure that implements the solutions obtained. A unique and one-of-a-kind book by M. D. Mesarovic, D. Macko and Ya. Takahara dwells at great depth on this cornerstone idea [51]. Accordingly, the authors introduce different terms to distinguish between the above three hierarchies: strata, layers, and echelons. The relationship between these three categories of hierarchy is elucidated as stratified, multilayered, and multi-echelon hierarchies.

Within the framework of the mathematical theory of systems the book presents various concepts of the hierarchy. Concepts of systems, subsystems, and their interrelationships are introduced by means of the set theory apparatus. The book substantiates the importance of formalization of multilevel hierarchical systems, which gives the opportunity to achieve the required accuracy of description, apply mathematical methods, and conduct necessary research. A formalization of the paramount problem of the theory advocated by the authors, that of coordination of elements of the hierarchical structure, is proposed. The formalization that they introduce enables the application of mathematical analysis tools, which is illustrated by the example of a two-level system.

Methodologically important is the "consistency (harmony) postulate" of goals the activities of management bodies of various levels aim to achieve. The fulfillment of this postulate is equivalent to the correct selection of goals and statement of problems for all management bodies that are part of the system. It also guarantees a reasonable combination of centralized and decentralized management of a large system. In this case, progress towards an overall goal can be achieved through appropriate coordination of the activities of subsystems, which are largely autonomous in terms of the way they operate. As long as the goals are compatible, the overall goal of the system and the goals of its subsystems are not contradictory, and the decisions taken at the lower levels correspond not to the overall goal, but to their own goals, which does not, nonetheless, prevent progress towards attaining the overall goal of the entire system.

The authors then present their own mathematical theory of coordination. The focus is on three possible principles of coordination: interaction prediction, interaction estimation; and interaction decoupling. The problem of modifications of objective functions for lower-level subsystems in a two-level system which would allow coordination of the previously uncoordinated system is considered. Some iterative methods are provided to address the coordination problem. The applicability of the principles of coordination under different assumptions about the nature of the problems (problems of linear or convex programming, solved with the aid of the Dantzig–Wolfe decomposition, etc.) is analyzed. Possible ways to improve the performance of the system as a whole are considered.

The book is not free from certain shortcomings. One of the most important of them is that the problems considered by the authors are formulated at such a high level of generality that so far it is possible to obtain a constructive solution for them only for the simplest linear systems. Nevertheless, the book provides a useful ideology on the theoretical principles of building large systems with a hierarchical structure and managing such systems.

Among other scant fundamental publications that are available on the subject of the theory of hierarchical multilevel systems the monograph by Marvin Lee Manheim "Hierarchical structure: Model of design and planning processes" [59] cannot go unnoticed. The introductory article to the Russian edition of the book contributed by Yu.V. Kovachich, B.M. Avdeev, and V.M. Levitsky [60] requires special consideration, which we will do after the presentation of the original book by M.L. Manheim.

In this book, the author uses the example of the highway location process to develop a problem-solving procedure in the form of a sequence of actions made up of one or more operators. Each operator has two main components: SEARCH: activities that generate a number of mutually exclusive operations, and SELECT: activities that result in developing a preference for one of the generated operations. Operators differ with respect to the cost of their implementation, the information about the solutions they implement, and their "level", i.e., in the level of granularity of the solutions. The proportion between levels allows to order the entire set of operators available for the decision-maker.

The concept of experiment is introduced, which means applying some operator to an operation performed previously so as to arrive at another operation. This new operation is the lower level one relative to the operation it is derived from, and it is included in the latter.

Each experiment requires a well-defined amount of resources. Operations identified as a result of some experiment and their costs are not known precisely. The goal of the decision-maker is to determine, at any stage of solving the problem, which experiment is most desirable at the next stage, taking into account the possible results of the experiment and the cost of performing it.

The model, which allows to identify the best experiment that is to be realized at the next stage, is formulated. The model is based on the Bayesian decision theory. It is assumed that the decision maker can attribute a subjective distribution of probabilities to each operation that was previously obtained. This probability distribution function is an a priori distribution. It is also assumed that each operator is characterized by its own distribution of conditional probabilities. For each given experiment, the distribution of probabilities of possible cost values of the generated operations is obtained from the distribution of similar probabilities for the previously performed operations to which the operator should be applied, and from the distribution of conditional probabilities for the given operator. The observed result of the experiment is the cost of the operation performed. Based on these results, previous distributions for one or more operations (selected according to specific rules) are adjusted according to the Bayes's rule.

In deciding which of the possible experiments to implement at the next stage, the task is to trade off the cost of carrying out the experiment with the benefits thereof, which is reflected in the search for solutions that would be less costly than the best solution found before. Thus, within the framework of the described probabilistic model, the expected cost criterion is used to find the best experiment.

Let us return to the above introductory article [60] to the Russian edition of the book by M.L. Manheim. It represents the methodology of the system design of complex engineering systems, which in turn represents the simultaneous development of both the control system, consisting of a number of subsystems, and the controlled object.

Let us consider a principle of the system design assuming that the general configuration of a system is established depending on constraints p_i that should be respected when designing the system. In addition to these constraints, the system is characterized by some evaluation function J (criterion) that serves as a measure of the advantage (the preference relation) that one variant of the system has over another.

The mathematical statement of the problem in the form of an optimization problem raises no objections, but a number of significant circumstances hinder the direct solution of the problem. First of all, one should point out the lack of a priori information necessary to find the optimal variant of the system, because its characteristics as a set of parameters p_j that the designer can adjust to influence criterion evaluation J are unknown.

Owing to the aforesaid it makes sense to construct the procedure of designing a system in the form of a multistage process so that the volume of data on the system and the granularity of its representation at each stage would increase. However, among the entire set of available variants there are those unacceptable in terms of either the limitations imposed on the system or the objective function, hence they should be ruled out when considering the next stage. On the other hand, taking into account the details of the system representation, it may be necessary to "generate" its additional variants.

An approach of this kind to designing a system can be linked to some hierarchical model, where each level of the hierarchy is characterized by a certain depth of elaboration (granularity) of the system. In this case, the design process can be represented in the form of an appropriate sequence of operations on the hierarchical model ("decision tree"). Moreover, following the performance of the operation, it is necessary to refine the new distribution of probabilities for the variant evaluation criterion, which can be the cost of the implementation of the variant. The connection between a priori and a posteriori distributions can be established using the Bayes's rule.

Thus, the introductory article [60] supplements Manheim's book [59] in terms of methods of building a hierarchical structure for the design process and the use of the Bayesian theory of decision-making for the purposeful selection of variants of the designed system.

Let us consider another approach to building a hierarchy of models of a complex system and preference criteria when choosing a variant of its design variants as presented in [61–63]. This approach is based on consideration of the tasks of external and internal design of a complex engineering system. At the stage of the external design the requirements to the main technical characteristics of the system are determined, which enables us to arrive at its defining, aggregated design parameters. Further detailing of the system appearance, designing subsystems and links between them, deciding on the parameters of specific elements of the system make up the process of the internal design.

The idea central to this approach is based on the assumption that the initial problem of the internal design in the form of a sufficiently detailed model of the system and the required full set of preference relations for all practical purposes is unsolvable due to the huge dimensionality of the model and the multiplicity of preference relations, which oftentimes prove contradictory. Therefore, in [61–63] it is proposed to replace the initial problem that is deemed unfeasible with a hierarchy of sub-problems ("top-down") that grow in complexity from one step to the next one. Interrelation of sub-problems in this hierarchical structure is ensured by consistent aggregation of the system parameters in the bottom-up fashion along with the necessary transformation of preference relations (criteria).

The authors note that the practical implementation of the hierarchical approach can be represented, for example, by a major design and engineering offices, in which each level of the problems hierarchy is implemented by a dedicated designer. In this case, the problem of coordination of aggregation and preference relations on the set of sub-projects proves relevant. Consistency of preference and aggregation relations means that the designers of the k-th and $(k+1)$-th levels held approximately the same views on what makes a "good" engineering system that they are designing. This means that when moving from one level of aggregation to another, a higher one, no additional criteria for evaluating the engineering system are introduced. This condition explains away to some extent the mutual obligations of designers in hierarchical design systems of the design and engineering office type. In the case of one designer in charge of all levels of the hierarchy, the above requirement disappears, but the authors do not cover this more general case.

It should be pointed out that this hierarchical approach actually merges the problems of external and internal designing of systems as it is expedient to formulate a sub-problem of the uppermost level of aggregation as a problem of the external designing.

The challenges related to information aggregation are addressed in [64] as applied to the task of planning in multilevel active systems, assuming that the control bodies of all levels are endowed with the property of activity, i.e., they have their own interests and pursue their own goals. In the case of decentralization of the system, there is a need to aggregate information as the level of a hierarchy increases, so the following problem proves relevant: what are the decentralization options for the planning workflow that have aggregation as not contributing to compromising the properties of such a workflow, including, first of all, the efficiency of control. It is noted that there is no general solution to the problem of aggregation of active systems, so the study deals with a number of specific cases bearing on the transition from a two-level to a three-level active system.

A method of multi-criteria evaluation and optimization of hierarchical systems is proposed in [65]. The problem is formalized as an operation of choosing the preferred option on the set of options when using the vector-valued choice function F. The logic driving the vector-based approach requires decomposition of function F into a set (vector) of choice functions f. The study provides a justification for the claim that any multi-criteria problem can be represented by a hierarchical system. In doing so, at its lower level the evaluation of the object by individual properties with the help of the criteria vector is carried out, while at its upper level the evaluation of the object as a whole is achieved by means of the composition procedure. The central problem then is the composition of the criteria by hierarchy levels. To this end, a compromise-based framework is adopted. The method of solving complex multi-criteria evaluation and optimization problems based on consideration of nested scalar aggregates of vector criteria is proposed. At the same time, a hierarchy can be both natural (multi-level systems with top-down subordination) and that arising as a result of decomposition of the object properties down to the level of individual criteria (a hierarchy of criteria).

Published research [66,67] offers hierarchical game-theoretical principles of how to study and control hierarchical systems. In [66], the authors perform formalization of the required methods of hierarchical controls as specific instances of principles of optimality within the framework of the game-theoretical model of hierarchical control, which takes into account the requirements of sustainable development of the system. The Master and the Slave players are considered, with the Master employing the following methods in relation to the Slave: coercion; inducement; and persuasion. The basic principle of optimality is the Stackelberg equilibrium. Let us note, that in [68] this general approach was implemented for decision-making related to electric power system expansion. In [67] a hierarchical structure is considered, in which there is a coordinating center (upper level) and coalition groups (lower level) that in addition to pursuing their own interests have to abide by the decisions of the center. The above study implements the principle of active equilibrium between coalitions, while the equilibrium in the hierarchy is Pareto-based under uncertainty of various kinds at both levels.

The research findings by various authors as expounded in this concise overview show a sufficiently comprehensive way for the general, in many respects overlapping, methodological views held on the subject of hierarchical systems, hierarchical modeling of large systems, and hierarchical control of such systems.

1.3 Generalized technology of hierarchical modeling of complex energy systems

Introductory remarks. Modern large organizational and engineering systems including energy systems have a complex heterogeneous structure, are known to be multi-dimensional, develop and operate under uncertainty of external conditions alongside the multi-criteria nature of the process of decision-making due to the presence of various preferences that often prove contradictory.

The structural heterogeneity is a fundamental feature of large systems. To a large extent, it determines the nature of the system's behavior and requirements for its development. The structural heterogeneity manifests itself through the presence of bottlenecks in the system (that is, limited transfer capability of links between its nodes), as a result of which a large system represents a set of highly coherent subsystems (in terms of strong links between the elements of the subsystem) and weak couplings of the subsystems. One has to identify the structural heterogeneity of large systems, quantify its characteristics, take into account these characteristics in the process of modeling, analysis, and substantiation of the development of large systems and operation control of them.

Uncertainty of external conditions as applied to the operation of a large system, and, even more so, to its development predetermines the multivariate nature of possible decisions on development and operation control of the system. The multi-criteria nature, especially when there are different, oftentimes contradictory, preferences held by the subjects of relations, significantly complicates the process of choosing the most preferable solutions from the set of available alternatives.

Due to the complexity and multi-dimensionality of large systems, the heterogeneity of their structure, the multivariate and multi-criteria nature of the rational choice, the availability of different preferences held by the subjects of relations when making decisions, the initial statement of the problem of substantiation of the development and/or operation control of a large system in the form of a general operations research problem proves unsolvable for all practical purposes. In order to overcome this fundamental difficulty, in what follows we will investigate the hierarchical technology as a hierarchy of interrelated mathematical models (models of the object) and criteria-preference relations used for making the rational choice in favor of some solutions (models of operations), as well as various features inherent in the application of this hierarchical technology. To be more definite in our investigation of the hierarchical technology, we will state the latter as applied to the problems of substantiation of the development of large energy systems with the electric power industry and electric power systems serving as our guiding examples. The reason for this being the unparalleled complexity of the problem that is instrumental in manifesting, to the largest extent possible, the diversity and inconsistency of external conditions, if compared to the problem of the operation control of such systems [67,68].

Hierarchical technology. The problem of substantiation of the development of a large energy system consists, firstly, in the choice of the most preferable, with respect to a set of criteria, of its variants out of a set of given alternatives and, secondly, in the identification of the most preferable parameters of elements (objects) of the system for the chosen option. Building a set of alternatives (variants) that represent as a whole a given area of the uncertainty of external conditions of development of the system, is a challenging problem of its own that does not easily lend itself to formalization and hence is not considered here. Each variant of the system has a corresponding well-defined set of parameters of elements that is the most rational (preferable) from the point of view of the set of the pre-defined criteria.

Let $X = \{X_1, X_2, \ldots\}$ be a set of alternatives available for making a choice (variants of the system); $x_i = \{x_{i1}, x_{i2}, \ldots\}$ is a set of parameters for variant i of the system; $\Phi = \{\Phi_1, \Phi_2, \dots\}$ is a set of preference relations for making a choice. Then the problem of rational choice in a rather general form can be stated as

$$X_0 = opt\,(X, \Phi)\,;\; x_0 = opt\,(x, X_0, \Phi)\,, \tag{1.1}$$

where *opt* means the above preference, rationality, or, in a narrower sense, optimality of choice under a set of given criteria.

Let us introduce $m+1$ levels of the hierarchical description of the problem and define a set of preference relations at each level, as well as their interrelation between the levels, as follows:

$$\Phi^m \to \Phi^{m-1} = V_{m-1}\left(\Phi^m\right) \to \dots \to \Phi^0 = V_0\left(\Phi^1\right). \tag{1.2}$$

The arrows in (1.2) indicate a change in the set of preference relations from being those of the upper level of description to those of the lower one, their modification, and possible detailing according to the composition and content of sub-problems at each level of the hierarchy, preferability of criteria, the composition of key parameters (those subject to optimization), etc. The generalized functional relations at each level of the hierarchy in (1.2) reflect the continuity of the composition of the criteria in refining the choice at the next lower level with respect to the upper level.

It should be pointed out that in many cases when solving real-life problems, the functional relations introduced in (1.2) are not formalized, and are understood intuitively, as it will be seen from what follows.

It is necessary to introduce a related set of descriptions of the structure and states of the system, its parameters, in other words - the hierarchy of models of the system in the following form:

$$x^0 \to x^1 = opt f_1\left(x^0, \Phi^1\right) \to \dots \to x^m = opt f_m\left(x^{m-1}, \Phi^m\right). \tag{1.3}$$

To follow the arrows in (1.3) means to have the sequential step-by-step aggregation of the description (model) of the system, which can be carried out at each level, in general, in the most rational (optimal) way in a certain sense. Here, it is assumed that the structure and parameters of the model of the system at the lower (zero) level of the hierarchy are known. Expression (1.3) also reflects the fact that, in addition to aggregation at each step of the model of the system, the model of the operation, represented by the set of preferences (criteria) assumed at each step in accordance with (1.2), in general, gets modified.

Let us clarify the above statement that the aggregation of the model of the system at each level of the hierarchy can (should be) carried out in the most rational way. It is logically sound to relate this rationality to heterogeneity of the system structure and to aggregate highly coherent subsystems, leaving as is weak couplings of subsystems. This is well-justified, since weak coupling in almost all cases is usually the "culprits" of emergency situations as a result of overloading of these links during changes in flow distribution in the system, disruptions of system stability, and unfolding of emergency processes, etc. In fact, one of the key problems of the system development is to strengthen the considered weak coupling in its structure, so it is expedient to leave weak coupling intact during aggregation.

In fact, transformations (1.2) and (1.3) serve as preliminary in the overall process of hierarchical modeling and studies of large systems. Subsequent actions represent a sequence of sub-problems for choosing solutions, which can be formalized as follows:

Here F stands for the transformation of a set of alternatives when solving, while moving successively from the top level of hierarchy to the bottom one, the sub-problems of the overall hierarchical problem of a choice of solutions. In the process of "moving" the top-down way in (1.4), some alternatives will be ruled out as inefficient, that being said additional alternatives can emerge so as to make it appropriate to include them in the list of alternatives to be considered. In general, this transformation of the set of alternatives can be written down as follows:

$$\begin{gathered} x_o^m = opt(f_m'\left(x^m,\ \Phi^m\right);\ F_m(X,\ \Phi^m)), \\ \downarrow \\ x_o^{m-1} = opt\left(f_{m-1}'\left(x_o^m,\ \Phi^{m-1}\right);\ \ F_{m-1}\left(X^m,\ \Phi^{m-1}\right)\right), \\ \downarrow \\ \vdots \\ \downarrow \\ x_o^0 = opt\left(f_0',\ (x_o^1,\ \Phi^0\right);\ \ F_0(X^1\Phi^0), \end{gathered} \tag{1.4}$$

$$X^m = X \rightarrow X^{m-1} = F_{m-1}(X^m) \rightarrow \cdots \rightarrow X^o = F_o(X^1). \tag{1.5}$$

In the case of sequential solving of sub-problems of choice in accordance with (1.4), to transform the solution obtained at level $m-i$, the next lower level $m-i-1$ will require the operation of disaggregation of the model of the system. The sequence of such disaggregation operations, in general, can be written down as follows:

$$x^m \rightarrow\ x^{m-1} = opt\left(f_{m-1}'\left(x^m,\ \Phi^{m-1}\right)\right) \rightarrow \cdots \rightarrow x^0 = opt\left(f_0'\left(x^1, \Phi^0\right)\right). \tag{1.6}$$

Here the *opt* operation has the same meaning as in (1.3). The "prime" superscript in the functional relation marks the disaggregation operation of the model as an inverse of aggregation. The subscript o in ratios (1.4) marks the optimality of the set of system parameters obtained at the next level of the hierarchy as per the set of criteria considered at this level.

It should be noted that in the process of solving the hierarchy of subproblems of choice in accordance with (1.4) it may be necessary to adjust the composition of the set of preference relations at some level of the hierarchy, which can certainly be done.

The solution to the initial problem (1.1) in the presented hierarchical statement will be X_o^0 and x_o^0 that, in general, are different from X_0 and x_0 in accordance with (1.1). Here, the superscript 0 indicates the lowest level of the hierarchical problem, while the lower index o marks the optimality of the obtained solution. It should be noted that the choice of X_o^0 and x_o^0 is more justified, because, in general, the integral hierarchical representation of the initial problem appears to be richer in the sense of detailing of the description of the model of the system and the model of the operation, than when solving the problem directly in the form of (1.1).

Determination of structural heterogeneity of electric power systems. Let us explain the possibility of system models aggregation/disaggregation as the example for electric power system by aggregation of coherent (strongly coupling) subsystems and keeping the weak couplings between subsystems.

Let the square matrix of indexes $\left[w_{ij}\right]$; $i, j = \overline{1, n}$ is, where n is the number of elements (generators) of the system. These indexes determine the strength of links between elements of the system. Clustering indexes gives the possibility to find the structure of the system which includes coherent subsystems and weak links between them. Based on these results of clustering the procedures of strongly coupling subsystem aggregation using (1.3) and disaggregation using (1.6) can be constructed [69].

Aggregation/disaggregation of model based on nodal voltage equations.

a. Elimination and restoration of nodes. Let initial model is represented by following system of nodal voltage equations:

$$\begin{aligned} \dot{Y}_{aa}\dot{V}_a + \dot{Y}_{ab}\dot{V}_b &= \dot{I}_a, \\ \dot{Y}_{ba}\dot{V}_a + \dot{Y}_{bb}\dot{V}_b &= \dot{I}_b. \end{aligned} \tag{1.7}$$

It is necessary to eliminate the group of nodes with index 'b'. The point over symbol means complex value. The aggregated model is presented by (1.8) taking into account (1.9), (1.10).

$$\dot{Y}_e\dot{V}_a = \dot{I}_{ae}, \tag{1.8}$$

$$\dot{Y}_e = \dot{Y}_{aa} - \dot{Y}_{ab}\dot{Y}_{bb}^{-1}\dot{Y}_{ba}, \tag{1.9}$$

$$\dot{I}_{ae} = \dot{I}_a - \dot{Y}_{ab}\dot{Y}_{bb}^{-1}\dot{I}_b. \tag{1.10}$$

Realization of (1.9), (1.10) can be made using well known procedures of nodes elimination

In (1.7) the currents $\dot{I}_b$ include in general case the generation $\dot{I}_{bg}$ and load $\dot{I}_{bl}$ parts. It is necessary to keep them after aggregation. It is possible to do this keeping by two time execution of (1.10) used except $\dot{I}_b$ firstly $\dot{I}_{bg}$ and after that $\dot{I}_{bl}$. In this case $\dot{I}_{be}$ can be presented following result:

$$\dot{I}_{ae} = \dot{I}_{ag} + \dot{I}_{al} + \dot{I}^*_{bg} + \dot{I}^*_{bl} = \left(\dot{I}_{ag} + \dot{I}^*_{bg}\right) + \left(\dot{I}_{al} + \dot{I}^*_{bl}\right), \tag{1.11}$$

where

$$\dot{I}^*_b = \dot{I}^*_{bg} + \dot{I}^*_{bl} = -\dot{V}_{ab}\dot{V}^{-1}_{bb}\dot{I}_b. \tag{1.12}$$

Disaggregation consists in implementing back motion of nodes elimination for voltages determination by:

$$\dot{U}_b = \dot{Y}^{-1}_{bb}(\dot{I}_b - \dot{I}_{ba}\dot{V}_a). \tag{1.13}$$

b. Amalgamation of nodes.

This simplified procedure is based on the assumption: if $\dot{y}_{ij} >> \dot{y}_{ik}$ means strong link between nodes i and j then it is possible to take into account $\dot{y}_{ij} = \infty$ and to aggregate the nodes i and j in one equivalent node. Formal procedure uses the summation of lines and columns i and j of matrix $\dot{Y}$. And it is necessary to make mean value of voltages $\dot{V}_i$ of aggregated nodes.

Disaggregation consists in appropriation the value of aggregated node for initial nodes.

It is important to draw the attention on one more method of this group – REI procedure by P. Dimo [70].

Aggregation/disaggregation of flow models [71]. On the top level of hierarchical modeling of electric power systems and for modeling pipeline systems the flow models on the graphs are usually used. It is possible to use linear flow models (1.14), (1.15):

$$AZ = B, \tag{1.14}$$

$$Z \leq D, \tag{1.15}$$

where Z, D are vectors of the flows and transfer capabilities of branches; B is flow vector of graph apexes; A is the matrix of incidences.

Aggregation of graph apexes i and j is permissible, if $d_{ij} >> d_{ik}$ and it is possible to consider $d_{ij} = \infty$, where $d_{ij}, d_{ik} \in D$. Aggregation procedure uses 'paste together' the apexes i and j for creation of aggregated apex e by summation of necessary lines and columns of (1.14) and determination of $b_e = b_i + b_j$, $d_{ek} = d_{ik} + d_{jk}$, $b_i, d_j \in B$.

Disaggregation means the separation z_{ek} of flow on initial parts in the proportion $z_{ik}, z_{jk} \in Z$ of transfer capabilities of branches d_{ik} and d_{jk}.

Determination of flow model parameters of EPS means the calculation of vector D members. The required estimation gives formula

$$d_{ij} = w_{ij} = E_i E_j y_{ij};\ i, j = \overline{1, n}, \tag{1.16}$$

where E_i is internal voltage of generator i; $\dot{y}_{ij}$ is conductivity between generators i and j.

Taking into account, that in flow models of top level the apex presents subsystems of bottom level, the transfer capability of link between such subsystems I and J is

$$w_{IJ} = \sum_{i \in I} \sum_{j \in J} w_{ij}. \tag{1.17}$$

Case study. The task of substantiation of the long-term development of the Unified Energy System (UES) of Russia, consisting in the choice of the structure of generating equipment from a number of types of units, the location of newly added units and power plants, the structure and parameters of the transmission network, taking into account the requirements of reliability of power supply to consumers, the acceptability of normal, post-emergency, and repair modes of the UES, ensuring the stability of the system in case of disturbances.

Taking into account the uncertainty of the external conditions of the UES development, let us assume that we have formulated two alternative variants of the system, i.e. $X = \{X_1, X_2\}$. We will consider two levels of the description of the problem, to this end at the upper level we will solve the sub-problem of choosing the structure of generating capacity units and their location, while at the lower level it will be the sub-problem of choosing the structure and parameters of the transmission network of the UES. Taking this into account, at the top level, when establishing preference relations, we will assume as criteria capital expenditures for newly added generation equipment and the volume of emissions into the environment due to the operation of this equipment in the form of ash, nitrogen, and sulfur oxides, etc. At the lower level, we will consider as criteria the capital expenditures for newly added transmission lines, the levels of reliability of power supply to consumers and the stability of the UES. Let us set the acceptability requirements for the operation modes when formulating the description (model) of the UES at the lower level.

Thus, we have the following sets of preference relations at the assumed two levels of the problem description:

$$\Phi^1 = \left\{\Phi^1_{ig},\ \Phi^1_e\right\};\ \Phi^0 = \left\{\Phi^0_{in},\ \Phi^0_r, \Phi^0_s\right\}, \tag{1.18}$$

where the indices "ig" and "in" correspond to capital expenditures for generation capacity and network; while "e", "r", and "s" correspond to criteria of environmental impact, reliability, and stability. The interrelation between the sets of criteria at the two considered levels of the problem description is provided through capital expenditures, since $\Phi_i = \Phi_{ig} + \Phi_{in}$ and it is usually necessary to find the minimum of Φ_i, while the ratio between its components can be adjusted in the transition from the top-level sub-problem to the entire set of the lower level sub-problems by refining the requirements for generation, taking into account the introduction of additional transmission lines, the need to ensure reliability and stability.

The UES models at the two levels of the problem description under consideration are as follows. At the lower level, in order to assess the acceptability of operation modes and to analyze the stability of the system, we will consider a detailed description of steady-state modes and transients in the UES in the generally accepted form, i.e., with the presentation of real or aggregated electrical lines, transformers, power plants, and load nodes with their parameters used for such a description on the basis of the system of equations of nodal voltages. In order to analyze the reliability of electric power supply to consumers, as well as to solve the top-level sub-problem, we will form an aggregate description of the UES in the form of a set of large nodes representing integrated energy systems or some other composition of subsystems, that have inherent couplings that do not limit power exchanges and therefore are not taken into account, while the aggregated nodes (subsystems) are linked to each other by some aggregated links with limited throughput capacity.

A provisional illustration of the described two-level modeling of the UES of Russia is presented in Fig. 1.1. Here, the conventional level of representation of the model reflects the "administrative division" principle of establishing aggregated nodes (the nodes correspond to integrated energy systems), while the refined level takes into account the availability of weak coupling within such integrated energy systems.

Thus, the upper level uses an aggregated model of the UES, while the lower level uses an extended set of models that includes the same aggregated model as well as more detailed models.

It is easy then to write down a sequence of sub-problems of type (1.4) formally following the proposed hierarchical choice procedure, but with respect to their content the composition of these sub-problems, taking into account the above clarifications, is quite clear and we will not overload the presentation with further technicalities.

As a result of the solution of a hierarchical sequence of sub-problems, one of the two alternative variants of the UES will be adopted and the parameters that are optimal in terms of the assumed criteria will be determined. The special aspects of multi-criteria choice are omitted from this presentation.

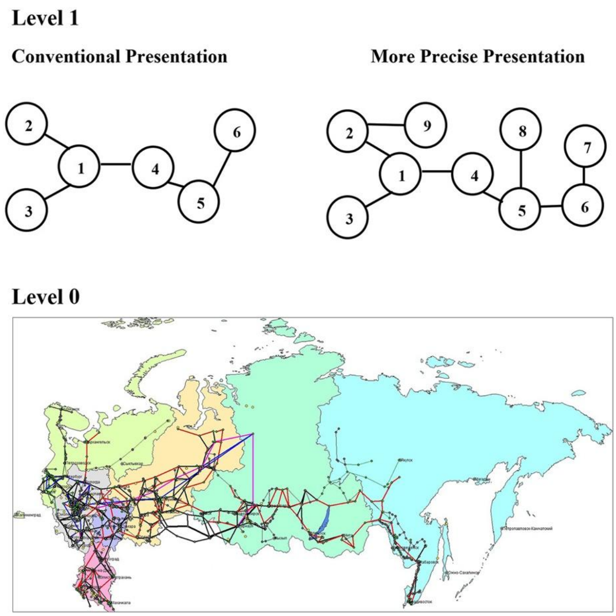


FIGURE 1.1 Two-level representation of the UES of Russia.

1.4 Decomposition and bilevel programming in hierarchical modeling of energy systems

This section describes the basic ideas that underly Danzig–Wolfe decomposition and bilevel programming and that are used, along with other approaches (Benders decomposition, hierarchical games, etc.), as a formal mathematical apparatus for implementing procedures that are simplified statements of real-life problems of hierarchical modeling of complex electric power systems. The models under consideration are quite simple and tentative, but they nevertheless allow us to understand how the general methodology gets tailored to specific examples. In our opinion, this is more important than giving a description of complex models that would be combined with an even more complex implementation of the proposed methods and procedures with the inevitable cumbersome detailing of secondary particulars.

The section presents a description of the necessary theoretical material and numerical examples. Danzig–Wolfe decomposition and bilevel programming are described in terms of finding an equilibrium (trade-off) solution. Decomposition models represent a perfect electric power market, whereas bilevel models represent an oligopolistic market.

1. Danzig–Wolfe decomposition. A great number of studies are devoted to decomposition methods for large-dimensional problems. Let us mention here the well-known monograph [72] and monograph [73] with applications to the electric power industry. We will briefly discuss the general scheme, and then move on to specific examples that most clearly emphasize the merits of the decomposition in question.

The problem under study is stated as follows

$$C(x) = c_1(x_1) + c_2(x_2) + \cdots + c_l(x_l) \to \min_{x,y}, \tag{1.19}$$

$$A_1x_1 + A_2x_2 + \cdots + A_lx_l + By = d, \tag{1.20}$$

$$x_i \in X_i \subset \mathbb{R}^{n_i}, i = 1, \ldots, l, \tag{1.21}$$

$$y \in Y \subset \mathbb{R}^q, \tag{1.22}$$

where $x = (x_1, \ldots, x_l)^T$ (T – the transposition symbol), $c_i(x_i)$ – continuous convex functions, A_i – $(m \times n_i)$-matrices, X_i, Y – convex closed sets, $i = 1, \ldots, l$, $d \in \mathbb{R}^m$, B – $(m \times q)$-matrix.

If we assume that equality constraints (1.20) are absent, we obtain a problem that has the property of separability: the objective function is the sum of functions of independent vector variables x_i, the admissible set X is the Cartesian product of $X = X_1 \times X_2 \times \cdots \times X_l$. The solution of the separable problem is decomposed into the solution of l independent problems

$$\min_{x \in X} C(x) = \sum_{j=1}^{l} \min_{x_j \in X_j} c_i(x_j). \tag{1.23}$$

The presence of *binding* equality constraints (1.20) violates the separability property of problem (1.19)–(1.22). Let us introduce a vector of Lagrange multipliers $\lambda \in \mathbb{R}^m$ that corresponds to constraints (1.20) and write down the Lagrange function

$$L(x, y, \lambda) = C(x) + \lambda^T(d - A_1x_1 - A_2x_2 - \cdots - A_lx_l - By). \tag{1.24}$$

Then let us write the Lagrange dual function

$$\varphi(\lambda) = \min\{L(x, y, \lambda) : x \in X, y \in Y\} \tag{1.25}$$

and the Lagrange dual problem

$$\varphi(\lambda) \to \max, \tag{1.26}$$

$$\lambda \in \mathbb{R}^m. \tag{1.27}$$

The vector λ is also called a vector of dual variables. It is known that if regularity conditions are satisfied [72–76], the solution to the primal problem (1.19)–(1.22) can be replaced by the solution to the dual problem

(1.26)–(1.27), namely, if solutions to the primal problem x^* and the dual one λ^* exist, then

$$C(x^*) = \varphi(\lambda^*). \tag{1.28}$$

In what follows, we will assume that the regularity conditions are satisfied; in particular, these conditions are automatically satisfied for problems with linear constraints, i.e., in the case where X_i and Y are polyhedral sets.

The function $\varphi(\lambda)$ is a concave function, hence the problem (1.26)–(1.27) is a problem of unconditional (i.e. unconstrained) convex optimization. The dual function itself is defined implicitly; to calculate its values it is necessary to solve the problem (1.25). Let us write down this problem in more detail

$$\varphi(\lambda) = \min\left\{\sum_{i=1}^{l} c_i(x_i) + d^T\lambda - \sum_{i=1}^{l}\lambda^T A_i x_i - \lambda^T By : x \in X,\ y \in Y\right\} =$$
$$= \min\left\{\sum_{i=1}^{l}\left(c_i(x_i) - \lambda^T A_i x_i\right) - \lambda^T By : x_i \in X_i,\ i = 1,\dots,l,\ y \in Y\right\} + d^T\lambda. \tag{1.29}$$

It follows from (1.29) that the problem of calculating the values of $\varphi(\lambda)$ is a separable problem, and therefore

$$\begin{aligned}\varphi(\lambda) &= \sum_{i=1}^{l}\min_{x_i\in X_i}\left\{c_i(x_i) - \lambda^T A_i x_i\right\} + \min_{y\in Y}\left\{-\lambda^T By\right\} + d^T\lambda \\ &= \sum_{i=1}^{l}\varphi_i(\lambda) + \psi(\lambda) + d^T\lambda,\end{aligned} \tag{1.30}$$

$$\varphi(\lambda) = \min_{x_i\in X_i}\left\{c_i(x_i) - \lambda^T A_i x_i\right\},\ \psi(\lambda) = \min_{y\in Y}\left\{-\lambda^T By\right\} \tag{1.31}$$

The functions $\varphi_i(\lambda)$, $i = 1,\dots,l$, $\psi(\lambda)$ are concave, not necessarily differentiable functions. The analog of the gradient for such functions is a vector called the subgradient [74]. The subgradients of the functions $\varphi_i(\lambda)$ and $\psi(\lambda)$ are vectors

$$g_i(\lambda) = -A_i x_i^*(\lambda),\ q(\lambda) = -By^*(\lambda) \tag{1.32}$$

respectively, where

$$x_i^*(\lambda) \in X_i^*(\lambda) = \arg\min_{x_i\in X_i}\left\{c_i(x_i) - \lambda^T A_i x_i\right\}, \tag{1.33}$$

$$y^*(\lambda) \in Y^*(\lambda) = \arg\min_{y\in Y}\left\{-\lambda^T y\right\}. \tag{1.34}$$

Problems (1.33), (1.34) can have non-unique solutions, so the sets $X^*(\lambda)$, $Y^*(\lambda)$ can consist of more than one point. The subgradient of the function $\varphi(\lambda)$ is a vector

$$p(\lambda) = g_1(\lambda) + g_2(\lambda) + \cdots + g_l(\lambda) + q(\lambda) + d = \tag{1.35}$$

$$= -A_1x_1^*(\lambda) - A_2x_2^*(\lambda) - \cdots - A_lx_l^*(\lambda) - By^*(\lambda) + d. \tag{1.36}$$

If we compare (1.20) and (1.36), it is easy to see that the gradient of the function $\varphi(\lambda)$ is nothing else but the residual of the equality constraints at point $(x^*(\lambda), y^*(\lambda))$.

Since $\varphi(\lambda)$ is a non-differentiable function, it can have several subgradients at point λ $\varphi(\lambda)$. The set of all subgradients of function $\varphi(\lambda)$ at point λ is called a subdifferential of $\varphi(\lambda)$ and is denoted as $\partial\varphi(\lambda)$. Undifferentiability of $\varphi(\lambda)$ is equivalent to non-uniqueness of its subgradients, and non-uniqueness of subgradients is a consequence of non-uniqueness of solutions in at least one of the problems (1.33)–(1.34). The subdifferential of the dual function $\varphi(\lambda)$ can be fully described as follows

$$\partial\varphi(\lambda) = \left\{ p \in \mathbb{R}^m : p = d - \sum_{i=1}^{l} A_i x_i - By : x_i \in X_i^*(\lambda),\ i = 1, \ldots, l,\ y \in Y^*(\lambda) \right\}. \tag{1.37}$$

If λ^* is the maximum point of the dual function, then according to the theory [77] $\partial\varphi(\lambda^*) \ni 0$, i.e., there is a null one among subgradients $p \in \partial\varphi(\lambda^*)$. Then (see (1.37)), there will be such $x_i^* \in X_i^*(\lambda^*)$ and $y^* \in Y^*(\lambda)$ that equality constraints (1.20) will be satisfied given $x = x^*$, $y = y^*$. Hence, (x^*, y^*) is an admissible point satisfying (1.28), i.e., (x^*, y^*) is a solution to the original problem (1.19)–(1.22).

Let us turn to the question of the method for solving problem (1.26)–(1.27). For this purpose we can use the subgradient method [75], which is described as follows

$$\lambda^{k+1} = \lambda^k + \nu_k \frac{p(\lambda^k)}{\|p(\lambda^k)\|},\ k = 1, 2, \ldots, \tag{1.38}$$

$\lambda^0 \in \mathbb{R}^n$ – the starting point. The numerical sequence should be chosen so that the following conditions are met

$$\lim_{k\to\infty} \nu_k = +\infty,\ \lim_{k\to\infty} \nu_k^2 = 0. \tag{1.39}$$

As the sequence ν_k, one can choose, for example, the elements of harmonic series $\nu_k = \frac{1}{k}$, $k = 1, 2, \ldots$. Then, if the solution λ^* exists, then $\lim\limits_{k\to\infty} \lambda_k = \lambda^*$. The subgradient method is in a certain sense an optimal method for solving convex non-differential optimization problems [76].

What is important for us in this method is the procedure for calculating the gradient $p(\lambda^k)$. The flowchart of the method is shown in Fig. 1.2. It is especially worth noting that problems (1.31) can be solved simultaneously and independently of each other. This is exactly the main idea behind the decomposition of the original problem (1.19)–(1.22). In Fig. 1.2 the block corresponding to the decomposition stage and containing problems (1.31) is shown with a dashed line.

In general, the subgradient method has a rather slow convergence. As a consequence, the implementation of the method should be modified, making maximum use of additional properties arising in specific problems of the type (1.19)–(1.22). Furthermore, the decomposition scheme discussed in this subsection has an important qualitative interpretation related to the idea of decentralization. These issues are discussed in detail in the next two subsections.

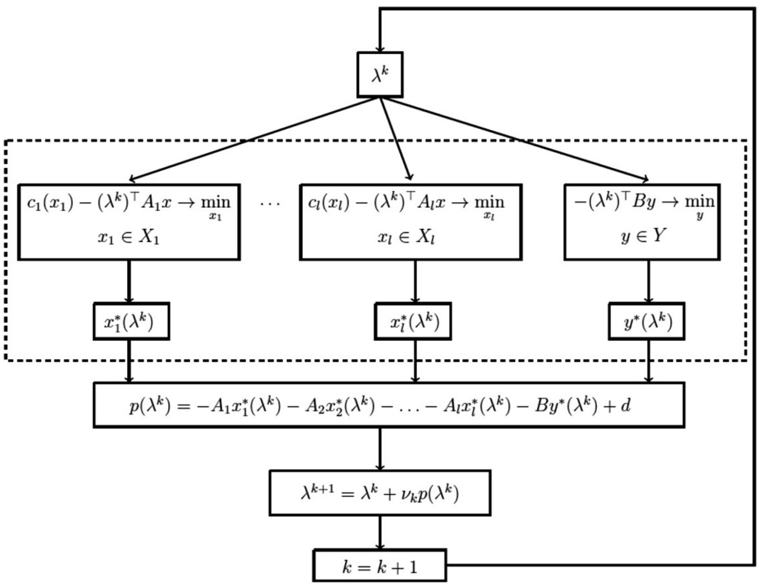


FIGURE 1.2 The flowchart of the subgradient method.

2. ***Model A.*** The mathematical model of the electric power system under study, consisting of n nodes, has the following form:

$$\sum_{j=1}^{n} c_j(x_j) \to \min_{x,y}, \tag{1.40}$$

$$x_j - \sum_{j'=1}^{n} a_{jj'} y_{jj'} + \sum_{j'=1}^{n} a_{j'j}\left(1 - \delta_{j'j}\right) y_{j'j} = d_j, \; j = 1, \ldots, n, \tag{1.41}$$

$$0 \le x_j \le \overline{x}_j, \ j = 1, \dots, n, \tag{1.42}$$

$$y_{jj'} \ge 0, \ j, j' = 1, \dots, n, \tag{1.43}$$

where x_j – power generated at node j, $y_{jj'}$ – power flow from node j to node j', $c_j(x_j)$ – the cost of power generation of the amount equal to x_j at node j, $\delta_{jj'}$ – losses in line $j - j'$, d_j – load at node j, $\overline{x}_j$ – maximum possible power at node j, $a_{jj'}$ – elements of the square adjacency $(n \times n)$-matrix that specifies the presence or absence of a link $j - j'$,

$$a_{jj'} = \begin{cases} 1, & \text{if there is a connection between nodes } j \text{ and } j', \\ 0, & \text{otherwise.} \end{cases}$$

We will assume that costs $c_j(x_j)$, $j = 1, \dots, n$ are strictly convex continuous functions.

Let us write down the Lagrange function

$$L(x, y, \lambda) = \sum_{j=1}^{n} c_j(x_j) + \sum_{j=1}^{n} \lambda_j \left(d_j - x_j + \sum_{j'=1}^{n} a_{jj'} y_{jj'} - \sum_{j'=1}^{n} a_{j'j} \left(1 - \delta_{j'j}\right) y_{j'j} \right) =$$
$$= \sum_{j=1}^{n} \left(c_j(x_j) - \lambda_j x_j \right) + \sum_{j=1}^{n} \sum_{j'=1}^{n} a_{jj'} \left(\lambda_j - \left(1 - \delta_{jj'}\right) \lambda_{j'} \right) y_{jj'} + \sum_{j=1}^{n} d_j \lambda_j, \tag{1.44}$$

the dual function

$$\varphi(\lambda) = \min_{x,y} \{ L(x, y, \lambda) : 0 \le x \le \overline{x}, \ y \ge 0 \}, \tag{1.45}$$

and the dual problem

$$\varphi(\lambda) \to \max, \tag{1.46}$$

$$\lambda \in \mathbb{R}^n. \tag{1.47}$$

Because of the separability property of the Lagrange function (1.44), the problem of calculating the values of the dual function (1.45) can be rewritten in the form

$$\varphi(\lambda) = \sum_{j=1}^{n} \min_{0 \le x_j \le \overline{x}_j} \left\{ c_j\left(x_j\right) - \lambda_j x_j \right\} + \sum_{j=1}^{n} \sum_{j'=1}^{n} \min_{y_{jj} \ge 0} a_{jj'} \left\{ \lambda_1 - (1 - \delta_{jj'}) \lambda_{j'} \right\} +$$
$$+ \sum_{j=1}^{n} d_j \lambda_j = \sum_{j=1}^{n} \varphi_j(\lambda_j) + \sum_{j=1}^{n} \sum_{j'=1}^{n} \psi_{jj'}\left(\lambda_j, \lambda_{j'}\right) + \sum_{j=1}^{n} d_j \lambda_j. \tag{1.48}$$

Due to the simplicity of the constraints $y_{jj'} \geq 0$, the problem of finding values of the functions $\psi_{jj'}(\lambda_j, \lambda_{j'})$ is easy to solve,

$$\psi_{jj'}(\lambda_j, \lambda_{j'}) = \begin{cases} 0, & a_{jj'}(\lambda_j - (1-\delta_{jj'})\lambda_{j'}) \geq 0, \\ -\infty, & a_{jj'}(\lambda_j - (1-\delta_{jj'})\lambda_{j'}) < 0. \end{cases} \tag{1.49}$$

Then, from (1.48)–(1.49) we get

$$\varphi(\lambda) = \begin{cases} \sum_{j=1}^{n} \left(\varphi_j(\lambda_j) + d_j\lambda_j\right), & a_{jj'}(\lambda_j - (1-\delta_{jj'})\lambda_{j'}) \geq 0, \\ -\infty, & a_{jj'}(\lambda_j - (1-\delta_{jj'})\lambda_{j'}) < 0. \end{cases} \tag{1.50}$$

Since in (1.46) the dual function is maximized, then, by virtue of (1.50) cases $a_{jj'}(\lambda_j - (1-\delta_{jj'})\lambda_{j'}) < 0$ should be excluded from consideration. Consequently, the dual problem (1.46)–(1.47) can be rewritten in the following form

$$\upsilon(\lambda) = \sum_{j=1}^{n} \left(\varphi_j(\lambda_j) + d_j\lambda_j\right) \to \max, \tag{1.51}$$

$$\lambda \in \Lambda = \left\{\lambda \in \mathbb{R}^n : a_{jj'}\left(\lambda_j - \left(1-\delta_{jj'}\right)\lambda_{j'}\right) \geq 0,\ j = 1, \ldots, n,\ j' = 1, \ldots, n\right\}, \tag{1.52}$$

i.e., the dual problem (1.46)–(1.47) is equivalent to the problem of maximizing the concave differentiable function $\upsilon(\lambda)$ under linear constraints (1.52). The functions $\varphi(\lambda_j)$ are specified implicitly as optimal values of auxiliary optimization problems

$$\varphi_j(\lambda_j) = \min_{0 \leq x_j \leq \overline{x}_j} \left\{c_j(x_j) - \lambda_j x_j\right\}. \tag{1.53}$$

Let the value of $x_j^*(\lambda)$ be a solution to the problem (1.53) given that λ_j is specified. Since $c_j(x_j)$ is a strictly convex function, such a solution exists and, moreover, it is unique. The latter means that $\varphi_j(\lambda_j)$ is a concave differentiable function and the derivative is $\varphi_j'(\lambda_j) = -x_j^*(\lambda_j)$. Consequently, despite the fact that (1.50)–(1.52) is an optimization problem with an implicitly given objective function υ, we have available not only the value of $\upsilon(\lambda)$ at point λ, but also the gradient of $\nabla\upsilon(\lambda) = d - x^*(\lambda)$. This information is quite sufficient to use gradient-type methods to solve the problem (1.51)–(1.52).

Let us consider in detail the main properties of the problem (1.51)–(1.52). The optimized variables are dual variables λ, corresponding to the balance equality constraints (1.41). Dual variables, in this case, are also called nodal prices, i.e., λ_j is the price at which the purchase and sale of power at node j. Then the product $\lambda_j x_j$ is the income that the generator receives at node j. The difference $\pi_j(\lambda_j, x_j) = \lambda_j x_j - c_j(x_j)$ is obviously the profit of generator j. From (1.53) it follows that

$$\varphi_j(\lambda_j) = -\max_{0 \le x_j \le \overline{x}_j} \pi_j\left(\lambda_j, x_j\right), \tag{1.54}$$

i.e., the calculation of the value of $\varphi_j(\lambda_j)$ *implies* the calculation of the maximum profit of the generator j at a given price λ_j. In other words, when determining the volume of power output, the generator j is governed by the principle of maximizing its profits.

Let us compare the conceptual interpretation of the primal problem (1.40)–(1.43) and the dual problem (1.51)–(1.52). In the primal statement, the variables to be optimized are powers x_j and flows $y_{jj'}$. By solving the primal problem and obtaining the optimal values of x_j^* and $y_{jj'}^*$, we directly specify what should be the produced power at the nodes and flows along the lines so that the total costs (1.40) would be minimal. If we assume that such a problem is solved by some controlling body, let it tentatively be called the system operator, then the solution to the primal problem corresponds to direct, prescriptive control. The generators in this case play the role of implementers.

Let us now turn to the dual statement. Its variables are nodal prices λ_j. The role of the system operator and generators changes significantly. The system operator sets nodal prices. Then, generators, according to the given prices, deliver amounts of power that maximize their profits, without taking the load at the nodes into account at all. Generators are transformed from passive implementers into active participants in the process, though of a purely self-centered nature. Covering the load of consumers at the nodes in this model is the task of the system operator. It sets nodal prices and receives in response the volumes of generated power at the nodes. If the load cannot be covered, then one has to change the nodal prices and repeat everything all over again. The question is how to change nodal prices. Let us assume that the primal problem (1.40)–(1.43) is solvable. Hence, according to the duality theory, the dual problem (1.51)–(1.52) is also solvable. Let $\lambda^* = \left(\lambda_1^*, \ldots, \lambda_n^*\right)$ be the solution to the dual problem. Then λ_j^* is the sought nodal price, at which both generators get the maximum profit and the consumers' load is covered. Finding prices λ_j^* corresponds to maximizing the dual function $\upsilon(\lambda)$ in (1.51). This is exactly what the rule for changing nodal prices, starting from some initial values, provides. If the current set of prices λ does not allow covering the load, then one has to change this set so that the value of the dual function $\upsilon(\lambda)$ would increase. The direction of an increase can be obtained by means of the gradient $\nabla\upsilon(\lambda)$, and it is, as follows from the above, available (can be calculated). Consequently, the change in prices should be made in the direction of increasing values of $\upsilon(\lambda)$ based on gradient $\nabla\upsilon(\lambda)$. A detailed computational scheme that implements this process is given below.

Suppose that using some method of the gradient type, a solution λ^* to the dual problem is found. From the solution of problems (1.54) we find $x_j^*(\lambda_j^*)$. It remains to find the flows between the nodes at which loads d_j will be covered. For this purpose, we will use the conditions of complementary non-rigidity: for the solutions of the primal and dual problems the following relations are satisfied

$$\lambda_j^* \left(d_j - x_j^* + \sum_{j'=1}^{n} a_{jj'} y_{jj'}^* - \sum_{j'=1}^{n} a_{j'j} \left(1 - \delta_{j'j}\right) y_{j'j}^* \right) = 0, \ j = 1, \ldots, n. \tag{1.55}$$

Let us assume here that $\lambda_j^* > 0$. Then there exists such a set of flows $y_{jj'}^*$, that the balance relations (1.41) are satisfied. The statement of the dual problem (1.51)–(1.52) is based on the analysis of expressions (1.48)–(1.49). So far, only the values of $\psi_{jj'}(\lambda_j, \lambda_{j'})$ that are found from the solution of the problems have been used

$$a_{jj'} \left(\lambda_j - \left(1 - \delta_{jj'}\right) \lambda_{j'}\right) y_{jj'} \to \min, \tag{1.56}$$

$$y_{jj'} \geq 0. \tag{1.57}$$

Let us analyze problems (1.56)–(1.57) given $\lambda = \lambda^*$. If $\lambda_j^* - (1 - \delta_{jj'})\lambda_{j'}^* > 0$, then the flow at line $j - j'$ is determined uniquely $y_{jj'}^* = 0$. If $\lambda_j^* - (1 - \delta_{jj'})\lambda_{j'}^* = 0$, then any non-negative value of the flow can be taken as a solution of the problem (1.56)–(1.57). It is necessary to choose such values at which the balance relations (1.41) are satisfied. Let us introduce an index set into the consideration

$$J^0 = \left\{ \left(j, j'\right) : a_{jj'} = 1, \ \lambda_j^* - \left(1 - \delta_{jj'}\right) \lambda_{j'}^* = 0 \right\}$$

and state the auxiliary problem

$$\sum_{j=1}^{n} \left(d_j - x_j^* + \sum_{j' : (j, j') \in J^0} a_{jj'} y_{jj'} - \sum_{j' : (j, j') \in J^0} a_{j'j} (1 - \delta_{j'j}) y_{j'j} \right)^2 \to \min \tag{1.58}$$

given constraints (1.57). It follows from the above that the stated convex quadratic programming problem always has the solution $y_{jj'}^*$, $(j, j') \in J^0$, such that the value of the objective function (1.58) is zero and, therefore, the obtained flows $y_{jj'}^*$, satisfy the balance relations.

Let us proceed to the description of the procedures for finding the optimal powers and flows on the basis of the dual problem (1.51)–(1.52) from the standpoint of the system operator. Since (1.51)–(1.52) is a conditional optimization problem, a method of conditional optimization of the first order, i.e., the method of gradient projections, will be used for its solution.

First, let us describe the DV(λ) (DV is an abbreviation for Dual Values) procedure for calculating the values of the dual function $\upsilon(\lambda)$ and its gradient $\nabla\upsilon(\lambda)$.

Procedure DV(λ)

Input data. *A vector of dual variables* λ.

Output data. *Value* $\upsilon(\lambda)$ *and gradient* $\nabla\upsilon(\lambda)$.

- Step DV.1. *For each* j *solve the problem*

$$\lambda_j x_j - c_j(x_j) \to \max_{x_j},$$
$$0 \le x_j \le \overline{x}_j.$$

  Let $x_j^*(\lambda)$ be the solution to the j-th problem, and let $\pi_j^*(\lambda)$ be the optimal value of the objective function.
- Step DV.2. *Calculate the value of the dual function*

$$\upsilon(\lambda) = \sum_{j=1}^{n} \Big(d_j\lambda_j - \pi_j^*(\lambda_j)\Big).$$

- Step DV.3. *Calculate the gradient*

$$\nabla\upsilon(\lambda) = d - x^*(\lambda),$$

  where $x^*(\lambda) = \big(x_1^*(\lambda_1), \ldots, x^*(\lambda_n)\big)$ is the set of solutions obtained at step DV.1.
- Step DV.4. *Stop*.

For the model under study, solving the problems at step DV.1 is trivial. In more complex models, these problems will no longer be trivial, the main point is that step DV.1 corresponds to the response of generators in response to the proposed nodal prices. The system operator knows neither the specific type of cost functions $c_j(x_j)$, nor the maximum possible power $\overline{x}_j$ of the generator j. Under the dual approach, the system operator does not need to collect information about the technical condition of all generating facilities. More precisely, the system operator gets rid of the necessity to solve a series of problems at step DV.1: this is the exclusive domain of generators. The system operator manages only nodal prices λ_j.

Let us now proceed to the DPG (Dual Projected Gradient) procedure for solving the dual problem (1.51)–(1.52).

The DPG procedure.

- Step DPG.0. *Set the initial set of nodal prices* $\lambda^0 = (\lambda_1^0, \ldots \lambda_n^0)$, $\lambda^0 \in \Lambda$, *where* Λ *is defined in* (1.53). *Set accuracy* $\varepsilon > 0$. *Set iteration counter* k *to zero:* $k = 0$.
- Step DPG.1. *Using procedure DV(*λ^k*), determine the value of the dual function* $\upsilon(\lambda^k)$ *and gradient* $\nabla\upsilon(\lambda^k)$.

- Step DPG.2. *Find scalar parameter* τ^k: $\upsilon(\lambda^k) < \upsilon\left(\lambda^k + \tau^k \nabla \upsilon(\lambda^k)\right)$.
- Step DPG.3. *Calculate vector* $\widehat{\lambda}^k = \lambda^k + \tau^k \nabla \upsilon(\lambda^k)$.
- Step DPG.4. *Find projection* $\widetilde{\lambda}^k$ *onto admissible set* Λ *of dual problem* (1.51)–(1.52):

$$\widetilde{\lambda}^k = \text{argmin}\left\{ \left\| \lambda - \widehat{\lambda}^k \right\|^2 : \lambda \in \Lambda \right\}.$$

- Step DPG.5. *Find scalar parameter* t^k:

$$t^k = \text{argmax}\left\{ \upsilon\left(t\lambda^k + (1-t)\widetilde{\lambda}^k \right) : t \in [0, 1] \right\}.$$

- Step DPG.6. *Calculate vector* $\lambda^{k+1} = t^k \lambda^k + \left(1 - t^k\right) \widetilde{\lambda}^k$.
- Step DPG.7. *If* $\left\| \lambda^k - \lambda^{k+1} \right\| > \varepsilon$, *then increase the iteration counter,* $k = k+1$ *and go to step DPG.1.*
- Step DPG.8. *Define the set*

$$J_k^0 = \left\{ (j, j') : a_{jj'} = 1,\ \lambda_j^k - \left(1 - \delta_{jj'}\right) \lambda_{j'}^k = 0 \right\}.$$

- Step DPG.9. *Solve the problem*

$$\sum_{j=1}^{n} \left(\nabla \upsilon(\lambda^k)_j + \sum_{j':(j,j') \in J_k^0} a_{jj'} y_{jj'} - \sum_{j':(j,j') \in J_k^0} a_{j'j} \left(1 - \delta_{j'j}\right) y_{j'j} \right)^2 \to \min,$$
$$y_{jj'} \geq 0,\ \left(j, j'\right) \in J^k$$

  here $\nabla \upsilon(\lambda^k)_j$ *is the* j*-the component of vector* $\nabla \upsilon(\lambda^k)$). *Let* $y_{jj'}^k$, $(j, j') \in J_k^0$ *be the solution.*
- Step DPG.10. *For index pairs* $(j, j') : (j, j') \notin J_k^0$ *set* $y_{jj'}^k = 0$.
- Step DPG.11. *Set* $\lambda^* = \lambda^k$, $x^* = d - \nabla \upsilon(\lambda^k)$, $y_{jj'}^* = y_{jj'}^k$.
- Step DPG.12. *Stop.*

To calculate the parameters τ^k at step DPG.2 and t^k at step DPG.5, we can employ conventional one-dimensional search algorithms [74].

The result of the DPG procedure is a system of optimal nodal prices λ^*, of the corresponding optimal volumes of generated power x^*, and the corresponding optimal flows $y_{jj'}^*$.

From the point of view of the system operator, the DPG procedure can be given the following conceptual interpretation. At step DPG.0 the system operator sets the initial set of nodal prices. Then, at steps DPG.1–DPG.7, the system operator successively adjusts the nodal prices based on the response of the generators. At step DPG.7 the system operator checks whether the adjustment is significant. If the adjustment is insignificant, the system operator then finds the flows.

TABLE 1.1 Demonstration example data.

k	Node 1	Node 2	Node 3	$v(\lambda^k)$	$\left\|\lambda^k - \lambda^{k-1}\right\|$
0	$\lambda_1^0 = 1$ $x_1^0 = 0$ $g_1^0 = 100$	$\lambda_2^0 = 1$ $x_2^0 = 0$ $g_2^0 = 120$	$\lambda_3^0 = 1$ $x_3^0 = 0$ $g_3^0 = 80$	333	–
1	$\lambda_1^1 = 729.398$ $x_1^1 = 80$ $g_1^1 = 20$	$\lambda_2^1 = 733.777$ $x_2^1 = 100$ $g_2^1 = 20$	$\lambda_3^1 = 726.446$ $x_3^1 = 120.043$ $g_3^1 = -40.315$	68298.473	732.777
2	$\lambda_1^2 = 732.584$ $x_1^2 = 80$ $g_1^2 = 20$	$\lambda_2^2 = 732.586$ $x_2^2 = 100$ $g_2^2 = 20$	$\lambda_3^2 = 725.260$ $x_3^2 = 120.228$ $g_3^2 = -40.043$	68385.989	3.186
3	$\lambda_1^3 = 733.707$ $x_1^3 = 80$ $g_1^3 = 20$	$\lambda_2^3 = 733.707$ $x_2^3 = 100$ $g_2^3 = 20$	$\lambda_3^3 = 726.370$ $x_3^3 = 120.318$ $g_3^3 = -40.228$	68386.326	1.123
4	$\lambda_1^4 = 734.251$ $x_1^4 = 80$ $g_1^4 = 20$	$\lambda_2^4 = 734.251$ $x_2^4 = 100$ $g_2^4 = 20$	$\lambda_3^4 = 726.908$ $x_3^4 = 120.361$ $g_3^4 = -40.318$	68386.396	0.544
5	$\lambda_1^5 = 734.516$ $x_1^5 = 80$ $g_1^5 = 20$	$\lambda_2^5 = 734.516$ $x_2^5 = 100$ $g_2^5 = 20$	$\lambda_3^5 = 727.171$ $x_3^5 = 120.362$ $g_3^5 = -40.318$	68386.413	0.266
6	$\lambda_1^6 = 734.646$ $x_1^6 = 80$ $g_1^6 = 20$	$\lambda_2^6 = 734.646$ $x_2^6 = 100$ $g_2^6 = 20$	$\lambda_3^6 = 727.300$ $x_3^6 = 120.393$ $g_3^6 = -40.383$	68386.417	0.130
7	$\lambda_1^7 = 734.710$ $x_1^7 = 80$ $g_1^7 = 20$	$\lambda_2^7 = 734.710$ $x_2^7 = 100$ $g_2^7 = 20$	$\lambda_3^7 = 727.363$ $x_3^7 = 120.399$ $g_3^7 = -40.393$	68386.419	0.063

Example 1. Let us look at an example that illustrates how the DPG procedure works. The mathematical model (1.42)–(1.43) has the following characteristics. Number of nodes $n = 3$, all nodes are connected to each other, i.e., $a_{jj'} = 1$ given $j \neq j'$, losses $\delta_{jj'} = 0.01$. Loads $d_1 = 100$, $d_2 = 120$, $d_3 = 80$. Maximum power $\overline{x}_1 = 80$, $\overline{x}_2 = 100$, $\overline{x}_3 = 200$. Cost functions

$$c_1(x_1) = 2x_1^2 + 7x_1 + 12, \; c_2(x_2) = x_2^2 + 9x_2 + 11, \; c_3(x_3) = 3x_3^2 + 5x_3 + 10.$$

Accuracy of $\varepsilon = 0.1$. Table 1.1 shows the results of applying the DPG procedure to the solution of this example.

Values g_1^k, g_2^k, g_3^k are components of vector $\nabla\upsilon(\lambda^k)$, $\nabla\upsilon(\lambda^k) = \left(g_1^k, g_2^k, g_3^k\right)$. For the specified accuracy, it took 7 iterations. Nodal price for the first node is $\lambda_1^7 = 734.710$, for the second node – $\lambda_2^7 = 734.710$, for the third node – $\lambda_3^7 = 727.363$. Powers $x_1^7 = 80$, $x_2^7 = 100$, $x_3^7 = 120.399$. The exact solution to this problem $\lambda_1^* = 734.772$, $\lambda_2^* = 734.772$, $\lambda_3^* = 727.424$, $x_1^* = 80$, $x_2^* = 100$, $x_3^* = 120.404$. After 7 iterations the problem of finding the flows corresponding to step DPG.9 was solved. Non-zero flows $y_{31}^7 = 20.202$, $y_{32}^7 = 20.202$. It is not difficult to confirm that the balance relations (1.41) are satisfied. Thus, by 7 corrective actions, the system operator manages to get a solution to the problem in question. In this case, generators, acting only in their own interests, supply the necessary amount of power to the grid, and the system operator manages to distribute the incoming power across the grid so as to cover the available load.

Summarizing the results, we can say the following: the use of the dual approach makes it possible to decentralize the control over the electric power system.

3. Model B. Let us supplement the model of the previous subsection with constraints on flows along the lines. For convenience of the presentation, let us write down the resulting model again:

$$\sum_{j=1}^{n} c_j(x_j) \to \min_{x,y}, \tag{1.59}$$

$$x_j - \sum_{j'=1}^{n} a_{jj'} y_{jj'} + \sum_{j'=1}^{n} a_{j'j}\left(1-\delta_{j'j}\right) y_{j'j} = d_j,\ j = 1,\dots,n, \tag{1.60}$$

$$0 \le x_j \le \overline{x}_j,\ j = 1,\dots,n, \tag{1.61}$$

$$0 \le y_{jj'} \le \overline{y}_{jj'},\ j, j' = 1,\dots,n. \tag{1.62}$$

The constants $\overline{y}_{jj'}$ in (1.62) set the constraints on the maximum flows along the lines.

The Lagrange function will be written in the same form (1.44), but the dual function will have the form

$$\varphi(\lambda) = \min_{x,y}\left\{L(x,y,\lambda) : 0 \le x \le \overline{x},\ 0 \le y \le \overline{y}\right\}. \tag{1.63}$$

Hereinafter in this section, we will understand the dual function $\varphi(\lambda)$ as the function defined in (1.63). The presence of the constraints $y \le \overline{y}$ does not allow one to reduce the dual problem (1.46)–(1.47) to the problem of differentiable convex optimization (1.51)–(1.52). The point is that due to the linearity of the Lagrange function with respect to the variables y, the problem in (1.63) may have a non-unique solution with respect to these variables. A consequence of non-uniqueness is the non-differentiability of the dual function $\varphi(\lambda)$ [76]; this function remains concave but loses its smoothness. The dual problem (1.46)–(1.47) for the model (1.59)–(1.62) is a convex non-differentiable optimization problem.

The analog of the gradient in the non-differentiable case is the subgradient. As is well known, the subgradient $g(\lambda)$ of the function $\varphi(\lambda)$ is defined as follows

$$g(\lambda) = d_j - x_j^*(\lambda_j) + \sum_{j'=1}^{n} a_{jj'} y_{jj'}^*(\lambda_j, \lambda_{j'}) - \sum_{j'=1}^{n} a_{j'j}(1-\delta_{j'j}) y_{j'j}^*(\lambda_{j'}, \lambda_j), \tag{1.64}$$

where $x_j^*(\lambda_j)$, as before, is a solution to the problem (1.53), and $y_{jj'}^*(\lambda_j, \lambda_{j'})$ is a solution to the problem

$$a_{jj'}\left(\lambda_j - (1-\delta_{jj'})\lambda_{j'}\right) y_{jj'} \to \min, \tag{1.65}$$

$$0 \le y_{jj'} \le \overline{y}_{jj'}. \tag{1.66}$$

Let us define the sets

$$J^- = \left\{(j, j') : a_{jj'} = 1, \lambda_j - \left(1-\delta_{jj'}\right)\lambda_{j'} < 0\right\},$$
$$J^0 = \left\{(j, j') : a_{jj'} = 1, \lambda_j - \left(1-\delta_{jj'}\right)\lambda_{j'} = 0\right\},$$
$$J^+ = \left\{(j, j') : a_{jj'} = 1, \lambda_j - \left(1-\delta_{jj'}\right)\lambda_{j'} > 0\right\}.$$

Then, obviously, $y_{jj'}^*(\lambda_j, \lambda_{j'}) = \overline{y}_{jj'}$ given $(j, j') \in J^-$, $y_{jj'}^*(\lambda_j, \lambda_{j'}) = 0$ given $(j, j') \in J^+$, but given $(j, j') \in J^0$ the magnitudes $y_{jj'}^*(\lambda_j, \lambda_{j'})$ can take any value from $\left[0, \overline{y}_{jj'}\right]$. The non-uniqueness of the subgradient definition in (1.64) is a direct consequence of the non-uniqueness of the optimal values of $y_{jj'}^*(\lambda_j, \lambda_{j'}) = 0$ given $(j, j') \in J^0$. We will select a particular subgradient from the set of all subgradients relying on the same considerations that were used in the previous subsection. The purpose of this choice is to satisfy the balance relations (1.60) to a maximum extent, i.e., to make the maximum number of vector $g(\lambda)$ components equal to zero in (1.64). To this end, given λ, it is sufficient to solve the problem of convex quadratic programming

$$\|g(\lambda)\|^2 \to \min_{y_{jj'}},$$

given constraints

$$y_{jj'}^*(\lambda_j, \lambda_{j'}) = \overline{y}_{jj'}, \ (j, j') \in J^-, \ y_{jj'}^*(\lambda_j, \lambda_{j'}) = 0, \ (j, j') \in J^+,$$
$$y_{jj'}^*(\lambda_j, \lambda_{j'}) = y_{jj'}, \ y_{jj'} \in \left[0, \overline{y}_{jj'}\right], \ (j, j') \in J^0.$$

Below is a description of the DSA (Dual Subgradient Ascent) subgradient procedure.

The DSA procedure

- Step DSA.0. *Set the initial set of nodal prices* $\lambda^0 = \left(\lambda_1^0, \ldots, \lambda_n^0\right)$. *Set accuracy* $\varepsilon > 0$. *Set iteration counter* k *to zero:* $k = 0$.

- Step DSA.1. *Using procedure DV(λ^k), determine the value of the dual function $\upsilon(\lambda^k)$ and gradient $\nabla\upsilon(\lambda^k)$.*
- Step DSA.2. *Calculate vector $x^k = d - \nabla\upsilon(\lambda^k)$.*
- Step DSA.3. *Define the sets*

$$J_k^- = \left((j,j'): a_{jj'} = 1, \lambda_j^k - (1-\delta_{jj'})\lambda_{j'}^k < 0\right),$$
$$J_k^0 = \left\{(j,j'): a_{jj'} = 1, \lambda_j^k - (1-\delta_{jj'})\lambda_{j'}^k = 0\right\},$$
$$J_k^+ = \left\{(j,j'): a_{jj'} = 1, \lambda_j^k - (1-\delta_{jj'})\lambda_{j'}^k > 0\right\}.$$

- Step DSA.4. *Lock the variables $y_{jj'} = \overline{y}_{jj'}$ for $(j,j') \in J_k^-$ and $y_{jj'} = 0$ for $(j,j') \in J_k^+$.*
- Step DSA.5. *Solve the convex quadratic programming problem*

$$\sum_{j=1}^{n}\left(d_j - x_j^k + \sum_{j'=1}^{n} a_{jj'}y_{jj'} - \sum_{j'=1}^{n} a_{j'j}\left(1-\delta_{j'j}\right)y_{j'j}\right)^2 \to \min,$$
$$y_{jj'} \in \left[0, \overline{y}_{jj'}\right],\ (j,j') \in J_k^0. \tag{1.67}$$

Let $y_{jj'}^k$ be the solution.
- Step DSA.6. *Calculate subgradient g^k with the components*

$$g_j^k = d_j - x_j^k + \sum_{j'=1}^{n} a_{jj'}y_{jj'}^k - \sum_{j'=1}^{n} a_{j'j}(1-\delta_{j'j})y_{j'j}^k.$$

- Step DSA.7. *Determine the scalar parameter τ^k:*

$$\tau^k = \arg\max\{\varphi(\lambda^k + \tau g^k) : \tau \geq 0\}. \tag{1.68}$$

- Step DSA.8. *Calculate $\lambda^{k+1} = \lambda^k + \tau^k g^k$.*
- Step DSA.9. *If $\|\lambda^k - \lambda^{k+1}\| > \varepsilon$, then increase the iteration counter, $k = k+1$ and go to step DSA.1.*
- Step DSA.10. *Stop.*

As a result of the DSA procedure we get an approximation of nodal prices λ^k, powers x^k, and flows y^k.

Example 2. In addition to Example 1, discussed in the previous subsection, let us add a constraint on flows $y_{jj'} \leq \overline{y}_{jj'} = 50$ for all lines and the constraint $y_{31} \leq \overline{y}_{31} = 10$ for line $3-1$. The flow over line $3-1$, found as per the methodology of the previous section, was equal to 20.202 and in the problem in question having constraints on flows, it is not admissible. The DSA procedure finds a solution in this case in 9 iterations:

$\lambda^9 = (742.825,\ 735.397,\ 728.043)$, $x^9 = (80, 100,\ 120.507)$. Flows $y_{31}^9 = 10$, $y_{32}^9 = 30.507$, the remaining flows are zero. The obtained solution within the specified accuracy coincides with the optimal one.

Obviously, the DSA procedure can also be applied to problems with no constraints on flows (it is sufficient to take the values of $\overline{y}_{jj'}$ that are very large). Nevertheless, it should be taken into account that the DSA procedure is oriented to solving a non-differentiable optimization problem. As a rule, non-differentiable optimization methods require many more iterations than smooth optimization methods.

4. Bilevel programming. Problem statement and properties. A bilevel programming problem is a system of two interrelated mathematical programming problems describing a hierarchical bilevel interaction between two participants. A formal description of the components of each problem, without taking into account the interaction between them, is as follows.

- The first participant or *the first level*, or *the leader*
  - controls the vector variable (strategy) $x \in \mathbb{R}^{n_1}$;
  - strives to minimize the first-level objective function $F : \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \to \mathbb{R}$ with respect to its variable: $F(x, y) \to \min\limits_x$;
  - respects inequality constraints $G(x, y) \le 0$, $G : \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \to \mathbb{R}^{m_1}$;
  - respects equality constraints $H(x, y) = 0$, $H : \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \to \mathbb{R}^{p_1}$;
  - respects the constraints its variable i subject to $x \in X \subset \mathbb{R}^{n_1}$.

  As a result, the components of the first level participant's problem or, simply, the components of the first level problem have the form

$$F(x, y) \to \min_x, \tag{1.69}$$

$$G(x, y) \le 0, \tag{1.70}$$

$$H(x, y) = 0, \tag{1.71}$$

$$x \in X. \tag{1.72}$$

- The second participant, or *the second level*, or *the follower*
  - controls the vector variable (strategy) $y \in \mathbb{R}^{n_2}$;
  - minimizes objective function $f : \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \to \mathbb{R}$ with respect to its variable: $f(x, y) \to \min_y$;
  - respects inequality constraints $g(x, y) \le 0$, $g : \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \to \mathbb{R}^{m_2}$;
  - respects equality constraints $h(x, y) = 0$, $h : \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} \to \mathbb{R}^{p_2}$;
  - respects the constraints its variable i subject to $y \in Y \subset \mathbb{R}^{n_2}$.

  Components of the second-level problem:

$$f(x, y) \to \min_y; \tag{1.73}$$

$$g(x, y) \le 0, \tag{1.74}$$

$$h(x, y) = 0, \tag{1.75}$$

$$y \in Y. \tag{1.76}$$

Let us remind again that (1.69)–(1.72) and (1.73)–(1.76) are merely formal enumerations of the components of each problem. There is no meaningful description of the interaction between them, and in this sense neither (1.69)–(1.72) nor (1.73)–(1.76) can be considered as correctly stated optimization problems. In (1.69)–(1.72), the minimization is performed with respect to the variable x, nothing is said about the variable y, and until this variable is defined, neither the minimization in (1.69) nor the constraints (1.70)–(1.71) are correctly defined. Similarly, in (1.73)–(1.76) the minimization is performed with respect to the variable y, and while the upper-level variable x is not specified, the lower-level problem is underspecified as well.

Let us proceed to the conceptual description of the interaction between problems (1.69)–(1.72) and (1.73)–(1.76). Within the framework of bilevel programming, the second-level problem (1.73)–(1.76) is a parametric optimization problem in which the vector x acts as a parameter. The second-level problem completion is quite simple: the first level selects some strategy $\tilde{x} \in X$ and passes it to the second level. The second level substitutes the given strategy $x = \tilde{x}$ into its problem, after which, the second level problem becomes a regular mathematical programming problem:

$$f(\tilde{x}, y) \to \min_y; \tag{1.77}$$

$$g(\tilde{x}, y) \leq 0, \tag{1.78}$$

$$h(\tilde{x}, y) = 0, \tag{1.79}$$

$$y \in Y. \tag{1.80}$$

A. Let us suppose that problem (1.77)–(1.80) proved solvable and $y^*(\tilde{x})$ is its solution. Then the second level returns vector $y^*(\tilde{x})$ to the first level and the first level checks if the conditions are met

$$G(\tilde{x}, y^*(\tilde{x})) \leq 0, \tag{1.81}$$

$$H(\tilde{x}, y^*(\tilde{x})) = 0. \tag{1.82}$$

If these conditions are violated, strategy $\tilde{x}$ is considered not allowable (unacceptable) and the first level is forced to seek another strategy. If conditions (1.81)–(1.82) are satisfied, the strategy $\tilde{x}$ is considered allowable and the upper level calculates the value of its objective function $F(\tilde{x}, y^*(\tilde{x}))$.

B. Let us now suppose that the constraints (1.78)–(1.80) are incompatible, i.e. the admissible set of the second-level problem is empty. Then there is no solution of $y^*(\tilde{x})$ defined and nothing to pass to the first level. In this case, the strategy $\tilde{x}$ is also considered inadmissible or unacceptable.

We now see that the second level problem is subordinate: it cannot be solved until the first level passes on its strategy x to the second one. At the same time, the second level has a certain freedom in that it chooses the response $y^*(x)$, respecting its interests, namely minimizing the objective function in (1.73).

The first-level problem (1.73)–(1.76) is not a parametric programming problem. As can be seen from the previous description, the variable y is not an external or exogenous, independent variable for the first participant. On the contrary, the second participant's variable or strategy depends on the choice of x and this fact is emphasized by the formal notation $y^*(x)$. By changing its strategy x, the first level thereby affects the response $y^*(x)$ of the second level as well. The problem of the first participant is to find such a strategy $x^* \in X$ that makes the second-level problem solvable, its solution $y^*(x^*)$, returned to the first level, together with x^*, satisfies the constraints (1.70)–(1.71): $G(x^*, y^*(x^*)) \leq 0$, $H(x^*, y^*(x^*)) = 0$, and the value of $F(x^*, y^*(x^*))$ is the minimum possible value.

Let us take the next step toward a more rigorous definition of the bilevel programming problem. Let us introduce a point-to-set (multi-valued) mapping of the *extremal type* $\Psi : \mathbb{R}^{n_1} \rightrightarrows \mathbb{R}^{n_2}$ which assigns to each point $x \in \mathbb{R}^{n_1}$ the set $\Psi(x) \subset \mathbb{R}^{n_2}$ of minima of the second-level problem:

$$\Psi(x) = \arg\min_{y} \{f(x, y) : g(x, y) \leq 0,\ h(x, y) = 0,\ y \in Y\}. \tag{1.83}$$

The term *extremal* is in line with the conceptual meaning of the mapping (1.83): the point x is mapped to a set of solutions to the optimization problem, i.e., to the *extremal* problem. The need to introduce point-to-set mappings is caused by the fact that $\Psi(x)$ can consist of more than one point. The symbol $\rightrightarrows$ emphasizes multi-valuedness. Oftentimes, the point-to-set mapping Θ, which for each point s from some set S, $s \in S$ maps to the subset $\Theta(s)$ of some set Q, $\Theta(s) \subset Q$ is denoted as follows: $\Theta : S \to 2^Q$. We can say that Θ is a single-valued (so "$\to$" is used) mapping of the set S to the set of all subsets Q (so the "2^Q" symbol is used). In what follows, the symbol "$\rightrightarrows$" will be used as a more compact symbol (compare the two notations: $\Psi : \mathbb{R}^{n_1} \rightrightarrows \mathbb{R}^{n_2}$ and $\Psi : \mathbb{R}^{n_1} \to 2^{\mathbb{R}^{n_2}}$).

The effective set of mapping Ψ is introduced in the standard way:

$$dom\,(\Psi) = \left\{x \in \mathbb{R}^{n_1} : \Psi(x) \neq \emptyset\right\} \tag{1.84}$$

and *the graph of mapping* Ψ:

$$graph\,(\Psi) = \left\{(x, y) \in \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} : y \in \Psi(x)\right\}. \tag{1.85}$$

It is well-known that $dom\,(\Psi)$ is a projection of $graph\,(\Psi)$ onto $\mathbb{R}^{n_1}$.

In what follows, until otherwise specified, Conjecture 1 will be assumed to be true.

Conjecture 1. *For any $x \in X$ solution $y^*(x)$ of the second-level problem, if it exists, is unique.*

Then the admissibility of some first-level strategy $\tilde{x} \in X$ is equivalent to satisfying two requirements:

1. $\Psi(\tilde{x}) \neq \emptyset$;
2. $G(\tilde{x}, y^*(\tilde{x})) \leq 0$, $H(\tilde{x}, y^*(\tilde{x})) = 0$.

Given the conjecture made, the condition $\Psi(\tilde{x}) \neq \emptyset$ is equivalent to the condition $\Psi(\tilde{x}) = \{y^*(\tilde{x})\}$, where $y^*(\tilde{x})$ is the only solution of the second-level problem. The conceptual interpretation of the bilevel programming problem, in this case, can be refined: the first level is looking for such an *admissible* strategy x^* for which the value of the objective function $F(x^*, y^*(x^*))$ is minimal.

Let us formulate the bilevel programming problem as stated by S. Dempe [77–79]:

$$F(x, y) \to \min_{y}, \tag{1.86}$$

$$G(x, y) \leq 0, \tag{1.87}$$

$$H(x, y) = 0, \tag{1.88}$$

$$x \in X, \tag{1.89}$$

$$y \in \Psi(x). \tag{1.90}$$

In this statement, the second-level problem is reflected by inclusion (1.91), which is called an *extremal*-type constraint. The problem (1.86)–(1.90) is correctly stated. The choice of $x \in X$ uniquely (by virtue of Conjecture 1) determines $y = y^*(x)$, then the constraints (1.87)–(1.88) are checked and, if they are satisfied, the value of the objective function in (1.86) is calculated, i.e., everything is determined by the choice of x and therefore minimization with respect to x in (1.86) only is correct. The statement (1.86)–(1.90) differs from (1.69)–(1.72) in that it adds the *extremal* constraint (1.90) and requires the satisfaction of Conjecture 1. As we will see later, it is the extremal constraint and the failure to satisfy Conjecture 1 that creates fundamental difficulties in solving the bilevel programming problem.

The bilevel programming problem can also be written down in J.F. Bard's statement [80], which differs from (1.86)–(1.90) only in the formalism of the notation reflecting the hierarchy under study:

$$F(x, y) \to \min_{x}, \tag{1.91}$$

$$G(x, y) \leq 0, \tag{1.92}$$

$$H(x, y) = 0, \tag{1.93}$$

$$x \in X, \tag{1.94}$$

$$f(x,y) \to \min_y; \tag{1.95}$$

$$g(x,y) \le 0, \tag{1.96}$$

$$h(x,y) = 0, \tag{1.97}$$

$$y \in Y. \tag{1.98}$$

The shift to the right in (1.92)–(1.98) emphasizes the fact that these relations specify the admissible set of the first-level problem, i.e., this admissible set is defined by inequalities (1.92), Eqs. (1.93), inclusion (1.94), and problem (1.95)–(1.98). The repeated shift to the right in (1.96)–(1.98) corresponds to the description of the admissible set of the second-level problem.

In what follows, we will need the following notation:

- weak admissible set Ω (in the terminology of J.F. Bard [80]),

$$\Omega = \{(x,y) \in X \times Y : G(x,y) \le 0,\ H(x,y) = 0,\ g(x,y) \le 0,\ h(x,y) = 0\}, \tag{1.99}$$

  i.e., the set obtained by combining the first- and second-level constraints;
- projection Ω_x of the weak admissible set onto the first-level strategy space,

$$\Omega_x = \left\{x \in \mathbb{R}^{n_1} : (x,y) \in \Omega\right\}; \tag{1.100}$$

- projection Ω_y of the weak admissible set onto the second-level strategy space,

$$\Omega_y = \left\{y \in \mathbb{R}^{n_2} : (x,y) \in \Omega\right\}; \tag{1.101}$$

- parametrically defined admissible set of the second-level problem $\mathcal{Y}(x)$,

$$\mathcal{Y}(x) = \{y \in Y : g(x,y) \le 0,\ h(x,y) = 0\}, \tag{1.102}$$

  the upper-level variable x acts as a vector parameter;
- reactive set $\mathcal{R}$,

$$\mathcal{R} = \left\{(x,y) \in \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} : x \in X, y \in \Psi(x)\right\}, \tag{1.103}$$

  it follows from (1.85) and (1.103) that $\mathcal{R}$ corresponds to the graph of the mapping Ψ, nevertheless in what follows we use the term "response set", since $\mathcal{R}$ is generated by the second-level "responses" to the first-level strategies;
- admissible set $\mathcal{D}$,

$$\mathcal{D} = \left\{(x,y) \in \mathbb{R}^{n_1} \times \mathbb{R}^{n_2} : x \in X,\ G(x,y) \le 0,\ H(x,y) = 0, y \in \Psi(x)\right\}; \tag{1.104}$$

- admissible set of the first-level problem $\mathcal{X}$,

$$\mathcal{X} = \left\{x \in \mathbb{R}^{n_1} : x \in X,\ G(x,y) \le 0,\ H(x,y) = 0,\ y \in \Psi(x)\right\}; \tag{1.105}$$

- function of the optimal value of the first level $\varphi : X \to \overline{\mathcal{R}}$ defined as a function of only its own strategy x:

$$\varphi(x) = \left(\begin{array}{ll} F(x, y^*(x)), & \text{if } x \in \mathcal{X}, \\ +\infty, & \text{if } x \notin \mathcal{X}. \end{array} \right. \tag{1.106}$$

Let us establish some relations between the introduced sets. From (1.100), (1.106), and definition $\Psi(x)$ in (1.83) it follows that $\mathcal{D} \subset \Omega$ or with (1.103)

$$\mathcal{D} = \Omega \cap \mathcal{R} \Rightarrow \mathcal{D} \subset \mathcal{R}. \tag{1.107}$$

Further, if the first-level constraints do not contain inequalities (1.88) ($m_1 = 0$) and Eqs. (1.89) ($p_1 = 0$), then

$$\Omega \cap \mathcal{R} = \mathcal{R} \Rightarrow \mathcal{D} = \mathcal{R}. \tag{1.108}$$

Set $\mathcal{X}$ is a projection of $\mathcal{D}$ onto $\mathbb{R}^{n_1}$:

$$\mathcal{X} = \left\{x \in \mathbb{R}^{n_1} : (x,y) \in \mathcal{D}\right\}. \tag{1.109}$$

Taking into account the introduced notations, the bilevel programming problem can be written in the following form:

$$f(x,y) \to \min_y; \tag{1.110}$$

$$(x,y) \in \mathcal{D}. \tag{1.111}$$

Let us note that this statement is correct because, by virtue of Conjecture 1, y is uniquely, though implicitly, determined by the choice of x.

Example 3. We consider an example of a bilevel programming problem from ([78], p. 197). Let us write it down in both the statement by S. Dempe and that by J.F. Bard:

The problem as stated by S. Dempe	**The problem as stated by J.F. Bard**
$F(x,y) = x - 4y \to \min_x$;	$F(x,y) = x - 4y \to \min_x$;
$x \in X = \{x \in \mathbb{R} : x \ge 0\}$;	$x \in X = \{x \in \mathbb{R} : x \ge 0\}$,
$y \in \Psi(x)$,	$f(x,y) = y$,
$\Psi(x) = \operatorname{Arg\,min}_y \{f(x,y) = y :$	
$g_1(x,y) = -x - y + 3 \le 0$,	$g_1(x,y) = -x - y + 3 \le 0$,
$g_2(x,y) = -2x + y \le 0$,	$g_2(x,y) = -2x + y \le 0$,
$g_3(x,y) = 2x + y - 12 \le 0$,	$g_3(x,y) = 2x + y - 12 \le 0$,
$g_4(x,y) = 3x - 2y - 4 \le 0$,	$g_4(x,y) = 3x - 2y - 4 \le 0$,
$y \ge 0\}$.	$y \in Y = \{y \in \mathbb{R} : y \ge 0\}$.

The dimension of the vector of variables x of the first level $n_1 = 1$, the inequality constraints as well as equality constraints in the first level problem are absent, $m_1 = 0$, $p_1 = 0$. Dimension of the vector of variables y of the second level $n_2 = 1$, the number of inequality constraints in the problem of the second level $m_2 = 4$, no inequality constraint, $p_2 = 0$. The geometric interpretation is given in Fig. 1.3. The weak admissible set Ω is a quadrilateral with vertices $v^1 = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$, $v^2 = \begin{pmatrix} 3 \\ 6 \end{pmatrix}$, $v^3 = \begin{pmatrix} 4 \\ 4 \end{pmatrix}$, $v^4 = \begin{pmatrix} 2 \\ 1 \end{pmatrix}$, shaded in gray. Gradient $\nabla f(x, y) = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ is shown in green. Let the first level strategy be $\tilde{x}^1 = 2$. The graphical illustration of the admissible set of the second level problem $\mathcal{Y}(2)$ is obtained as follows: draw the vertical line $x = 2$ (blue dashed line in Fig. 1.3) and find its intersection with Ω (green dashed line in Fig. 1.3), then project the resulting segment onto the ordinate axis (axis y) (the projection is shown by green arrows). We end up with $\mathcal{Y}(2) = \{y : 1 \le y \le 4\}$. Algebraically (see (1.103)) the admissible set of the second-level problem is defined by substituting $x = 2$ into inequalities $g_i(x, y) \le 0, i = 1, 2, 3, 4$:

$$
\begin{aligned}
g_1(2, y) &= -2 - y + 3 = -y + 1 \le 0 \Rightarrow y \ge 1, \\
g_2(2, y) &= -2 + y = -4 + y \le 0 \Rightarrow y \le 4, \\
g_3(2, y) &= 4 + y - 12 = y - 8 \le 0 \Rightarrow y \le 8, \\
g_4(2, y) &= 6 - 2y - 4 = -2y + 2 \le 0 \Rightarrow y \ge 1,
\end{aligned}
$$

which also gives $\mathcal{Y}(2) = \{y : 1 \le y \le 4\}$ (obviously, inequality $y \ge 0$ is satisfied). The second-level problem corresponding to the first-level strategy $\tilde{x} = 2$

$$
\begin{gathered}
y \to \min, \\
y \in \Psi(2) \Leftrightarrow 1 \le y \le 4,
\end{gathered}
$$

has the unique solution $y^*(2) = 1$. Therefore, $\tilde{x} = 2$ is an admissible strategy and the value of the objective function of the first level $F(\tilde{x}, y^*(\tilde{x})) = F(2, 1) = -2$. In the same way we find

$$
\begin{array}{lll}
\mathcal{Y}(1) = \{2\}, & y^*(1) = 2, & F(1, 2) = -7, \\
\mathcal{Y}(1.5) = [1.5, 3], & y^*(1.5) = 1.5, & F(1.5, 1.5) = -4.5 \\
\mathcal{Y}(2.5) = [1.75, 5]\,, & y^*(2.5) = 1.75, & F(2.5, 1.75) = -4.5, \\
\mathcal{Y}(3) = [2.5, 6]\,, & y^*(3) = 2.5, & F(3, 2.5) = -7, \\
\mathcal{Y}(3.5) = [3.25, 5], & y^*(3.5) = 3.25, & F(3.5, 3.25) = -9.5, \\
\mathcal{Y}(4) = \{4\}, & y^*(4) = 4, & F(4, 4) = -12.
\end{array}
$$

The second level's aspiration to minimize its objective function is shown in the graphical representation by the green downward-pointing

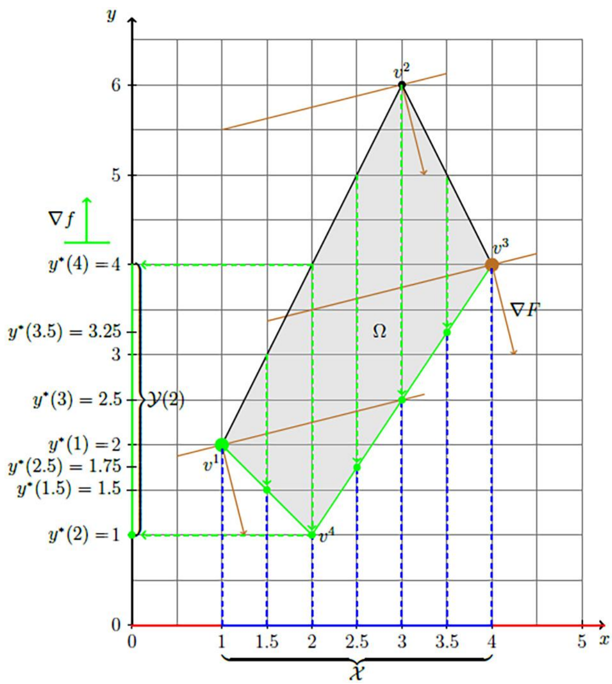


FIGURE 1.3 The geometric interpretation of example 3.

arrows. It is not difficult to establish that $\mathcal{Y}(0.5) = \emptyset$ just like $\mathcal{Y}(5) = \emptyset$, i.e., the strategies $x = 0.5$ and $x = 5$, even though they belong to the set X, are not admissible. The set of inadmissible first-level strategies $x \in X$ ($\mathcal{Y}(x) = \emptyset$) is the union $[0, 1) \cup (4, +\infty]$ and is shown in red in Fig. 1.3. The set of admissible strategies $\mathcal{X}$ (in this case $\mathcal{X} = \{x \in X : \mathcal{Y}(x) \neq \emptyset\}$) is the segment $[1, 4]$, which is shown in blue in Fig. 1.3. In this example, Conjecture 1 holds: the solution to the second-level problem $y^*(x)$ is unique for any admissible strategy $x \in [1, 4]$ and is defined as follows

$$y^*(x) = \begin{cases} 3 - x, & 1 \le x \le 2, \\ \dfrac{3}{2}x - 2, & 2 \le x \le 4. \end{cases} \tag{1.112}$$

The extremal mapping $\Psi(x)$ defined in (1.83) consists of one point, $\Psi(x) = \{y^*(x)\}$ given $x \in [1, 4]$ and for the entire set X has the form

$$\Psi(x) = \begin{cases} \emptyset, & 0 \le x < 1, \\ \{3 - x\}, & 1 \le x \le 2, \\ \left\{\dfrac{3}{2}x - 2\right\}, & 2 \le x \le 4, \\ \emptyset, & 4 < x. \end{cases} \tag{1.113}$$

The reactive set $\mathcal{R}$ is a polygonal chain connecting the vertices v^1, v^4, v^3 and is shown in green in Fig. 1.3:

$$\mathcal{R} = \begin{cases} \emptyset, & 0 \le x < 1, \\ \{(x, 3-x)\}, & 1 \le x \le 2, \\ \left\{\left(x, \frac{3}{2}x - 2\right)\right\}, & 2 \le x \le 4, \\ \emptyset, & 4 < x. \end{cases} \tag{1.114}$$

Since in the first-level problem there are no general inequality constraints and equality constraints, then $\mathcal{R} = \mathcal{D}$ (see (1.109)) and by virtue of (1.110)–(1.111) the bilevel programming problem under consideration is the problem of minimizing the upper-level objective function $F(x, y) = x - 4y$ on the polygonal chain $v^1 - v^4 - v^3$, which is the admissible set $\mathcal{D}$. It is not difficult to see that $\mathcal{D}$ is a nonconvex set, hence this *bilevel programming problem is a global (multi-extremal) optimization problem*. Gradient $\nabla F(x, y)$ is shown in Fig. 1.3 in brown. From the geometric interpretation, we can see that the problem has two extrema: the vertex v^1 (shown in green) is the point of local minimum of $F(x, y)$ on $\mathcal{X}$, $F(v^1) = -7$; the vertex v^4 (shown in brown) is the point of global minimum of $F(x, y)$ on $\mathcal{X}$, $F(v^4) = -12$. Obviously, the point v^4 is the solution to the bilevel programming problem.

The optimal value function of the first level (1.106) given (1.112) will be of the following form

$$\varphi(x) = \begin{cases} +\infty, & \text{if } 0 \le x < 1, \\ 5x - 12, & \text{if } 1 \le x \le 2, \\ -5x + 8, & \text{if } 2 \le x \le 4, \\ +\infty, & \text{if } 4 < x. \end{cases}$$

The graph of the function $\varphi(x)$ is shown in Fig. 1.4, within the segment $[1, 4]$ φ it is a piecewise-linear concave function, the local minimum is reached at point $x = 1$, $\varphi(1) = -7$, the global minimum is reached at point $x = 4$, $\varphi(4) = -12$.

Let us discuss, based on this example, the influence of the second-level objective function on the solution of the bilevel programming problem as stated by J.F. Bard (1.91)–(1.98). The exclusion of requirement (1.95) from the consideration means that the first level fails to take into account the interests of the second level, so the second level problem turns into the system of constraints (1.96)–(1.98). Since the first level makes a decision in its own interest taking into account the constraints (1.92)–(1.94), (1.96)–(1.98), as a result, we obtain the minimization problem $F(x, y)$ with respect to the set of variables (x, y) on the weak admissible set Ω, i.e., the conventional linear programming problem. Its solution is the vertex

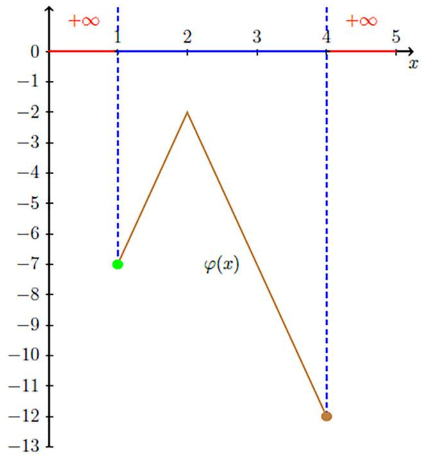


FIGURE 1.4 Graph $\varphi(x)$.

$v^2 = \begin{pmatrix} v_1^2 \\ v_2^2 \end{pmatrix} = \begin{pmatrix} 3 \\ 6 \end{pmatrix}$ and the value of the objective function $F(v^2) = -21$, which is less than the optimal value of the bilevel programming problem $F(v^4) = -12$. The difference between the values of $F(v^2)$ and $F(v^4)$ reflects the effect of taking into account the interests of the second level. The vertex v^4 is "suboptimal" from the standpoint of the second level and is therefore unacceptable, $v^4 \notin \mathcal{D}$. From the point of view of the entire bilevel programming problem as stated by S. Dempe (1.86)–(1.90), the extremal inclusion (1.90) is violated: $v_2^2 = 6 \notin \Psi(v_1^2) = \Psi(3) = \{2.5\}$. The extremal constraint (1.90) isolates from Ω the nonconvex boundary $\mathcal{R} = \mathcal{D}$ and turns a bilevel programming problem into a single-level global (multi-extremal) optimization problem.

5. Bilevel programming. The non-uniqueness of the second-level problem solution. Let us now abandon Conjecture 1. In this case the set $\Psi(x)$ in (1.83), if it is not empty, may consist of more than one point. Let us assume for simplicity that the given first-level strategy $\tilde{x} \in X$ corresponds to the set $\Psi(\tilde{x})$, consisting of two points, $\Psi(\tilde{x}) = \left\{y^{*,1}(\tilde{x}), y^{*,2}(\tilde{x})\right\}$, and the corresponding pairs $(\tilde{x}, y^{*,1}(\tilde{x}))$, $(\tilde{x}, y^{*,2}(\tilde{x}))$ satisfy the inequalities (1.88). Then the ambiguity arises as to what to take as the value of the first-level objective function: $F(\tilde{x}, y^{*,1}(\tilde{x}))$ or $F(\tilde{x}, y^{*,2}(\tilde{x}))$? From the point of view of the second level, both solutions $y^{*,1}(\tilde{x})$, $y^{*,2}(\tilde{x})$ are equivalent: $f(\tilde{x}, y^{*,1}(\tilde{x})) = f(\tilde{x}, y^{*,2}(\tilde{x}))$. The second level can return to the first one either $y^{*,1}(\tilde{x})$, or $y^{*,2}(\tilde{x})$ if, furthermore, $F(\tilde{x}, y^{*,1}(\tilde{x})) < F(\tilde{x}, y^{*,2}(\tilde{x}))$, and the second level returns $y^{*,2}(\tilde{x})$, then it is obviously not beneficial to the first one, but the first level can not influence this situation in any way.

In the case of non-uniqueness of the second-level solution, the first-level optimal value function φ in (1.106) is not defined, since it is not clear what to choose as $y^*(x)$. The way out of this situation is proposed as follows: we introduce the optimistic function

$$\varphi_0(x) = \begin{cases} \min_y \{F(x, y) : y \in \Psi(x)\}, & \text{if } x \in \mathcal{X}, \\ +\infty, & \text{if } x \notin \mathcal{X}, \end{cases} \tag{1.115}$$

and the pessimistic function

$$\varphi_p(x) = \begin{cases} \min_y \{F(x, y) : y \in \Psi(x)\}, & \text{if } x \in \mathcal{X}, \\ +\infty, & \text{if } x \notin \mathcal{X}. \end{cases} \tag{1.116}$$

In both the optimistic and pessimistic cases, the second level achieves its goal: $y \in \Psi(x)$. In the optimistic case, the second level sees no reason not to respond in the way most favorable for the first level, so an additional minimization with respect to y appears in (1.115). In the pessimistic case, the first level aims at determining the most unfavorable, i.e. the worst result for itself, so in (1.116) the maximization operation with respect to y is used.

The bilevel programming problem in the optimistic statement is the problem of optimization of the optimistic function

$$\varphi_o(x) \to \min, \tag{1.117}$$
$$x \in \mathcal{X}. \tag{1.118}$$

Accordingly, the bilevel programming problem in the pessimistic statement is the problem of minimization of the pessimistic function

$$\varphi_p(x) \to \min, \tag{1.119}$$
$$x \in \mathcal{X}. \tag{1.120}$$

Let us also introduce the point-to-set mapping $\Phi : \mathbb{R}^{n_1} \rightrightarrows \mathbb{R}$, which serves as a generalization of the function φ:

$$\Phi(x) = \{\xi \in \mathbb{R} : \xi = F(x, z),\ z \in \Psi(x)\}. \tag{1.121}$$

In what follows, our analysis will be related to the point-to-set mapping Ψ from (1.82) and therefore we will state the bilevel programming problem as stated by S. Dempe.

Example 4. The problem is of the following form:

$$F(x, y) = x + y \to \min_y, \tag{1.122}$$
$$x \in X = \{x \in \mathbb{R} : -1 \le x \le 1\}, \tag{1.123}$$

$$y \in (x), \tag{1.124}$$

$$\Psi(x) = \arg\min_{y} \{xy : -1 \le y \le 1\}. \tag{1.125}$$

In this case $\mathcal{X} = X = [-1, 1]$, the set $\Psi(x)$ for each $x \in [-1, 1]$ is defined by the sign x:

$$\Psi(x) = \begin{cases} \{1\}, & \text{if } x < 0, \\ \{-1, 1\}, & \text{if } x = 0, \\ \{-1\}, & \text{if } x > 0. \end{cases} \tag{1.126}$$

The graph of the point-to-set mapping Ψ is shown in Fig. 1.5a. The second-level problem has the unique solution $y^*(x)$ for any $x \neq 0$, hence, the value of $F(x, y^*(x))$ is uniquely defined as $\forall x \neq 0$. The mapping φ is defined as follows:

$$\Phi(x) = \begin{cases} \{x + 1\}, & \text{if } x < 0, \\ \{-1, 1\}, & \text{if } x = 0, \\ \{x - 1\}, & \text{if } x > 0. \end{cases} \tag{1.127}$$

The graph of mapping Φ is shown in Fig. 1.5b.

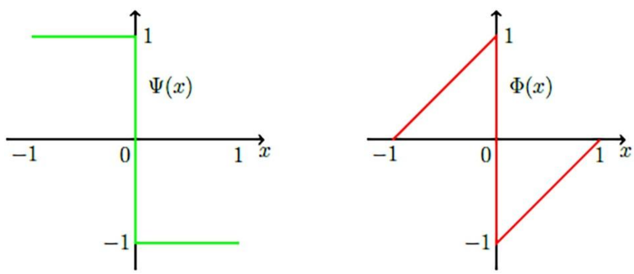


FIGURE 1.5 Graphs of mappings: a) Ψ; b) Φ.

If $x \to +0$, then unambiguously $y^*(x) = -1$ and $F(x, y^*(x)) \to -1$, with $F(x, y^*(x)) > -1 \ \forall x > 0$. If the first level chooses the strategy $x = 0$, then the second level can return as the response any value from the segment $\{-1, 1\}$, including $y = 1$. In this case, the value of the upper-level objective function jumps from a value, however close to the most favorable -1, to the most unfavorable 1. The problem here is that given $x = 0$ the first level has no effect on the choice of the response of the second one, it only limits that response to the segment $\{-1, 1\}$.

If $x \neq 0$, then $\varphi_o(x) = \varphi_p(x)$. Given $x = 0$ according to (1.115), (1.116), and (1.127)

$$\varphi_o(0) = \min\{F(0, y) : y \in \Psi(0)\} = \min\{y : y \in [-1, 1]\} = -1,$$

$$\varphi_p(0) = \max\{F(0, y) : y \in \Psi(0)\} = \max\{y : y \in [-1, 1]\} = 1.$$

Full description of functions ϕ_o and φ_p:

$$\varphi_o(x) = \begin{cases} x+1, & \text{if } x<0, \\ -1, & \text{if } x=0, \\ x-1, & \text{if } x>0, \end{cases} \quad \varphi_p(x) = \begin{cases} x+1, & \text{if } x<0, \\ 1, & \text{if } x=0, \\ x-1, & \text{if } x>0. \end{cases}$$

The graphs of functions φ_o and φ_p are shown in Figs. 1.6a and 1.6b.

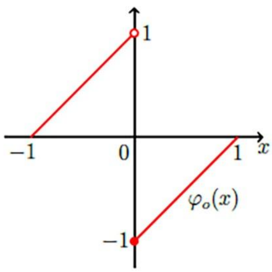


FIGURE 1.6 Graphs of the function: a) φ_o and b) mapping φ_p.

Obviously, the minimization problem $\varphi(x)$ on $\mathcal{X}$ has the solution $x^{*,o} = 0$, and the minimization problem $\varphi_p(x)$ on $\mathbb{X}$ has no solution. If we take $x > 0$ arbitrarily close to 0, then the value of the pessimistic function $\varphi(x)$ will be arbitrarily close to -1, i.e., to the minimum value of the optimistic function $\varphi_o(0) = -1$. In the general case, as will be shown in the following example, this property is not satisfied: even if the minimum value of the pessimistic function exists, it may differ significantly from the minimum value of the optimistic function.

6. Model C. Let us return again to the model discussed in subsection 3. Let us assume that the price of power π depends linearly on its total amount

$$\pi(x) = \rho - \omega \sum_{j-1}^{n} x_j. \tag{1.128}$$

In this case, each generator j can influence the price by changing the amount of power x_j it delivers. Let us emphasize this influence by writing the dependency of price on power as follows

$$\pi(x_j, x_{-j}) = \rho - \omega \sum_{j-1}^{n} x_j. \tag{1.129}$$

The symbol x_{-j}, as adopted in game theory, denotes the vector x without the component j: $x_{-j} = (x_1, \ldots, x_{j-1}, x_{j+1}, \ldots, x_n)$. The generator j profit according to (1.129)

$$R_j(x_j, x_{-j}) = \pi(x_j, x_i)x_j - c_j(x_j). \tag{1.130}$$

The notation $R_j(x_j, x_{-j})$ reflects the fact that the generator j, by varying x_j, can achieve an increase in its profits. It is natural to assume that the generator will strive to increase profits within its capabilities

$$R_j(x_j, x_{-j}) \to \max_{x_j}, \tag{1.131}$$

$$0 \le x_j \le \overline{x}_j. \tag{1.132}$$

Since the profit of the $-j$-th generator $R_j(x_j, x_{-j})$ depends on the behavior of other generators x_{-j}, it cannot solve the problem (1.131)–(1.132) by itself, it must know the values of x_{-j}, otherwise the problem (1.131)–(1.132) is underspecified. Consequently, each generator depends on the behavior of the other generators, each seeking to maximize its profits. We get *a system of interrelated optimization problems*:

$$\begin{cases} R_1(x_1, x_{-1}) \to \max\limits_{0 \le x_1 \le \bar{x}_1}, \\ R_2(x_2, x_{-2}) \to \max\limits_{0 \le x_2 \le \bar{x}_2}, \\ \vdots \\ R_n(x_n, x_{-n}) \to \max\limits_{0 \le x_n \le \bar{x}_n}. \end{cases} \tag{1.133}$$

The solution to the systems of problems (1.133) will be understood as the Nash equilibrium: the vector x^* such that

$$R_j(x_j^*, x_{-j}^*) \ge R_j(x_j, x_{-j}^*) \forall x_j \in \left[0, \bar{x}_j\right], \; j = 1, \dots, n.$$

The meaning of the Nash equilibrium is that if an equilibrium is reached, then each generator alone (using only its variable x_j with the behavior x_{-j}^* of the others fixed) cannot increase its profits. In accordance with the terminology of game theory, the power x_j will also be called the generator (player) strategy j.

In the general case, an equilibrium may not exist. If it exists, it may be non-unique. Further, if it is known theoretically that an equilibrium exists, then finding an equilibrium can prove a difficult combinatorial problem. The model (1.129), (1.130), (1.131) we are considering is a variant of the Cournot model.

In addition to the interests of generators (1.131)–(1.132) it is necessary to take into account the grid component, namely the power x_j, delivered by generators must satisfy the grid constraints

$$x_j - \sum_{j'=1}^{n} a_{jj'} y_{jj'} + \sum_{j'=1}^{n} a_{j'j}(1 - \delta_{j'j}) y_{j'j} = d_j, \; j = 1, \dots, n, \tag{1.134}$$

$$0 \le y_{jj'} \le \bar{y}_{jj'}, \;\; j, j' = 1, \ldots, n. \tag{1.135}$$

In contrast to the situation considered earlier (when generators acted as price takers), in the model considered here, the generators set the price (see (1.128)). The demand $d = (d_1, \ldots, d_n)$ becomes a variable. It is necessary to comment on the following assumption. If we sum up Eqs. (1.134), we obtain

$$\sum_{j=1}^{n} x_j - \sum_{j=1}^{n} \sum_{j'=1}^{n} \delta_{jj'} y_{jj'} = \sum_{j=1}^{n} d_j$$

– the total supply of power less grid losses is total demand. Unlike with the Cournot model, here the total supply does not equal the total demand. Since the price depends on the power supply (1.128) and not on demand, we will assume that the grid losses are at the expense of the consumer.

The final model in question consists of relations (1.129), (1.130), (1.133), (1.134), and (1.135). If in (1.133) the generator j could choose its strategy independently of the others, $x_j \in [0, \bar{x}_j]$, then now, by virtue of the constraints (1.134)–(1.135), the choice of the strategy x_j depends on the choice of strategies of the other generators. The Nash equilibrium with dependent choice of strategies is called the generalized Nash equilibrium.

The main property of the model under consideration is the linearity of the function (1.128). Because of this property, the model in question has the so-called property of *potentiality* [81]. The potentiality of the equilibrium model allows one to reduce the search for equilibrium to the conventional optimization problem. The objective function in such a problem is called a potential. The point of maximum potential is the equilibrium point.

The potential in our model is a concave quadratic function and has the form

$$\Pi(x) = -\frac{\omega}{2} x^T H x + \rho \sum_{j=1}^{n} x_j - \sum_{j=1}^{n} c_j(x_j), \tag{1.136}$$

$$H = \begin{pmatrix} 2 & 1 & \ldots & 1 \\ 1 & 2 & \ldots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \ldots & 2 \end{pmatrix}.$$

The search for equilibrium is now reduced to solving the problem of maximizing the potential $\Pi(x)$ with respect to the set of variables (x, y, d) under constraints (1.132), (1.134), (1.135), which we will further call a potential problem.

The potential $\Pi(x)$ is a strictly concave function x and does not depend on flows y and demand d. As a consequence, the solution of the potential problem is unique with respect to x and is non-unique with respect to y and d. This fact can be used to get the maximum desired values of demand.

So, let the constants d_j^0 set the desired demand. As before, we will assume that maximum satisfaction of demand is the goal of the system operator. Let us state a corresponding bilevel problem.

The first-level problem is the problem of the system operator:

$$\sum_{j=1}^{n}(d_j - d_j^0) \to \min_{\overline{y}_{jj'}}, \tag{1.137}$$

$$0 \le \overline{y}_{jj'} \le v_{jj'}, \ j, j' = 1, \dots, n. \tag{1.138}$$

The second-level problem is to find an equilibrium between the generators

$$\Pi(x) \to \min_{x,y,d}, \tag{1.139}$$

$$x_j - \sum_{j'=1}^{n} a_{jj'} y_{jj'} + \sum_{j'=1}^{n} a_{j'j}(1 - \delta_{j'j}) y_{j'j} = d_j, \ j = 1, \dots, n, \tag{1.140}$$

$$0 \le x_j \le \overline{x}_j, \ j = 1, \dots, n, \tag{1.141}$$

$$0 \le y_{jj'} \le \overline{y}_{jj'}, \ j, j' = 1, \dots, n. \tag{1.142}$$

The system operator controls the maximum capacity of the lines $\overline{y}_{jj'}$. By setting these capacities, they pass them on to the second level. The second level solves the problem of finding an equilibrium between generators for given capacities. The resulting demand vector d is returned to the first level to the system operator. The system operator checks how much the obtained demand deviates from the specified demand d^0, changes the maximum capacities without exceeding the specified ones $v_{jj'}$, and the whole procedure is repeated again.

This bilevel model is undoubtedly provisional in nature. Our goal here is to demonstrate the possibilities of bilevel programming. It is not guaranteed to fully meet a given demand, the goal is to find such capacities at which the resulting demand will be the least deviating from the given demand.

The bilevel solution problems, as well as the Nash equilibrium search problems in the general statement, are extremely difficult to solve. For the purposes of this description, we will not dwell on the solution methods; we will refer only to monographs [80–82] and a review article [79] containing 1,362 references.

Example 5. This example is a continuation of Example 2. $\rho = 800$, $\omega = 0.143$. Specified demand $d^0 = (100,\ 120,\ 80)$. At the maximum capacities given in Example 2, $\overline{y}_{jj'} = 50$, $\overline{y}_{31} = 10$, the solution of the second-level problem (1.139)–(1.142) is as follows: power is $x^{*,1} = (80, 100,\ 122.377)$, flows are $y_{31}^{*,1} = 5.09$, $y_{32}^{*,2} = 3.26$ (the others are zero), demand is $d^{*,1} = (85.043,\ 103.226,\ 114.024)$. The deviation from the specified demand (the value of the objective function (1.137) at $d = d^{*,1}$) is 34.024. Note that the above solution is a second-level problem given initially specified maximum capacities, the minimization of the first-level objective function was not performed. The solution to the bilevel problem is as follows. Variables of the first level: obtained maximum capacities are $\overline{y}_{31}^{*,2} = 44.780$, $\overline{y}_{32}^{*,2} = 11.166$, demand is $d^{*,1} = (104.2433,\ 111.0546,\ 86.7223)$, deviation from the specified demand is 8.945. Variables of the second level powers $x^{*,1} = (80,\ 100,\ 122.377)$, flows $y_{31}^{*,1} = 24.488$, $y_{32}^{*,2} = 11.166$. Recall the nodal prices of Example 2 $\lambda^* = (742.825,\ 735.397,\ 728.043)$. The price obtained by solving the bilevel problem $\pi^* = 756.76$.

1.5 Intelligent information technologies in hierarchical modeling of energy systems

Introductory remarks. The dissemination of the concepts of Smart Grid [18,23] and Digital Energy [83–85] in Russia generates the need to take into account the fact that their adoption is that concerning two distinct interrelated areas: technological infrastructure and information and telecommunication infrastructure. The success of the digital transformation of the energy sector largely depends on the successful application of modern information technologies. In turn, the application of the latter makes sense if there is a developed modern technological infrastructure. Solutions for the development of technological infrastructure, of course, belong to the class of strategic decisions. The Melentiev Energy Systems Institute SB RAS for decades has conducted hierarchical energy studies, the results of which can be used to justify strategic decisions on energy development.

To justify and support such decisions, it is advisable to use intelligent information technologies. These are primarily the technologies of semantic modeling and knowledge management that are developed by a team under the guidance of the authors and used to create intelligent systems to support strategic decision making in the energy sector. We have proposed an approach to the construction of such an intelligent system (multi-agent development environment). It integrates mathematical and semantic methods and models, and software tools for their support development.

Hierarchical system studies of the energy sector. The key research areas of such studies include the theory of building energy systems, complexes, and plants, and their control; theoretical foundations and mechanisms for implementing the energy policy of Russia and its regions [86]. The studies within the framework of these areas focus on energy systems (electricity, gas, oil, oil products, heat), Russia's energy security, regional energy issues, interactions between energy and economy, promising energy sources and systems, and studies in the applied mathematics and computer science [83,85].

Until recently, the main tool for such studies has been mathematical modeling and computational experiment. In the context of the new development trends in Russia's energy sector (Smart Grid and Digital Energy), much attention is paid to the development and application of intelligent information technologies. The Digital Economy Program implemented in Russia is now actively developed. The federal project "Digital Energy Sector" is a part of this Program. The authors believe that the federal project "Digital Energy Sector" does not pay enough attention to such areas as intelligent support of strategic decision-making on the development of the technological infrastructure of the energy sector and cybersecurity of critical energy facilities. Below we consider the former area in more detail. A major role in making strategic decisions should be played by their scientific justification that is to employ the state-of-the-art scientific knowledge.

Traditionally, a hierarchical research scheme is used, where economic and mathematical models are used at the aggregated level of the studies of the energy sector and industry-specific energy systems, whereas physical and mathematical models are used at the lower levels (Fig. 1.7) [87]. These models have to be coordinated. Research into projecting energy development is carried out at the top level, based on the results obtained in the studies on the development of industry-specific energy systems at the lower levels. The scheme includes several blocks, each of which corresponds to a set of mathematical methods, models, and software systems that are used to perform computational experiments using these methods and models [83,84].

The results of these studies can be used to substantiate the strategic decisions on energy sector development through a formal integration of software and information support to improve the hierarchical technology to justify the development of the energy sector as a whole, and its industry-specific and territorial components. The main attention, however, should be paid to the development of software and information interfaces between tasks in horizontal (between energy systems) and vertical (energy systems – energy sector - external conditions) terms.

The development and implementation of such interfaces should provide the following advantages of a complex hierarchical research technology: a) confidentiality of the main detailed data arrays supporting specific tasks should be preserved (ensured with the necessary refinement of the required software tools); b) the information exchange should be formalized and thereby accelerated, and the uniqueness of the exchanged data should be provided; c) the information models used in solving various problems should be unified, which will need to be implemented to coordinate and develop interfaces; d) in general, the "harmony" and the validity of the hierarchical technology should be increased for substantiating the development of the energy sector and its components.

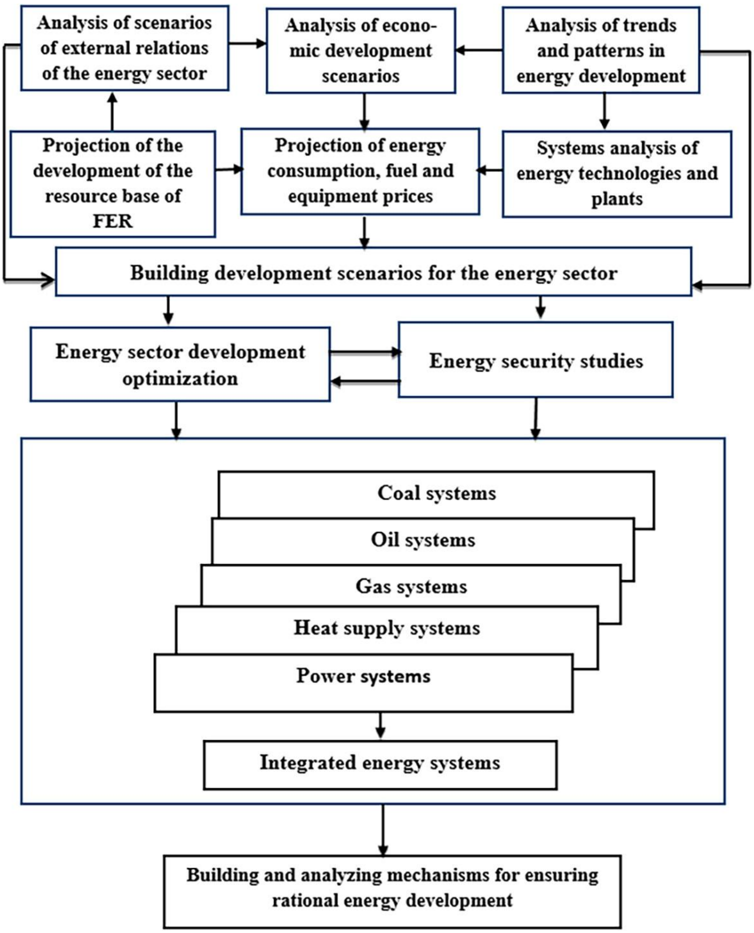


FIGURE 1.7 A general scheme of hierarchical studies to substantiate the development of the energy.

The integration of software, information support and intelligent information technologies. Implementation of the proposed integration capabilities can be provided using the following information technologies: a) a common information and communication environment for software components; b) semantic integration of data, knowledge, and software components; c) tools for case-based management and semantic modeling.

This study proposes the implementation of a unified information and communication environment for the interaction of software components in the form of a cloud service. This service will provide network access to a common pool of configurable computing resources (for example, servers, storage devices, applications, and services, etc.) on demand. To ensure the necessary level of security, it is advisable to implement the information and communication environment in the form of a corporate cloud [88].

For semantic integration of data, knowledge, and software components, we propose using the concept of knowledge management and applying it as a methodological fractal approach to structuring the knowledge [89].

The main idea of the fractal approach is that it introduces the concepts of information space and information worlds (subspaces). The Fractal Stratified (FS) model is defined as a set of disjoint strata (information worlds) and their mappings in the information space. Each level has its stratum of this space, and, therefore, its information world; the sequence of mappings reflects the process of cognition. Graphically, the FS-model is conveniently represented as a set of nested spherical shells. An information object, conventionally designated by a dot on one of the spheres, in turn, can be stratified, if necessary, to study it in more detail. Mappings are from any stratum into any other stratum are introduced. Since we, as a rule, consider a part of the information space (our own "fractal" of knowledge), it can be represented by a "clipping" from the information space, which can be represented as a cone or a pyramid, corresponding, for example, to selected disciplines when we study the real world. The application of the FS-model is illustrated in Fig. 1.8 [89].

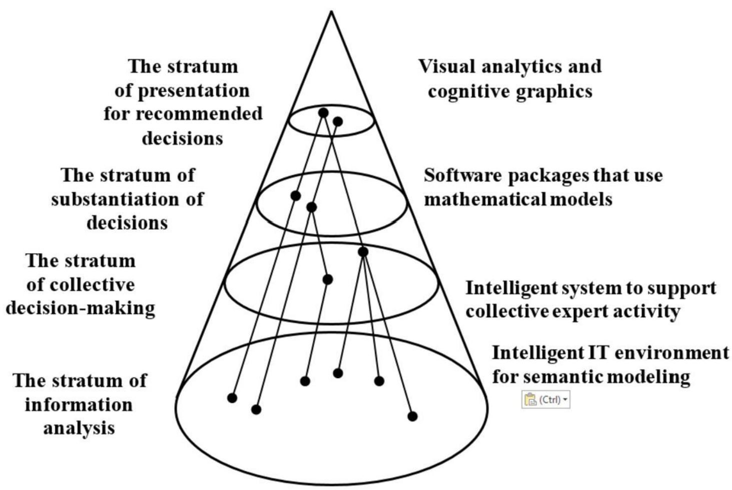


FIGURE 1.8 FS-model of strata (stages) of studies (left) and the tools to support them (right).

There are two approaches to knowledge management: classical (based on a combination of existing, already proven technologies for support of various subprocesses of working with knowledge) and semantic (based on the use of an interconnected set of methods and technologies for working with meaning, or semantics of data, information, and knowledge) [90].

In the framework of the latter approach, one uses ontologies of subject areas, technologies for their construction and maintenance, semantic metadata, semantic search, logical inference systems, semantic profiling of expert knowledge, semantic portals, and networks, etc. As a rule, they are accompanied by appropriate technological support for description languages, models, software tools, and systems. The team led by the authors is developing the second approach.

The integration of mathematical and semantic modeling tools is proposed to justify strategic decisions on energy sector development. Below we consider the concepts and content of semantic modeling.

A semantic model in a generalized form is an information model that reflects the concepts of the subject area and relationships between them. The authors consider semantic modeling as exemplified by ontological, cognitive, event, and probabilistic (based on Bayesian belief networks) models [88,89]. Table 1.2 shows a comparison of semantic modeling technologies applied to energy security studies.

TABLE 1.2 Comparison of ontological, cognitive, event, and probabilistic modeling.

Technology	Purpose of use	Apparatus for formalized representation	Use in energy security (ES) studies
Ontology modeling	To describe declarative pieces of knowledge	Ontologies (purpose-made languages (OWL, RDF, XML, etc.))	To identify, classify, and specify basic concepts in energy research
Cognitive modeling	To identify causal relationships between concepts	Cognitive maps (graph theory)	To analyze energy security threats
Event modeling	To build behavioral models. To identify the dynamics of unfolding of an emergency	Event Maps (Joiner Networks Theory)	To analyze development and consequences of emergencies
Probabilistic modeling	To construct probabilistic models. To assess the risk of ES threat occurrence	Bayesian Belief Networks	To assess risks of emergencies

Ontological modeling is the construction of ontologies, in both their graphical form and formalized form. Ontologies are defined as a knowledge base of a special kind, or as a “specification of a conceptualization” of a subject domain [90]. The latter means the classification of the basic terms of the subject area with the definition of basic notions (concepts) and the establishment of relations between them. In turn, the specification process consists in describing the ontology in a graphical form ('soft' or heuristic ontologies) or in one of the formal languages (XML, RDFS, OWL, etc.) ('hard', or logical ontologies). When cooperating with subject area experts a graphical representation of ontologies is used. Ontologies are stored using their representation in XML.

Cognitive modeling is the construction of cognitive models, or, in other words, cognitive maps (directed graphs), in which the vertices correspond to factors (concepts) and the edges correspond to the links between factors (positive or negative), depending on the nature of the causal relationship. In the simplest case, the weights of the links can have the values of $+1$ or -1 or take fuzzy values from the interval $[-1, 1]$ or some linguistic scale. The use of cognitive models is most consistent with the qualitative analysis [91].

Event modeling is the construction of behavioral models, and both people and engineering facilities can act as objects of modeling. The essence of the event modeling method is to track the sequence of events by the model in the same order in which they would occur in a real system. The sequence of events defined by the model — the chain of events — describes scenarios of the system's response to the occurrence of a triggering event at the beginning of the chain. As a result, the event model allows obtaining many alternative scenarios for the development of a given situation in the system, which is the main goal of event modeling [92].

Probabilistic modeling is the construction of graphical models that display the probabilistic dependencies of many variables, and allow probabilistic inference using these variables. Recent publications in this area merge the findings of the studies carried out mainly in the 1980s. The results of the application of this approach by the authors to the energy sector using Bayesian belief networks are presented, for example, in [93].

Semantic models are developed based on expert knowledge and allow the use of both explicit and implicit knowledge based on the experience, erudition, and intuition of experts. For example, cognitive models that display causal relationships can be used to describe and analyze scenarios of external relations of the energy sector, scenarios of economic development and development of the energy sector. Event and probabilistic models allow us to consider options for the development of various situations determined by the selected scenarios. After an expert evaluation of various development options using semantic models, conventional software systems that implement mathematical models of industry-specific energy systems and the energy sector are employed, and optimization problems are solved to substantiate the recommended solutions.

In our study, the case-based management concept is used in line with the works by D.A. Pospelov and his students [94]. Recently, this concept is recommended to use for operational control, but we believe it can be applied to the field of substantiation of strategic decisions. We rely on a modern interpretation of case-based management as considered in [95]. The case-based management concept is used to justify and support decision-making to ensure energy security. This is considered, in particular, in [96].

The integration of mathematical and semantic modeling tools is proposed to justify strategic decisions in the energy sector [97]. In this case, both basic technologies are used: agent-oriented and cloud computing on a par with problem-oriented semantic and mathematical modeling. The two-level technology for the research integrating semantic and mathematical modeling and supporting its intelligent IT environment is developed. The latter includes semantic modeling tools and enables integration with conventional software systems (Fig. 1.9) [98].

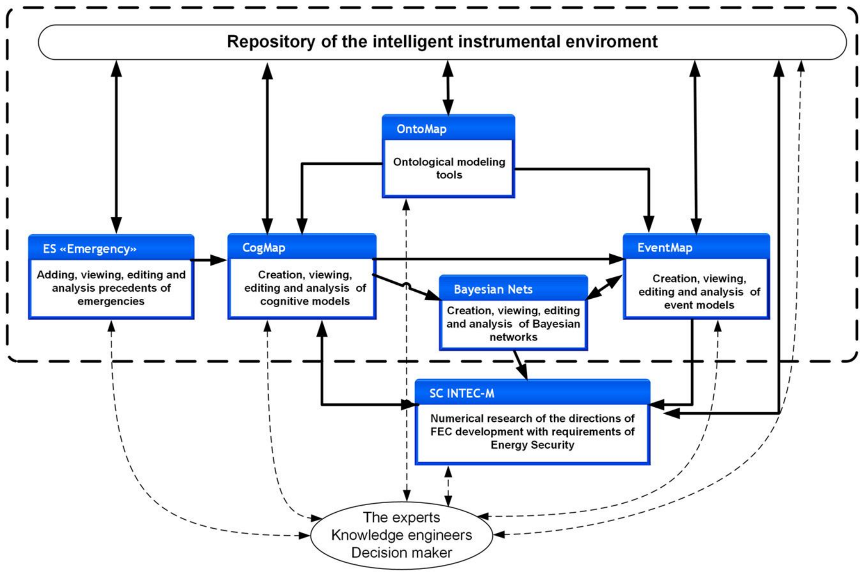


FIGURE 1.9 Interaction of tools in the Intelligent IT environment.

Tools supporting the upper (qualitative) level of the proposed technology are circled by a dotted line. OntoMap, CogMap, EventMap, and Bayesian Nets, respectively, are tools for supporting the ontological, cognitive, event, and probabilistic modeling. The 'Emergency' expert system contains precedents of emergencies in the energy sector, which can be used in the construction of semantic models. 'Geocomponent' is a 3D-geovisualization tool. The bottom left of the block shows the multi-agent software system INTEK-M, used at the second, quantitative level of the proposed technology for state estimation and prediction of development options for the energy sector.

An intelligent IT environment is treated as a prototype Multi-Agent Intelligent Environment (MAIE) to support hierarchical studies. Its diagram is shown in Fig. 1.7. The following levels (stages) of studies and the supporting tools are identified for this workflow (Fig. 1.10). Their stratification using the FS model is shown in Fig. 1.8.

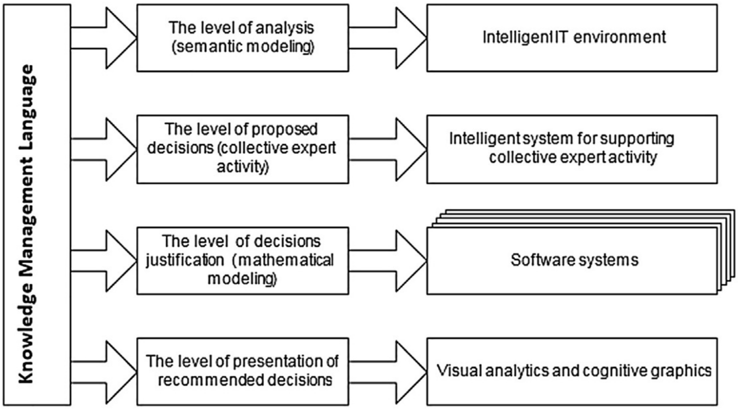


FIGURE 1.10 Levels (stages) of energy systems studies and the tools to support them.

These levels are:

1. The level of information analysis (using semantic modeling), supported by the Intelligent IT environment.
2. The level of collective implementation of coordinated decisions (one can use semantic modeling, methods for coordinating decisions, and other methods) supported by the Intelligent Support System for Collective Expert Activity [96].
3. The level of substantiation of decisions (the options proposed at the previous stage are calculated using conventional software systems for studying the energy sector and energy systems).
4. The level of presentation of the proposed decisions (using visual analytics and cognitive graphics).

The MAIE architecture was developed to support the adoption of strategic decisions in the energy sector using the proposed methodological approach and scientific prototypes of tools (Fig. 1.10) [99].

The main components (agents) of the MAIE are:

1. Software Systems and Databases for studies of the energy sector together with Software and Databases employed, for example, for energy security studies.
2. Data and Knowledge Warehouse.
3. Intelligent IT environment to support semantic modeling.
4. An intelligent system for supporting collective expert activity.
5. Software component for visual analytics (geovisualization component).
6. Repository for storage of descriptions of all intelligent and information resources supported by the MAIE.

7. Knowledge Management Language (KML) to ensure the interconnection and interaction of all components (agents) of the MAIE.
8. Portal supporting Ontological Knowledge Space in the field of energy studies.

Knowledge Management Language is used for the integration of these components and for calling a required component.

We have developed a methodological approach to the construction of multi-agent systems and propose it to implement MAIE (Fig. 1.11). Its novelty is due to the fact that a method is proposed to control the interaction of agents based on algebraic networks. For the implementation of the method, event models of agent interaction scenarios are developed. This approach was tested in the development of a multi-agent system for the state estimation of electric power networks (Fig. 1.12) [99].

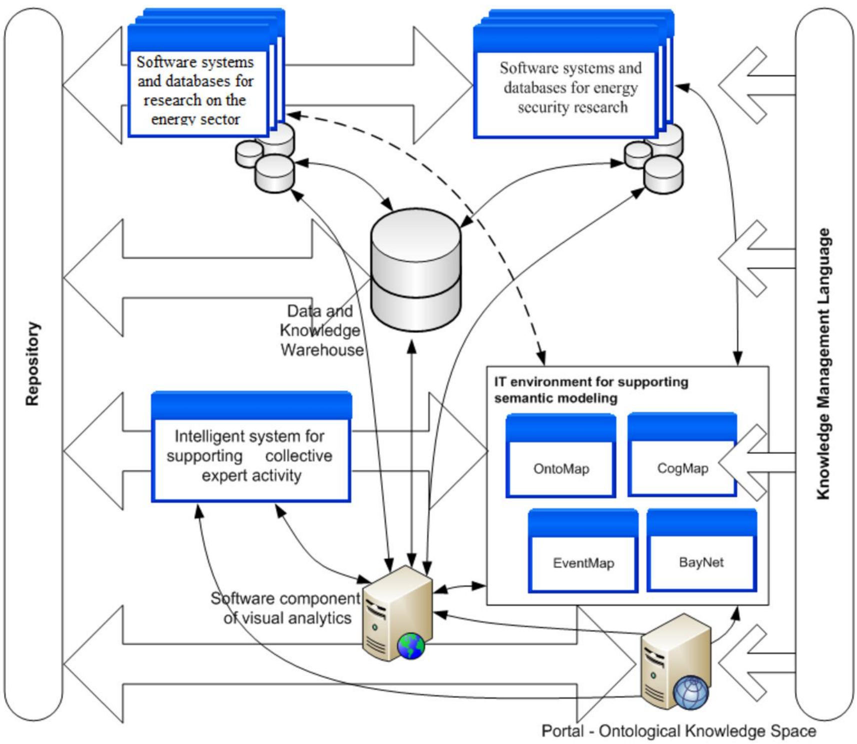


FIGURE 1.11 The architecture of the multi-agent intelligent environment (MAIE).

Now we have scientific prototypes of all basic components of this workflow (2–8), which can be used after their adaptation, and integration in the implementation of the MAIE. Further testing of the method is required to solve practical problems in this area.

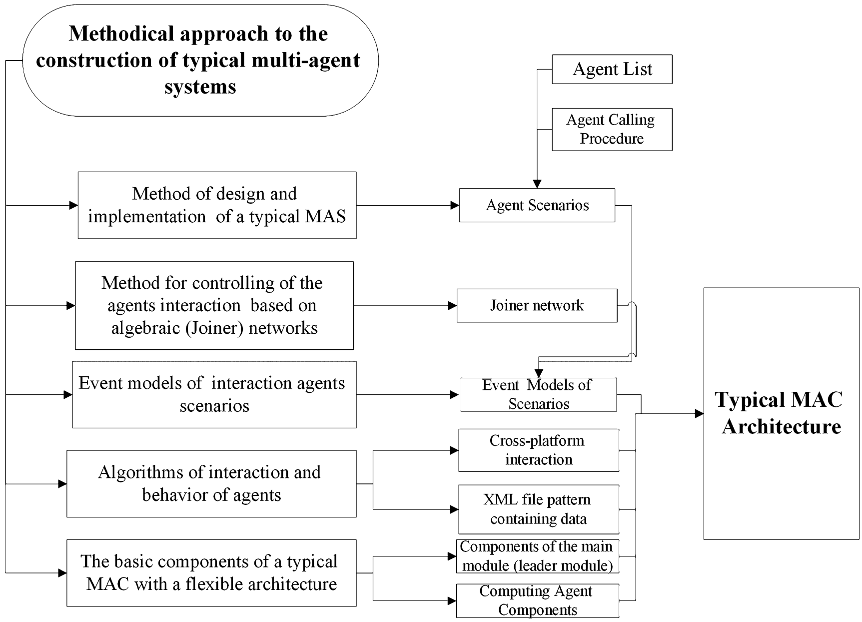


FIGURE 1.12 Methodological approach to the construction of a multi-agent system.

Complete incorporation of the software and databases for studies of the energy sector and energy systems as agents into the MAIE (item 1 of the above list) will require their re-engineering since most of them have been relegated to the category of legacy software. At the first stage, one can limit the process of incorporating the software and database at the level of information exchange. In this case, the studies are carried out independently, their results are transferred to the Data and Knowledge Warehouse, and the fact of the transfer is recorded in the Repository.

The above architecture does not include cybersecurity tools, as this should be a set of measures that take into account possible cybersecurity vulnerabilities and reflect the current state of cybersecurity tools (aimed at preventing cyber attacks). The authors also contributed to the body of published research in this area [100].

Generally speaking, the study emphasizes that the concept of digital energy fails to pay attention to such issues as intelligent support for strategic decisions on the development of the technological infrastructure of the energy sector and those on cybersecurity of critical energy facilities. We proposed eliminating these shortcomings by using the results of the hierarchical studies conducted at the MESI, which integrate the existing results into mathematical and semantic modeling; case-based management; agent, cloud, and intelligent computing. We presented an approach to integrating software, information support, and intelligent information technologies required for research activities. We proposed the architecture of a multi-agent intelligent environment integrating heterogeneous components and reviewed the state of its development.

Acknowledgments

The research was carried out under State Assignment Project (no. FWEU-2021-0001) of the Fundamental Research Program of Russian Federation 2021–2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] N.I. Voropai, V.A. Stennikov, Energy strategy of Russia: a changing view on the development of the electric power industry, Energeticheskaya Politika 2 (2013) 66–70 (in Russian).
[2] N.I. Voropai, A.B. Osak, Electric power systems of the future, Energeticheskaya Politika 5 (2014) 60–63 (in Russian).
[3] V.V. Bushuev, Electric power industry in the energy strategy of Russia, Elektrichestvo 8 (2014) 4–9 (in Russian).
[4] N.I. Voropai, Electric power system transformations: a review of main prospects and challenges, Energies 13 (2020) 5639, https://doi.org/10.3390/en13215639.
[5] X.-P. Zhang, Ch. Rehtanz, B. Pal, Flexible AC Transmission Systems: Modelling and Control, Springer, Verlag, Berlin–Heidelberg, 2006, p. 383.
[6] Z.A. Styczynski, F. Adamek, N.I. Voropai, et al., Electric Energy Storage Systems, CIGRE, Paris, 2011, p. 95.
[7] G. Allee, W. Tschudi, Edison redux: 380V DC brings reliability and efficiency to sustainable data centers, IEEE Power & Energy Magazine 10 (6) (2012) 50–59.
[8] B.T. Patterson, DC come home: DC microgrid sand the birth of the “Enernet”, IEEE Power & Energy Magazine 10 (6) (2012) 60–69.
[9] N.I. Voropai, Smart grid: myths, reality, prospects, Energeticheskaya Politika 2 (2010) 9–14 (in Russian).
[10] Yin Wei, D. Kundur, Two-tier hierarchical cyber-physical security analysis framework for smart grid, in: IEEE PES General Meeting, San Diego, USA, July 22–27, 2012, p. 5.
[11] A.B. Osak, D.A. Panaseckij, E.Ja. Buzina, Reliability and safety aspects in the design of digital substations, in: International Science and Technology Conference “Modern Directions of Development of Power-System Protection”, Yekaterinburg, Russia, June 3, 2013, p. 7 (in Russian).
[12] V.A. Stennikov, On reforming the heat supply industry of Russia, Energosberezhenie 5 (2015) 63–66, Energosberezhenie 6 (2015) 62–67 (in Russian).
[13] N.N. Novitsky, Methodological problems of making pipeline systems intelligent and directions of the hydraulic circuits theory development aimed to solve them, in: Mathematical Models and Methods of Analysis and Optimal Synthesis of Developing Pipeline and Hydraulic Systems, Melentiev Energy Systems Institute SB RAS, Irkutsk, 2014, pp. 301–318 (in Russian).
[14] Pike research: smart energy revenue $420 billion by 2015, https://www.environmentalleader.com/2012/06/pike-research-smart-energy-revenue-420-billion-by-2015/#/ixzz3dCj1XlPd, 2012. (Accessed 11 June 2012).
[15] N.I. Voropai, V.A. Stennikov, Integrated intelligent energy systems, Izvestija RAN. Energetika 1 (2014) 64–78 (in Russian).

[16] Grid 2030: a national version for electricity's second 100 years, Office of Electric Transmission and Distribution, US State Department of Energy, Washington, July, 2003, p. 36.
[17] European Smart Grid technology platform: Vision and strategy for Europe's electricity networks of the future, European Commission, Brussels, 2006, p. 23.
[18] V.V. Dorofeev, A.A. Makarov, Active adaptive grid: a brand-new quality of the unified energy system of Russia, Energoekspert 4 (2009) 28–34 (in Russian).
[19] N.I. Voropai, Intelligent power systems: the concept, current state, and prospects, Avtomatizacija i IT v Energetike 3 (20) (2011) 11–16 (in Russian).
[20] J. Momoh, Smart Grid: Fundamentals of Design and Analysis, John Wiley and Sons, New York, 2012, p. 216.
[21] Jiang Zhenhua, Li Fangxing, Qiao Wei, Sun Hongbin, et al., A vision of smart transmission grid, in: IEEE PES General Meeting, Calgary, Canada, July 26–30, 2009, p. 10.
[22] Yusheng Xue (Some viewpoints and experiences on Wide Area Measurement Systems and Wide Area Control Systems), in: IEEE PES General Meeting, Pittsburgh, USA, July 20–24, 2008, p. 6.
[23] R.N. Berdnikov, V.V. Bushuev, S.N. Vasil'ev, N.I. Voropai, The concept of the intelligent electric power system of Russia with an active and adaptive grid, in: V.E. Fortov, A.A. Makarov (Eds.), Federal Grid Company of Unified Energy System JSC, Moscow, 2012, p. 219 (in Russian).
[24] S.N. Vasil'ev, N.I. Voropai, V.V. Dorofeev, D.N. Efimov, et al., Theoretical foundations, methods, and models of the control of large electric power systems, in: N.I. Voropai (Ed.), Federal Grid Company of Unified Energy System PJSC, Moscow, 2015, p. 188 (in Russian).
[25] U. Haeger, Ch. Rehtanz, N. Voropai (Eds.), Monitoring, Control and Protection of Interconnected Power Systems, Springer, Heidelberg, 2014, p. 391.
[26] K. Yuasa, Ya. Fuji, Developing advanced metering (the ubiquitous metering systems), in: XXV, World Gas Conference, June 4–8, 2012, p. 9.
[27] M. Pionno, T. Carretero, R. Jane, et al., Smart gas meters and middleware for energy efficiency embedded, in: XXV World Gas Conference, June 4–8, 2012, p. 7.
[28] G. Gervigni, M. Di Castelnuovo, S. Cagnoli, et al., The policies for the large-scale deployment of smart gas meters in some European countries and draw policy implications, in particular for Italy, in: XXV World Gas Conference, June 4–8, 2012, p. 8.
[29] M.G. Suharev, The current state of the problem and methods of ensuring the reliability of gas supply systems. Reliability of energy systems: problems, models, and methods of solving them, in: N.I. Voropai (Ed.), Nauka, Novosibirsk, 2014, pp. 165–189 (in Russian).
[30] N.I. Voropai, B.G. Saneev, S.M. Senderov, V.A. Stennikov, Energy of the future: complex problems of innovative development and management, in: Russia's Energy Sector in the 21st Century, Innovative Development and Management, Proceedings of the All-Russian Conference, Irkutsk, September 1–3, 2015, pp. 10–21 (in Russian).
[31] Web resource, http://celsiuscity.eu/.
[32] Linking Heat and Electricity Systems. Co-generation and District Heating and Cooling Solutions for a Clean Energy Future, IEA Publishing, Paris, 2014, p. 62.
[33] Web resource, http://dbdh.dk.
[34] Web resource, http://www.ens.dk/.
[35] Web resource, http://eu-smartcities.eu, https://eu-smartcities.eu/sites/all/files/Smart%20Thermal%20Grids%20%20Smart%20Cities%20Stakeholder%20Platform.pdf.
[36] Web resource, http://www.energymonitor.tudelft.nl/.
[37] D. Connolly, H. Lund, B.V. Mathiesen, S. Werner, B. Möller, U. Persson, et al., Heat roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system, Energy Policy 65 (2014) 475–489.

[38] M.A. Ancona, L. Branchini, A. De Pascale, F. Melino, Smart district heating: distributed generation systems' effects on the network, Energy Procedia 75 (2015) 1208–1213.
[39] S. Heinen, M. O'Malley, Power system planning benefits of hybrid heating technologies, in: Proc. IEEE PowerTech, Eindhoven, Netherlands, June 29 – July 2, 2015, pp. 1–6.
[40] H. Wang, W. Yin, El. Abdollah, R. Lahdelma, W. Jiao, Modelling and optimization of CHP based district heating system with renewable energy production and energy storage, Applied Energy 159 (2015) 401–421.
[41] Th. Nuytten, B. Claessens, Kr. Paredis, J.V. Bael, D. Six, Flexibility of a combined heat and power system with thermal energy storage for district heating, Applied Energy 104 (2013) 583–591.
[42] X.S. Jiang, Z.X. Jing, Y.Z. Li, Q.H. Wu, W.H. Tang, Modelling and operation optimization of an integrated energy based direct district water-heating system, Energy 64 (2014) 375–388.
[43] T. Fang, R. Lahdelma, Genetic optimization of multi-plant heat production in district heating networks, Applied Energy 159 (2015) 610–619.
[44] A.M. Kler, N.P. Dekanova, E.A. Tjurina, et al., Thermal and Power Systems: Optimization Studies, Nauka, Novosibirsk, 2005, p. 236 (in Russian).
[45] P. Basak, S. Chowdhury, S.P. Chowdhury, et al., Automated demand side management strategy of microgrids, in: IEEE Power Con 2012, Auckland, New Zealand, October 30 – November 2, 2012, p. 6.
[46] G.T. Constanzo, Guchuan Zhu, M.F. Anjos, G. Savard, A system architecture for autonomous demand side load management in smart buildings, IEEE Transactions on Smart Grid 3 (4) (2012) 2157–2165.
[47] N.I. Voropai, M.V. Gubko, S.V. Kovalev, et al., Issues of development of the digital energy in Russia, Problemy Upravleniya 1 (2019) 2–14 (in Russian).
[48] The strategy of scientific and technological development of the Russian Federation: Decree of the President of the Russian Federation of December 1, 2016, No. 642, https://online.mai.ru/StrategySTD%20RF.pdf?referer=https%3A%2F%2Fwww.google.com%2F, 2016. (Accessed 1 December 2021) (in Russian).
[49] N.I. Voropai, Hierarchical technology for electric power system expansion planning, in: Budapest PowerTech, Budapest, Hungary, August 29 – September 2, 1999, p. 5.
[50] N.I. Voropai, S.V. Podkovalnikov, V.V. Trufanov, et al., Substantiation of the Development of Electric Power Systems, Methodology, Models, Methods, and Their Application, Nauka, Novosibirsk, 2015, p. 448 (in Russian).
[51] M.D. Mesarovic, D. Macko, Ya. Takahara, Theory of Hierarchical, Multilevel Systems, Academic Press, New York – London, 1970, p. 344.
[52] M.D. Mesarovic, Ya. Takahara, General Systems Theory: Mathematical Foundations, Academic Press, New York – London, 1975, p. 311.
[53] B.S. Fleishman, Fundamentals of Systemology, Radio i Svjaz', Moscow, 1982, p. 368 (in Russian).
[54] Optimization and Control in Large Energy Systems, vol. 1, Siberian Energy Institute, Siberian Branch of the Academy of Science of the USSR, Irkutsk, 1970, p. 450 (in Russian).
[55] A.A. Makarov, Methods and Models of Alignment of Hierarchical Decisions, Nauka, Novosibirsk, 1979, p. 296 (in Russian).
[56] L.A. Melentiev, System Studies in Energy. Elements of Theory and Directions for Development, Nauka, Moscow, 1983, p. 456 (in Russian).
[57] Hierarchy in large energy systems, in: Proceedings of the Symposium, vol. 1, Siberian Energy Institute, Siberian Branch of the Academy of Science of the USSR, Irkutsk, 1978, p. 278 (in Russian).
[58] Hierarchy in large energy systems, in: Proceedings of the Symposium, vol. 2, Siberian Energy Institute, Siberian Branch of the Academy of Science of the USSR, Irkutsk, 1978, p. 266 (in Russian).

[59] M.L. Manheim, Hierarchical Structure: a Model of Design and Planning Processes, Mir, Moscow, 1970, p. 179 (in Russian).
[60] Yu.V. Kovachich, B.M. Avdeev, V.M. Levitsky, System engineering and hierarchical structures, Introduction to the Russian edition, in: M.L. Manheim (Ed.), Hierarchical Structure: a Model of Design and Planning Processes, Mir, Moscow, 1970, pp. 5–11 (in Russian).
[61] P.S. Krasnoshhekov, V.V. Morozov, V.V. Fedorov, Decomposition in design tasks, Izvestija AN SSSR. Tekhnicheskaja Kibernetika 2 (1979) 7–17 (in Russian).
[62] P.S. Krasnoshhekov, V.V. Morozov, V.V. Fedorov, Sequential aggregation in the tasks of the internal design of engineering systems, Izvestija AN SSSR. Tekhnicheskaja Kibernetika 5 (1979) 5–12 (in Russian).
[63] P.S. Krasnoshhekov, V.V. Morozov, N.M. Popov, V.V. Fedorov, Hierarchical design workflows and numerical decomposition methods (in Russian), Izvestija RAN. Teorija i Sistemy Upravlenija 5 (2001) 80–89 (in Russian).
[64] D.A. Novikov, S.N. Petrakov, K.A. Fedchenko, Decentralization of planning mechanisms in active systems, Avtomatika i Telemekhanika 6 (2000) 143–155 (in Russian).
[65] A.N. Voronin, A method of multi-criteria evaluation and optimization of hierarchical systems, Kibernetika i Sistemnyj Analiz 3 (2007) 84–92 (in Russian).
[66] G.A. Ugol'nickij, Game-theoretic study of some methods of hierarchical control, Izvestija RAN. Teorija i Sistemy Upravlenija 1 (2002) 97–101 (in Russian).
[67] A.N. Govorov, A.F. Tarakanov, Coalition-hierarchical game under uncertainty, Izvestija RAN. Teorija i Sistemy Upravlenija 3 (2008) 75–80 (in Russian).
[68] N.I. Voropai, E.Yu. Ivanova, Hierarchical game technology problem for electric power system expansion planning, in: 2003 IEEE Bologna Power Tech, Italy, June 23–26, 2003, p. 5.
[69] N.A. Abramenkova, N.I. Voropai, T.B. Zaslavskaya, Structural Analysis of Electric Power Systems (in the Problems of Modeling and Synthesis), Nauka, Novosibirsk, 1990, p. 224 (in Russian).
[70] P. Dimo, REI Models and Operation Parameters. Interconnected Power Systems, Energoatomizdat, Moscow, 1987, p. 392 (in Russian).
[71] H. Frank, I.T. Frisch, Communication, Transmission, and Transportation, Addison Wesley, London, 1970, p. 448.
[72] L.S. Lesdon, Optimization of Large Systems, Nauka, Moscow, 1975, p. 432.
[73] P. Ranganathan, K.E. Nygard, Distributed Linear Programming Models in a Smart Grid, Springer, Heidelberg, 2017, p. 213.
[74] A.G. Sukharev, A.V. Timokhov, V.V. Fedorov, A Course on Optimization Methods, Fizmatlit, Moscow, 2005, p. 368 (in Russian).
[75] B.T. Polyak, Introduction into Optimization, Nauka, Moscow, 1983, p. 384 (in Russian).
[76] Yu.E. Nesterov, Introduction into Convex Optimization, MCNMO, Moscow, 2010, p. 280 (in Russian).
[77] S. Dempe, Foundations of Bilevel Programming, Kluwer Academic Publishers, Dordrecht, 2002, p. 306.
[78] S. Dempe, V. Kalashnikov, G.F. Perez-Valdes, N. Kalashnikova, Bilevel Programming Problems, Theory, Algorithms and Applications to Energy Networks, Springer, Heidelberg, 2015, p. 325.
[79] S. Dempe, Bilevel optimization: Theory, algorithms and applications, Preprint 2018-11, Fakultät für Mathematik und Informatik, Technical University, Freiberg, 2018, p. 86.
[80] J. Bard, Practical Bilevel Optimization. Algorithms and Applications, Kluwer Academic Publishers, Dordrecht, 1998, p. 473.
[81] V.V. Mazalov, Mathematical Game Theory and Applications, Lan Publishing, Saint-Petersburg, 2016, p. 448 (in Russian).
[82] M. Bazara, K. Shetty, Non-linear Programming. Theory and Methods, Mir, Moscow, 1982, p. 584 (in Russian).

[83] N.I. Voropai, M.V. Gubko, S.P. Kovalev, L.V. Massel, D.A. Novikov, A.N. Raikov, S.M. Senderov, V.A. Stennikov, Problems of the development of digital energy in Russia, Problemy Upravleniya 1 (2019) 2–14, https://doi.org/10.25728/pu.2019.1.1 (in Russian).

[84] Expert and analytical report, Digital transition in the electric power industry of Russia, https://www.csr.ru/issledovaniya/tsifrovoj-perehod-v-elektroenergetike-rossii/, 2018. (Accessed 8 October 2018) (in Russian).

[85] Proceedings of the 2nd Industry-Specific Conference "Digital Transformation of the Electric Power Industry of Russia", Moscow, http://digitenergy.ru/, October 2017. (Accessed 11 December 2017) (in Russian).

[86] N.I. Voropai (Ed.), System research in the energy sector: a retrospective of scientific areas, Nauka, Novosibirsk, 2010, p. 686 (in Russian).

[87] N.I. Voropai, A.M. Kler, Yu.D. Kononov, B.G. Saneev, S.M. Senderov, V.A. Stennikov, Methodological foundations of strategic planning for energy industry development, Energeticheskaya Politika 3 (2018) 35–44 (in Russian).

[88] L.V. Massel, V.V. Gribova, A.N. Kopaygorodsky, "Cloud" structure of energy-information systems, in: V.M. Batenin, V.V. Bushuev, N.I. Voropay (Eds.), Innovative Electric Power-21, Energiya Publishing Center, Moscow, 2017, pp. 556–577 (in Russian).

[89] L.V. Massel, Fractal approach to constructing ontological knowledge space, in: 2018 3rd Russian-Pacific Conference on Computer Technology and Applications (RPC), IEEE, 2018, pp. 1–5, https://doi.org/10.1109/RPC.2018.8482138, https://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=8469127.

[90] A.F. Tuzovsky, S.V. Chirikov, V.Z. Yampolsky, Knowledge Management Systems (Methods and Technologies), NTL Publishing House, Tomsk, 2005, p. 260.

[91] L.V. Massel, A.G. Massel, Semantic technologies based on the integration of ontological, cognitive, and event modeling, in: Proceedings of the III International Scientific and Technical Conference OSTIS-2013, Belarus, Minsk, BSUIR, 2013, pp. 247–250 (in Russian).

[92] L.V. Massel, A.G. Massel, Intelligent computing in studies of direction of energy industry development, Vestnik Tomskogo Politekhnicheskogo Universiteta, Management, Computer Engineering, and Computer Science 321 (5) (2012) 135–141 (in Russian).

[93] L.V. Massel, E.V. Pyatkova, The use of Bayesian belief networks for the intelligent support of research on energy security problems, Vestnik ISTU 2 (2012) 8–13 (in Russian).

[94] D.A. Pospelov, Case-Based Management, Theory and Practice, Nauka, Moscow, 1986, p. 284 (in Russian).

[95] V.I. Vasiliev, B.G. Ilyasov, Intelligent Control Systems, Theory and Practice, Radiotekhnika, Moscow, 2009, p. 392 (in Russian).

[96] N.I. Pyatkova, L.V. Massel, A.G. Massel, Methods of case-based management in studies of energy security issues, Izvestija RAN. Energetika 4 (2016) 156–163 (in Russian).

[97] L.V. Massel, Integration of semantic and mathematical modeling in studies of energy security issues, in: Proceedings of the International Conference "Modeling-2012", G.E. Pukhov, Institute for Modelling in Energy Engineering, NAS of Ukraine, Kyiv, 2012, pp. 270–273 (in Russian).

[98] L. Massel, A. Massel, Intelligent support tools for strategic decision-making on Smart Grid development, in: Proceedings of the International Conference 'Green Energy and Smart Grids' (GESG 2018), 2018, pp. 1–8, https://doi.org/10.1051/e3sconf/20186902009.

[99] L.V. Massel, V.I. Galperov, Development of multi-agent systems for the distributed solution of energy problems using agent scenarios, Vestnik Tomskogo Politekhnicheskogo Universiteta 326 (5) (2015) 45–53 (in Russian).

[100] A.G. Massel, A technique of threat analysis and risk assessment of information-technological security breaches of energy complexes, in: Proceedings of the XX Baikal All-Russian Conference Information and Mathematical Technologies in Science and Management, vol. III, 2015, pp. 186–195 (in Russian).

CHAPTER

2

Hierarchical modeling in energy sector

Yu.D. Kononov, B.G. Saneev, S.M. Senderov, S.P. Popov, A.V. Lagerev, A.D. Sokolov, I.Yu. Ivanova, R.I. Muzychuk, A.G. Korneev, N.I. Pyatkova, and D.S. Krupenev

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

The modern energy industry is a complex elaborate infrastructure aggregate of components that are formed as a set of complex geographically dispersed energy systems (electric power, heat/cold, gas, oil, and petroleum products supply systems, and a few others), interacting and mutually influencing each other under standard and, all the more so, emergency conditions.

There are many methodological problems in the study of such large-scale complex energy sector. It is impossible to solve with acceptable results above mentioned problems without hierarchical modeling. This chapter includes some key directions of implementing hierarchical methodology to energy sector modeling. First of all, the evolution of hierarchical modeling technology is discussed concerning the projection studies of long-term energy sector development in the context of energy-economy interactions. After that hierarchical methodology is presented for energy sector development of the country and its regions (for energy sector of Russia as an example) taking into account cross-border fuel and energy interrelations. And last but not least, the hierarchy of models for energy security study at national and regional levels is considered.

Hierarchical Modeling of Energy Systems
https://doi.org/10.1016/B978-0-44-313917-8.00011-0

2.1 The evolution of hierarchical modeling in the projection studies of long-term energy sector development in the context of energy-economy interactions

Introductory remarks.

A long-term projection is the initial stage of the systems studies and substantiation of prospects for energy development. It is intended to outline the space of possibilities for feasible and efficient development of the national energy sector; identify the matters of concern and the bottlenecks to be addressed while pursuing such development; to set targets, the framework, and data required to further and detail the research when working out the energy strategy and policy, general schemes (master plans) and programs for the development of industry-specific and regional energy systems, as well as strategic plans of energy companies. A long-term projection is also crucial for laying the forward-looking groundwork in a broad area of knowledge related to the energy industry development.

The objective and significant growth of uncertainty in both external and internal conditions of the energy sector development contributes to the increased importance of long-term projections yet hinders the enhancement of their quality.

Improvement and elaboration of the employed economic and mathematical models are considered to be the main strategy to build trust and confidence in projections. Significant progress has been made in this area in Russia and other countries. It seems unlikely, however, to expect further successful combating uncertainty by relying solely on greater disaggregation of modeled objects and on detailing of the external and internal links of systems and their properties. The approach to delineating and narrowing down the projection range, which sequentially identifies and solves the main problems while taking into account the uncertainty of the input data and requirements for the quality of solutions (see Table 2.1), appears more promising.

An important role in factoring in the uncertainty when making a long-term projection of the energy sector development is played by the scenario approach, i.e., model calculations under various possible states of the external environment. It is the analysis of a set of options considered to be optimal under certain conditions that basically defines the projection range (“the uncertainty cone”) of the long-term development of the energy sector.

Narrowing down of this range is facilitated by further improvement in methodological tools, identification of the most important problems for each time frame segment, and determination of a rational hierarchy of models to solve these problems.

TABLE 2.1 The sequence of projection studies of the national energy sector and main problems to be solved.

Steps	Problems
1. Defining scenarios and conditions for the energy sector development	Scenarios of economic development and the state of global energy markets. Projection of the maximum possible range of energy demand and prices and that of scientific and technological advances. Assessment of temporal barriers (factoring in inertia).
2. Generating and analyzing energy sector development options for each scenario of external conditions	Stage 1 Generating available options under maximum uncertainty of the input data. Stage 2 Narrowing down the uncertainty range through the following: the models used to refine projections of the state of regional energy markets, to assess investment barriers to new capacity additions, and to factor in regional variations. Stage 3 Narrowing down the uncertainty range through the following: the models for the analysis of the sensitivity of options to changes in the imposed constraints and requirements, the models of detailing the features and possibilities of development of the electric power industry and other systems of individual industries. Risk assessment of energy and fuel supply options. Identifying invariants (for a given scenario).
3. Generalization of the findings of scenario studies	Delineating the overall projection range of the energy sector development (for all scenarios). Delineating the areas of invariants and areas of instability. Highlighting major strategic-level threats. Making approximate estimates of energy security metrics thresholds. Preparing supporting materials to back the working out of energy strategy and programs for the development of the energy sector industries, research activities, and technology.

Evolution of the applied models for energy sector development.
The recognition of the important part played by long-term projections in developing strategic decisions was instrumental in developing the methodology of projections based on the systems analysis methods. A major contribution to the development of such methods and economic and mathematical models as applied to the energy industry was made by the Siberian Energy Institute, Siberian Branch of the Academy of Sciences of the USSR (nowadays, the Melentiev Energy Systems Institute (MESI) of Siberian Branch of the Russian Academy of Sciences), where, in the 1970s, the energy sector optimization model, the first one in the USSR, was developed [1], and a system of models for long-term projections of energy development was created. Apart from the energy sector model, it included an input-output optimization model, a regression model of energy con-

sumption, and a model of the requirements set by the energy sector with respect to its development that are to be met by linked industries and production facilities. A structurally similar system of models was employed back then to make the world energy projection at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria [2].

The evolution of the models and their applications as employed in projections of energy industry development initially followed the path of gradual sophistication by way of an increasingly more elaborate representation of the economy in energy models and a more detailed description of the energy sector in models of the economy. However, by as early as the 1980s, in the USSR and other countries, the concept of employing hierarchically-built models to take account of the interactions between the energy sector and the economy gained wide acceptance, with macro-economic models coming into ever more prominence. Abroad, it was mostly econometric models built upon the notion of the general equilibrium, while in the USSR and other planned economies input-output model served the same purpose.

The changes in the social environment and business administration rules brought about by the 1990s set the task of updating the time-honored methods and tools employed for energy sector projections. The new economic order made it indispensable to take account of emerging energy markets and their role. Nowadays, cross-national differences in modeling interactions between the energy industry and the economy have grown much less pronounced.

As the scope of problems extended with the complexity of the tasks growing further, the tendency toward building computational systems that imply the use of capable computers and state-of-the-art information technology was becoming more and more conspicuous. The two basic approaches to the problem have come to dominate the discourse.

The first one is based on the ad hoc choice of certain models out of an available pool of various economic and mathematical models, which are indispensable for solving specific problems of long-term projections of energy industry development. However, interactions between models in the systems to be built do not have to be automated. Such an approach has been implemented, for example, at the MESI, where the experience accumulated over several decades helps to adapt the models sensibly and build their combinations catered to a specific projection. The adjustment of input data and constraints during the controlled iterative calculations and harmonizing various models make it possible to solve the problem of considering and reconciling different optimality criteria.

An alternative approach to model integration is about striving to automate calculations and use a unified database (the integrating module) and even a common optimality criterion. This approach is exemplified by the powerful NEMS (The National Energy Modeling System) computer system [3]. It was designed and implemented by the Energy Information Administration (EIA) of the US Department of Energy (DOE) in 1993 and have since been used to estimate possible consequences of alternative cases of various (probable) energy market conditions for the energy, the economy, the environment, and the national security. NEMS is made up of over a dozen models (modules), including but not limited to the following: the macro-economic activity module, the international energy module, four supply modules; two conversion modules; four end-use demand modules, etc. The system ensures the balance between supply and demand for energy commodities for nine aggregated regions covering all the US States.

In Russia, new modeling and information systems that are based on the integration of existing and newly built mathematical models underpinned by the cutting-edge information technology are developed to ensure systems assessment of efficiency and risks for various scenarios of the energy development, with the latter treated as an integral part of the economy. Such models are meant to enable us to capture possible consequences of decisions worked out by top-level political and economic government agencies of the country. One such system that proved successful is SCANER [4], which is being developed and maintained at the Energy Research Institute of the Russian Academy of Sciences.

Alongside vertical (cross-level) interactions, the SCANER modeling system allows for strong horizontal links, i.e., those between regional energy sector models, energy sector industries and companies, as well as between functional (that is, product demand, production and transportation, economy and financing, etc.) and temporal modules of a model of the same economic entity. Dedicated methods of horizontal harmonization of solutions obtained by optimization models have been developed to properly take account of such links. They provide for the iterative exchange of information between a given model and all the other models of the same hierarchical level on production (consumption) volumes and prices (cost-effectiveness) of each energy source used in each of the regions in each of the years of a given time frame.

The state-of-the-art computer and information technologies enable us to build arbitrarily complex systems of models. It is unreasonable, however, not to allow for the following: large and ever-growing uncertainty of input data; dependence of required accuracy of calculations on the time frame and the problem-specific context; the complexity of analyzing the results under the enormous number of variables, links, and criteria; the practicality of involving experts in some of the calculation steps. These features make us be cautious when building multi-model systems for simultaneous (joint) optimization of energy and economy development.

Such systems that feature fully automated calculations are not only hard to debug but, what is of more importance, do not lend themselves

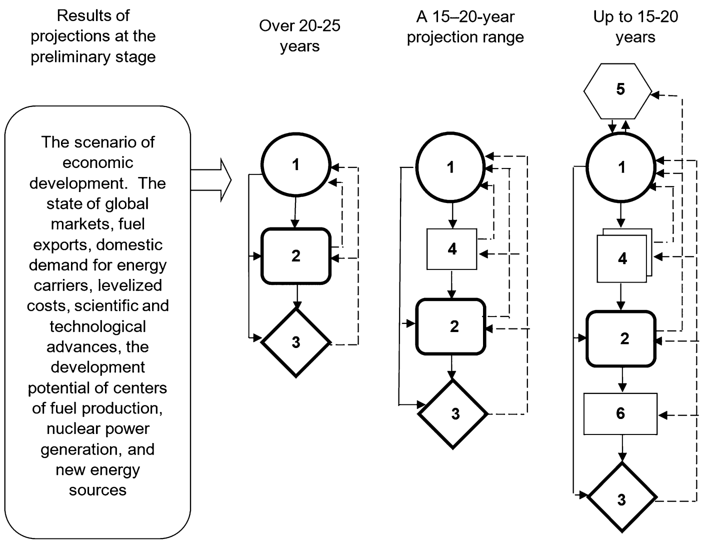


FIGURE 2.1 Hierarchy of problems and models at various temporal stages of working out and studying the options of long-term development of the energy sector: 1 - energy sector; 2 - state of regional energy markets (demand and prices); 3 - barriers and threats; 4 - industries of the energy sector; 5 - macroeconomic conditions; 6 - energy companies.

naturally to tracking the contributions of individual variables and links and interpreting the results afterward. An informal approach that implies an analysis of the information that serves as the output of one model and then fed into another model significantly simplifies the study of complex problems.

An important principle of model improvement is matching the accuracy of calculation results with the accuracy of the input data [5]. The principle is similar to the nearly proverbial Occam's razor principle and assumes building models that are as simple as possible yet capable of accounting for defining properties of the studied system that are required to appropriately solve the task under given conditions. This echoes the following quote attributed to Albert Einstein as well: "Everything should be made as simple as possible, but not simpler".

The principle of correspondence between research tools used and uncertainty of input data is fulfilled by a two-stage approach to narrowing down the uncertainty range of conditions and results by way of iterative calculations with the aid of models of various hierarchical levels employed at each temporal stage (Fig. 2.1) and by way of reconciliation of totals in time [6]. In so doing, at the initial stage one assumes the maximum time frame (over 25 years) and the minimum number of hierarchical levels and models (see Fig. 2.1).

The two-stage approach to making projections by moving in a retrograde fashion from the more remote future to the near future proposed herein does not preclude one from the subsequent reverse iteration of projection studies: i.e., the adjustment of long-range projections to the results obtained by more detailed analysis of a shorter time frame. Iterative calculations carried out (top-down and bottom-up) in each temporal stage make it possible to take account of the features specific to the development of systems (their opportunities and requirements) of varying hierarchical levels that form the national energy system.

It seems that the mix of the models and the degree of their aggregation should depend on a given time frame, given that as the projection time frame increases, on the one hand, the uncertainty of the input data grows, and, on the other hand, the requirements for the accuracy of projections get less stringent.

An important advantage of using a hierarchy (system) of economic and mathematical models for modeled projection studies of the energy sector is the possibility of adjusting the constraints set in each model by taking into account not only direct links but also the feedback between the models during iterative calculations. A special role here is played by the inclusion in the projection workflow of regional energy market models and taking into account the price elasticity of demand, i.e., the impact of changes in the cost of energy carriers on the demand for them.

At the stage of making projections of the energy sector for the time period of up to 15-20 years, it is important to assess the possible macroeconomic consequences of changes that take place in the course of iterative calculations with respect to a) constraints imposed on the availability of investment resources, b) energy prices, and c) other indicators. Optimization dynamic models are used for such an assessment. A concise overview of such models developed in Russia and abroad is given in [7].

In any hierarchy of models used in projections of the national energy sector development, optimization models of the energy sector play a key role. They allow tentatively singling out the balanced options of new capacity additions in the electric power industry and the fuel industry that satisfy the predefined demand for energy carriers as per a given criterion.

An overview of such a model employed at the MESI is presented in [8]. The balance between production and consumption of energy carrier e in region r in year t is stated in the model as follows:

$$\sum_{p\in P_r} a^t_{epr} X^t_{pr} + \sum_{r'} Y^t_{er'r} + I^t_{er} = \sum_{r'} b^t_{err'} Y^t_{err'} + \sum_{d} D^t_{edr} + E^t_{er} \tag{2.1}$$

for all $e \in 1, \ldots, E; r \in 1, \ldots, r', \ldots, R; t \in 1, \ldots, T$, where X^t_{pr} - the production capacity of energy facility p in region r in year t; a^t_{epr} - the ratio that determines the output (consumption) of energy carrier e at energy facility

p in region r in year t; $Y^t_{er'r}$ - the desired quantity of energy carrier e from region r' entering region r in year t; I^t_{er} - energy carrier e imported to region r in year t; $Y^t_{err'}$ - possible supplies of energy carrier e from region r to region r' in year t (with losses due to transportation factored in $b^t_{err'}$); D^t_{edr} - consumption of final energy carrier e by consumer categories d in region r in year t; E^t_{er} - energy carrier e exported from region r in year t.

The objective function of the model is the sum of present values of all costs (for all regions and time frame segments):

$$\sum_t \left[\sum_r \left(\sum_{e,p} c^t_{epr} X^t_{pr} + \sum_{e,r'} c^t_{er'r} Y^t_{er'r} + \sum_{e,r'} c^t_{err'} Y^t_{err'} + \sum_e v^t_{er} I^t_{er} + \sum_{e,s_d} z^t_{es_d r} S^t_{es_d r} + \sum_{e,a,p} \eta^t_{eapr} A^t_{eapr} - \sum_e q^t_{er} E^t_{er} \right) Dis^t \right] \rightarrow min \quad (2.2)$$

where $c^t_{epr}, c^t_{er'r}, c^t_{err'}, z^t_{es_d r}$ - levelized costs related to production (conversion), transportation, energy conservation of energy carrier e in region r in year t; v^t_{er} - projected prices of energy carrier e imported to region r in year t; q^t_{er} - projected prices (delivered at frontier) for energy carrier e exported from region r in year t; η^t_{eapr} - costs related to adopting and operating technologies a to reduce harmful emissions c at energy facilities p in region r in year t; E^t_{er} - the quantity of energy carrier e exported from region r in year t.

Additional assessment of the efficiency and adjustment of the obtained options may call for an analysis of the specific features and opportunities for the development of systems of individual industries of the energy sector by employing dedicated models. First of all, this refers to optimization models designed to project the development of the electric power industry [9,10]. If compared to energy sector models, they treat in a more comprehensive way the conditions of electric power generation and consumption, constraints on cross-regional power flows, and other factors.

The weight of optimization models of the electric power industry, as well as that of other systems of individual energy industries, in the hierarchy of projection models of the national energy sector, decreases as the projection time frame extends.

It is worth noting that the planning of individual energy systems can be considered as hierarchically organized. This means that when making their projections and strategically planning their development, one should make use of hierarchies of models specific to them.

Multiple criteria and aggregation in the hierarchy of models employed for energy sector projections.

Different levels of the hierarchy suggest using models with different criteria to come up with rational solutions. The inherent multi-criteria nature of economic systems, when it comes to the practical implementation, gives way to choosing a single most important criterion, while the rest of them serve as boundaries of the feasible range of values of alterations in key factors. In optimization models of the energy sector, such a criterion is the minimum present value of costs inclusive of the investment component (levelized costs) that are required to meet a given demand for energy carriers. These prices generally do not match market prices, which distorts the actual competitiveness of new production capacities. If they differ greatly, it is advisable to carry out additional model calculations based on the maximum profit criterion (considering the difference between market prices and levelized costs). In doing so, it is important to take into account the constraints on new capacity additions due to high investment risks.

When considering the prospects for up to 15-20 years, it is practical to incorporate the level of energy companies, i.e., that of potential investors, and investment risk assessment into the workflow of modeled projection studies. This allows specifying the limits set on possible new capacity additions while optimizing the development of energy systems.

Optimization models used in energy sector projections are usually deterministic. They unambiguously identify the factors that influence the decision. Contingency calculations and analysis of sensitivity to changes in individual parameters only partially capture the uncertainty of the input data but fail to take into account the likelihood of such changes. The scenario approach, which is widely used in real-life projections, allows assigning the probability of the covered scenarios of external conditions by experts, singling out the reference case as the most probable one. However, in doing so this does not arrive at the likelihood of other scenarios and fails to take into account the interval uncertainty of the input data.

A step-by-step approach to long-term projections of the energy sector and the inclusion of regional energy supply models in the iterative workflow, along with models that simulate the behavior of potential investors, make it necessary to take into account the relative riskiness of the options under consideration as it is perceived from the point of view of potential investors. The use of stochastic models makes it possible.

In stochastic models, the input data, operation and development conditions of the modeled entity are presented by random variables. The main parameters of such models are defined not deterministically, but as governed by the laws of their probability distributions [11]. In the practice of making projections, a hybrid approach can be used to combat uncertainty and take account of the stochastic nature of data, i.e., a combination of deterministic optimization models with the method of statistical tests (Monte Carlo method) [12]. Such an approach is used at the MESI (MISS-EL models) [13] for a comprehensive assessment and risk analysis of energy supply options for individual aggregated regions.

In the projections of long-term development of such a complex and multi-functional system as the energy sector, it is advisable to use stochastic models in the final stages of making projections: when solving the

TABLE 2.2 The scope of problems where the application of stochastic models is feasible when making projections of the national energy sector development.

Model types	Projection time frame	Problems to be solved
Deterministic Primary: optimization models of the energy sector and the electric power industry	Over 20-25 years	Identification of the invariants (sustainable solutions) and the boundaries of the projection range (the uncertainty cone).
Auxiliary: disaggregated models of systems of individual industries of the energy sector, macro-economic models, models of demand for energy carriers, and their cost dynamics by aggregated regions	Up to 20-25 years	Identification of possible issues and strategic threats. Clarification of the goals and objectives of further research
Stochastic Models of regional energy and fuel supply, regional energy markets, and development of energy companies	Up to 15-20 years	Quantitative assessment of strategic threats and energy security metrics thresholds. Price elasticity of demand for fuel and electricity. Development prospects of regional energy systems and new sources of electricity. Risk analysis of large-scale projects and programs

most significant problems within each time frame segment (see Table 2.2). The problems identified based on the analysis of the projection range include the following: quantitative assessment of investment risks, strategic threats and threshold values of energy security indicators, projections of interrelated dynamics of prices and demand in regional energy markets, assessment of the competitiveness of new technologies and fundamental changes in the make-up of electricity and fuel production and consumption. When solving these problems, one should take into account regional variations (economic, energy, environmental, and others).

In the case of large uncertainty of the input data, large size, and complexity of the models behind projections, the issue of their rational aggregation arises.

Methods of iterative information aggregation in hierarchically-built systems are mature and well-understood [14]. In the 1970s and 1980s, they underwent active development and were applied to the coordination of decisions obtained from industry-wide and regional model hierarchies of energy systems that accounted for both the production and consumption sides [15]. Such methods assume aggregation and disaggregation of all interrelated models at each iteration step. In so doing, the end of calculations is marked by achieving an acceptable level of aggregation. The latter is defined as the optimality criterion for the upper-level model taking the same value for two successive iterations. Such models include the following ones: applicable to medium-range energy sector forecasts: a dynamic macro-economic model (with the maximum GDP or maximum final consumption of goods and services as the optimality criterion); applicable to long-range projections: an aggregated model of the national energy sector (with the present value of the least cost of production and transportation of energy carriers as the optimality criterion).

Rational aggregation of models employed in making real-life projections entails assessing and considering the effect of the input data uncertainty on the probable error of key variables to be projected. It is also essential to understand what magnitude of the projection error can be considered acceptable when making timely decisions (investment, managerial, or strategic).

The priority and complexity of efforts to accommodate these factors are determined by the projection time frame and the particulars of the problem. The wider the range of the input data uncertainty (which grows as the time frames increase), the greater the inevitable projection error, which thus makes it all the more justified to use more aggregated models.

2.2 Hierarchical modeling of energy sector development of the country and its regions with cross-border interrelations

Introductory remarks.

Notwithstanding all the shared goals of the development of the energy sector of any country and any territory as related to the reliable fuel and energy supply to consumers, the specific tasks of justification of the development of the energy sector differ significantly depending on the specific conditions and on the policy adopted by the state. In this section, we will consider the features of the hierarchical approach to modeling the development of the energy sector of the country and its regions while taking into account the expedient stirring up of mutually beneficial energy cooperation with other countries.

Studies of problems of formation and comprehensive development of the country's energy sector considering the trends of energy cooperation with other countries require both the improvement of existing methods, models, and information support and that of new ones. Within the framework of the overall research workflow, MESI has developed the basic scheme (Fig. 2.2), corresponding methods, models, software and information support of the complex research of the problem stated above.

Of the entire array of methods and models of the basic scheme of hierarchical modeling as applies to the studies of the development of the energy sectors of the country and its regions, Fig. 2.2 below presents the basic methods and models (systems of models) of this overall scheme, which

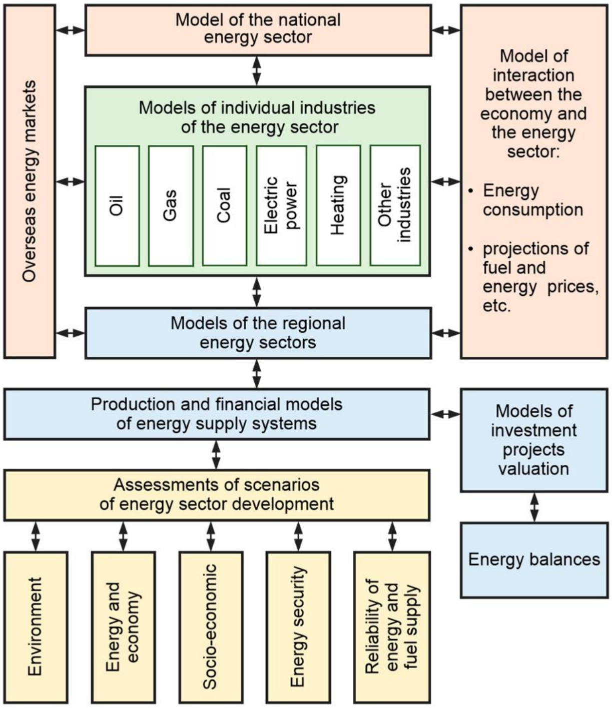


FIGURE 2.2 Basic scheme of hierarchical modeling in the study of national and regional energy sector development taking into account cross-border energy interactions.

are the basis for the implementation of the hierarchical principles of modeling in the set of research tasks of the development of energy sectors of the country and its regions, namely:

1. methods and models for studying cross-border energy markets;
2. methods and a dynamic model for studying and making projections of the country's energy sector;
3. methods and models for studying regional energy sectors and systems;
4. methods and models for justification of the development of energy supply systems for stand-alone consumers.

Methods and models for the study of cross-border energy markets.

One of the main external factors affecting the development of the national energy sector of an energy surplus country and its regions (regional/subnational energy sector) is the need to fulfill its obligations on energy exports, as well as the provision of energy services to external consumers. In the long term, these obligations are a consequence of the implementation of an energy strategy (energy policy) aimed at maximizing the effect of utilizing the country's energy resources and its participation in global and regional energy cooperation.

A two-level hierarchy of problems is used to assess the capacity of regional markets of energy carriers and the competitiveness of promising export projects. The top level describes the international infrastructure and systems of transportation of energy carriers, it provides a study of the comparative effectiveness of projects. At the same time, the lower level describes specific energy export projects and allows for their comprehensive analysis, the core of which are financial and economic assessments. Projections, or a preliminary stage of the study of the domestic market of importing countries, is the most important preparatory step in the study of external relations of the energy sector of the country and its regions in the long term. Oftentimes, this stage is comparable in complexity and information requirements to research into the prospects of development of the country's energy sector itself.

Energy-exporting countries are increasingly faced with the need to diversify their trading partners. This circumstance is caused by the growing influence of political factors related to the statement of energy security policies in Europe, East Asia, the United States, the Middle East, and North Africa.

The relevance of studies of markets of energy carriers to estimate their import potential is determined by the relative capacity, geographical proximity, and accessibility of the considered facilities of the import infrastructure of the target energy carriers in relation to the energy resources of the exporting country.

The need to assess long-term imports and the search for the most feasible foreign markets for selling energy sector products is caused by two main factors: a) the transformation of energy markets in line with the paradigm of "Carbon-free energy" (the prevailing paradigm "Carbon-free energy" has as its ultimate goal the abandonment of the use of fossil fuel resources (coal, oil, and natural gas), referring to the requirements of climate change (their prevention) and the desire to reduce the negative anthropogenic impact on the natural environment) and concerns about the depletion of readily available resources of fossil fuels, b) the growing importance of the geopolitical factor, which has a significant impact on the energy security of most energy-importing countries.

Research methodology.

The methodological framework for research on overseas energy markets, developed at the MESI, was formed on the basis of elements of methodological approaches adopted in international practices for research and projections of global, regional, and national energy markets. These approaches consist in the development of so-called technical models (bottom-up models) and macroeconomic models (top-down models), followed by the establishment of relationships between them. This two-level technology is fully consistent with the ideology of hierarchical modeling discussed in this book. Bottom-up models generally minimize the total costs of the system to meet energy demand, and there are both industry-specific models and models describing the entire energy sector. Top-down models describe the relationships between the economy and energy, with energy demand determined according to macroeconomic parameters. International Energy Agency (TIMES model [16], World Energy Model [17]), US Energy Information Administration (World Energy Projection System Plus [18]), International Institute for Applied Systems Analysis (MESSAGE model [19]), Japan Energy Economics Institute (methodological approach to making projections of energy markets as described in [20, p. 8-11], [21, p. 242]) and Energy Research Institute of the RAS (SCANER model and information system) are among the internationally-acclaimed research organizations engaged in energy markets modeling [22]. Apart from that, various research centers, energy companies, major international banks, and consulting firms are currently developing their own models.

The following steps are carried out when solving the problem of estimating the energy imports requirements for each of the countries included in the prospective regional energy market [23,24]:

1. Projecting the scale and structure of final energy consumption to supply energy services to consumers (providing them with useful energy).

2. Projection of the development of the energy carriers transformation and transportation sectors that result in an estimate of the total consumption of energy resources.

3. Assessment of the competitiveness of different options (scenarios for the development of the energy sector of the importing country in the long term) of energy imports (or the feasibility of their exports for those actors who are exporters).

Since the process of projecting the development of the national energy system is fundamental not only for energy industries but also for the economy of any country, it should be carried out based on the close interaction of three types of actors: the Government (state administration at all levels of the national hierarchy), the Business community (representatives of all concerned sectors of the economy with energy industries treated as a special subset), and the Public (non-profit social and political organizations of the population that make up a special subset in the "*Government*" group).

Accordingly, here and below the institutions of interaction between actors structured in this way are considered for two separate expert groups, conventionally called *technological* and *economic*. The *technological* group faces the task of finding the scale of application of energy technologies and the pace of their adoption, which meet the technical and economic criteria for assessing the development of the national energy system, while the *economic* group is guided by the socio-economic criteria. The purpose of arranging the interaction of these expert groups is to simulate the development institutions (and/or implementation of the energy strategy) for a given country of the cross-border regional energy market. The task of

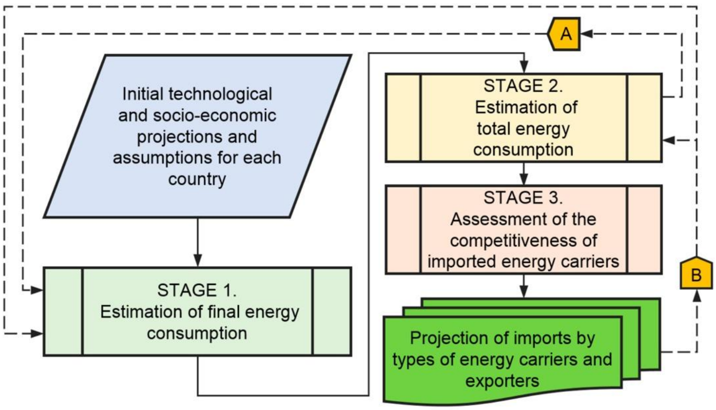


FIGURE 2.3 Stages of estimating the demand for energy carriers by importing countries.

implementing such a strategy is to organize the most effective process of transformation of the energy system for society, in other words - to pursue an effective energy policy. Technological tools of an energy policy are the substitution of energy technologies in the sectors of final energy consumption as well as in the sectors of the energy sector in the production, transportation, and transformation of energy resources.

Fig. 2.3 shows the stages of solving the problem of estimating the demand for energy imports for each country (or a group of countries deemed small/homogeneous with respect to energy) of the region, representing an overseas energy market. The result of the second stage is an estimate of energy imports for each country (group of countries) in the region, obtained on the basis of projections of total energy consumption and taking into account the possibilities of primary energy production based on its own energy resources.

These estimates can be directly used as external factors (estimates of the maximum energy export market) that affect the development of the energy sector of the exporting country and its regions. In fact, the third stage of the proposed methodology acts as a stage of its own for justification of external demand for energy resources for the energy sector of the country, and therefore those of its individual regions. The common tools used are production and transportation models of individual industries (electric power, coal, gas, oil, and petroleum products) for the target cross-border regional energy market in question [25–27] and financial and economic models for implementing international energy projects in the exporting country.

Both at the first and the second stages, the directions and rates of change in the structure of energy consumption of any country in a region of the external energy market for the entire projection time frame (the range of which is usually from 15 to 35 years, that is one or two investment cycles) should be consistent with the assumptions about its socio-economic development. The mechanism of agreement is a trade-off agreed upon at each stage between the technological and economic expert groups. Such a formal compromise is a solution to the multi-criteria problem describing the interaction of two complex hierarchical systems, the economy and the energy sector. As a rule, at the upper level of such systems, one considers a dynamic optimization model of the energy sector with the criterion of minimum standardized costs, and a dynamic national economy model with a detailed description of the relationship of energy sectors and the economy, including imports/exports of energy carriers, energy equipment, and services. The criterion of the national economic model is the maximum gross domestic product of the country at constant prices (added value).

The key task of the first two stages is to project the scale and pace of diffusion of innovative energy technologies. As a tool, to this end, one employs the control over of technological, financial, and economic standards, regulations, and other parameters that allow business actors to ensure an appealing rate of return while maintaining the prerequisites for the competitiveness of the relevant markets to achieve the required goals of socio-economic development of society within a given projection time frame. Such a vector of controllable parameters should be produced by national and international energy institutions undergoing the transformation. Institutional factors related to the specifics of the economic policy and regulatory environment in the countries (a group of countries) of the external regional energy market are captured in the models used at each of the three stages of estimating the demand for energy imports by countries (a group of countries) in this region, in the form of constraints and coefficients of the variables.

Estimation of final energy consumption.

The first stage is fundamental for countries with a high degree of dependence on energy imports because it forms the structure of final energy consumption to meet the prospective needs of society in energy services. Under the "energy transition" paradigm the introduction of technologies enabling the use of synthetic fuels (fuels that can ultimately be produced only on the basis of RES), as well as the introduction into energy supply systems and infrastructure development of a fundamentally new energy carrier (hydrogen) are becoming urgent tasks. The three-step flowchart of the first stage is shown in Fig. 2.4.

The basic assumptions for the projection of final energy consumption of import-dependent countries of the external regional energy market are: a) assumptions about the socio-economic development of the country; b) estimates of technical and economic parameters of energy technologies (directly related to the stage of final energy consumption, i.e., provision of energy services); c) ratio of prices of energy carriers (both in overseas markets and for energy carriers produced domestically).

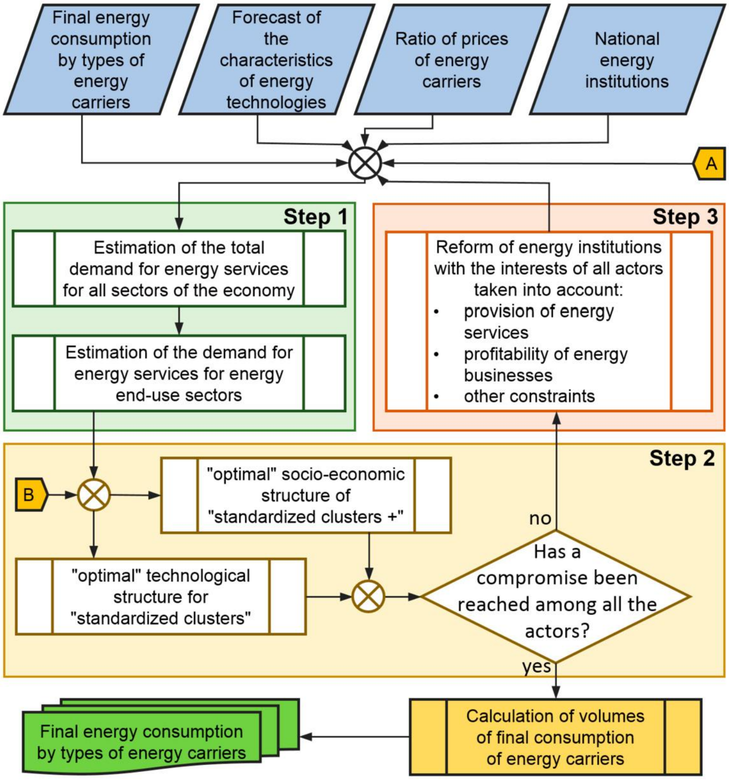


FIGURE 2.4 Estimating final energy consumption.

The first step determines the total demand of the economy for energy services for the entire projection period, which is then disaggregated down to *clusters*. Such clusters represent aggregated entities of the national economy that constitute a set of consumers of useful energy (energy services) operating under similar conditions and that are unambiguously interpreted within the boundaries of the system that are clear to both expert groups.

The selection of clusters should be carried out by the expert groups jointly at the preparatory step of the first stage. Clusters are identified on the basis of natural and climatic, technical, social, economic, and other significant factors that together form the specific conditions for these consumers of energy services. One of the most important factors is the ratio of prices of energy carriers that is typical for all entities of this cluster. The main consumers of energy services are large end-use sectors such as buildings, transportation, and industry, each of which has its own set of clusters assigned to them. At the first stage of the first step, we assess the admissibility of achieving the specified values of indicators of elasticity of energy consumption in the country under the adopted scenario assumptions about its socio-economic development and the assumed advances in energy technologies. Exogenous variables for this step are as follows: macro-economic indicators (population, GDP volume, etc.); target technical and economic indicators by economic sectors (cargo and passenger transportation volumes, average living space, volume of residential and public buildings, scale and structure of industrial production, etc.); estimates of technical and economic indicators of promising technologies for energy services (hydrocarbon-based distributed cogeneration and/or RES, "low-carbon" transportation systems: hybrid, battery-powered, with internal combustion engines (ICE) replaced by fuel cells, etc.).

At the second stage of the first step, we carry out the disaggregation of previously aligned indicators of the elasticity of energy consumption of the country to the level of large sectors and subsectors of final energy consumption, down to the level of clusters. Thus, for each country of the external regional energy market under consideration, the condition of matching of scenario assumptions about socio-economic development between the *technological* and *economic* expert groups is ensured. As a result, the first step forms a projection of energy services consumption for the three levels of representation of final energy consumption: the country as a whole, sectors (for the main consumer groups: buildings, industry, transport), and clusters (within sectors and consumer groups).

At the second step, the best option for the development of energy systems for each cluster is sought according to technological, technical, and economic, and socio-economic criteria. The optimization of energy systems for each cluster is performed by each of the expert groups simultaneously using specific methods and models inherent in the engineering and socio-economic sciences. The purpose of the first stage of this step is to evaluate the optimal mix of energy technologies, which is performed by each group of experts for the entire set of clusters of end-use energy consumers. In this case, the *economic* expert group uses socio-economic criteria for the considered cluster of final energy consumers in terms of the optimality of energy technologies used at the level of the economy as a whole. The task of the *technological* expert group is to assess the optimality of energy technologies for the considered cluster of final energy consumers on the basis of technical and technical and economic criteria. It should be noted that the meaning of all applied criteria should be unambiguously determined by the adopted system of regulatory norms and standards of technical, environmental, financial, and economic nature, representing the result of the operation of national energy institutions in the country.

At the second stage of the second step, the divergence of optimal solutions obtained by both expert groups is assessed, which is due to the difference in the optimality criteria. Next, at this stage, we develop the requirements to the process of search for control actions, which is aimed at convergence of the choice of "optimal" energy technologies for each cluster of final energy consumption with the entire frame of the projection of the development of energy supply systems in the country. "Optimality" means reaching a compromise of expert groups to solve multi-criteria problems of the development of hierarchical dynamic energy systems that determine the final consumption by the country and the corresponding sectors of its economy.

The solution found should ensure the achievement of the socio-economic objectives of the development of the energy system of the country through the "optimality" of the energy technology adopted to provide energy services (in other words, the final consumption of energy).

The first stage ends with the calculation of the mix and scale of energy consumption by final energy consumers for the entire projection period, which corresponds to the adopted scenario assumptions and also establishes the compromise reached between interests of actors represented by the state (including its independent public subsystem) and the business community. As a rule, to justify the priority areas of technological development of the energy industry and to coordinate the rate of replacement of fixed assets on a new technological basis, a mandatory requirement is the consideration of the so-called "reference case" scenario of energy consumption. The other scenarios are characterized by differences in the rate of implementation of control parameters and the scale of the manifestation of external factors relative to this ("reference case") scenario.

Estimating primary energy consumption.

The second stage considers the direction and pace of reform of the national energy system and provides an estimate of the country's total energy consumption, including external energy import and export relations. The main problem to be solved at this stage is to estimate the rate of change in the structure of total energy consumption, and hence the structure and volume of imports of energy carriers for countries (a group of countries) of the external target region that experience a shortage of energy. The above problem should be solved by providing an estimate based on simulation modeling of technological development in the sectors of energy transformation and transportation. At the same time, the main condition is to maintain an acceptable ratio of energy prices for end-users, as the achievement of the planned values of indicators of socio-economic development of society depends on it. The flowchart of the second stage, consisting of three steps as well, is shown in Fig. 2.5.

As is the case with the previous stage, we use the method of parallel consideration of the criteria for the effectiveness of the development of energy systems by two expert groups. In addition to the assumptions used at the first stage, the following ones are taken into account: a) the scale and structure of energy consumption for final consumption (as obtained at the first stage); b) estimates of technical and economic parameters of energy

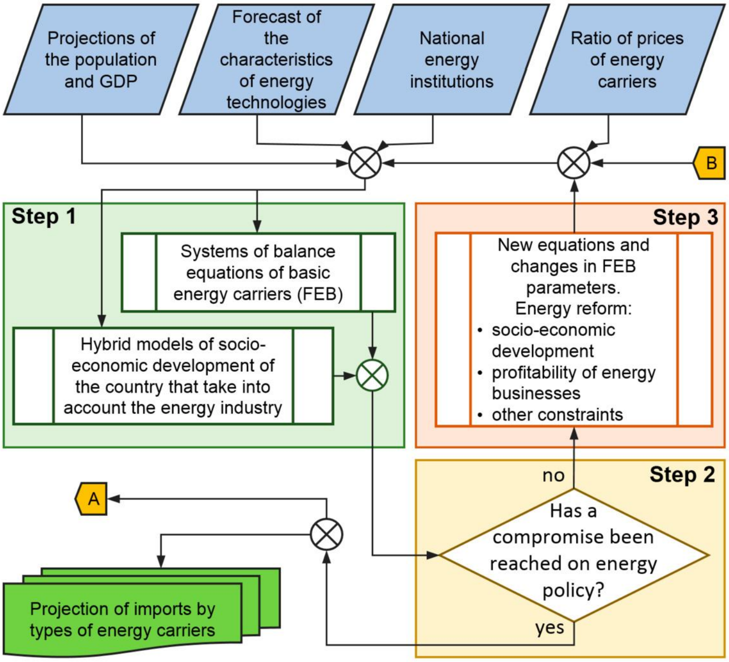


FIGURE 2.5 Estimation of total energy consumption.

transformation and transportation technologies; c) projected price ratios for imported energy carriers. Clusters are selected in a similar fashion: at this stage, they represent the aggregated entities of the energy transformation and transportation sectors and are also unambiguously interpreted within the system boundaries understandable to both expert groups.

When there are given ratios between the prices of imported energy resources, one of the most important factors for identifying clusters in the sectors of energy carriers transformation is the comparative efficiency and reliability of network and decentralized systems of energy supply to end-users of energy services. As the first step, as is the case with the first stage of the study, for each cluster we search for options that are optimal in terms of technological and socio-economic criteria of cluster development that cover all systems of transformation and transportation of energy carriers. Similarly, each of the expert groups, based on the methods, research tools, and optimality criteria specific to each group, selects the rational mix of energy technologies. Examples of such criteria are the reduction of the total standardized cost to provide a unit of final energy consumption (*technological* expert group), the maximization of added value at the national level (*economic* expert group).

At the second step, we evaluate the divergence of the optimal solutions obtained by both expert groups for each cluster of energy conversion and transportation: motor fuel production, generation, and transportation of electrical and thermal energy, etc., up to hydrogen and synthetic fuels based on it (e-fuels). The clusters under consideration can represent complex large-scale spatial systems, such as unified electric power and gas supply systems on a national scale. At the same time, synergies may exist in the joint operation of such systems, for which it is not possible to estimate the effect of emergence on the basis of a single-criteria approach. At the second step, it is also necessary to ensure mutual understanding between the expert groups, since the procedures applied in practice for finding a compromise solution boil down to reaching a consensus between the experts. At this step, such a consensus on the question of the presence of the signs of "optimality" for the considered solution to the problem of developing the energy carriers transformation sector of the energy system should be achieved not only between the *economic* and *technological* expert groups but also within them. Achieving the "Optimal" state in the energy transformation and transportation sector indicates that there is a coordinated decision on the structure and dynamics of changes in the production capacity of the country's main energy industries, including production of energy carriers based on primary energy production as well as transportation, imports, and exports of energy carriers. "Optimality" of the solution for energy industries promotes the interests of the energy businesses with respect to obtaining a sufficient rate of return, and, from the standpoint of society, promotes obtaining environmentally acceptable, cost-effective, and socially affordable energy services. In fact, at this stage, an estimate of the demand for energy imports is generated, which serves as the starting point of the next, final stage of the study of international energy markets. In addition, the obtained price ratios for the energy carriers converted and supplied to consumers are used as prerequisites for optimizing the mix of energy end-use technologies at the first stage of the study.

If there is no such consensus, a third step is required at this stage, where new operating conditions, standards, regulations, and similar management measures are developed. Taken together, they involve ensuring the process of transforming the national energy system (energy sector) to meet the criteria of optimality, after returning to the previous steps of estimating total and/or final energy consumption, and reassessing the development of energy systems, taking into account the adjustments introduced. Since the technical parameters of the energy technologies considered cannot be changed due to their belonging to external variables of projection models, it is necessary to seek solutions based on: a) the search for synergies of energy technologies, and b) the reform of energy institutions. Examples of the former option are changes in the ratio of boundaries and scale of clusters of centralized and decentralized energy supply, increasing the

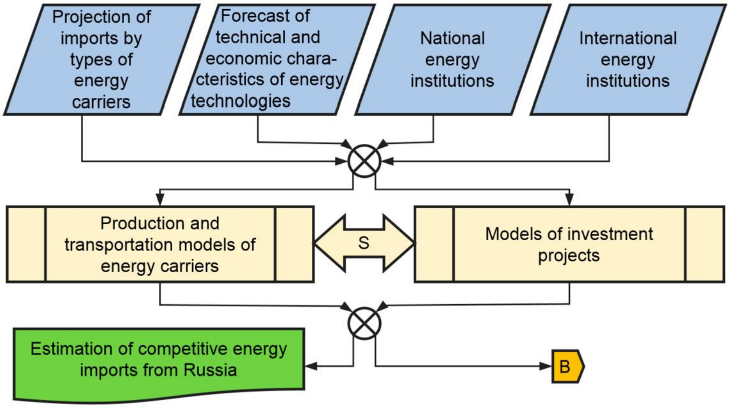


FIGURE 2.6 Assessing the competitiveness of imports of energy carriers in regional energy markets.

share of renewable and nuclear energy, the introduction of new energy carriers. Examples of the latter option are improving competitiveness in energy industries, changing back-up capacity standards to ensure reliable and secure energy supply to consumers, introducing financial incentives that increase the profitability of energy businesses (or allow the creation of new markets), introducing environmental restrictions, etc. Depending on the degree of deviation of the resulting solution from the "optimal" solution agreed upon by expert groups, it will be necessary to return to the step of searching for compromise solutions for the energy carriers transformation sector, or even to the stage of searching for new solutions in the final consumption sectors (Link A), under changed conditions and standards of technological, economic, environmental, etc. regulation.

Assessment of competitiveness in international energy markets.

The third and final stage of the study of energy markets in Northeast Asian countries, performed jointly with the preparatory step of the first stage in the basic scheme of projecting the development of Russia's energy sector, as well as the module "Development of the resource base and options for the use of FERs" of the scheme of development of regional energy programs, is to assess the structure and scale of external links of energy systems of individual industries. At this stage, the energy infrastructure facilities are considered at the following levels (Fig. 2.6):

- international production and transportation systems for the main types of energy carriers;

- energy investment projects that ensure the development of international systems of transportation of energy carriers.

Comparison of individual facilities of international energy infrastructure and energy transportation routes is carried out at the level of models of international production and transportation systems (models of regional markets of energy carriers), taking into account technical, economic, social, environmental, and political criteria.

To assess the competitiveness of energy sources and supply routes to the external regional market of energy carriers, one employs network production and transportation optimization models of regional markets for individual energy carriers (gas, electricity, "green" hydrogen). Such models make it possible to identify the most competitive suppliers and estimate the volume of energy carriers transportation along each route.

In the models, the given demand for energy carriers, their production, storage, and processing are described at nodes that represent conventional links in the value chain. The results of modeling are the volumes of production, storage, and consumption of the energy carrier at the nodes, the volume of transportation of the energy carrier along each route, estimates of the cost of the energy carrier at the nodes of production and transport infrastructure (nodal prices). Nodal prices are not predictive of market prices because actual market prices are the result of the action and interaction of many forces, including those of non-economic nature, that are often not directly related to the energy sector and are not directly accounted for in the production and transportation models. At the same time, nodal prices are the result of reconciling the economic interests of sellers and buyers and thus reflect the ratio and overall dynamics of market prices.

Production and transportation optimization models allow one to identify the most competitive suppliers and supply routes, to estimate the volume of energy carriers transportation along each route, and to assess the comparative efficiency of energy supply directions as the difference between the nodal prices and the costs arising at each stage of the supply chain.

To analyze the options for improving the competitiveness of suppliers and improve the technical and economic performance of individual facilities of production and transportation systems requires the construction of production and financial models of appropriate investment projects.

Production and financial models set and calculate the main financial performance indicators from revenues to profitability, they provide an estimate of the minimum level of selling prices and tariffs needed to ensure the given payback period of the project. These prices and tariffs come into play as basic assumptions in models of regional markets of energy carriers. In turn, one of the main assumptions in production and financial models are estimates of the volume of production, transportation, storage, and processing of energy carriers. This iterative interaction of the two-level models is shown by the bidirectional arrow S in Fig. 2.6.

The interrelation of models makes it possible to assess, on the one hand, the financial/economic and production/technical parameters of the project, necessary to achieve a given level of competitiveness, and, on the other hand, the level of competitiveness with given financial/economic and production/technical parameters. For example, as a result of optimization modeling of the gas market of the countries (group of countries) of the external regional energy market one can obtain an assessment attesting to the lack of competitiveness of liquefied natural gas (LNG) produced in the Gulf of Mexico Coast compared to LNG produced in the Yamal Peninsula. In this case, actors interested in the implementation of Gulf of Mexico Coast LNG projects need to find a combination of control parameters (changes in standard values and other available control options) that will allow them to achieve a greater level of competitiveness and make this project a positive outcome for these investors (and other stakeholders).

Furthermore, the impact of changes in energy markets (commodity flows and prices) on the development of the economies of countries (a group of countries) of the external regional energy market is assessed through the interaction of production and financial models and models of energy markets. Based on the production and financial models of projects, their contribution to the added value is calculated, and then, through the aggregation of projects, taking into account the role of each country (group of countries) of the external regional energy market in its implementation, one calculates the industry contribution to the GDP of participating countries. The contribution of export-oriented projects to the GDP of energy-importing countries can be achieved by exporting technology, services, equipment, and components from these countries.

The search for solutions that are "optimal" for the authors and the search for consensus between them in the field of security, sources of project financing and ownership structure through special mechanisms of economic development regulation (national and international energy institutions) provides a solution to hierarchical multi-criteria problems. What matters in these processes is whether the actors belong to the parties to the cooperation: whether they are representatives of an energy-importing country or an energy-exporting country. The latter circumstance allows us to consider this stage of the study on forming of external relations of the energy sector of the exporting country and the external regional market of energy carriers as quite independent. It is successfully used both in scientific research and for practical needs in solving operational (spot) and strategic (long-term) tasks of commodities trading. The provision of energy services, such as uranium enrichment or system services in cross-border electric power systems (system services), should be based on mutually agreed models of operation and/or development of the subsystems (systems) in question.

Methods and models for projecting the development of the country's energy sector.

The ongoing crisis in Russia's economy, the uncertainty of its development in the future, do not allow speaking unequivocally about the sustainable long-term development of the energy sector of the country and its individual regions. Therefore, the development of projections and scenarios for the country's energy sector requires careful deliberation and a comprehensive study of the possible consequences (energy, economic, environmental, safety, etc.) of their implementation.

This, in turn, requires the improvement of existing and the development of new methods, models, and information support in the following areas:

- comprehensive consideration of innovative directions of development of the energy sector of the country and its regions in the process of development of models;
- well-grounded approaches to assess the efficiency and scale of exports (imports) of energy resources and energy carriers;
- well-grounded consideration of the impact of harmful emissions and greenhouse gases on the environment and climate and the development of measures to reduce them;
- proper ways of accounting for economic categories (prices, taxes, profits, credits, etc.) in the models.

The optimization dynamic model of the energy sector of the country [8,28–31] developed at the MESI and constantly updated can serve as the methodological basis for energy projections at the country level.

The basic scheme of projections of the development of the energy sector at the country level using the proposed model consists of three stages (Fig. 2.7).

At the first stage, a set of major factors affecting the development of the energy sector (socio-economic, technological, environmental, etc.) is formed based on past experience, expert judgments and projections, and a limited set of combinations of external conditions of its development is assigned.

At the second stage, for each of the considered combinations of external conditions, we define scenarios for the development of the country's energy sector.

At the third stage, based on the analysis of the obtained scenarios: a) we identify generalized patterns and trends of energy sector development during the projection period; b) we evaluate the impact of individual factors on the development of the country's energy sector.

The purpose of studies that are based on the model of the country's energy sector is to provide information for the development of mutually agreed areas of regional energy development having considered different scenarios for the development of the country's energy sector and having analyzed the consequences of their possible implementation.

The proposed scheme implements the "top-down" principle (from the country to the regions) of making projections. This ensures the methodological consistency of building the projections of the development of the energy sector of the country and regions. Development projections of

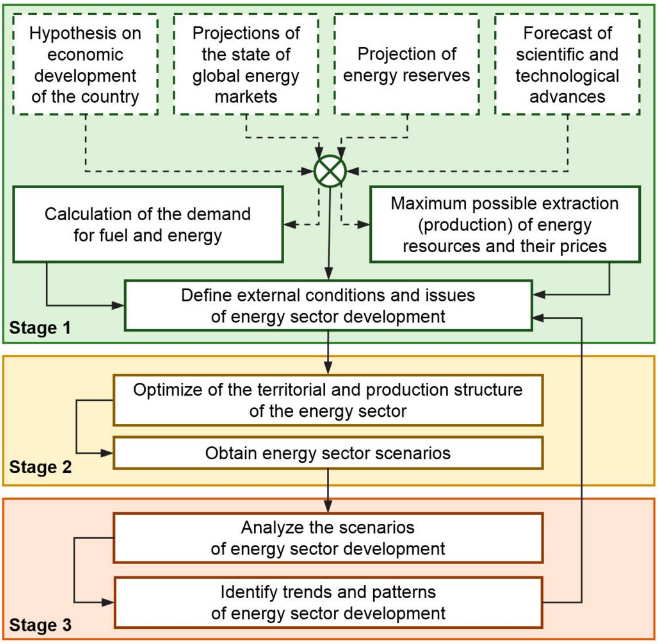


FIGURE 2.7 Basic scheme of projections of the development of the country's energy sector.

lower hierarchical levels (regions) are developed in conjunction with the projections of the higher level (country). In this case, the energy sector projection of the higher level in the procedure for coordinating decisions (vertical links) prevails. However, in the presence of convincing proposals received from the regions, it is allowed to adjust the decisions at the country level, i.e., in the scheme of the projection, there can be both direct and reverse links directed from the regional energy sectors to the country's energy sector [15].

The country's energy sector model allows the following:

- outlining for each of the scenarios considered for the development of the country's energy sector the preferred levels of development of major fuel bases, major energy facilities, and rationally allocate the resulting energy resources and energy carriers across the country, and within each of the selected regions by major aggregated categories of consumers;

- obtaining the lower limit of "market" prices for fuel and energy for each of the selected regions as found by taking into account the consumer effect;

- assessing the technological mix of the energy sector in the regions at the country level, depending on scenarios for the dismantling of existing

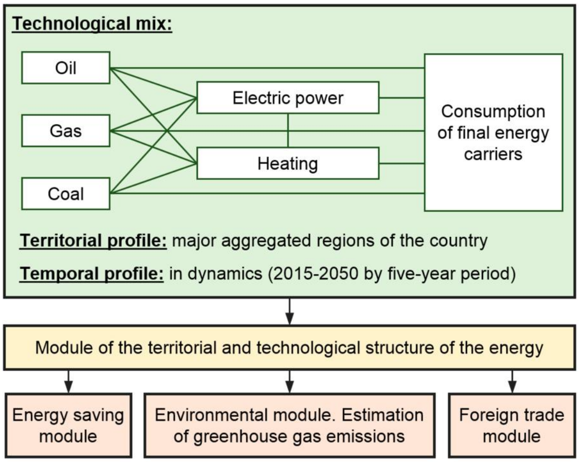


FIGURE 2.8 Structure of the dynamic optimization model of the country's energy sector.

equipment in energy sector industries, the scale and efficiency of the introduction of new technologies and the investment environment;

- evaluating the comparative efficiency and scale of foreign trade in energy carriers;

- evaluating the scale of the negative impact of various scenarios of energy sector development on the environment and identifying ways to reduce harmful emissions through the introduction of environmentally friendly and cost-efficient technologies and environmental protection measures.

Let us note the most important features of the considered model of the country's energy sector.

1. The model captures the development of the energy sector in dynamics.

2. The model quite adequately describes the country's energy sector by the regions considered, in terms of the mix of industries (oil, gas, coal, electricity, and district heating), the way they represent technologies and territories, the number of primary energy resources and final energy carriers.

3. The model is an optimization model: levelized costs that ensure self-sufficiency of the energy facilities in question are considered as the coefficients of the functional, see Eq. (2.2).

The proposed model allows taking into account the territorial and technological structure of production and consumption of primary energy resources, electricity, district heating, boiler and furnace fuel, and also includes the following modules: energy saving, environment, and foreign trade (Fig. 2.8).

The territorial aspect of the model describes the country's energy sector in terms of aggregated regions.

The production and technology aspect is modeled by groups of existing and prospective energy facilities (oil, gas, coal deposits, refineries, power plants, centralized boiler houses, etc.) in each region, grouped by technological features and type of energy carriers used (produced).

In general, the energy facility is described by three groups of indicators: technological, economic, and environmental.

The technological aspect of an energy facility (or a group of facilities) is described by the following metrics: coefficients that determine the share of each input or output energy carrier in the total consumption and production of energy carriers by this facility (or group of facilities); the efficiency of the equipment used at this facility; the operating conditions (in the case of the power plant, it is installed capacity utilization factor (ICUF)); the service life of the facility.

To represent each of the considered primary energy resources (oil, natural gas, coal, nuclear energy, hydro power) in the model, we rely on the principle of the successive description of the main stages of energy resource conversion (extraction, processing/conversion, distribution, and consumption of final energy carriers).

The *energy saving* module determines rational energy-saving levels for individual (selected) energy-intensive consumers or their groups.

For all energy carriers, the amount of their final consumption by consumers in the region is assumed to be a fixed value.

Rational levels of energy savings for individual consumer groups are determined by introducing energy-saving technologies for these consumers and the resulting fuel and energy savings with the corresponding additional costs of these activities.

The *environment* module of the model determines the total and specific greenhouse gas emissions in each region and the economically feasible scale of implementation of measures to reduce them, taking into account emission limits.

The *foreign trade* module describes the conditions of energy exports from the region. In general, the feasibility and scale of energy exports will depend on export prices, the volume of extraction (production) and domestic consumption of energy carriers (with their cross-regional redistribution, energy conservation, and substitution by other types of energy factored in), the state of the existing domestic and export transportation network and the prerequisites for the construction of a new one, and the costs of energy production and transportation.

The proposed model allows one to obtain in the general case (for the country and regions under consideration) the following (see also Eq. (2.1)):

- Balances of primary energy resources;
- Balances of boiler and furnace fuel (gas, fuel oil, coal, other);

- Balances of electricity and district heating;
- Cross-regional supplies of fuel and electricity;
- The array and scale of adoption of new technologies and measures to improve the efficiency of energy resources utilization;
- Feasibility and scale of foreign trade (exports, imports) in energy carriers;
- Evaluation of greenhouse gas emissions and measures to reduce them;
- Required investments for energy development.

Methods and models for projecting the development of the energy sector in a region.

State regulation should include a stage of long-term projection in the form of regional energy strategies so as to determine the key parameters of a regional energy policy and to identify areas of improvement for the structure of production and consumption of fuel and energy resources on the basis of intensive development of innovative energy technologies.

The development of regional energy strategies should be preceded by a projection of the economic development strategy, which allows one to consider such programs as integral and interrelated parts of the socio-economic development projections of the respective regions.

The main goal of regional energy strategies is to ensure highly efficient and reliable energy supply to consumers in the region through the rational (in economic, social, and environmental terms) development of their own fuel and energy bases and mutually beneficial use of energy resources of other regions.

The diversity and uniqueness of regional energy strategies require each time an individual approach while preserving the general methodological principles of solving emerging problems [13,32–36].

The regional energy strategy should generally include the sections shown in Fig. 2.9.

The energy sector development scenarios are formed in line with the scenarios of socio-economic development of the region. Each scenario of energy sector development, depending on the characteristics of the region, may have several options for energy supply.

The development of regional energy strategies involves a variety of methods for calculation and technical and economic analysis, which cannot be applied without extensive use of the methodology and a stack of formal means (methods, models, modern software and computing tools) of the systems approach [34–36].

As a toolkit for the development of regional energy strategies, one employs a hierarchy of mathematical models, each of which faithfully describes the list of tasks set in the corresponding subprogram [30,34,36–45].

Now that the economies of a number of countries are in recession, burdened by the imposition of sanctions, the need to improve their energy efficiency is increasing. To achieve this priority, one of the significant

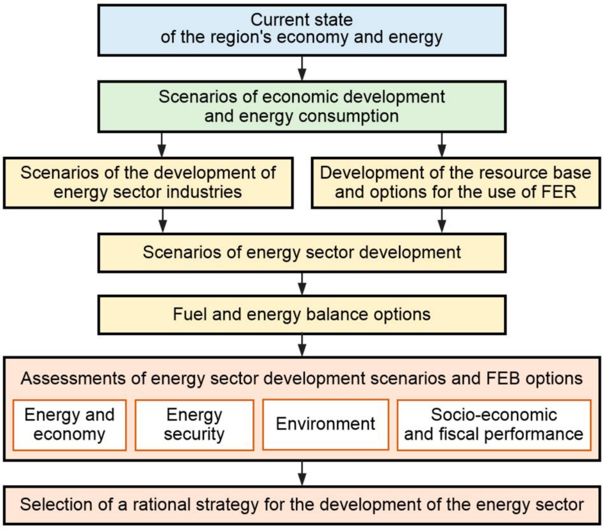


FIGURE 2.9 Scheme of the development of regional energy strategies.

mechanisms of state energy policy is reporting and projecting fuel and energy balances (FEB), which provide comprehensive and most complete information on the performance of the energy sector in the region [44,45].

The analysis of the reported FEB, the determination of energy efficiency metrics on its basis, the identification of existing imbalances, and their elimination in the projected FEB, serve as a tool for managing the development of the energy sector and its industries.

The MESI has developed a methodological approach to the systematic assessment of energy efficiency metrics of the regional economy on the basis of the FEB. The methodological approach is based on the use of a software package, which consists of two interrelated components: the information and reference system (IRS) and the system of models (Fig. 2.10).

The IRS, the first component of the software package, is employed to improve the efficiency of the research process of regional energy sector development. The purpose of the IRS, as a decision support system, is to provide an interface to access data that are presented in a user-defined and convenient form (tables, graphs, charts), that is, a tool for preparing data for the decision-maker. The software shell, implemented in the MS Visual Basic programming language, covers MS Excel files containing information about the energy sector of the regions in question. The visualization of the shell allows one to easily access and navigate through the data of interest with a user-friendly interface.

The second component of the software package is a system of models that combines: models of boiler and furnace fuel (BFB) balances and con-

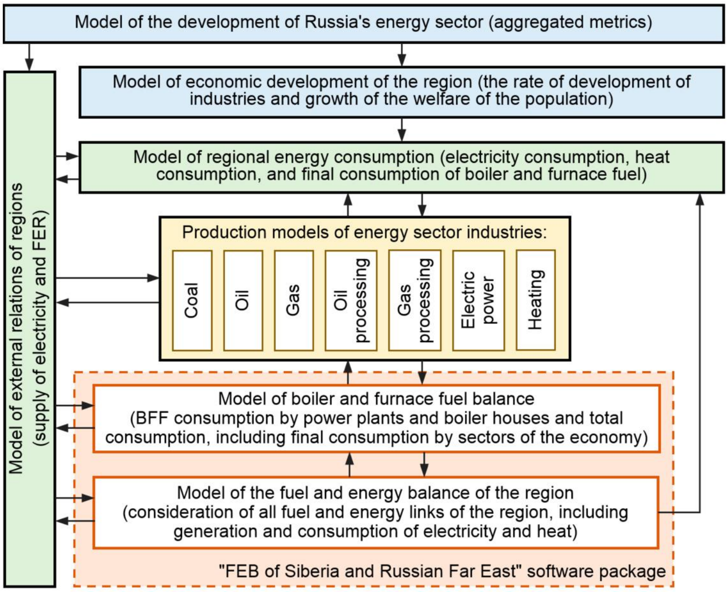


FIGURE 2.10 A system of models for projecting the development of the energy sector of the region and forming fuel and energy balances.

solidated fuel and energy balances. In addition, the input information for the BFB balance and FEB is the information coming from the models of a higher hierarchical level. If the inflows and outflows in the projection models of the BFF balance and the FEB are not reconciled, feedbacks from other models come into play and as a result of one or two iterations the inflows and outflows get reconciled.

Aggregated model of regional energy consumption projection.

An important point of departure for long-term projections of the energy sector development is the projection of the demand for energy resources on the part of the economic system of the country and its regions. This is a methodologically complex and time-consuming process, and for the study of strategic directions of the energy sector development, as a rule, one uses already available metrics from government projections of energy consumption, which are presented in the Energy Strategies of the country systematically developed for the 15-year period and other strategic-level documents. However, when projecting the development of the energy sector with a projection time frame that extends more than 2050 years into the future up to 2050, researchers need to estimate on their own the level of energy consumption on the basis of certain methods and models.

Within such a distant projection horizon, the extremely high uncertainty of the state of the production structure, innovation, economic dynamics (recessions and sanctions), social (standard of living and quality of

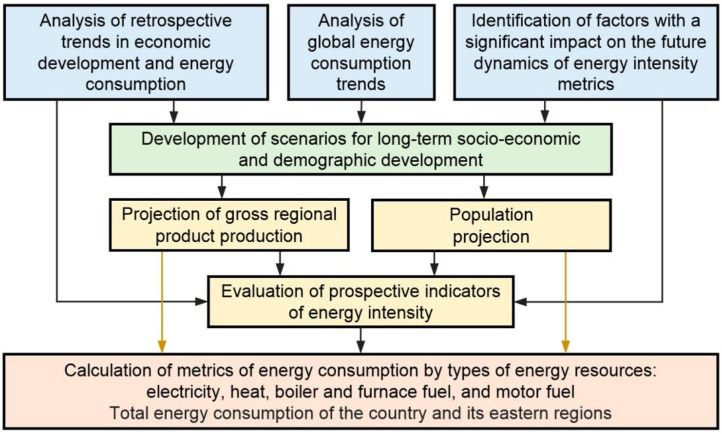


FIGURE 2.11 Step-by-step scheme of making a long-term projection of regional energy consumption.

life), geopolitical, and other factors are a serious limiting factor in the use of multi-product models of energy consumption, as the most information-rich ones. Given these conditions of making projections, the maximum aggregation of activities of the economic systems of the country and its individual regions is allowed up to the production of a single product in monetary terms, i.e., the gross regional product (GRP) or gross output (GO) [32].

Here, we consider the proposed aggregate simulation model, which is based on the method of direct counting to project future energy consumption to 2050. The projection is done by region for four types of fuel and energy resources: electricity, heat, final consumption of boiler and furnace fuel, and motor fuel with a breakdown by the economic system and the population.

The basic metrics for calculating the projected levels of energy consumption are: gross regional product, population and specific consumption of electricity, heat, boiler and furnace, and motor fuel per unit of the GRP produced and per capita.

The general scheme of energy consumption projections is shown in Fig. 2.11.

The macro-projection if compared with the detailed multi-sectoral projection of gross regional product production has both advantages and disadvantages. But many of its shortcomings associated with the high aggregation of the economy and metrics of its energy intensity are largely overcome by the building scenarios for future economic development.

Projections of gross regional product production and the population of the country and regions are made in line with the established scenarios of economic development

GRP projection. A given growth rate of investment is considered as the main factor of economic development and GRP production.

The GRP growth rate is linked to the scenario-driven growth rates of investment in economic development, taking into account periodic economic recessions, international sanctions, and investment restrictions on domestic and foreign financial markets, as well as possible structural shifts in the economy towards increased manufacturing of products with a higher share of added value, the possibility of intensive adoption of new technologies in the production sector, etc. These factors directly or indirectly affect the level and dynamics of the rates of return on investment with respect to the GRP and, accordingly, the growth rate of the GRP.

Population projection. Federal state statistics services regularly perform long-term population projections on a professional basis. However, their projections should be treated with caution, since the methodology for population projections takes virtually no account of the economic factor associated with the possible implementation of state programs for the intensive development of underdeveloped territories. In this regard, it is advisable to use official population projections for the regions with correction factors.

Next, one evaluates the dynamics of look-ahead indicators of specific consumption of energy resources in physical terms per ruble of the GRP produced and per capita according to the scenarios of economic development and the projected population size. Their dynamics is formed using different methods, in particular, using methods of regression analysis, the method for comparative analysis of levels and dynamics of energy intensity of the GDP with advanced countries, the method for assessing the dynamics of elasticity and energy intensity with respect to sustainable prospective baseline indicators of socio-economic development, etc.

At the final stage, one calculates prospective demand for individual energy resources for GRP production and for the needs of the population in the country as a whole and for individual regions on the basis of projected GRP and population metrics and given specific energy resource consumption in physical terms per ruble of the GRP produced and per capita.

The main information sources for quantitative analysis and projections of energy consumption by country and individual regions are:

- national and regional statistical reference handbooks;
- government strategies, projections, and programs of economic and energy development of the country and its regions;
- long-term projections of the scientific and technological development of the country;
- reported electric power and energy balances of the country and its regions;
- statistical forms on the production and consumption of energy resources;

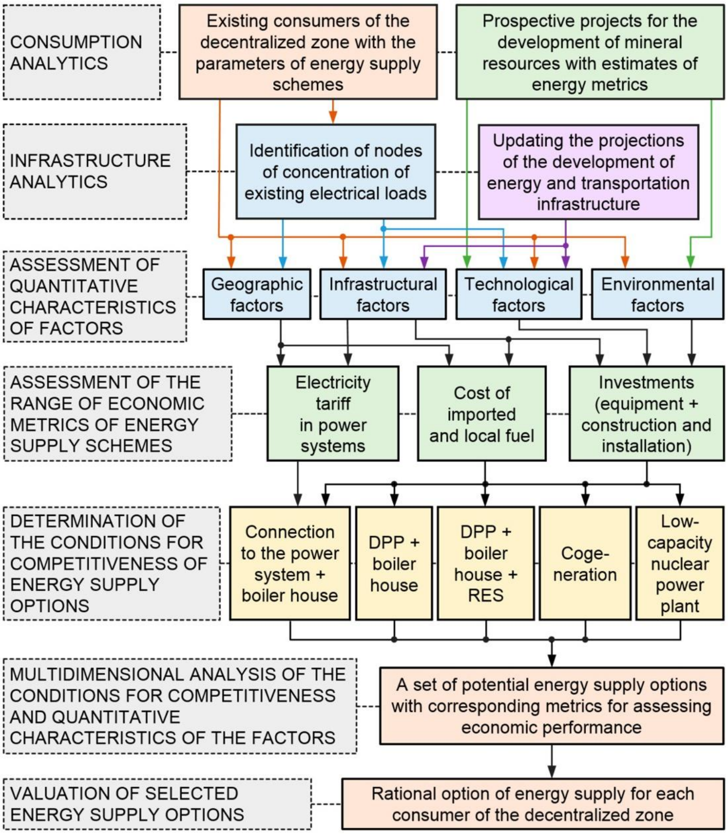


FIGURE 2.12 Methodological approach to the justification of rational options for power supply to decentralized consumers.

- domestic and foreign published research, Internet resources, corporate reports, project feasibility studies, etc.

Principles, methods, and models in the process of justification of rational options for the energy supply of decentralized consumers in the region. The multistage methodological approach developed at the MESI allows carrying out multidimensional studies to justify rational options for energy supply to existing and new consumers located in areas isolated from energy systems. The consumer is understood as a settlement, an industrial facility, or a set thereof.

The methodological approach includes several stages: analysis, expert judgments, economic calculations, and recommendations issued (Fig. 2.12).

During *the analysis stage of the study* in the administration unit under consideration, we systematize information on all existing consumers with decentralized electric power supply. Promising projects for the development of mineral resources are identified, their parameters, the degree of readiness and timing of implementation are updated, and prospective electrical and thermal loads are evaluated. At the same stage, in parallel, the projection of energy and transportation infrastructure development within the territory under consideration is updated and research is conducted to identify nodes of concentration of existing electrical loads for the purpose of possible integration into power nodes with prospective enterprises of mineral resources extraction.

At *the stage of expert judgments*, one evaluates the ranges of quantitative characteristics of significant factors affecting the efficiency of alternative energy supply options. The most significant factors include remoteness from possible power centers, accessibility to local fuels, fuel logistics, renewable energy resource potential indicators, and environmental constraints [46].

The obtained quantitative characteristics of the factors serve as a basis for determining the economic indicators of alternative options for centralized and autonomous electric power supply.

At *the stage of economic evaluations*, one determines the conditions of competitiveness of alternative energy supply options in the range of changes in the indicators of each of them for a given territory. For this purpose, one uses a system of simulation models developed at the MESI for determining the boundaries within which the efficiency of each alternative energy supply option is equal to that of the conventional option being DPP + boiler house. The calculated dependencies of the main economic metric of the option on the change in the indicator of the conventional option are derived from the equality of the total discounted costs. A detailed description of the models is given in [47].

Based on a multi-dimensional analysis of the obtained prerequisites of competitiveness and quantitative characteristics of the factors, at the stage of *issuing recommendations*, a rational option for energy supply is justified for each existing consumer and prospective project within the area under consideration. At this stage, one employs production and financial models. The criterion for justifying a rational energy supply option for existing utility users is the maximum reduction of budget subsidies, and for new consumers, it is the minimum of the standardized cost of energy.

The methodological approach implements the following principles:

- all technologically possible options for energy supply to consumers are considered in a comprehensive way;
- the uncertainty of information is taken into account: quantitative characteristics of influencing factors are treated as ranges of their values, and the sensitivity of economic indicators on changes in the characteristics of the factors is analyzed;

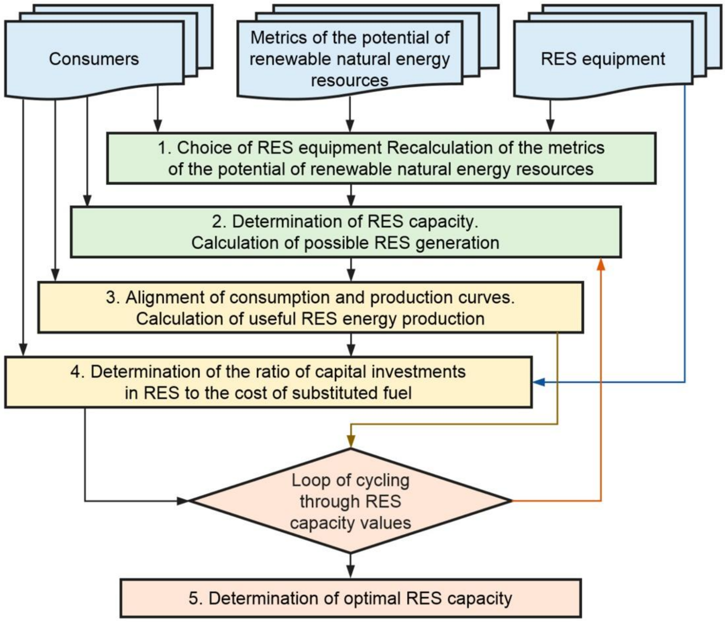


FIGURE 2.13 Algorithm of express methodology for determining the optimal capacity of a renewable energy source for the decentralized consumer.

- structuring and reduction of the amount of preparatory and analyzed information are achieved by reducing the number of economically viable options for energy supply [47,48].

The methodological approach is implemented as a set of simulation and financial and production models for the purpose of conducting research. The models adapted to the conditions of the territory under consideration through the quantitative characteristics of the influencing factors and economic performance indicators of alternative energy supply options.

For options of using renewable energy sources (RES), we perform preliminary research to determine their optimal capacity for each consumer in terms of the ratio of natural and cost indicators.

It is exactly decentralized consumers that this stage is important for, the reason being that in case of overestimating the capacity of RES, its share of contributing to covering energy demand increases and, accordingly, the volume of substituted fossil fuels as well, but at the same time, the total capital investment also increases. To determine the optimal RES capacity for a decentralized consumer, an express methodology was developed, its algorithm is shown in Fig. 2.13.

At the initial stage, the type and unit capacity of RES is selected from the equipment database according to the load of the consumer. In the first iteration, the unit capacity of the equipment is selected so as not to exceed the minimum load of the consumer in order to fully utilize all possible energy production. Furthermore, this provides for recalculation of the renewable energy resource potential specified in reference handbooks and atlases, according to the characteristics of the selected equipment and location. Possible RES energy production is calculated on the basis of the distribution of the obtained energy resource values by years and the technical specifications of the equipment.

The determination of useful RES energy production is based on the comparison of curves of possible energy production and consumption. Based on the values of useful energy production and economic parameters that characterize the consumer, we calculate the volume and cost of fossil fuels to be substituted, assess capital investment in renewable energy as per the specifications of the selected equipment.

Next, we perform iterative calculations for the assumed unit capacity of the RES with an increase in the number of units. The condition for completing iterations is the constraint that required the minimum value of RES energy production to be not less than the maximum value of consumption.

The criterion of optimality of RES capacity is the minimum ratio of capital investment in the renewable source and the cost of a substituted organic fuel due to its operation, the amount of which depends on the specifications of energy resources. A detailed description of the express methodology for determining the optimal RES capacity for a consumer isolated from the power system is given in [49,50]. The findings of the studies are given in [51,52].

It should be noted that the presented methodological propositions of projecting the development of the energy sector and energy systems of the region, as well as the providing the rationale for the development of energy supply systems of decentralized consumers of isolated areas, include methods to assess the environmental and socio-economic consequences of energy development of the region or isolated area in question. A detailed description of the approaches developed for this purpose is given in [53–56].

2.3 Hierarchical models of energy security

Special methodological aspects of energy security studies.

The system of mathematical models used to study the national and regional energy security (ES) problems is largely based on mathematical models designed to study reliability. At the same time, reliability, being a complex metric of an energy system, includes such a feature of this system as survivability. The need to pay attention to survivability arises mostly when the energy system operates under conditions other than normal, i.e., when the system components fail due to internal and external reasons, or due to a variety of external impacts. While the reliability is interpreted as a property of the energy system or the entire energy sector, energy security is a state of being protected against the threats of a failure to meet energy needs with affordable energy resources of acceptable quality and the threats of interruptions in the energy supply (due to emergencies) in a certain region of the world, various groups and unions of states, individual countries, their regions, territorial and industrial entities, etc. [57,58]. Thus, energy security as a subject of research is not so much of a state of the energy sector itself but of its (energy sector) relationship with economic, social, foreign policies, and other aspects of the existence of citizens, society, and the state as a whole. This reality captures a broader meaning of the energy security concept, the research of which also includes the reliability issue of the energy sector and energy systems.

Therefore, we will consider the basic principles of the study of the energy system reliability based on hierarchical modeling, with the emphasis on the specifics of energy security studies.

The principles of studying the reliability of energy systems.

The reliability of energy systems, following [59], is the ability of energy systems to ensure an uninterrupted supply of appropriate energy carriers of agreed quality and according to agreed delivery schedules, avoiding the situations where the danger for people and the environment exceeds a certain level. Reliability, being a complex metric, includes the feature of "survivability" or the ability of energy systems to withstand large disturbances, preventing their cascade development with mass outages of consumers [60]. For complex energy systems, there is always a risk of major, cascading accidents that turn into "system-wide" failures under unfavorable circumstances, which can negatively affect fuel and energy supply to consumers. Reliability and survivability are the properties of energy systems themselves and represent predominantly technical categories, which have an economic meaning only because comprising them often entails economic damage.

The assessment of the energy sector capabilities to ensure uninterrupted fuel and energy supply under various operating conditions of the entire energy sector requires the identification of such capabilities of systems of individual industries, including those pertinent in the event of large-scale disturbances. The subject of the study here is how disturbances occur, the response of energy systems, the consequences for final energy consumers, and the method of compensation for undesirable consequences [61]. The need to study the operation of energy systems under emergencies is driven by the general methodological principle stated in [62]: it is quite sufficient to test simple systems under normal conditions, whereas complex systems need testing in extreme situations.

A large number of studies have been devoted to the reliability and survivability of large energy systems and the energy sector, and, in particular, to the hierarchical modeling in the study of these issues, see, for example, [63–68]. The MESI has gained extensive experience in studying various aspects of interconnected operation of energy industries within a single energy sector, including the studies of these systems in terms of their survivability and continuous fuel and energy supply to the consumer [69–73].

Methodological features of energy security studies.

In the mid-1990s, the MESI launched energy security research, which was a continuation of the studies on the reliability of the energy sector and energy systems. Among other things, the research determined the essence and main aspects of the energy security problem and identified "bottlenecks" in the national economy and energy sector in terms of energy security. Based on an analysis of the performance of the energy sector and the prospects for its development, the study also established and classified the energy security threats, the occurrence of which both in an individual energy system and in the entire energy sector can lead to serious failures accompanied by significant energy shortages for the consumer.

When considering the methodological aspects of energy studies in the context of energy security, one should keep in mind the following important features [57]:

- The emergencies and major accidents of extreme nature are unique in terms of the probability and conditions of their occurrence, the nature of the phenomena and processes, the nature and severity of their consequences for energy systems and consumers;
- Studying energy systems requires them to be represented in sufficient detail due to a large scale of the disturbances, the possibility of development of adverse events, the need to model the response of energy facilities and consumers (given their structure and properties), since different components of energy systems and different consumers can respond differently to a large disturbance, etc.
- The need to prioritize the consumers facing the energy supply problems in case of emergency.

The aforementioned determines the use of a simulation approach as the main methodological principle of the energy research that deals with energy security and the justification of measures to increase the survivability of energy systems and to ensure energy security. The list of the scenarios covered, among other things, is determined by the specific threats to energy security, whose materialization is considered possible in the study. The analyzed set of disturbances in specific conditions can be quite large. Since the scale of the considered disturbances is large, the materialization of possible energy security threats will inevitably result in fuel and energy shortages for consumers, and energy consumption limitations, which are associated with economic damage to the industry, agriculture, and other sectors of the economy, the public utilities sector, and the energy sector itself (lower profit, higher fines, etc.). The sizes of these shortages, energy consumption limitations, and damages are metrics that can be used to assess the severity of the energy consequences of specific disturbances when various energy security threats materialize and to evaluate the comparative effectiveness of energy security measures [74–78].

Modeling principles for the assessment of consequences of large-scale energy system failures for the energy consumer.

A general scheme has been designed to assess the consequences, from the standpoint of the consumer, of disruptions in the operation of an energy system that is part of the energy sector for the energy consumer. Solving the problems of survivability of each energy system requires a certain level of hierarchy and detail of the models used. The following aspects need to be detailed [60]:

- *The structure of energy systems*. A detailed analysis of the consequences of major accidents and the development of emergencies in the energy sector requires that the transport components of individual energy systems be presented at the level of specific energy facilities and relevant transport links, at least in the studied area and across a wide area that surrounds it. Emergencies can occur in any place of energy systems, therefore, sufficiently detailed modeling of their structure at the national and regional levels is needed.

- *The operating conditions of energy systems*. Under normal operating conditions, energy facilities perform the functions assigned to them as per their operating characteristics. In the event of emergencies, when their operating characteristics are compromise or one or more of these facilities cease to operate, the production capabilities of the corresponding energy system or even several interconnected energy systems decrease and may be inadequate. In this case, the resulting energy shortage will cause a restriction of energy supply to consumers. Consideration of such situations as part of the research necessitates sufficiently detailed modeling of the energy system operation.

- *Representation of energy consumers*. Detailed representation of consumers is necessary due to the large-scale potential disturbances leading to restrictions in the fuel and energy supply to consumers and disruptions of their production processes. The detailed structural representation of energy systems makes it possible to show each major consumer while accounting for its production process and energy supply conditions. It also allows determining the resources for the consumer adaptation to energy shortages and interruptions in energy supply. In this regard, modeling the emergencies in energy systems is associated with an analysis of the energy system behavior and measures to increase the survivability only in the most typical situations defined by the characteristic points of the consumer load curves (maximum/minimum load, etc.), the mix of equipment operating in the system and its loading [60]. Thus, at the level of energy systems under various types of emergencies, there is a 'point-in-time' modeling of their operating conditions [60].

Due to the impossibility of conducting large-scale experiments on spatially extended energy systems, the most convenient way to study their survivability is to use a simulation approach when the study of the considered phenomena involves the investigation by sequentially putting forward "working hypotheses" and experimentally testing them [73]. The simulation approach is the main methodological principle of energy studies from the standpoint of providing continuous fuel and energy supply to the consumer and the rationale for measures to improve the survivability of energy systems. A general scheme for studying the survivability of energy systems, representing the relationship between the main problems, is shown in Fig. 2.14 [57,79–82].

Building a set of disturbance scenarios that reflect the most representative or characteristic combinations of external conditions for the development and operation of energy systems is an important component of the research. The number of such characteristic situations for a complex energy system can be extremely large. This creates the problem of making a reasonable choice of the most representative set of characteristic situations that are referred to as design situations. The resulting estimates and solutions should be invariant for different combinations of the conditions.

The next two problems, those of the identification of "bottlenecks" in the fuel and energy supply to consumers and assessment of the effectiveness of measures for specific disturbance scenarios, have their specific features in terms of object modeling. As already mentioned, the study of the energy system survivability solves a set of subproblems at various levels of spatial and technological hierarchy where while moving from the upper levels of the hierarchy down to the lower levels, the ideas about the structure and properties of the system studied get refined and detailed. In some cases, if it is necessary to present the features of an energy system or a region, it may be appropriate to refer to industry-specific or regional models to clarify individual points.

Another problem is to assess the acceptability and effectiveness of measures intended to increase the survivability of energy systems and ensure uninterrupted fuel and energy supply to consumers under specific disturbance scenarios. The models of energy systems based on linear programming methods can optimize the choice of measures when the functional to be optimized and model equations are set in a certain manner. The substantiation of measures aimed at improving the survivability of energy systems and ensuring continuous fuel and energy supply to consumers is significantly complicated by the uniqueness of the considered phenomena and their consequences for the energy sector and consumers. One of the main effects of the indicated measures is the reduction in direct and indirect damage due to a decrease in energy shortage, a reduction in the risk of interrupting energy supply to essential consumers, a lower number of social consequences, etc. Damage components that can be assessed

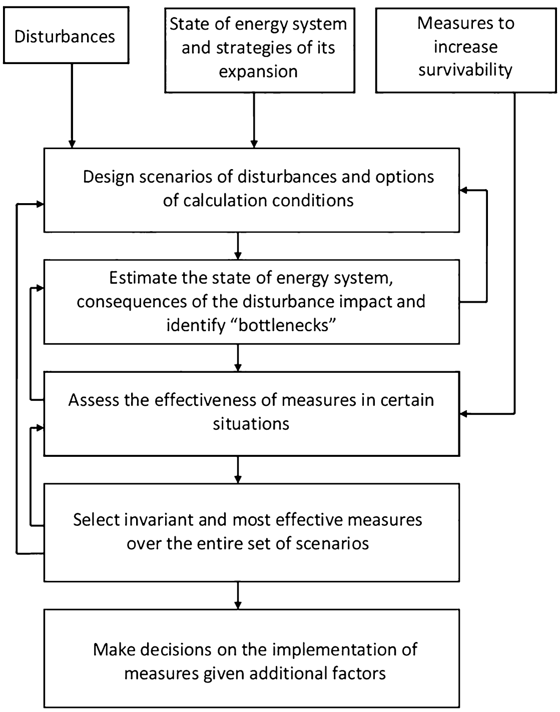


FIGURE 2.14 The relationship between the main problems in the research into the energy systems survivability.

economically should be considered when analyzing the economic feasibility of the measures. The economic feasibility of the discussed measures mainly depends on the probabilities of potential disturbances, critical and emergency conditions, and situations. Under normal operation of the energy sector, these probabilities are relatively small, and therefore, despite rather severe consequences of such situations, only the measures that can prevent them and do not require large additional costs can be acceptable.

The final stage of the studies suggests making a decision on the implementation of the measures to increase the survivability of energy systems, which is considered at the level of decision-makers. The decision-making process can also employ models and expert judgments on other factors, for example, the conditions for the implementation of the measures in terms of the entire economy; environmental, social, and other requirements and constraints, etc.

Quantitative indexes and measures for increasing the survivability of energy systems and the energy sector, at which one arrives by means of the approach presented above, are used as a basis for assessing the energy security of the country and its regions.

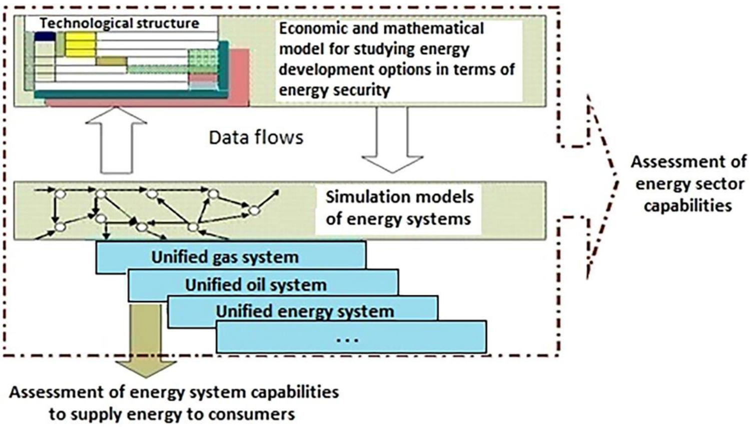


FIGURE 2.15 The relations of linear optimization models for the study of energy security issues.

A two-level approach to the study of energy security.

To study the energy security problems MESI has proposed a two-level technology that integrates the stages of qualitative and quantitative analyses. At present, the stage of the quantitative analysis is most developed. This stage involves a study of the extent the energy sector operation and development meets energy security requirements. The study is based on linear optimization models of the energy sector and individual energy systems. It also relies on the technical and economic characteristics of energy facilities, reported data on the performance of energy systems, and the findings of energy sector development studies that provide grounds for the selection of a long-term strategy and formulation of an energy policy. Based on the socio-economic development program adopted for the future for the national economy, which determines the demand for fuel and energy resources, the expected energy consumption levels are analyzed and assessed.

The stage of the qualitative analysis suggests the use of the above characteristics and the analysis of threats to energy security with the view to formulating the calculation conditions for the computational experiment that is carried out at the stage of quantitative analysis. Based on the presented hierarchy of problems to be solved and models developed for this kind of research, a two-level system of models was proposed [83]. A methodological approach that rests on a multi-level hierarchy of energy optimization studies was used to coordinate the models of different levels of hierarchy in the considered studies. The main problems to be solved and relations between the models are presented in Fig. 2.15.

In this approach, the upper-level models are constructed by appropriate aggregation of the lower-level models. At the same time, the lower-level models are simulation models of energy systems that are designed to analyze the development options of the energy systems, estimate their state, and identify “bottlenecks” under various operating conditions. The aggregated solutions found using the upper-level models are transferred to the lower-level models and used by them as boundaries within which a detailed solution is sought.

The upper level of the hierarchy is a system of models for research aimed at assessing the performance of the energy sector in case of possible disturbances and their impact on the fuel and energy supply to consumers from the energy security standpoint [83]. These models are interconnected by balance and technological (structural) relationships but differ in the duration of the considered time interval, Fig. 2.16:

1. a model for estimating the current performance of the energy sector under normal and emergency operating conditions;

2. a model for optimizing the territorial and production structure of the energy sector (based on the adopted energy development strategies given the possibility of emergencies).

The models used present the country’s territory in detail, highlighting the federal districts and constituent entities of the Russian Federation. Energy systems of individual industries including backup facilities are presented in sufficient detail. The models are oriented to the representation of seasonal irregularity, with a possible transition from the annual representation to the quarterly and, if necessary, to the daily representation. They are also aimed at determining the directions and scale of the optimal development of the energy industry (given structural redundancy in the form of capacity reserves, fuel reserves, and the possibilities of interchangeability of fuel and energy resources), the optimal distribution of energy resources consumed, and the shortage of fuel and energy resources on the consumes side. The objective function includes not only the costs of energy development but also the fines for possible energy under supply to consumers.

Mathematically, the problem of the optimization of fuel and energy balances in the regions of the country given possible disturbances, is a classical linear programming problem that is solved using the above models. Conceptually, the approach is based on the territorial and production model of the energy sector with the modules of electric power-, heat-, gas-, coal supply, and refinery operations (fuel oil supply).

Formalized constraints of the above optimization problem are written as a system of linear equations and inequalities:

$$S_H + AX - \sum_{t=1}^{T} Y^t - \sum_{h=1}^{H} S_k^h = 0 \tag{2.3}$$

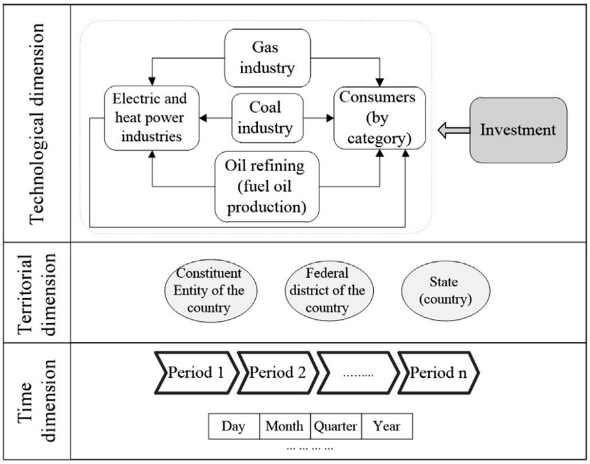


FIGURE 2.16 The structure of the energy sector model.

$$0 \leq X \leq D, \tag{2.4}$$

$$0 \leq Y^t \leq R^t, \tag{2.5}$$

$$0 \leq S_k^h \leq \overline{S^h}, \tag{2.6}$$

$$\sum_{h=1}^{H} \overline{S}^h \leq S, \tag{2.7}$$

where t is consumer categories; h is reserve categories; X is the desired vector characterizing the intensity of the use of energy facilities (production, processing, conversion, transportation of energy resources); Y^t is the desired vector characterizing the consumption of individual fuel and energy types by certain categories of consumers (t); S_k^h is the desired vector characterizing the volumes of fuel reserves of a given category (h) at the end of the period in question; S_H is a specified vector with its components equal to the initial levels of energy reserves; A is a matrix of input-output ratio of production (mining, processing, conversion) and transmission of certain types of fuel and energy; D is a vector determining technically feasible intensities of using individual process methods; R^t is a vector with components equal to the volumes of specified consumption of individual fuel and energy types by certain categories of consumers; $\overline{S}^h$ is a vector whose components reflect the standard volume of reserves of category h; S is a vector with components equal to the capacity of storage of a given energy resource.

The objective function is of the following form:

$$(C,x)+\sum_{t=1}^{T}(r^t,g^t)+\sum_{h=1}^{H}(q^h,\overline{S}^h-S_k^h)\rightarrow min. \quad (2.8)$$

The first component of the objective function reflects the costs associated with the operation of the energy systems in the energy sector. Here C is the vector of unit costs for individual methods of operation of existing, reconstructed, or upgraded, and newly constructed energy facilities.

The second component is the damage from the shortage of each type of fuel and energy resources for each considered consumer category. Energy shortage (g^t) for the consumer of category t corresponds to the difference ($R^t - Y^t$). The magnitude of non-accumulation of energy reserves g^h corresponds to the difference $\overline{S}^h - S_k^h$. Vectors r^t and q^h consist of components conventionally called 'specific damages'. To minimize such damages, the model uses a scale of priority in satisfying the demand for certain fuel and energy types of consumers of the considered categories. The third component is similar to the second one and corresponds to the damages from the non-accumulation of reserves.

An analysis of the optimization calculation results for the considered situation enables us to determine:

- the value of a shortage of certain types of fuel and energy resources for the considered categories of consumers as the value of discrepancy between the given demand and the possibility of supplying this type of energy resource;

- the values of a change in the throughput capacity of energy transportation links;

- rational volumes of the utilization of production capacities of energy facilities and distribution of certain types of energy resources by consumer categories (the basis for choosing rational values are dual estimates, which are a system of interrelated specific economic indicators of the costs of providing additional demand for each type of fuel and energy resource).

The lower level of the hierarchy is represented by sectoral models [69–72], which make it possible to assess the potential capabilities of gas, oil, and petroleum product systems, and also the capabilities of the electric power system to satisfy consumers with appropriate energy resources under various operating conditions, including standard and emergency ones. The essence of the models of the Unified oil and petroleum product system (UOS) and the Unified Gas Supply System (UGSS) of Russia is elucidated below in this section. The model of the electric power system operation has its specific features and is presented below.

The study on the UOS and the UGSS survivability involves solving the linear programming problem in a network statement and using the simulation flow models of the corresponding systems. In addition to the production and transport modules, the models include the modules of gas, oil, and petroleum products consumption. The main consumers of the considered energy resources are represented by regions, large industrial hubs, and importing countries. There are 90 territorial units in total.

The model for assessing the production capabilities of the unified oil and petroleum product system under extreme situations is presented in detail in [69]. The UOS is understood as both the oil system and the petroleum product system. The two "related" systems are integrated through oil refining facilities. It is assumed that the production capabilities of system facilities depend on the availability of resources, and the loss of some quantity of any of the resources leads to a decrease in the production capabilities of the facility. Mathematically, the UOS is represented by a network that changes in time and changes as a result of a disturbance. The nodes of the network contain the entities involved in production, conversion, and consumption of material flows that implement material relations between the facilities. When estimating the state of a system after a disturbance, the criterion for the optimality of the flow distribution is the minimum energy shortage for the consumer at the minimum costs of energy delivery to the consumer. In other words, the problem of the flow distribution in the system is solved to maximize the supply of energy to consumers, i.e., the problem is formalized as the maximum flow problem [84]. Two dummy nodes are added to the graph simulating the oil and petroleum product system: O is the total inflow; S is the total outflow. In this case, additional sections are also introduced to connect node O with all sources, and all consumers - with node S.

Mathematically, the problem is written as follows:

$$max\ f \tag{2.9}$$

subject to

$$\sum_{i \in N_j^+} x_{ij} - \sum_{i \in N_j^-} x_{ji} = \begin{cases} -f, j = O \\ 0, j = O, S \\ f, j = S \end{cases} \tag{2.10}$$

$$0 \le x_{ij} \le d_{ij},\ \forall (i, j) \tag{2.11}$$

Here N_j^+ is a subset of edges incident to the node j; N_j^- is a subset of edges outgoing from the node j; f is the value of the total flow throughout the network; x_{ij} is a flow at the edge (i, j); d_{ij} are constraints on the flow at the edge (i, j).

The maximum flow problem (2.9)–(2.11) generally has a non-unique solution. The next step is to solve the problem of the maximum flow at minimum cost, i.e., the cost functional is minimized:

$$\sum_{(i,j)} C_{ij} x_{ij \to min}, \tag{2.12}$$

where C_{ij} is the price or specific costs of energy transportation.

The models define the networks of main oil pipelines and main oil product pipelines, and the network of discrete transport of oil and petroleum products. A unique feature of the UOS study is that it is necessary to find out the production capacities of the system on three interrelated graphs (oil, light oil products, and fuel oil). This calls for two stages of the study. Stage 1 assumes solving the problem of minimizing the total shortage in the oil system, given the oil balance at the network nodes, constraints on the transmission capacity of edges, and production capacities of sources (fields) and consumers (refineries, export points). Stage 2 is aimed at solving a similar problem in the petroleum product system (sources are refineries and oil product import points; consumers are the entities of a country (for example, federal subjects of the Russian Federation), large industrial centers, and export points).

The comprehensive approach to solving the stated problems along the entire UOS process flow from oil production to petroleum product consumption, which is implemented in the model, provides a general assessment of the production capabilities of the entire system under corresponding disturbances in the operation of the industry.

The model for assessing the production capabilities of the UGSS under various kinds of disturbances [70] is treated as a combination of three subsystems: gas sources, main transmission network, and consumers. The above facilities also include underground gas storage (UGS) facilities that, as the case may be, play the role of either consumers or sources. During the year when gas demand is lower than the average annual, gas from the system is injected into the UGS, while in the opposite case (mainly during the heating period), gas is withdrawn from the UGS to the system to compensate for the seasonal non-uniformity of its consumption. To solve this problem, as in the case of the UOS, linear programming technique is used in a network setup. Its application makes it possible to determine the optimal volumes of natural gas resource to provide its supply to the consumer while minimizing the costs of gas production, transmission, and withdrawal from underground storage facilities. The solutions to the problem are the values of the gas shortage at the consumption nodes.

The calculation results obtained using the models of individual industries serve as input data for the energy sector models whose output can be used to comprehensively assess the possibilities for the energy systems and energy sector to cope with the situation in question and serve as the basis for the formulation of the energy security requirements. Model calculations using a two-level system of models were mainly carried out to assess the consequences of the emergencies in energy systems of individual industries and to identify directions for energy development from the standpoint of energy security. An example of such a study can be an analysis of the case with the disconnection of a major intersection of gas pipelines in the north of the Ural Federal District [85]. As calculations show, a relative gas shortage throughout the country due to this disconnection can reach 14% in the days of the accident. The consumers of the North-Western (37% gas shortage) and Central (21% gas shortage) Federal Districts are most likely to suffer most. An analysis of the results obtained with the upper-level model (the level of the energy sector) showed that given the possibilities of replacing gas with heating oil and using the reserves in energy systems of individual industries, gas shortages throughout the country in this case can be reduced to 4.5% of the needs during the specified period. The fuel oil shortage will be 1.6%. In general, this emergency may cause a relative shortage of fuel and energy resources for the consumer that would amount to 3% of the total quarterly demand for them.

Models of operation of an electric power system to determine power and electricity shortage in case of materialization of the threat to energy security.

The energy security factor is extremely important to make control decisions in electric power systems. However, it is difficult to factor it in because its general and economic assessment is problematic. The difficulty lies in the fact that the effect of the same measure intended to ensure the security of a system facility or an entire electric power system can differ for different electric power systems and even for different conditions of its use within one electric power system. This effect depends on where in the system the measure is adopted, the time of its adoption, and, most importantly, on the technical and economic characteristics of the system where the measure is taken. It can be concluded that to correctly assess the effectiveness of the proposed measure while managing the expansion or operation of the electric power system or its facilities in terms of energy security, one should consider the operation of the entire electric power system and, if possible, within the national and regional economy. A local assessment of this effect can lead to wrong conclusions about the feasibility of a particular measure.

One of the most difficult tasks, in this case, is to reliably quantify the level of energy security itself, since this requires laborious calculations using optimization methods and models, calculations of operating conditions, etc. As already noted, one of the critical infrastructures that impacts energy security is the electric power system. Given the unique nature of the electric power system operation that consists in simultaneous production, transmission, distribution, and consumption of electric energy and power, the materialization of threats to energy supply has an instant effect on electricity consumers.

The spatial and temporal decomposition of the problems of energy security research governs the conditions for the hierarchical construction of the models. The general trend in the area of building electric power system models is in line with the above principles: the closer the horizon of studying the electric power system operation to the present moment, the more detailed presentation of the model is required to be; the larger the electric power system, the more aggregated its parameters should be. Modeling of electric power systems for energy security studies is performed in the following sequence:

1. Form a set of input data. The input data in the general case may include the topology of the design or operation scheme of the electric power system; values of available generation capacities; values of transfer capabilities of power lines included in the cross-zone links; data on hourly load curves in the electric power system zones; characteristics of planned maintenance schedules for energy equipment of electric power systems (since disturbances in the system operation can occur at any time, it is necessary to capture in a sufficiently accurate way the actual operating conditions of the electric power system, planned maintenance of equipment including).

2. Build a scenario for the case of a disturbance.

3. Model operating conditions of an electric power system. In this case, each condition characterizes the operation of the electric power system for one hour.

4. Determine electricity and power shortages due to the disturbance.

The model [86,87] can be used to model the electric power system operating conditions for energy security studies. At the same time, it is necessary to minimize the power shortage arising in the electric power system due to the energy security threat materialization:

$$\sum_{i=1}^{I} (\overline{y_1} - y_i) \rightarrow \min, \tag{2.13}$$

Given the balance constraints

$$x_i - y_i + \sum_{j=1}^{J} \left(1 - a_{ij} z_{ji}\right) z_{ji} - \sum_{j=1}^{J} z_{ij} = 0,\ i - 1, \ldots, I,\ j = 1, \ldots, J, i \neq j, \tag{2.14}$$

and linear inequality constraints on variables

$$0 \leq y_i \leq \overline{y}_i,\ i = 1, \ldots, I, \tag{2.15}$$

$$0 \leq x_i \leq \overline{x}_i,\ i = 1, \ldots, I, \tag{2.16}$$

$$z_{ij} \leq \overline{z}_{ij},\ z_{ji} \leq \overline{z}_{ji},\ i = 1, \ldots, I,\ j = 1, \ldots, J, \tag{2.17}$$

$$y_i \geq 0,\ x_i \geq 0,\ z_{ij} \geq 0,\ z_{ji} \geq 0,\ i = 1, \ldots, I,\ j = 1, \ldots, J,\ i \neq j \tag{2.18}$$

where: $\overline{y}_i$ is the value of the maximum load at a node of the electric power system, MW (depending on electric power system aggregation, a node can be represented by the buses of the substation and electric power plant or an area that includes part of the electric power system with a set of substations and electric power plants); y_i is load covered at node i, MW; $\overline{x}_i$ is available generating capacity at node i, MW; x_i is capacity utilized at node i, MW; $\overline{z}_{ij}$ is the throughput capacity of the link between nodes i and j, MW; $\overline{z}_{ji}$ is transfer capability of the link between nodes j and i, MW; z_{ij} is power flow from node i to node j, MW; z_{ji} is power flow from node j to node i, MW; a_{ij} is coefficients of specific losses of power when transmitted from node i to node j.

In this problem, the balance is to be reconciled for active power only, but the statement of this problem with quadratic power transmission losses is a fairly accurate approximation of the balance of active and reactive powers [87].

As already noted, there can be different representations of electric power systems depending on modeling conditions. In the case of a long-term (15-20 years) modeling of an electric power system of a country (e.g. Russia) for the study of energy security, for instance, so as to develop an energy strategy, a national electric power system (e.g. the Unified Energy System (UES) of Russia) can be by Interconnected Power Systems (Fig. 2.17).

For a horizon of the development planning reduced to short-term or medium-term periods of up to 10 years, the studies of energy security can be based on such a representation of the UES of Russia where a zone can be represented by a constituent entity of the Russian Federation.

Electric power systems can be divided into zones according to other criteria, for example, the system operator of the electric power system, when managing an electric power system, controls the sections that limit power transmission within the UES of Russia. Thus, the partitioning can be done along these controlled sections, and then the number of zones in Russia's UES may remain the same as when the system is divided into zones along the borders of the constituent entities but the borders themselves may shift. As to the regional aspect of electric power system modeling for the study of energy security, a regional electric power system model can be based on the complete topology of the power system, the zones can be represented by load substations and power plants, and internal power lines can act as cross-zone links.

Depending on the structure of the electric power system and the specific features of its operation, the level of its stability also varies. Some disturbances in different electric power systems can lead to a cascading development of the emergency. In the model (2.13) - (2.18) this situation is not considered. In this case, the materialization of this threat and its consequences should be factored in by the models aimed at assessing the

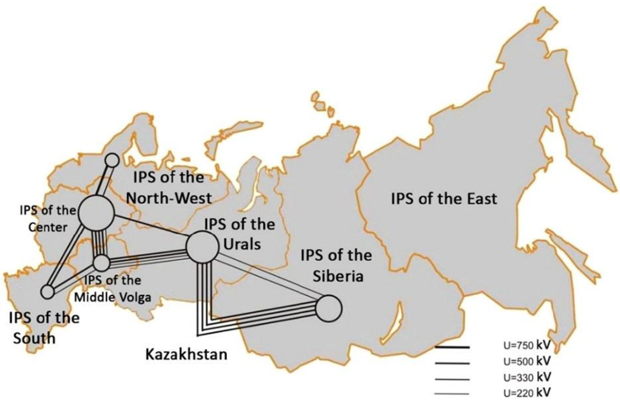


FIGURE 2.17 Representation of Russia's UES for a long-term energy security study.

stability of the electric power system and the development of cascading failures.

Consequently, the system of mathematical models employed in the study on national and regional energy security is largely based on mathematical models designed to study reliability. Moreover, the hierarchy of models in the study of energy security nowadays is considered in terms of its two main aspects:

- spatial: from regions and aggregated centers of energy consumption to entities at the level of districts, countries, their unions, and regions of the world;

- structural: covering the entire structure of the energy economy - from energy facilities of individual industries, included in the unified production and functional complex, and the links between them to large-scale (national and cross-border) technologically connected energy systems to unified energy sectors of countries and regions of the world where energy systems of individual industries operate interconnected.

This section has outlined the principles of hierarchical modeling as applied to main technologically connected large-scale energy systems including a unified oil and petroleum product supply system, a unified gas supply system, and a unified electric power system of the country. The above findings indicate that individual regional energy systems can also be studied in terms of the energy security of corresponding regions while relying on the principles of hierarchical modeling, both in spatial and structural dimensions.

Acknowledgments

The research was carried out under State Assignment Projects (no. FWEU-2021-0003 and FWEU-2021-0004) of the Fundamental Research Program of Russian Federation 2021-2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] L.D. Krivorutsky, A.S. Makarova, A.A. Papin, Methods for working out long-term energy industry development strategies, in: Issues of Projections of the Energy Sector, Siberian Energy Institute, Irkutsk, 1974, pp. 65–81 (in Russian).

[2] Energy in a Finite World: A Global Systems Analysis, Ballinger Publishing Company, Cambridge, MA, 1981.

[3] US Energy Information Administration, The National Energy Modeling System: an overview [Electronic Publication], U. S. Energy Information Administration, 2014, http://www.eia.gov/oiaf/aeo/overview/, 2015. (Accessed February 2015).

[4] A.A. Makarov, Energy Systems Development Analysis, Moscow Power Engineering Institute Publishing House, Moscow, 2015 (in Russian).

[5] L.A. Melentiev, Systems Research in Energy: Elements of Theory and Directions for Development, Nauka, Moscow, 1979 (in Russian).

[6] Yu.D. Kononov, Approaches to Improve the Validity of Long-Term Projections of Energy Sector Development, Nauka, Novosibirsk, 2015 (in Russian).

[7] Yu.D. Kononov, E.V. Galperova, D.Yu. Kononov, et al., Methods and Models for Projections of Energy-Economy Interactions, Nauka, Novosibirsk, 2009 (in Russian).

[8] A.V. Lagerev, A dynamic territorial and production model for the development of scenarios of a mutually aligned development of Russia's energy industry as concerns its federal subjects, Izvestiya RAN. Energetika 4 (2004) 26–32 (in Russian).

[9] N.I. Voropai, V.V. Trufanov, Mathematical modeling of electric power systems development under current conditions, Elektrichestvo 5 (2000) 2–9 (in Russian).

[10] A.A. Makarov, F.V. Veselov, E.A. Volkova, A.S. Makarova, Methodological Grounds for Working Out the Prospects of the Development of the Electric Power Industry, Energy Research Institute of the Russian Academy of Sciences, Moscow, 2007 (in Russian).

[11] L.I. Lopatnikov, Economic and Mathematical Dictionary: The Dictionary of Modern Economics, Delo, Moscow, 2003 (in Russian).

[12] S.M. Ermakov, Monte Carlo Methods and Related Problems, Nauka, Moscow, 1975 (in Russian).

[13] Yu.D. Kononov, V.N. Tyrtyshny, Assessment of the impact of the nature of uncertainty in future conditions on the competitiveness of fuel supply options, Energeticheskaya Politika 4 (2011) 50–56 (in Russian).

[14] L.M. Dudkin (Ed.), Iterative Aggregation and Its Application to Planning, Ekonomika, Moscow, 1979 (in Russian).

[15] A.A. Makarov (Ed.), Methods and Models for Harmonizing Hierarchical Decisions, Nauka, Novosibirsk, 1979 (in Russian).

[16] R. Loulou, U. Remne, A. Kanudia, A. Lehtila, G. Goldstein, Documentation for the TIMES Model, 2005, p. 78, http://iea-etsap.org/docs/TIMESDoc-Intro.pdf, 2019. (Accessed 2 July 2019).

[17] World energy model documentation, IEA, 2018, p. 82, https://www.iea.org/media/weowebsite/energymodel/WEM2018.pdf, 2019. (Accessed 2 July 2019).

[18] World energy projection system plus model documentation, https://www.eia.gov/outlooks/ieo/weps/documentation/, 2019. (Accessed 2 July 2019).

[19] The MESSAGEix framework, https://message.iiasa.ac.at/en/stable/. (Accessed 2 July 2019).

[20] Energy outlook for Asia and Pacific, ADB, APEC, 2013, p. 543, https://www.adb.org/sites/default/files/publication/30429/energy-outlook.pdf, 2019. (Accessed 2 July 2019).

[21] IEEJ Outlook 2019, IEEJ, p. 288, https://eneken.ieej.or.jp/data/8122.pdf, 2019. (Accessed 2 July 2019).
[22] A.A. Makarov, L.M. Grigoriev, T.A. Mitrova (Eds.), Evolution of World Energy Markets and Its Consequences for Russia, Energy Research Institute of the Russian Academy of Sciences, Analytical Center for the Government of the Russian Federation, Moscow, 2015(in Russian) .
[23] S.P. Popov, Methodological approach to estimating the demand for Russian energy resources in East Asian markets, in: The Seventh Melentiev Readings, Energy Research Institute of the Russian Academy of Sciences, Moscow, 2013, pp. 116–127 (in Russian).
[24] S.P. Popov, East Asia as an object for Russia-Mongolia energy cooperation, Energy Systems Research 1 (4) (2018) 45–55.
[25] S.P. Popov, The institution of international multilateral cooperation in energy: APEC practice, Energeticheskaya Politika 3 (2013) 60–70 (in Russian).
[26] S.P. Popov, The gas industry of China: a new resource for development, Prostranstvennaya Ekonomika 2 (2013) 22–48 (in Russian).
[27] S.V. Podkoval'nikov, V.A. Saveliev, L.Yu. Chudinova, Study of the systemic energy and economic efficiency of forming the cross-border association for electricity co-operation of Northeast Asia, Izvestiya RAN. Energetika 5 (2015) 16–32 (in Russian).
[28] B.G. Saneev, A.D. Sokolov, G.V. Agafonov, et al., Methods and Models for Regional Energy Programs Development, Nauka, Novosibirsk, 2003 (in Russian).
[29] N.I. Voropai (Ed.), Systems Studies of Energy Problems, Nauka, Siberian Publishing Company of the RAS, Novosibirsk, 2000 (in Russian).
[30] Yu.D. Kononov, E.V. Galperova, D.Yu. Kononov, Methods and Models for Projections of Energy-Economy Interactions, Nauka, Novosibirsk, 2009 (in Russian).
[31] N.I. Voropai, S.V. Podkoval'nikov, V.V. Trufanov, et al., in: N.I. Voropai (Ed.), Justification of the Development of Electric Power Systems: Methodology, Models, Methods, and Their Application, Nauka, Novosibirsk, 2015 (in Russian).
[32] E.V. Galperova, Yu.D. Kononov, V.N. Tyrtyshny, A stack of models for long-term projections of the state of regional energy markets, in: Baikal All-Russian Conference "Informacionnye i Matematicheskie Tekhnologii v Nauke i Upravlenii", Irkutsk, Russia, June 28 – July 7, 2014, pp. 14–21 (in Russian).
[33] B.G. Saneev (Ed.), Regional Energy Programs: Methodological Foundations and Past Experience of Developing Them, Nauka, Siberian Publishing Company of the Russian Academy of Sciences, Novosibirsk, 1995 (in Russian).
[34] N.I. Voropai (Ed.), Energy Systems Studies: The Siberian Energy Institute, Energy Systems Institute Schools of Thought in Hindsight, Nauka, Novosibirsk, 2010 (in Russian).
[35] A.Z. Gamm, A.A. Makarov, B.G. Saneev, et al., Theoretical Foundations of Systems Analysis in Energy, Nauka, Novosibirsk, 1986 (in Russian).
[36] B.G. Saneev, A.D. Sokolov, S.Yu. Muzychuk, R.I. Muzychuk, Principles, methods, and models of projections and studies of regional energy sector development, Energeticheskaya Politika 4 (2011) 30–42 (in Russian).
[37] B.G. Saneev, A.D. Sokolov, Methodology of systemic economic valuation of investment projects, in: Methods and Models for Regional Energy Programs, Nauka, Novosibirsk, 2003, pp. 104–110 (in Russian).
[38] B.G. Saneev, A.D. Sokolov, S.Yu. Muzychuk, R.I. Muzychuk, Fuel and energy balances in the system of a comprehensive study of the development of the regional energy sector, Izvestiya RAN. Energetika 2 (2011) 21–35 (in Russian).
[39] G.V. Agafonov, B.G. Saneev, A.D. Sokolov, et al., Methods and models for optimizing the development of systems in the coal industry, in: Methods for Research and Management of Energy Systems, SEI, SB AS of the USSR, Irkutsk, 1986, pp. 56–58 (in Russian).
[40] A.D. Sokolov, L.N. Takaishvili, Implementation of the information support for projections of coal industry development in regions of Russia, Sovremennye Tekhnologii. Sistemnyi Analiz. Modelirovaniye 1 (41) (2014) 126–133 (in Russian).

[41] B.G. Saneev, A.D. Sokolov, S.Yu. Muzychuk, Assessment of the effectiveness of integration processes in the energy industry, Energetik 6 (2001) 4–6 (in Russian).
[42] B.G. Saneev, E.P. Maysyuk, I.Yu. Ivanova, Factoring in regional specifics in methods for assessing the impact of energy on the natural environment, Izvestiya RAN. Energetika 6 (2016) 79–85 (in Russian).
[43] A.V. Lagerev, K.S. Smirnov, Methodological approach to comparative valuation of electricity export projects, Izvestiya RAN. Energetika 4 (2014) 15–26 (in Russian).
[44] A.D. Sokolov, S.Yu. Muzychuk, R.I. Muzychuk, Fuel and energy balances of the Irkutsk region in physical and cost terms: methods for development and key research findings, Izvestiya IGEA 1 (87) (2013) 124–129 (in Russian).
[45] B.G. Saneev, A.D. Sokolov, S.Yu. Muzychuk, R.I. Muzychuk, Methodological approach to assessing the energy efficiency of the economy when changing the structure of the fuel and energy balance (a case study of the Baikal region), Prostranstvennaya Ekonomika 4 (2013) 90–106 (in Russian).
[46] I.Y. Ivanova, Significant factors affecting the selection of rational options for power supply in an off-grid zone, E3S Web of Conferences 77 (2019) 02006, https://doi.org/10.1051/e3sconf/20197702006.
[47] I.Yu. Ivanova, T.F. Tuguzova, Justification of rational options for energy and fuel supply of decentralized consumers of the region: a methodological approach and research findings, Energeticheskaya Politika 4 (2011) 42–49 (in Russian).
[48] T.F. Tuguzova, I.Yu. Ivanova, Directions for increasing efficiency in the zone of decentralized energy supply, Region: Ekonomika i Sociologiya, Special Issue “The Energy sector of Russia’s East: priorities and mechanisms for the implementation of development directions” (2010) 184–199 (in Russian).
[49] B.G. Saneev, I.Yu. Ivanova, T.F. Tuguzova, Renewable energy sources in regional energy programs in Russia’s east: prerequisites and rational scale, Energetik 3 (2014) 6–9 (in Russian).
[50] I.Yu. Ivanova, T.F. Tuguzova, N.A. Khalgaeva, Determination of the optimal renewable energy source capacity for the consumer isolated from the power system, Izvestiya RAN. Energetika 1 (2014) 22–28 (in Russian).
[51] B.G. Saneev, I.Yu. Ivanova, T.F. Tuguzova, A.K. Izhbuldin, Stand-alone energy sources in the North of the Russian Far East: characteristics and directions of diversification, Prostranstvennaya Ekonomika 1 (2018) 101–116, https://doi.org/10.14530/se.2018.1.101-116 (in Russian).
[52] I.Yu. Ivanova, T.F. Tuguzova, V.A. Shakirov, N.A. Khalgaeva, Revisiting the issue of the need to take into account various factors when justifying the use of photovoltaic power potential for electric power supply purposes: the case of the Republic of Sakha, Izvestiya RAN. Energetika 2 (2018) 41–54 (in Russian).
[53] E.P. Maysyuk, Environmental factor in energy strategies of eastern regions, Energeticheskaya Politika 4 (2011) 56–61.
[54] E.P. Maysyuk, Principles and methods for assessing the effectiveness of environmental protection measures in the energy sector, Energeticheskaya Politika 4 (2017) 92–98 (in Russian).
[55] A.G. Korneev, K.A. Bobkov, Methodological approaches to the assessment of tax revenues of oil and gas complex in the areas of new development, Problemy Ekonomiki i Upravleniya Neftegazovym Kompleksom 12 (2007) 16–28 (in Russian).
[56] A.G. Korneev, A.S. Tsapakh, K.A. Bobkov, Fiscal performance of energy development, Region, Special Issue “Energy sector of Russia’s East: priorities and mechanisms for implementation of development trends” (2010) 223–235 (in Russian).
[57] V.V. Bushuev, N.I. Voropai, A.M. Mastepanov, Yu.K. Shafranik, et al., Energy Security of Russia, Nauka, Siberian Publishing Company of RAS, Novosibirsk, 1998 (in Russian).
[58] N.I. Voropai (Ed.), Energy Security. Terms and Definitions, IAC Energy, Moscow, 2005 (in Russian).

[59] Yu.N. Rudenko (Ed.), Reliability of Energy Systems and Their Equipment. In 4 volumes, Handbook on General Models of Analysis and Synthesis of Reliability of Energy Systems, vol. 1, Energoatomizdat, Moscow, 1994 (in Russian).
[60] G.F. Kovalev, E.V. Sennova, M.B. Cheltsov, et al., in: N.I. Voropai (Ed.), Reliability of Energy Systems: Achievements, Problems, Prospects, Nauka, Siberian Publishing Company of the Russian Academy of Sciences, Novosibirsk, 1999 (in Russian).
[61] G.N. Antonov, G.N. Cherkesov, L.D. Krivorutsky, et al., Methods and Models for Studying the Survivability of Energy Systems, Nauka, Sib. Branch, Novosibirsk, 1990 (in Russian).
[62] Yu.A. Shreider, Special aspects of the description of complex systems, in: Systems Studies. Methodological Problems. Yearbook 1984, Nauka, Moscow, 1983, pp. 107–124 (in Russian).
[63] Yu.N. Rudenko, I.A. Ushakov, Revisiting the issue of determining the survivability of complex energy systems, Izvestiya AN SSSR, Energetika i Transport 1 (1979) 14–20 (in Russian).
[64] Yu.N. Rudenko, I.A. Ushakov, Reliability of Energy Systems, Nauka, Novosibirsk, 1989.
[65] N.I. Voropai, L.D. Krivorutsky, Yu.N. Rudenko, I.A. Sher, The main methodological principles of studying and ensuring the survivability of energy systems, in: Methods and Models for Studying the Survivability of Energy Systems, Nauka, Sib. Branch, Novosibirsk, 1990, pp. 9–17 (in Russian).
[66] G.N. Antonov, G.N. Cherkesov, L.D. Krivorutsky, et al., Evaluation of options for the national energy development in terms of survivability, in: Methods and Models for Studying the Survivability of Energy Systems, Nauka, Sib. Branch, Novosibirsk, 1990, pp. 44–48 (in Russian).
[67] O.A. Agarkov, N.I. Voropai, V.P. Kychakov, et al., Investigation of some issues of survivability of electric power systems given non-traditional controls, in: Methods and Models for Studying the Survivability of Energy Systems, Nauka, Sib. Branch, Novosibirsk, 1990, pp. 198–203 (in Russian).
[68] N.I. Voropai, S.M. Klimenko, L.D. Krivorutsky, Regional Aspects of Energy Security in Russia, The Knowledge Society of Ukraine, Kyiv, 1997 (in Russian).
[69] S.M. Klimenko, S.M. Senderov, V.A. Yanchenko, Study of the problems of increasing the reliability and environmental safety of main oil and petroleum product pipelines, in: New Information Technologies for Managing the Development and Operation of Pipeline Energy Systems, SEI SB RAS, Irkutsk, 1993, pp. 119–126 (in Russian).
[70] A.V. Khramov, S.M. Enikeeva, N.M. Khrustaleva, et al., in: Yu.N. Rudenko (Ed.), Software and Information Support for Solving Survivability Problems of the Unified Gas Supply System of the USSR. Methods and Models for Studying the Survivability of Energy Systems, Nauka, Sib. Branch, Novosibirsk, 1990, pp. 86–91 (in Russian).
[71] N. Voropai, S. Senderov, A. Edelev, Detection of "bottlenecks" and ways to overcome emergencies in gas transportation networks on the example of the European gas pipeline network, Energy 42 (2012) 3–9, https://doi.org/10.1016/j.energy.2011.07.038.
[72] S. Senderov, A. Edelev, Formation of a list of critical facilities in the gas transportation system of Russia in terms of energy security, Energy 184 (2019) 105–112, https://doi.org/10.1016/j.energy.2017.11.063.
[73] M.I. Pichurina, S.M. Senderov, V.A. Yanchenko, A model for assessing the state of a unified oil and oil product system as a tool for studying its survivability, in: Methods of Analysis and Optimal Synthesis of Pipeline Systems, SEI SB AS USSR, Irkutsk, 1991, pp. 130–138 (in Russian).
[74] Hongfang Lu, FengYing Xu, Hongxiao Liu, Jun Wang, D.E. Campbell, Hai Ren, Emergy-based analysis of the energy security of China, Energy 181 (2019) 123–135, https://doi.org/10.1016/j.energy.2019.05.170.
[75] M.J. Bambawale, B.K. Sovacool, India's energy security: a sample of business, government, civil society, and university perspectives, Energy Policy 53 (2011) 113–123, https://doi.org/10.1016/j.enpol.2010.11.053.

[76] G.C.K. Leung, China's energy security: perception and reality, Energy Policy 55 (2011), https://doi.org/10.1016/j.enpol.2010.12.005.
[77] J. Lilliestam, S. Ellenbeck, Energy security and renewable electricity trade – Will Desertec make Europe vulnerable to the "energy weapon", Energy Policy 39 (6) (2011) 3380–3391, https://doi.org/10.1016/j.enpol.2011.03.035.
[78] L. Hughes, A generic framework for the description and analysis of energy security in an energy system, Energy Policy 79 (2012) 77–89, https://doi.org/10.1016/j.enpol.2011.11.079.
[79] L.D. Krivorutsky, Simulation System for Studying the Development of the Energy Sector, Nauka, Novosibirsk, 1983 (in Russian).
[80] N.I. Voropai (Ed.), Systems Research in the Energy Sector: the Siberian Energy Institute. Energy Systems Institute Schools of Thought in Hindsight, Nauka, Novosibirsk, 2010 (in Russian).
[81] S.M. Senderov, N.I. Pyatkova, V.I. Rabchuk, Impact of natural gas market on power generation development in Russia, in: 2008 IEEE PES General Meeting, Pittsburgh, PA, USA, July 20–24, 2008, pp. 30–35.
[82] N.I. Voropai, S.M. Klimenko, L.D. Krivorutsky, et al., Basic tenets and the methodology of the monitoring and indicator-based analysis of the energy security of Russia and its regions, Preprint No. 4, Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, Irkutsk, 1998 (in Russian).
[83] N.I. Pyatkova, S.M. Senderov, M.B. Cheltsov, et al., Application of a two-level research technology in solving energy security problems, Izvestiya RAN. Energetika 6 (2000) 31–39 (in Russian).
[84] L.R. Ford, D.R. Fulkerson, Flows in Networks, Princeton University Press, 1962.
[85] S.M. Senderov, S.V. Vorobev, Approaches to the identification of critical facilities and critical combinations of facilities in the gas industry in terms of its operability, Reliability Engineering & Systems Safety 203 (2020) 107046, https://doi.org/10.1016/j.ress.2020.107046.
[86] G.F. Kovalev, L.M. Lebedeva, Reliability of Power Systems, Springer, New York, 2019.
[87] G.F. Kovalev, L.M. Lebedeva, A set of models for optimizing the conditions of design states when assessing the reliability of electric power systems, Preprint, Melentiev ESI SB RAS, Irkutsk, 2000 (in Russian).

CHAPTER

3

Hierarchical modeling in expansion planning of electric power systems

N.I. Voropai[a,†], *S.V. Podkovalnikov*[a], *V.V. Trufanov*[a], *V.V. Khanaev*[a], *P.S. Drachev*[a], *G.I. Sheveleva*[a], *V.V. Selifanov*[a], *O.V. Khamisov*[a], and *K.V. Suslov*[b]

[a]**Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia,** [b]**Irkutsk National Research Technical University, Irkutsk, Russia**

3.1 Hierarchical expansion planning of electric power systems

Some examples of hierarchical problems. Recently, the hierarchical approach to the problems of the expansion of EPSs has been increasingly used in connection with the objective tendency of increasing the "activity" of the electrical network: both transmission [1,2, etc.] and distribution [3,4, etc.] networks. For the electrical network to be active implies the use of automatic means of controlling the configuration and parameters of the network, as well as its automatic self-recovery in order to rationally (optimally) meet the requirements of the economic performance of normal, repair, post-emergency, and other operating conditions, the reliability of electricity delivery to consumers, and the quality of electric power delivered to them in the context of significantly increased demands with respect to reliability and quality on the part consumers due to digitalization and computerization of their technological processes.

[†]Deceased.

Hierarchical Modeling of Energy Systems
https://doi.org/10.1016/B978-0-44-313917-8.00012-2

Given the drastically increased importance of the requirements for the reliability of electricity supply to consumers and electric power quality, as well as the need to justify the means of ensuring the activity of electrical networks, it becomes mandatory to analyze these factors in the study of the conditions of EPS serviceability when planning their expansion.

Among the existing approaches to solving hierarchical problems of expansion planning of the EPS, first of all, we should note various modifications of the Benders decomposition method as applied mainly to planning the development of micro-systems [5,6, etc.]. In [5], when decomposing the general problem of expansion planning of the micro-system by the Benders method, an investment model of integer optimization of the mix of the generating units to be commissioned is considered as a master problem, while as a subproblem one considers a model of minimization of operating costs of electricity generation by own generating units, including unused (preserved in storage) electricity and the cost of electricity purchase in the electric power system to which the micro-system is connected. When solving the subproblem, uncertainties in the price of the electricity purchased from outside, load profiles, electricity generation by sources that run on renewable energy resources, as well as damage to consumers in case of emergency disconnection of micro-system connection to the EPS, are set as special constraints. A year is considered as the planning interval.

In [6], the problem of planning the expansion of micro-systems under uncertainty is treated using Benders decomposition. The problem of minimizing investment in generating units that run on renewable energy and are to be put into operation is treated as a master problem. As a subproblem, the authors state the problem of minimizing the current costs of operation of the micro-system during the year, taking into account the uncertainty in the parameters of the constraints of the given subproblem A robust optimization method that adapts to the uncertainty of constraint parameters is used to solve the subproblem.

Another approach to expansion planning of a flexible electrical distribution network when taking into account the points for charging electric vehicles is proposed in [7]. The authors consider a multi-criteria bilevel mixed-integer linear programming problem solved using an immune genetic algorithm. The decision-makers who define their criteria are, on the one hand, the distribution network operator minimizing investment in network development, including the construction of electric vehicle charging points, while factoring in the cost of electricity purchased in the electricity market, losses of active power in the network, compensation for consumer damages from undersupplied electricity, and, on the other hand, the owners of charging points minimizing their costs of purchasing electricity to charge electric vehicles. The constraints in the bilevel optimization problem are defined by a complete model of the electric distribution network in the form of equations of steady-state operating conditions.

The uncertainty of the charging process of electric vehicles and the power extraction from them when treated as energy storage devices is handled using the scenario approach. The bilevel problem eventually results in a set of Pareto-optimal solutions. The final solution based on the Pareto set is chosen by using the apparatus of fuzzy logic.

This list of studies of the use of hierarchical modeling in solving the problems of EPS expansion planning, even though it is far from being exhaustive, attests to a growing interest in the hierarchical approach. It is important to emphasize the fundamental fact of problem statements that is associated with the mathematical formalization of the hierarchical representation of complex problems by using the Benders decomposition apparatus and other methods.

The hierarchical problem of expansion planning of the interconnection. In this part of the section, following the generalized hierarchical modeling technology for the study of large systems outlined in section 1.3, we will consider in detail one of the most complex problems of the electric power industry, that of expansion planning of a large power interconnection (for example, the Unified Energy System (UES) of Russia, the Interconnected Electric Power System (IEPS) of the Siberian federal district, etc.) [8,9]. In doing so, we will go beyond the concept of the power interconnection, if necessary, for a more general interpretation of certain statements.

The general problem of power interconnection expansion planning is divided into the following three subproblems:

1. State strategies and programs for the development of the electric power industry and power interconnections at the federal, cross-regional, or/and regional levels.
2. Strategic development plans of electric power companies (generating companies, power grid companies) operating in the area served by the power interconnection in question.
3. Investment programs and projects for new power and electrical installations (power plants, substations, transmission and distribution network lines), the introduction of which is planned by the state strategy and strategic plans of companies.

We will consider the problem of power interconnection expansion planning as part of the state strategy of development of the country's electric power industry, which determines the necessary amount of new equipment to be put into operation in accordance with the state policy in general, as well as with the state priorities, such as those of the promotion of innovative technologies, renewable energy, etc. We also develop the mechanisms to stimulate power interconnection expansion activities. At the next stage, these mechanisms of incentives are taken into account directly along with other criteria and constraints when developing strategic development plans for electric power companies.

The state strategy for the development of the electric power industry and power interconnections should take into account the interests and, accordingly, the criteria of all entities of relations in the complex process of development and operation of this important infrastructure facility. When formulating the initial statement of the problem of choice in the form of (1.1) we will consider the following criteria (preference relations):

1. Capital outlays;
2. Operating costs;
3. Fiscal charges;
4. Environmental fines;
5. Electricity price;
6. Reliability of electric power supply to consumers;
7. Stability and resilience of the power interconnection.

We will consider the following as the entities of relations interested in the effective development and operation of the power interconnection:

1. Generating companies;
2. Federal grid company;
3. Consumers;
4. State authorities.

In accordance with the established practice of power interconnection expansion planning [8,9, etc.], let us assume the following hierarchy as the hierarchical sequence of subproblems of the general original problem in the form of (1.1):

A) Determination of the optimal amount of new generating capacity additions by type of equipment and its optimal placement within the area served by the power interconnection;

B) Determination of directions for the optimal development of the main power grid of the power interconnection;

C) Ensuring the required level of reliability of electric power supply to consumers served by the power interconnection;

D) Study of operating conditions of the future power interconnection (ensuring the stability of the interconnection under design conditions, determining the reserves of transmission capacity of connections, determining the requirements for the development of emergency control system of the power interconnection, etc.);

E) Comprehensive analysis and choice of decisions on the optimal development of the power interconnection.

Note that the presented hierarchy of subproblems corresponds to the hierarchy of models: subproblem A) corresponds to an aggregated power interconnection flow model represented by large aggregated nodes and transmission capacity of the connections between them; subproblem B) is a similar flow model, but it is a more detailed power interconnection model with disaggregated nodes and transmission transfer capability of the connections between them; subproblem C) is similar to subproblem B) or a more detailed flow model of the power interconnection in case of a study of adequacy at this level, or a model of electrical operating conditions of the system in case of an analysis of the security; subproblem D) corresponds to models of steady-state operating conditions and electromechanical transients of the power interconnection. Subproblem E) can be non-formalized and solved at the level of expert judgment on the part of the decision-maker.

Let us consider the correspondence of the entities of relations and decision justification criteria for each of the listed subproblems A) - E).

Generating companies are interested in solving subproblem A) if the following criteria are minimized: capital outlays (criterion 1) for new generating capacity; operating costs (criterion 2) to ensure the normal operation of all generating units of the future power interconnection; fiscal charges (criterion 3) associated with new generating capacity; environmental fines (criterion 4) for harmful emissions into the environment of the new generating units. The Federal Grid Company is interested in solving subproblem B) given the minimum values with respect to the following criteria: capital outlays (criterion 1) for new electrical equipment of the main power grid (substations, transmission lines, secondary equipment); operating costs (criterion 2) to ensure the normal operation of the future power interconnection; fiscal charges (criterion 3) associated with new electrical equipment. Consumers are interested in maximizing the reliability of their electricity supply (criterion 6) by solving subproblem C) and minimizing the price of electricity (criterion 5) by solving subproblem E). Public authorities are interested in maximizing fiscal charges (criterion 3) in solving subproblems A), B), C), and ensuring the stability and resilience of the power interconnection (criterion 7) in solving subproblem D).

Attention should be paid to some of the conditions and assumptions adopted in the above structuring of the hierarchy of the subproblems, taking into account the demonstration nature of the example under consideration: power grid equipment has no harmful environmental impact; when solving subproblem C) fiscal charges are in place since additional equipment must be introduced to ensure the required level of reliability of electric power supply to consumers; ensuring the stability and resilience of the power interconnection is associated with the prevention of major system accidents but the cost of its development is not factored in.

From the above we see that in comparison with the initial general statement of the problem in the form of (1.1) with 7 criteria, the number of criteria at each level of the hierarchy of the subproblems is reduced, and in some cases significantly so: subproblem A) is considered with 4 criteria; subproblem B) - with 3 criteria; subproblem C) with - 2 criteria; subproblem D) with - 1 criterion; and subproblem E) - with 1 criterion. At the same time, several criteria in some of the subproblems, given the actual conditions, can be translated into constraints (for example, criteria 6 and 7). As a result, each subproblem is much simpler in terms of its statement, which naturally makes it easier to solve. One of the additional advantages of such decomposition of the original general problem into a hierarchy of subproblems is the separation of different types of system models for solving different subproblems (for example, as linear constraints in the form of equalities and inequalities in subproblem A) and in the form of systems of nonlinear ordinary differential and algebraic equations in subproblem E)). Such separation of models for different subproblems drastically simplifies formalization of subproblems and their solution and at the same time allows one to consider more detailed descriptions of the system at different levels of the hierarchy in comparison with the general statement of the problem in the form of (1.1).

The hierarchical technology under consideration has a number of other advantages. In particular, if necessary, at some level of the hierarchy of subproblems it is possible to introduce additional criteria that were not foreseen in the original statement of the problem. Moreover, it is possible to introduce an additional level to describe a subproblem or to exclude one of the hierarchy levels. For example, in some obvious cases, as the hierarchy of preceding subproblems is implemented, it may prove unnecessary to solve subproblem D), which was originally taken into account.

The above considerations present a general scheme of stating and solving a hierarchical multi-criteria problem of EPS expansion planning. In what follows in this chapter, there are examples of some specific problems of this field that are solved by employing the technology of hierarchical modeling.

3.2 Hierarchical expansion planning of power plants based on the game-theoretic approach

Let us consider the case of interaction between the state, which uses "soft" regulation of the development of the EPS, and electric power companies (for definiteness, we will consider generating companies and the development of their power plants) according to the following scheme [8,9]:

- At the upper level, the state policy on the development of the electric power industry is shaped (incentives for various innovative energy technologies, determination of social requirements for the electric power industry as an infrastructure industry, etc.), and economic, legal, and institutional mechanisms are worked out to encourage generating companies to make decisions on their development in line with the priorities of the state policy;

- At the lower level, generating companies plan their expansion while taking into account the state policy in the field of electric power industry development and mechanisms of its implementation, as well as coordinate their decisions with other companies.

To formalize the presented problem, we will use the cooperative hierarchical game in its normal form [10,11] between the regulating level of the agent A_0 and regulated generating companies B_l, $l = \overline{1, L}$; L is the number of companies.

In the general case, we have the set I of options for the expansion of generating capacity, the set J of scenarios of external conditions, and the set K of criteria for evaluating decisions on the expansion of generation, and $K = [K_A, ..., K_Z]$ includes subsets of criteria for each of the entities of relations interested in the expansion of generating capacity [8]. With this in mind, for each generating company, the initial conditions are defined by the ratios where x_{ij}^k is the quantitative assessment of the development option of the i-th company with respect to the criterion k given that the scenario of external conditions j is realized.

$$X^k = \left\{x_{ij}^k\right\}; \quad i = \overline{1, I}; \quad j = \overline{1, J}; \quad k = \overline{1, K}. \tag{3.1}$$

In the hierarchical game in question, the agent A_0 distributes the regulatory actions among the players of the lower-level $B_1, ..., B_L$. Such regulatory actions can be budgetary subsidies, tax breaks, concessional loans, etc. Thus, the agent A_0 chooses L vectors of regulatory actions of the type $w = (w_1, ..., w_L)$ from the set

$$W = \begin{cases} w = (w_1, ..., w_L): \ w_l \geq 0; \quad w_l \in R^n, \\ \sum\limits_{l=1}^{L} w_l \leq b, \quad b \geq 0, \end{cases} \tag{3.2}$$

where n is the number of types of regulatory actions; b is the constraints on the capabilities of the regulating agent A_0.

The capabilities of the generating company B_l are determined by the regulatory actions w_l received from the agent A_0, with the company implementing solutions from the set $z_l(w_l) \in Z$. The sets $z_l(w_l)$ for all w_l include elements with zero values and expand monotonically with inclusion, i.e. it follows from $w_l' > w_l$ that

$$z_l'\left(w_l'\right) \supset z_l(w_l) \tag{3.3}$$

except $z_l(0) = 0$. The latter means the inability of the agent A_0 to regulate with zero regulatory actions. In (3.3), w_l' means the regulatory action, which is introduced in the next step after the implementation of the regulatory action w_l.

Let $z = (z_1, ..., z_L)$ be decisions on the expansion of the generating companies $B_1, ..., B_L$. The payments of these players under regulatory actions w_l are chosen based on the conditions

$$\varphi_l (z_l) \geq 0; \;\; l = \overline{1, L}. \tag{3.4}$$

Payments of the agent A_0 are defined by the function

$$f (\varphi_1 (z_1), ..., \varphi\Phi_L (z_L)) - g (w_1, ..., w_L) \geq 0, \tag{3.5}$$

where $g (w_1, ..., w_L)$ is a non-negative function that evaluates the level of regulatory actions of the agent A_0.

The regulatory agent A_0 has the right of the first turn and thus determines the ability of regulated generating companies to implement its policies. The goal of the agent A_0 is to minimize their regulatory actions. The goal of each of the players B_l may be the minimum cost of developing their company.

Solving the presented hierarchical game problem can be performed as follows.

Let each lower-level player have a set of solutions $i_l = \overline{1, I}; \;\; l = \overline{1, L}$. The initial conditions are defined by (3.1).

At the initial step, without regard to the regulating agent A_0, the basic set of preferred solutions i_{lb} is determined based on the evaluation of the multi-criteria utility function E_i for each solution. The nature of the game at the lower level can be cooperative, for example, by finding estimates of the Shapley vector. Let us look at these possibilities in more detail.

Let us have a set of estimates with respect to (3.1) for all generating companies. The definition of a cooperative game solution using the Shapely vector is that the total income of a coalition of players (money, resources, etc.) is distributed among its participants. The Shapely vector can be thought of as a weighted sum of a player's limited contributions to all coalitions in which they participate.

Let us introduce the following notations: $M = \{1, ..., m\}$ is set of players; T_i, $i = \overline{1, M}$ are coalitions of the set M, t is the number of players in the coalition T. Then the value Φ_i of the Shapely vector can be represented as [8,12].

$$\varphi_i [v] = \sum_{\substack{T \subset M \\ i \in T}} \frac{(t-1)!\,(m-t)!}{m!} \left[v (T) - v(T/\{i\})\right], \tag{3.6}$$

where $v (T)$ is the characteristic function of the coalition T.

Determining the characteristic function is the main issue in cooperative game problems using the Shapely vector. Usually, the cost function is taken as a characteristic function [13–16, etc.]. In the general case, a utility function can be used [8,10], the procedures for constructing this function for multiple criteria are developed in [8,9].

The additive multi-criteria utility function has, as a result, the form of

$$U_{ij} = \sum_{k=1}^{K} \lambda^k u^k (x_{ij}^k). \tag{3.7}$$

The choice of solutions given the set of external conditions is performed using estimates of expected utility according to the expression

$$E_i^p = \sum_{j=1}^{J} p_j U_{ij}, \quad i = \overline{1,I}. \tag{3.8}$$

If the utility value with respect to (3.8) is calculated for each possible coalition of players, then the maximum component of the Shapley vector for a particular coalition is determined by the expression (3.6). This makes it possible to assess the contribution of each participant when forming the coalition. A stable solution results from further negotiations between the participants, which can actually take place in the continuation of the game.

Difficulties in calculating the Shapley vector values for a large number of players led to the introduction of the so-called bilateral Shapley estimates. Such estimates are used for a fully decentralized and two-way negotiation process between participants when using their estimates. This approach is also convenient for the problem in question since it makes it possible to evaluate all possible coalitions of participants and the individual player in the interaction. The bilateral Shapley estimate for some coalition T_i in the bilateral coalition T is defined as

$$\varphi_{\{T_i,T_j\}}(T) = 0,5v(T_i) + 0,5(v(T) - V(T_j)). \tag{3.9}$$

Both coalitions T_i and T are called the bases of T; $v(T)$ means the coalition's T own estimate.

At the next step, after completing the considered cooperative game, the agent A_0 proposes a set of regulating actions from (3.2), which results in forming the solutions i'_l. This means that additional solutions are added to (3.1), hence the set I is expanded. Next, the values of the multi-criteria utility function $E_{i'}$ are calculated for each company. If $E_{i'}$ is better than E_i, the solutions are optimized with respect to the minimum of the function (3.4) for each company, as a result of which the problem is solved. If $E_{i'}$ is worse than E_i, the agent A_0 modifies its regulatory actions to create more acceptable incentives for lower-level players. After that, the next step of the game is performed.

Let us look at an example of using this method. At the lower level, two vertically integrated electric power companies are taken for analysis, each of which supplies electric power to consumers in the service area. The price of electricity of the first company is objectively lower than that of the

TABLE 3.1 Scenarios of external conditions for the first company.

Scenarios	Electric power consumption levels	Fuel prices	Electricity sales
A	Max	Min	No
B	Min	Max	No
C	Max	Min	Yes
D	Min	Max	Yes

second company, so the first company is interested in introducing additional generating capacity to sell electricity to the second company, and the second company is interested in buying cheaper electricity than that generated by its own power plants. The upper regulatory level stimulates the development of non-conventional renewable energy sources (wind power plants – WPPs) through regulatory actions.

Scenarios of external conditions for the first company are shown in Table 3.1. Scenarios of external conditions for the second company have a similar meaning.

Given the demonstration nature of the example in question, we will take the probabilities of occurrence of the scenarios under consideration to be the same and equal to 0.25 each.

The options for expansion of the power plants of the two companies differ by types of generating units to be commissioned in terms of the fuel used, its combustion technologies, etc. We consider four options with different combinations of coal-fired and gas-fired generating units, with the conditions forming these combinations being the same for both companies, but fuel prices for the first company are somewhat lower than for the second.

Decisions on the expansion of each company are made taking into account the criteria of three groups of the entities of relations: electric power companies, authorities, and consumers. Each group of entities of relations has the same rights, weighting coefficients for each criterion are determined in accordance with the methodology set out in [8–10]. The solutions are evaluated according to the following criteria: d is capital cost; τ is operating costs (mln. USD); β is fiscal charges (mln. USD/year); γ is electricity prices (US cents/kWh). The first two criteria reflect the interests of power companies, the third – those of the authorities, and the fourth – those of the consumers.

Table 3.2 shows the utility estimates for the solution options at the initial step of the game without taking the regulating agent A_0 into account. It is possible to determine an acceptable option for both companies under these conditions by searching for a trade-off value of the price of electricity sold by the first company, using estimates of the Shapley vector. The solution to the game (omitting the process of finding a compromise) shows that option 4 should be taken for further consideration.

TABLE 3.2 Evaluating options at the initial step of the game.

Options Solutions	Utilities and ranking of options (in parentheses)	
	Company 1	**Company 2**
1	0.5284(2)	0.2873(4)
2	0.5154(3)	0.6371(2)
3	0.5302(1)	0.5287(3)
4	0.5117(4)	0.7201(1)

TABLE 3.3 New generation capacity additions for Company 1.

Options	Capacity to be added, MW	Including WPP, MW
5, 6, 7	122	10

TABLE 3.4 New generation capacity additions for Company 1.

Criteria	Options Solutions	External conditions			
		A	**B**	**C**	**D**
α	4	170.3	170.3	1761.5	1761.5
	5	192.2	192.2	1783.6	1783.6
	6	182.6	182.6	1773.8	1773.8
	7	179.3	179.3	1770.5	1770.5
τ	4	90.1	102.5	96.3	110.8
	5	89.9	107.4	96.1	110.7
	6	89.8	102.2	96.0	110.5
	7	89.7	102.1	95.9	110.4

At the next steps of the hierarchical game when introducing regulatory actions by the agent A_0 we will consider only the first two criteria: capital expenditures α and current costs τ. This is well-justified because the regulatory actions given the adopted set of criteria only affect the criteria related to generating companies and do not appreciably affect the interests of the authorities and consumers.

Table 3.3 shows three additional options for the expansion of the companies while taking into account the incentive for adding 10 MW of wind power capacity by the first company within the total maximum amount of 122 MW of power generation additions. These options differ in the price of electricity sold by the first company to the second company and, depending on the price, in the amount of purchase and, consequently, in the amount of total generation capacity to be added for Company 1.

The results of calculations for the first company according to the two criteria adopted at this step are shown in Table 3.4. These results show that it is not profitable for Company 1 to introduce WPPs due to higher capital expenditures in all three additional options compared to conventional coal- or gas-fired units under any external conditions out of the assumed set.

TABLE 3.5 Comparison of the utilities of options for the development of Company 1.

Options	Utilities
4	0.5117
5	0.5107
6	0.5115
7	0.5117

Introducing a stimulating regulatory action in the form of, for example, a $10 million budget subsidy improves the utility estimates for the additional options, but they remain lower than those for Option 4 (Table 3.5). Increasing the budget subsidies to $13 million leads to the situation shown in Table 3.5, when at least one option (option 7) is equivalent to the original Option 4 in terms of utility. The same option turned out to be the best for Company 2. Thus, option 7 can be taken as a solution to the game.

3.3 Hierarchy of models for expansion planning of generating capacities and backbone electrical network taking into account demand side management

Optimization of the prospective mix of generating capacity. The choice of a rational mix of the generating capacity of the EPS for the future time period of about 10–20 years is one of the major challenges of projecting and designing their expansion.

The problem is solved under certain external conditions of expansion, the most important of which are: the prospective demand for electricity, constraints on the possible use and prices of fuel for power plants in the future, the production capacity of industries of energy mechanical engineering and energy construction, etc. Determining these conditions is the task of look-ahead studies of the development of other industries.

The time estimate period is 10 to 15 to 20 years. In accordance with this period, the results of solving the problem are used in the design of regional EPSs and to determine the requirements for the energy mechanical engineering base (prospective demand for equipment). Depending on the calculation period, this may involve the design of power plants and power engineering enterprises, the justification of decisions on the construction of power plants, and the planning of appropriate groundwork in construction.

The specifics of the problems of the development of electric power systems are determined by the need to consider the EPS as a technologically unified object, regardless of the organizational structure and forms of ownership of its constituent energy facilities. Due to the heterogeneity of generating capacities, technological and territorial complexity of the EPS structure, significant irregularity of electricity consumption in the daily, weekly, seasonal profiles, and in terms of the territorial aspect, it is important to describe in sufficient detail the entire set of possible operating conditions of the EPS during the calculation period [8].

Expansion planning of complex and extended, territory-wise, EPS is associated with significant difficulties also because of the need to take into account the following: the requirements of the reliability of system operation and uninterrupted power supply to consumers, strong external relations, uncertainty of future conditions of EPS development, the risk of possible extreme conditions in the development of the system, and other important factors.

The leading trend of improving mathematical models to solve the problem in question was the pursuit of a more accurate description of the operating conditions of generating equipment in order to take into account technical limitations and, accordingly, of an acceptable accuracy of cost estimates for the operation and development of the EPS. One such model is the SOYUZ mathematical optimization model described below.

Its most significant difference from other known models of the development of the structure of the EPS is a more accurate description of the operating conditions of generating equipment and cross-system power and electricity flows by modeling the coverage of multiple representative daily profiles of the electric load of the EPS within unified calendar time. This made it possible to determine more reasonably the requirements for the transmission capacity of cross-system electric connections and take into account the main components of the system effect of integration and joint operation of EPSs.

The electric power system in the SOYUZ mathematical model is a multinode network, the nodes of which are territorial electric power systems (integrated and regional electric power systems, and their parts – depending on the territorial level of the investigated electric power system and the detail of its representation), and the cross-node connections represent the set of specific cross-nodal power transmission lines. Power plants of electric generation systems are described by a set of groups of same-type units that have similar technical and economic performance [8].

Important parts of the description of the expansion process are the initial mix of generating capacity, the assumed amount of dismantling and technical re-equipment of generating equipment, facilities under construction.

The model has a modular structure and includes modules of power balances of nodes, balances of zones of daily load profiles by nodes, flows over cross-node connections, as well as modules describing the operation and development of different types of generating equipment: peak CPPs and CPPs proper (and NPPs) with a single zone energy characteristic, CHPPs, HPPs, and PSPs.

The functional that is subject to minimization in the general case represents the total discounted costs of development and operation of the EPS:

$$\sum_{jis\tau} C_{jis\tau} X_{jis\tau} + \sum_{ji} C_{ji}^{\Sigma} X_{ji}^{\Sigma} + \sum_{ji} C_{ji}^{n} X_{ji}^{n} + \sum_{ii'} C_{ii'}^{\Sigma} X_{ii'}^{\Sigma} + \sum_{ii'} C_{ii'}^{n} X_{ii'}^{n}. \quad (3.10)$$

Here: j is the number of the same-type group of generating equipment, i is the number of the electric generation system, s is the number of characteristic daily load profile, τ is the index (duration) of load zone in the daily profile; $X_{jis\tau}$ is the load of the j-th type of equipment at the node i in the daily profile s in the zone of the duration of τ hours; $C_{jis\tau}$ are corresponding specific variable costs; X_{ji}^{Σ}, X_{ji}^{n} are installed capacity and new (commissioned) capacity of the j-th equipment at the node i to be selected; C_{ji}^{Σ}, C_{ji}^{n} are specific constant annual expenses and the discounted capital expenditures for this equipment; $X_{ii'}^{\Sigma}$ is the transmission capacity of cross-system electric connection between the nodes i and i'; $C_{ii'}^{\Sigma}$ is specific constant annual costs of this connection; $C_{ii'}^{n}$ is new (added) transmission capacity of the cross-system connection $i-i'$; $C_{ii'}^{n}$ is corresponding specific discounted capital expenditures [8].

Here and below in the description of the model, the optimized variables are denoted by the letter X with the corresponding indices.

The first two sums in the objective function determine the annual variable and fixed costs at the power plants, the third sum corresponds to the discounted capital expenditures for their implementation, and the last two sums determine the annual fixed costs and discounted capital expenditures for electric connections.

The main constraints of the model are as follows.

Power balance of the node i at the hour t

$$\sum_{j} \beta_{ji} X_{ji}^{\Sigma} - \sum_{i'} X_{ii't}^{B} + \sum_{i'} X_{i'it}^{B} \geq P_{it} + R_i, \ \ i = 1, ..., I, \quad (3.11)$$

where X_{ji}^{Σ} is installed capacity of power plants (for HPPs – available capacity under low-water year conditions), β_{ji} is the equipment availability factor, $X_{ii't}^{B}$, $X_{i'it}^{B}$ are balance power flows at the hour t from the node i to i' and back, P_{it} is irregular (with random deviations factored in) load of the node i at the hour t, R_i is the demand for emergency reserve capacity of the node i.

Power balances of nodes are formed for the hour of the combined maximum load of the EPS as a whole and the hours of maximum load of nodes that differ from it.

The required emergency capacity reserve

$$R_i = R_i^{sa} - \sum_{i'} k^{res} X_{ii'}^{res}, \quad (3.12)$$

where R_i^{sa} is the required emergency capacity reserve of node i at its stand-alone operation, and the

$$\sum_{i'} k^{res} X_{i'i}^{res} \leq R_i^{sa} - R_i^{conc} \tag{3.13}$$

describes the possible reduction in the reserve requirement of the node i due to the expansion of $X_{i'i}^{res}$ the transmission capacity of connections of this node with adjacent nodes i'. Here: k^{res} is a specific reduction in the required node reserve per unit of the cross-system transmission capacity increment (0.5 - 1.0), R_i^{conc} is the part of the EPS reserve considered as concentrated and attributable to the share of node i power plants.

As follows from the description of annual power balances, the model describes the effect of mismatching the time of the maximum load taking place in the power districts of the system, there is a possibility of minimizing the required total emergency capacity reserve through the development of cross-system connections and its optimal location; the contribution of hydropower plants to the power balance is factored in given low-water year conditions.

The demand for electricity at each node is set so as to take into account its irregular nature in the seasonal, weekly, and daily profiles through a set of daily load profiles. A typical set of profiles includes winter and summer days off and working days.

The annual energy balance of the power districts in the model is described by a set of balances of the zones of representative daily profiles of electric load with the transition to the annual indicators in the functional of the model through the coefficients of the "equivalent number of days in the year". When modeling the daily operation profile, the "zone optimization" principle is used according to the partitioning of the daily load profile into horizontal zones with the duration of τ hours, corresponding to the load increments in different hours of the day (see Fig. 3.1).

To account for the calendar time of day, where necessary, the appropriate variables are used with the index t, which is the calendar hour of the load profile.

Below is a fragment of writing down the zone balances of the daily load profiles of the two nodes i and i', taking into account the flows $X_{ii'}^{t1}, \ldots, X_{ii'}^{t2}$, from the node i to the node i' at the hours $t1$ and $t2$ and the return flows $X_{i'i}^{t1}, \ldots, X_{i'i}^{t2}$:

$$\sum_j X_{ji\tau-2} + X_{ii'}^{t1} - X_{i'i}^{t1} = P_{i\tau-2},$$

$$\sum_j X_{ji\tau-1} - X_{ii'}^{t1} + X_{i'i}^{t1} + X_{ii'}^{t2} - X_{i'i}^{t2} = P_{i\tau-1},$$

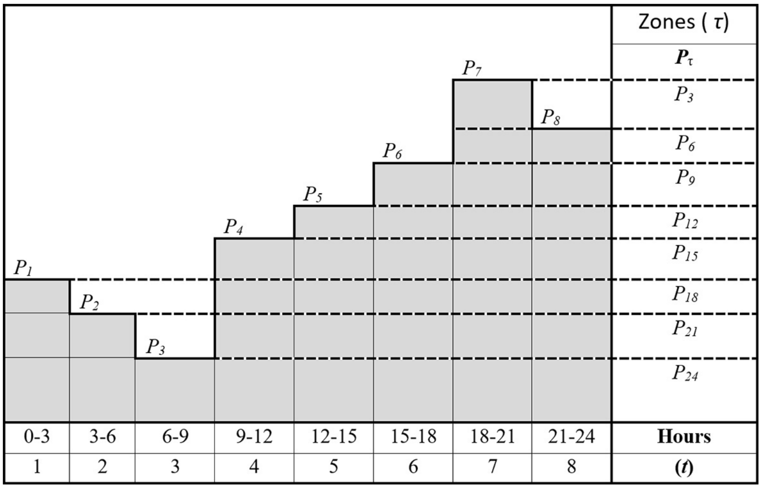


FIGURE 3.1 Illustration of delimiting zones in the daily load profile [8,17].

$$\begin{aligned}
&\sum_j X_{ji\tau} - X_{ii'}^{t2} - X_{i'i}^{t2} = P_{i\tau},\\
&\sum_j X_{ji\tau-1} - X_{ii'}^{t2} - X_{i'i}^{t2} = P_{i'\tau-1},\\
&\sum_j X_{ji'\tau} - X_{ii'}^{t1} + X_{i'i}^{t1} + X_{ii'}^{t2} - X_{i'i}^{t2} = P_{i'\tau},\\
&\sum_j X_{ji'\tau+1} + X_{ii'}^{t1} - X_{i'i}^{t1} = P_{i'\tau+1}.
\end{aligned} \tag{3.14}$$

Here, the first sum in each equation is the contribution of all the node power plants in covering the zone of an individual daily profile (the index s of the day and loss factors in power transmission lines are omitted for simplicity), and the right sides are the powers of the daily profile zones.

As can be seen from this notation, the "transformation" of the load profile zones is used in describing the hourly power flows. So, for example, the flow $X_{ii'}^{t1}$ at the hour $t1$ from the node i to the node i' (see Fig. 3.1) leads to a decrease in the demand to cover the zone with a duration of $\tau - 2$ hours and an increase in the power demand of the adjacent zone with a duration of $\tau - 1$ at the node i, and, accordingly, to a decrease in the demand of the zone $\tau + 1$ and an increase in the zone τ of the receiving node i'.

Such a description of an EPS operating conditions allows one to optimize as part of the model the synchronous (with respect to time) operating conditions of generating equipment of all nodes and electric connections

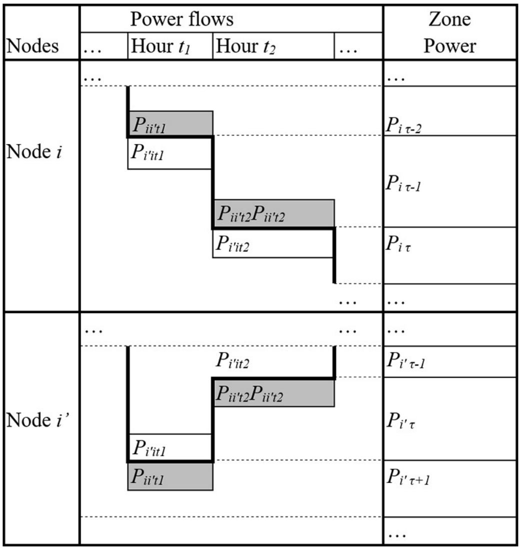


FIGURE 3.2 Illustration of the description of cross-nodal flows [8,17].

between them, in particular, to take into account the mismatch of time of going through load peaks at different system nodes [8].

The total daily load of each group of generating equipment of the same type is, in the simplest case, limited to the amount of capacity that is available to cover the load:

$$\sum_{\tau} X_{jis\tau} \le \beta_{jis} X_{ji}^{\Sigma}. \tag{3.15}$$

For different types of generating equipment, we consider specific constraints on their operating conditions: the possibility of starting up / shutting down, minimum safe output, etc. (for the CHP), the maximum base load and the possibility of power generation by seasons of the year (for HPP), operating conditions of loading of the CHP in line with the cogeneration cycle, etc. [8].

For pumped-storage power plants (PSPs), the charging mode is described by hourly load variables, and one applies a similar "transformation" of zones in the load profile zone balances for them as well as when describing the flow through transmission lines (Fig. 3.2). In case of constraints on the load of a pumped-storage plant in the turbine mode of the form (3.15), the capacity of the PSP in each hour t is limited by the value of

$$X_{jst}^{pump} \le \gamma_{ji}^{pump} \sum_{\tau} X_{jis\tau} \tag{3.16}$$

given the ratio of the values of generated and accumulated electricity

$$\sum_{\tau} \tau X_{jis\tau} \leq \eta_{ji} \sum_{t} X_{jist}^{pump} \tag{3.17}$$

and the constraint on the volume of the upper reservoir of the PSP through the average daily number of hours of its utilization

$$\sum_{t} X_{jist}^{pump} \leq h_{ji} \beta_{jis} X_{ji}^{\Sigma}. \tag{3.18}$$

Here: λ_{ji}^{pump} is the ratio of capacities of pump and turbine modes of the PSP, η_{ji} is the efficiency factor, h_{ji} is the limiting number of hours of the utilization of the installed capacity of the PSP.

The conditions for the expansion of all types of power plants are of the form:

$$X_{ji}^{\Sigma} - X_{ji}^{n} \leq N_{ji}^{exist} \text{ given } N_{ji}^{min_{ji}^{\Sigma}{}_{ji}^{max}}, \tag{3.19}$$

where N_{ji}^{exist} is the existing installed capacity (as determined taking into account the dismantling and technical re-equipment), N_{ji}^{min}, N_{ji}^{max} are the limit values of the installed capacity of this type of equipment.

The use of power transmission lines in the balances of load profile zones is limited by their transmission capacity:

$$X_{ii's}^{t} + X_{i'is}^{t} \leq X_{ii'}^{\Sigma} \tag{3.20}$$

on the balance flows in the power balances:

$$X_{ii't}^{B} + X_{i'it}^{B} + X_{ii'}^{res} \leq X_{ii'}^{\Sigma}, \tag{3.21}$$

given the constraints on the development of electric connections:

$$X_{ii'}^{\Sigma} - X_{ii'}^{n} \leq N_{ii'}^{exist} \text{ given } N_{ii'}^{min} \leq X_{ii'}^{\Sigma} \leq N_{ii'}^{max}, \tag{3.22}$$

where $N_{ii'}^{exist}$, $N_{ii'}^{min}$, $N_{ii'}^{max}$ are the existing and possible range of values of the transmission capacity of the electrical connection.

For all power plants, we also introduce interval limits on the annual consumption of fuel of different types and for the expansion of certain types of generating equipment in different power districts or groups thereof, determined by local conditions or based on the ability to produce equipment by power engineering companies or its purchase.

Since the advent of the SOYUZ model, a great deal of experience has been accumulated in using the model to solve various practical problems of the development of the Unified electric power system of the USSR, and then of Russia and its regions. Along with the traditional use of the model to assess and choose rational options for the expansion of the EPS in the future [18–20, etc.], some specialized studies were conducted: analysis of means to ensure the maneuverability of the EPS [21], assessment of the effectiveness of measures to improve the energy security of the country [22], multi-criteria analysis of options for EPS expansion [23], assessment of the effectiveness of the integration of an EPS into the UES of Russia and of the components of the cross-system effect [24], efficiency of load shape modifying consumers and energy conservation [25], etc.

As an example of using the SOYUZ model, here are some of the results of studies for the UES of Russia to 2030. Several levels of electricity consumption were considered for the future.

As the "baseline" scenario we assumed the "reference case" electricity consumption scenario as formed by the Ministry of Energy and the Agency for forecasting electric power energy balances, which corresponds to the "General scheme (Master plan) of placement of energy facilities to 2030", the approved Energy Strategy of Russia, and the main projection documents of the Ministry of Economy. The average annual electricity consumption growth rate in this scenario is about 2.2%, electricity consumption within the UES in 2030 is 1.490 bln. kWh. We also considered the minimum scenario with the level of consumption in 2030 of 1.150 billion kWh (referred to as the "min" scenario below).

For the baseline scenario of electricity consumption, in addition to the "reference case" option of the UES development specified in the above documents, we also considered options with optimization of generation and the UES reliability level (option "optbas") and option "sei", taking into account possible delays in commissioning at NPPs, significant growth of small GTU-CHPP capacity based on existing boiler houses and distributed generation.

Estimated values of inputs of generating capacities in the UES to 2030 are shown in Fig. 3.3.

In the reference case scenario, the total capacity additions at UES power plants by 2030 were 170 million kW, in the minimum scenario – 93 million kW.

The mix of capacity by type of power plant can be seen in this figure. The largest differences in the structure with respect to options are in condensing power plants. The "ESI" option drastically differs from the other options by a significant increase in CHPP capacity additions at the expense of GTU-CHPPs at gas-fired boilers and a lower level of NPPs.

The analysis of power flows of power systems in these options shows that the projected mix of generating capacity, in general, ensures coverage of daily profiles of electric load, including dips that take place in the hours of the minimum values. The maneuvering capacity of power plants is enough to cover the variable part of the load. For nuclear power plants and solid fuel CPPs, the base operating conditions are ensured. In

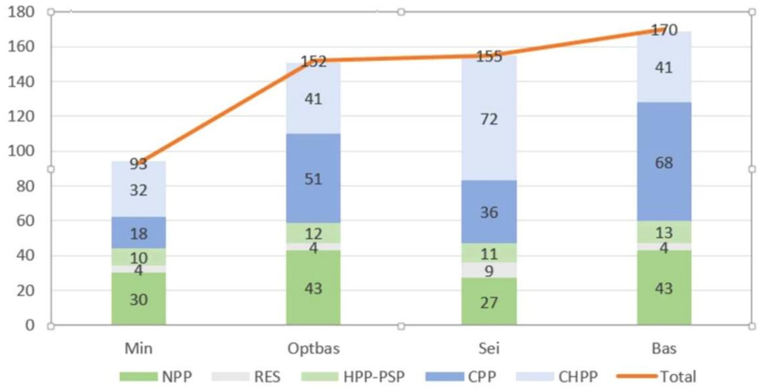


FIGURE 3.3 UES generating capacity additions by 2030, million kW.

European IPSs, the requirements for equipment maneuverability are the maximum ones. It is required to completely unload (within their maneuvering capabilities) condensing units that run on gas fuel in these systems at the hour of minimum winter working hours.

Given the uncertainty of future prices of fossil fuels for power plants, we performed an analysis of the impact of this uncertainty on the development of CPPs.

We calculated the following four options: the reference option described above ("ref"), and three optimization options with high ("expgas"), medium ("medgas") and low ("cheapgas") gas prices with reduced requirements to the value of UES capacity reserves. On average, the ratio of gas and coal prices per ton of fuel equivalent of the last three options is, respectively, 2:1, 1.5:1, and 1:1. Estimated values of installed capacities of coal- and gas-fired condensing power plants in the UES by 2030 are shown in Fig. 3.4.

The figure shows that with the assumed price variations, the ratios of the capacity of gas-fired and solid fuel-fired CPPs differ significantly.

The values of installed capacity of gas-fired CPPs by 2030 in the reference case and options with cheap and medium-priced gas are close to each other and amount to about 60 million kW. In the option with expensive gas, by 2030, the capacity of coal-fired CHPs increases to the maximum over all considered options, which amounts to 73 million kW, while the capacity of gas-fired CHPs decreases to a minimum level of 15 million kW.

As the cost of gas at power plants decreases due to the growth of the share of gas-fired capacity of flexible CPPs, the corresponding decrease in the required capacity of hydroelectric power plants occurs.

Optimization of the development of the main electrical network. The problem of selecting a rational (optimal) electrical network is one of the main and most complex problems to be solved in the process of manag-

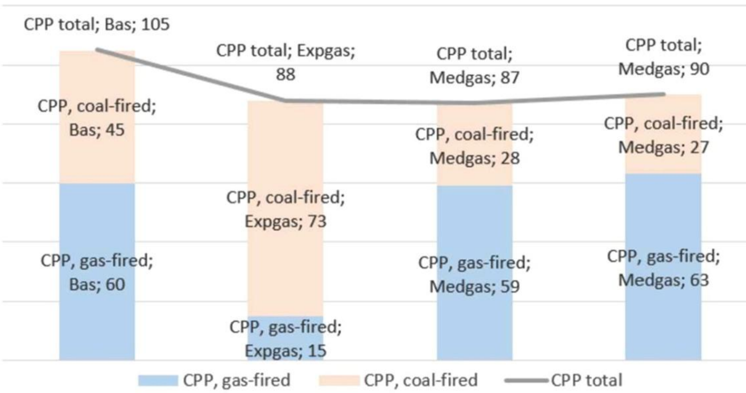


FIGURE 3.4 Installed capacity of CPPs by 2030 given the variation of fuel prices, million kW.

ing the development of the EPS. Its solving is a hierarchically organized sequential process of interrelated solving of various problems at all levels of the territorial and temporal hierarchy of EPS development problems. In practice, the design of power grid development consists of performing a set of design work, including the development of schemes for the development of the UES and IEPSs, district power systems, schemes for the development of distribution networks of EPS or grid areas, and, finally, schemes for external power supply of economic and social facilities.

In the process of designing the development of the power grid, there is a mutual exchange of information and coordination of decisions on the development of grids of different levels and the development of generating capacity.

Decisions on the development of the backbone power grid at the level of the UES of Russia with a lead time of about 15 years include the following main components: identification of the vision statement and technical policy for forming the UES power grid, feasibility study of rational integration of power systems within the UES, the degree of territorial expansion of the UES and configuration of the UES, the main parameters of development of backbone power connections (transmission capacity, technical parameters, and timing of commissioning of power facilities that of cross-system significance).

Further detailing of these solutions is carried out in the process of designing the electrical network as part of the development of IPS development schemes. Here, because decisions are made with a shorter lead time, more accurate initial information is known about consumer loads, the development of generating capacities, and cross-system connections of the UES, and specific decisions are made on the start of designing and building new power grid facilities (power lines, substations, etc.). Technical issues are to be solved: selecting the best options for the scheme (configuration) of the network, determining the transmission capacity and parameters of the main power transmission lines, determining the long-term needs for electrical equipment and materials. The lead time of the solution to this problem is 5 to 10 years.

Now, and even more so in the future, after the ongoing process of forming a system of markets in the electric power industry is completed, power grids are becoming the main technological infrastructure element of the market environment. Power grids ensure the implementation of the main parameters of a developed market in the electric power industry: availability of electricity to consumers, free access to the market for electricity producers, and broad competition for all market participants. Thus, the role of the power grid in the market power industry increases significantly, and the responsibility and cost of decisions on its development grow. At the same time, in the market environment, the complexity of the task of developing the power grid increases due to the need to consider, when making decisions, the interests of all participants in the electric power market and the growing uncertainty in the parameters of supply and demand for electricity.

To solve this problem, it is necessary to develop appropriate mathematical models. Below we present the statement of problems and the outline mathematical models for the conventional statement focused mainly on the centralized system of management of power industry development, and the statements of the problems with explicit consideration of the market specifics of the power grid development.

Modeling the expansion of the electrical network under market conditions.

As mentioned earlier, during the transition to the market-driven electric power industry operation, power grids become the main technological infrastructure element of the market environment, ensuring the availability of electricity to consumers, free entry into the market of electricity producers, and broad competition of all market participants.

In the market environment, the complexity of the task of developing the power grid increases due to the need to consider, when making decisions, the interests of all participants in the electric power market and the growing uncertainty in the parameters of supply and demand for electricity.

Below we present problem statements and mathematical models used in making decisions on the development of the power grid, explicitly taking into account (with some level of detail) the impact of the decisions made on the participants of the markets in the electric power industry.

Analysis of the potential of the existing power grid. The initial step in making decisions on the expansion of the power grid is to analyze the existing grid in terms of the following:

– technological possibilities of power flows through it, determining the reserves of transmission capacity at individual sections of the network, identifying bottlenecks in the network with the maximum load;

– the economic effects of increasing power flows along individual transmission lines or sections in the grid.

A variety of mathematical models can be used for such analysis. In particular, mathematical models for calculating steady-state power flows, static stability analysis models, and other models describing physical laws of the flow distribution in the existing power grid can be used to analyze the technical potential of the existing power grid.

Practical experience in the operation of the power grid, retrospective analysis of power flows along lines and "bottlenecks" based on the data by supervision control services are also important.

Mathematical models of the spot electricity market can be used to assess the *economic feasibility* of the use of the existing power grid.

The simplest model of a multi-node spot market (with modeling of flows in line with the "constant current" model) has the following form:

it is necessary to maximize the total profit (the level of "public welfare") of consumers and suppliers of electric power

$$\max \sum_i \left(L_i\left(s_i\right) - G_i\left(p_i\right)\right) \tag{3.23}$$

while observing capacity balances at the nodes

$$p_i + \sum_k t_{ki}\left(1 - d_{ki}\right) - \sum_k t_{ik} = s_i, \;\; i \in I \tag{3.24}$$

constraints on the maximum generation at the nodes

$$0 \le p_i \le P_i \tag{3.25}$$

and constraints on power flows across power lines

$$0 \le t_{ik} \le T_{ik}, \;\; ik \in J. \tag{3.26}$$

Here i is the network node number; I is the set of nodes; ik is the electrical connection of the nodes i and k (in the $i \to k$ direction); J is the set of all connections; p_i is the generation at the node i; P_i is the maximum possible generation; s_i is the consumption (demand) at the node i; $L_i(s_i)$ is the consumer income at the node i

$$L_i\left(s_i\right) = \int_0^{s_i} p_i^S\left(v\right) dv, \tag{3.27}$$

where $p_i^S(\mathrm{v})$ is the demand curve at the node i; $G_i(p_i)$ is the generation costs at the node i,

$$G_i(p_i) = \int_0^{p_i} p_i^G(v)\,dv, \tag{3.28}$$

where $p_i^G(v)$ is the supply curve at the node i; t_{ik} is the power flow from the node i to the node k; d_{ik} is the specific power loss; T_{ik} is the transmission capacity of the line $i - k$.

The model variables p_i, s_i, t_{ik} to be optimized are non-negative.

The variables λ_{ik} of the dual problem solution that correspond to the constraints (3.36) of this model are numerically equal to the specific increase in the problem functional (i.e., the increment of the total profit) per unit of the increment in the transmission capacity of the connection ik.

According to these variables, which determine the efficiency of strengthening the transmission lines of the existing network, it is possible to rank these lines according to the degree of effect. Naturally, the lines that top this list (with the largest λ_{ik} are the first-priority candidates for development. As a rule, these are lines with a limit load with respect to the condition (3.26).

The assessment of the *technological potential* of the existing power grid ("network supply") is determined by the capacity of electricity transmission through the grid to cover the additional demand for electricity at individual nodes of the grid or in the system as a whole.

Let us consider the problem of maximum utilization of the power grid to determine the maximum possible consumption of electricity in *the electric power system as a whole* without the expansion of the grid.

Problem statement: find the maximum total excess power (or maximum generation) in the system

$$\max \sum_i (g_i - s_i) \tag{3.29}$$

where g_i is the load coverage at the node i

$$g_i = p_i + \sum_k t_{ki}(1 - d_{ki}) - \sum_k t_{ik}, \quad i \in I, \tag{3.30}$$

when covering the electricity demand of all nodes

$$g_i \geq s_i, \quad i \in I \tag{3.31}$$

at the given maximum generation at the nodes of the system

$$0 \leq p_i \leq P_i \tag{3.32}$$

and constraints on power flows

$$0 \le t_{ik} \le T_{ik}, \quad ik \in J. \tag{3.33}$$

Here, the variables p_i, g_i, t_{ik} that are to be optimized are non-negative.

Specified are: s_i is consumption at nodes, P_i is limit load of power plants at nodes, T_{ik} is power transmission lines capacities. Ration $\sum_i g_i$ will be lower than the total maximum possible generation $\sum_i P_i$ by the amount of electricity losses in the grid to cover the load of nodes that are not provided with their own capacity. In fact, the problem determines the minimum level of power losses in the grid for the given electricity demand and its production capacity.

The obtained values of excess power $(g_i - s_i)$ determine the places of possible load growth by consumers in the system without the need to strengthen the power grid of the system.

Transmission lines where power flows were at the limit (3.33) form a set of loaded network elements, that is to say, possible candidates for expansion. The dual variables corresponding to the constraints (3.33) determine the specific efficiency of these lines (increment of generating capacity per unit of transmission capacity growth).

For a more detailed assessment of the technological capabilities of the power grid, let us consider the following *modified problem*: we need to determine the maximum total excess power (or maximum generation) at a single node k

$$g_{kj}^{max} = \max \ (g_k - s_k) \tag{3.34}$$

given the constraints (3.30)–(3.33), where the generation at some other node j is not constrained (P_j is a larger value a priori).

Solving this problem for each combination of (k, j), we obtain the matrix $\{g_{kj}^{max}\}$, the elements of which determine the possible increment of consumer load at the node k when capacity is added at the node j, i.e., the transmission capacity of the existing power grid when additional power is transferred from the node j to the node k. In this case, the loads of consumers of other nodes should be covered taking into account possible power flows in the power grid.

The maximum-load electric connections (as per the condition (3.33)) in each solution form a corresponding "subnetwork to be expanded," defining the lines that require their strengthening when implementing this measure to increase consumer load at some node by adding generating capacity at another node.

The matrix $\{g_{kj}^{max}\}$ and the corresponding "subnetworks to be expanded" can be viewed as the "network supply" of the existing electrical network.

Elements of the "network supply" can be used directly in solving individual specific problems of the development of the power grid: to implement the output of new generating capacity at a particular node and (or) the supply of new consumers at a particular node.

In the more general case, when consumption and generation at multiple nodes change, one needs specialized models of the development of the power grid of the EPS as a whole. However, even in this case, the above elements of the "network supply" of the existing power grid can be included in the elements of the redundant network, from which the selection of the optimal network in such models usually takes place.

Model for the expansion of the power grid under market conditions. Decisions on the expansion of the EPS are usually made after decisions on the expansion of generating capacity, due to the shorter implementation period of grid-related decisions and their lower capital intensity.

The demand for electricity is largely determined by – in the goals of the expansion of the power grid too, at least for the largest consumers of electricity, with long periods of construction of their enterprises.

Thus, the expanding power grid should, first of all, ensure the output of the capacity of new generating sources and electric power supply to new power consumers, i.e., ensure coverage of the capacity balances of all nodes in the EPS.

At the same time, there are always some deviations in the expansion of generation and the location of electricity consumers from the projected values that earlier served as the basis for the location of power plants and consumers. Compensation for these deviations is possible through the additional expansion of the power grid.

In the electricity market environment, the location of consumers and the cost of electricity purchases by consumers are also significantly affected by the established level of electricity prices. This level may also be different from the projected values taken into account when making earlier decisions about the location of generating sources and consumers.

Thus, there may be situations in which, even if the balances of the nodes are fully covered, it is economically feasible to develop the power grid additionally to implement more efficient electricity trade for consumers and (or) generating organizations.

The efficiency of greater loading of the most economical generating sources due to the construction of new transmission lines ("operating conditions" effect) is usually low as the cost of the line does not cover the reduction of costs of generation. The differences in the cost of electricity generation at different types of power plants are not very significant. However, in some cases, it is also advisable, e.g., when connecting stand-alone power districts (or large consumers), which were supplied by the most inefficient of local sources of electricity (diesel power plants running on expensive imported fuel, etc.) to the EPS.

The construction of additional transmission lines to redistribute the electricity consumed among electricity consumers can have a much greater effect. The efficiency of electricity use varies considerably among consumers in different industries. These differences are much greater than the differences in electric power generation efficiency. In the presence of consumers so different with respect to the efficiency of electricity use, the expediency of building additional transmission lines so as to ensure the conditions for competition for electricity consumption becomes real.

Thus, in general, to assess the effectiveness of various options for the construction of power transmission lines it is necessary to compare the costs of the practical implementation of these options (capital expenditures and annual costs of operating the lines) and the effects on the electricity market (annual yearly effect: an increment of the total profit of market participants).

This statement of the problem is considered below. It should be noted that with completely defined values of generation and consumption metrics, when the market effect is actually set outside the model, the problem is reduced to the conventional problem of minimum costs for the expansion and operation of the power grid.

To estimate the annual effect in the market, it is required (due to the differences in operating conditions in the annual profile) to simulate the operation of the electricity market throughout the entire year. Such modeling is possible due to the description in the model of a number of characteristic moments of time during the year, that in their entirety are representative enough to describe the annual effect. The annual effect, in this case, will be represented as the sum of the market effects at these selected points in time.

Below, in accordance with the above, is the statement of a mathematical model of the expansion of the power grid (in the static statement) that takes into account the market effects.

Let i be the node index of the electric power system, $i \in I$, where I is the set of indices of all nodes; t is the time moment (hour) in the year of the end of the calculation period, $t \in T$, where T is the set of characteristic time moments in the year; ik is the electrical connection index of nodes i and k, $ik \in J$, where J is the set of all electrical connections of the power system; n_{it} is the duration of the time moment t in year at the node i; K_{ik} is specific capital investment in the line ik; U_{ik} is relative (with respect to capital investment) fixed annual costs of operation of the line ik; E is capital investment efficiency factor.

It is required to maximize the total economic effect of market participants, taking into account the costs of construction and operation of power transmission lines

$$F = \max \sum_i \sum_t n_{it} \left(L_{it}(s_{it}) - G_{it}(p_{it}) \right) - \sum_{ik} (E + U_{ik}) K_{ik} t_{ik}^{new} \qquad (3.35)$$

subject to: capacity balances at the nodes

$$p_{it} + \sum_k t_{kit}(1 - d_{ki}) - \sum_k t_{ikt} = s_{it}, \quad i \in I, \ t \in T, \tag{3.36}$$

constraints on power flows and the development of transmission lines

$$t_{ikt} - t_{ik}^{new} \le T_{ik}^{\text{exist}}, \quad ik \in J, \ t \in T, \tag{3.37}$$

$$t_{ik}^{new} \le T_{ik}^{new}, \quad ik \in J, \tag{3.38}$$

constraints on generation at the nodes

$$p_{it} \le P_i, \quad i \in I, \ t \in T. \tag{3.39}$$

Here p_{it} is generation at the node i at the hour t; P_i is maximum possible generation; s_{it} is consumer load at the node i at the hour t; t_{ikt} is flow from the node i to the node k at the hour t; T_{ik}^{exist} is the transmission capacity of the $i - k$ connection at the beginning of the calculation period; T_{ik}^{new} an increase in the transmission capacity of the $i - k$ link; $L_{it}(s_{it})$ is consumer income at the node i at the hour t

$$L_{it}(s_{it}) = \int_0^{s_{it}} p_{it}^S(v)\, dv, \tag{3.40}$$

where $p_{it}^S(v)$ is the demand curve at the node i at the hour t; $G_{it}(p_{it})$ is the cost of generation at the node i at the hour t

$$G_{it}(p_{it}) = \int_0^{p_{it}} p_{it}^G(v)\, dv, \tag{3.41}$$

where $p_{it}^G(v)$ is the supply curve at node i per hour t.

The demand curves of each node are formed for the hour of maximum load of the node and characteristic moments of time t during the year. Forming them can be done on the basis of the so-called load duration profile that reflects the duration within a year of a load not more than a certain value, or the node frequency distribution profile during the year, $f(p)$ that reflects the frequency (or duration) of having the load p in a year. Based on these profiles, the n_{it} values in the model can be determined. The demand curves in this model are short-term in nature and describe only the immediate response of the consumer to changes in electricity prices, without taking into account the events of changes in demand, which are of a long-term nature (lasting over a year).

The supply curves of each node for the peak hour should reflect the available capacity of all the node's power plants. Supply curves for other characteristic moments of the season of year t should take into account the decrease in the available capacity of power plants during the year due to the withdrawal of capacities for repairs, changes in CHPP load in the cogeneration operation during the heating and non-heating periods, seasonal changes in the output of HPPs, and, probably, other seasonal factors.

Optimization of the prospective mix of generating capacity given the management of electricity consumption. Taking into account the possibilities of electricity consumption management (increasing the energy efficiency of consumers) when planning the expansion of the electric power industry and EPS is an important aspect of the general methodology of projecting the development of the industry. At the same time, improving the energy efficiency of consumers should not be opposed to the development of generating capacity, but both measures should be seen as a reasonable and well-balanced complement to each other.

The daily profiles of electric loads of the EPS are made up of the profiles of individual consumers, which, as a rule, are irregular. It is known that the density and irregularity of the load profile have a strong impact on the economic performance of the EPS. Changing the profiles of electric loads (consumed power) of consumers as a result of improving their energy efficiency makes it possible to adjust the total profile of electric load of the EPS towards reducing the need for generating capacity and the current cost of electricity generation and transmission.

The main tool for improving energy efficiency is electric load management or demand management.

Electricity demand management can be divided into two main components: measures to save electricity and measures to control electricity consumption, i.e., the use of load shape modifying consumers, by which we mean consumers who have the ability to change load profiles without affecting their technological process.

Taking into account electric electricity saving measures and load shape modifying consumers behavior when optimizing the development of EPS is one of the types of problems of complex optimization of EPS development and consumers of electricity requiring for its solution the use of specialized mathematical models

The fullest effect of electric power saving and electricity consumption control measures can be achieved by look-ahead and joint study of the mix, energy and economic characteristics of consumers of electricity, the mix of the generating capacity of the EPS, as well as the use of cross-system connections, i.e., through solving the problem of comprehensive optimization of the mix of generating capacity of EPS and electricity consumers. To solve this problem, we used the SOYUZ model with the appropriate modification achieved by adding appropriate models.

Modeling of electric electricity saving measures to optimize the development of electric power systems. When carrying out optimization calculations to choose a rational structure of the EPS in terms of the types of power plants and equipment, electricity-saving measures can be considered as one of the "ways" to cover the load of the EPS, i.e., to compare them with the electric power generation at power plants. Such activities are characterized by the following main parameters:

- the effect in the areas of electricity-saving or electric power conservation itself;
- capital expenditures of the reconstruction or replacement of current-using equipment (production and auxiliary equipment, lighting fixtures, etc.);
- the costs of operation and ongoing maintenance of the equipment that has been reconstructed or replaced (upkeep of maintenance personnel, repairs, spare parts, etc.).

Let the k-th electric power consumer take a measure or a number of measures aimed at improving the efficiency of electricity use (electricity saving). The mathematical model of this consumer can be represented as follows:

$$N_k - N_k' = \Delta N_k, \tag{3.42}$$

$$\sum_{\tau} \Delta N_{ks\tau} \leq \beta_{ks} \left(N_k - N_k'\right), \tag{3.43}$$

$$\beta_{ks} = (1 - g_{ks} - \beta_{ks}^{rep}), \tag{3.44}$$

$$k_{udk} = K_k/(N_k - N'_k), \tag{3.45}$$

$$\Delta Z_{Tk} = Z'_{Tk} - Z_T, \tag{3.46}$$

$$\Delta I_k = \Delta Z_{Tk}/\Delta N_k. \tag{3.47}$$

In this model, the expression (3.41) determines the energy effect or the value of electricity savings ΔN_k, which is the difference between the consumer load before the electricity-saving measure N_k and after N_k'.

Under normal operating conditions, some of the current-using equipment items belonging to the consumer may not be used or may be under repair. Then, in accordance with the proposal to "cover" the load by means of electric electricity-saving measures, the expression (3.41) can be written in the form of (3.42), where $\Delta N_{ks\tau}$ is the total power of the effect in terms of electric power saving of the k-th power consumer who contributes to covering the zone with a duration of τ hours of the load profile of the sth design day. The parameter β_{ks} defines the maximum share of the power of the current-using equipment involved in the operation in their total installed power, it is in fact the coefficient of "availability" of the consumer's power and is determined as per the dependency (3.44).

In the expression (3.44), the values g_{ks} and β_{ks}^{rep} are the coefficients of emergency downtime and scheduled current and overhaul repairs of process equipment of the kth consumer for the sth design day, respectively.

The meaning of the expression (3.43) is that the total electric electricity-saving capacity of the kth power consumer after implementation of electricity-saving measures cannot exceed the total installed electricity-saving capacity of the process equipment used by it, with repair, emergency, and process-induced downtime.

The capital expenditures and operating costs necessary to carry out electricity-saving measures are determined according to Eqs. (3.45)–(3.47). The meaning of these equations is as follows:

Let us suppose that before the implementation of electricity-saving measures, the technological process of the kth power consumer was characterized by the current costs Z_{Tk}. After the implementation of electricity-saving measures that requiring for their implementation some capital expenditures K_k, the technological process will be characterized by the current cost Z'_{Tk}.

In this case, the specific capital investment, which allows one to implement an electric saving measure, will be determined according to (3.45) and equal to the ratio of capital costs K_k and the effect in terms of electricity saving.

In turn, the annual costs that accompany the process of operation of equipment or current costs (expressed in monetary and material terms) are characterized by the dependency (3.46). If the operating cost of the electricity consumer decreases after the implementation of measures to save electricity, the value of ΔZ_{Tk} can be negative.

Taking into account (3.46), the specific operating costs, measured in rubles per kW and allowing for electricity savings, can be written in the form of (3.47).

The dependency of costs on the operating conditions of the electricity consumer is not taken into account, so variable costs are included in the annual costs.

In order to identify the possibility of applying the SOYUZ mathematical model to solve the problems of overall optimization of the EPS and electricity consumers, we assessed the effectiveness of modernization of lighting sources, which involve the replacement of widespread conventional incandescent lamps with energy-saving ones that are identical in terms of the luminous flux.

According to the results of the calculations, it is clear that the modernization of electric lighting sources is a fairly effective measure for saving electricity, see Fig. 3.5.

The greatest effect from the considered measure can be achieved in the Central, Urals, and Siberian IPSs (1.2; 1.0, and 1.0 GW, respectively), due to a significant increase in the projected levels of electricity consumption in these IPSs and, accordingly, the need to add large amounts of generating capacity or search for alternative measures to cover profiles of electricity load.

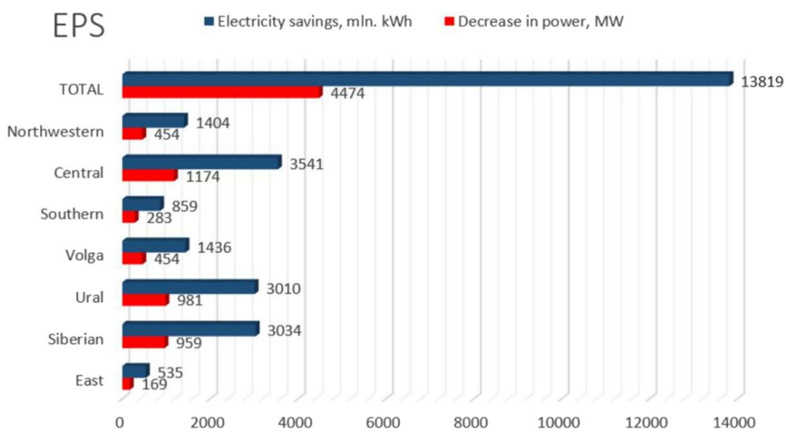


FIGURE 3.5 Scope of modernization of electric lighting.

TABLE 3.6 Metrics of the economic performance of measures to modernize electric lighting.

Metrics	Unit	Value
Reducing the present value of implementation costs	mln. USD	312
Reducing fuel costs	mln. USD	4,148
Savings in capital expenditures	mln. USD	4,552
Decrease in fuel consumption	mln. tons of fuel equivalent	73

Overall, the option of development of the UES of Russia with the modernization of lighting sources with respect to estimated discounted costs of development and operation of the UES and consumers analyzed is significantly cheaper than the original option, which does not provide for such measures, see Table 3.6. These electricity-saving measures result in annual fuel savings of 73 million tons of fuel equivalent, or $4.1 billion in monetary terms. In total, this measure reduces the new capacity additions by 4,5 GW for the UES as a whole.

Modeling of load shape modifying consumers in optimizing the expansion of electric power systems. There are a number of points to consider:

- both the switching over to the load shape modifying consumers mode of conventional power consumers and the creation of new load shape modifying consumers require some capital expenditures;
- the component of the cost of electricity used in the consumption mode can be accounted for in the power plants that ensure the EPS operating conditions as a result of optimization, rather than in the current costs of the consumer;
- when the capacity of the load shape modifying consumer shifts from the peak zone of the load profile to the dip zone, part of the generating

capacity of power plants is released, this mode can be represented as 'generation' by the load shape modifying consumer;
- the operation of the load shape modifying consumer in the dip zone can be regarded as the "consumption" mode.

Taking into account the above, the mathematical model of the load shape modifying consumer as applied to the problem of optimization of EPS development can be written in the following form:

$$\sum_{\tau} N_{ks\tau} \le \beta_{ks} N_k, \tag{3.48}$$

$$N_{kst} \le \gamma_k \beta_{ks} N_k, \tag{3.49}$$

$$\beta_{ks} = (1 - g_{ks} - \beta_{ks}^{rep}), \tag{3.50}$$

$$\sum_{\tau} \tau N_{ks\tau} \le \eta_k (\sum_{t} N_{kst}) \tau_s^{max}, \tag{3.51}$$

$$\tau_s^{max} \sum_{t} N_{kst} \le h_k \beta_{ks} N_k. \tag{3.52}$$

Eqs. (3.48) and (3.49) determine the share of electric power of the kth load shape modifying consumer in the "generating" and "consuming" modes, respectively. Here N_k is the total power of current-using equipment of the load shape modifying consumer; N_{kst} is the power of the "generating" mode of operation with a duration of τ hours in the sth day; N_{kst} is the power of the "consuming" mode at the hour t in the sth day. Just like in the "Electricity-saving measures" model, β_{ks} is the consumer's capacity availability factor (the share of the capacity of electric consumers involved in the operation relative to their total installed capacity) and is determined according to (3.50). In the expression (3.49), γ_k is the coefficient of the ratio of powers of "generating" and "consuming" modes.

Eq. (3.48) is a constraint on the use of power of the load shape modifying consumer in the "generation" mode and determines that it cannot physically exceed the total power of all current-using equipment with the availability factor taken account of. In turn, the dependency (3.49) shows that the power of the "consuming" mode also cannot exceed the total power of all current-using equipment in the "consumption" mode with the availability factor taken account of.

The expressions (3.48) and (3.49) for load shape modifying consumers are supplemented by Eq. (3.51) that links "generating" and "consuming" modes through energy and the constraints on the average daily number of hours of utilization h_k (3.52).

The meaning of Eq. (3.51) is that physically the energy of the "generating" mode cannot exceed the energy of the "consuming" mode.

Here τ_s^{max} is the duration of one interval; η_k is the efficiency factor, which is less than unity, if the work of the load shape modifying consumer is related to intermediate accumulation or transformation of electric power: e.g., batteries of electric car, water reservoir at the PSP, etc.

The limit on the energy consumption (3.52) is determined by the volume of production, the duration of the work shift, etc.

Using the upgraded "SOYUZ" model, we determined the optimal scale of prospective load shape modifying consumers.

The effectiveness of the latter was evaluated in different federal districts of the Russian Federation to 2030. We considered the scenario of the country's economic development with the level of electricity consumption by 2030 equal to 2,165 billion kW.h. At the same time, in addition to the "competition" of load shape modifying consumers with conventional types of generating equipment, there was also "competition" within them. The results obtained were compared with the initial option of optimizing the development of the UES of Russia, which does not provide for the use of load shape modifying consumers. Household, industrial, and agricultural consumers, electric heating units with heat storage, refrigeration units, hydrogen production, and electric cars were considered as promising load shape modifying consumers. The results of the study performed are presented in Table 3.7.

The option of the expansion of the UES of Russia given the adoption of load shape modifying consumers, is by 491 thousand tons more economical in terms of fuel, as well as requires 3,930 million dollars and 623 million dollars less capital expenditures and estimated costs, respectively.

According to the results of the calculations, it is clear that the most efficient types of load shape modifying consumers are industrial and agricultural consumers. The optimal volumes of their utilization are close to the available potential.

Hydrogen cars and domestic consumers are the least efficient for their use as load shape modifying consumers. The reason for this is the high outlay costs of the first and high operating costs of the second type of these consumers.

Financial and economic simulation model for the expansion of generating companies in the electric power industry (FINECOM). The conditions for further reform of the electric power industry and the development of its generating companies are changing. The interest in the problems of their investment appeal and assessment of the market value of these companies remains unchanged.

FINECOM was developed as a tool for developing strategic solutions to increase the efficiency of corporate governance in the context of increasing the investment appeal of generating companies in the electric power industry (hereinafter referred to as generating companies) [26–28]. Its differences from other models in this area are in the compliance of the fundamental modules ("Financial Results", "Balance Sheet", and "Cash Flow"), the mix and content of the resulting key financial metrics with GAAP requirements (Generally Accepted Accounting Principles) and the effects of

TABLE 3.7 Optimal volumes of application of different load shape modifying consumers (LSMC) and changes in the mix of generating equipment additions by federal districts of the Russian Federation, 2030.

No.	Federal district	Type of load shape modifying consumers	Optimal volume of the application of the load shape modifying consumers, MW	Changes in the structure of generating equipment additions, MW
1	Northwestern	Manufacturing Agricultural	1.177 27	Decrease in K-300u additions by 1294 MW
2	Central	Manufacturing Agricultural	2.024 58	No change
3	Volga	Manufacturing Agricultural	808 54	No change
4	Southern	Manufacturing	456	Increase in K-300u additions by 592 MW
5	Ural	Electric cars Electric heating Manufacturing Agricultural	905 695 1.393 14	Decrease in K-300u additions by 1589 MW
6	Siberian	Electric heating Manufacturing Agricultural	120 1.288 40	Increase in K-300u additions by 983 MW
7	Far Eastern	Electric cars Refrigeration units Electric heating Manufacturing Agricultural	1.104 74 886 130 2	Decrease in K-300u additions by 2289 MW

corporate governance in the interests of investors [29–33]. In our opinion, GAAP requirements are more in line with the interests of investors, unlike the Russian accounting standards, which have a clear fiscal orientation. The effects of corporate governance in the interests of investors were determined by the values of key financial indicators accepted in the world practice, at which the growth of the share price of companies is possible. For generation companies, they corresponded to the average in the ranges of "satisfactory" values of each of these indicators.

When developing FINECOM, the industry specifics of generating companies were taken into account, primarily those related to the continuity and simultaneity of energy generation, transmission, distribution, and consumption processes. In this regard, when using FINECOM, components of work-in-process and finished goods available in stock should be excluded from companies' current assets. Compared to the widely used

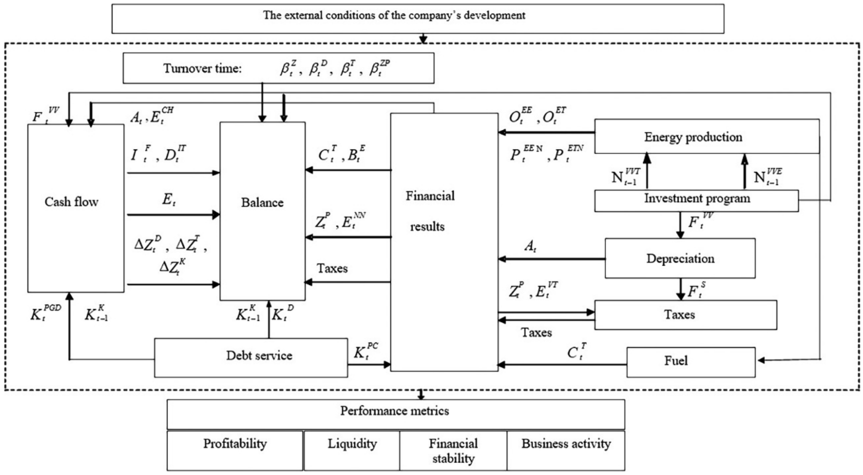


FIGURE 3.6 FINECOM workflow.

approach, we have made changes in the definition of working capital and net working capital values in the cash flow calculations, mainly due to the seasonal nature of reserves and covering cash flow gaps.

An aggregated flowchart of FINECOM is shown in Fig. 3.6.

The external parameters of the generating company's development are combined in the external module of basic input information "External conditions of the company's development. This information is represented, in particular, by the rates of taxes in force, prices of electricity to be sold and purchased, tariffs for selling and buying thermal power, interest rates on loans and credit facilities, and the price of the reference fuel.

Fig. 3.6 presents the fundamental modules of FINECOM ("Financial Results", "Balance", and "Cash Flow") and stand-alone modules: "Working Capital Turnover Periods", "Debt Service", "Energy Production", "Investment Program", "Depreciation", "Taxes", and "Fuel". Making them stand-alone is due to the need for additional analysis of the factors that determine the value of the resulting metrics calculated therein for the fundamental modules of the model and, as a consequence, the values of key financial metrics of generating companies.

Each of the listed model modules has its own description, including the assumptions made and the rationale for a particular sequence of calculations. These modules are closely interconnected with each other. Their outputs were the input information for calculations in other modules.

Among the many metrics calculated by the model in these modules, only their resulting metrics in the calculation year are given below, as shown in Fig. 3.6. These metrics are listed according to the model modules presented above.

Assets – A_t^{IT}. Shareholders' equity – C_t^A. Energy sales – B_t^E. Salaries and wages – Z_t^P. Retained earnings running total – E_t^{NN}. Net income – E_t^{ch}. Change in accounts receivable – $\triangle Z_t^D$. Change in fuel reserves – $\triangle Z_t^T$. Change in accounts payable – $\triangle Z_t^K$. Additional stock issue – E_t. Corporate monetary funds – D_t^{IT}. Financial investments – I_t^F. Days sales in inventory – β_t^Z, accounts receivable settlement – β_t^D fuel suppliers – β_t^T, wage/salary payment – β_t^{ZP}. Long-term and short-term loans – K_t^D, K_{t-1}^K, respectively. Amount of repayment of long-term loans – K_t^{PGD}. Total interest payments on all loans – K_t^{PC}. Net supply of electricity – O_t^{EE}, heat – O_t^{ET}. Purchased electricity – P_t^{EEN} and purchased heat – P_t^{ETN}.

The investment program of the generating company is simplified and presented in the form of given values of inputs of generating capacity N_t^{VVE}, N_t^{VVT}. Total cost of added capacity (fixed assets) for energy production – F_t^{VV}. Average annual fixed assets – F_t^S. Depreciation of fixed assets – A_t. The cost of fuel equivalent for energy production – C_t^T.

The metrics calculated in the fundamental modules of FINECOM are basic for determining the key financial indicators of the generating company: profitability, liquidity, financial stability, and business activity. Their numerical values are considered as the output result parameters of the model.

In the context of Russia, we determined the range of numerical values of key financial performance metrics of generating companies (optimal, satisfactory, borderline, critical), affecting the value of their market share price. These financial performance metrics in their expanded form and the ranges of their numerical values are given in Table 3.8 [26,27].

According to the data presented in Table 3.8, a generating company was considered appealing for investment if the values of the vast majority of key financial performance metrics did not fall below the average values of the range of "satisfactory" values. The level of its investment appeal increased with the increase in the numerical values of key financial performance metrics from the average values of the range of "satisfactory" values in the direction of achieving the "optimal" values by them. If the values of key financial performance metrics took values beyond the lower boundary of the range of "satisfactory" numerical values and fell into the "borderline" range, then the generating company was of low appeal to potential investors. At "critical" values the investment appeal is very low. In any case, generating companies require additional corrective corporate decisions and contingency calculations of the dynamics of key financial indicators in order to increase the investment appeal of stocks, taking into account changes in external development conditions.

TABLE 3.8 Values of key financial performance metrics.

Metrics	**optimal**	**satisfactory**	**borderline**	**critical**
Profitability				
Return on sales	>0.15	0.05–0.15	0–0.05	<0
Return on assets	>0.03	0.012–0.03	0–0.012	<0
Return on equity	>0.05	0.02–0.05	0–0.02	<0
EBITDA return	>0.20	0.10-0.20	—	—
Liquidity				
Absolute liquidity ratio	>0.15	0.03–0.15	0.01–0.03	<0.01
Acid-test (quick) ratio	>0.95	0.75–0.95	0.5–0.75	<0.50
Current ratio	>2.00	1.2–2.00	1.0–1.2	<1.00
Financial stability				
Leverage ratio	>0.80	0.65–0.80	0.5–0.65	<0.50
Business activity				
Accounts receivable dynamics	<(-0.10)	(-0.10)–0	0–0.10	>0.10
Accounts payable dynamics	<(-0.10)	(-0.10)–0	0–0.10	>0.10
Ratio of accounts receivable and accounts payable	>1.2	1.0–1.2	0.8–1.0	<0.8

A detailed list of key financial performance metrics as output parameters of the model implies their use in the analysis of the investment appeal of stocks of generating companies by different groups of long-term investors. These investors have different goals for investing and, accordingly, their individual approaches to assessing this appeal. They analyze the key financial performance metrics of generating companies according to their interests. Lenders are usually interested in performance metrics related to creditworthiness and the prospects for repayment of credit facilities provided. Strategic investors seeking to enter the business of these companies mainly assess the market and real value of the installed generating capacities, their depreciation and modernization costs, future sales markets, and tax legislation. Institutional investors (pension funds, etc.) are mainly interested in the future free cash flow of generating companies in order to receive stable dividends from their net profits for years to come. What matters to portfolio investors is the generating companies' ability to develop sustainably, increase the market price of their shares and, as a result, increase their market capitalization.

The detailed list of key financial performance metrics offered in the model as its output parameters was not exhaustive for its use in financial analysis. They are taken as the basic metrics. The model included the calculation of additional components and combinations thereof to better match the targets of generating companies and the interests of various groups of long-term investors. In particular, a telling example of such a combination is DuPont formula well-known in the best global finance practices (see Table 3.9).

TABLE 3.9 DuPont formula.

Net income	(ROE) =	Net income	·	Income from sales	·	Assets
Shareholder Equity		Income from Sales		Assets		Shareholder Equity

The presence of two additional components ("income from sales" and "assets") in this formula for determining ROE allows generating companies over a number of reporting periods to expand their ability to increase their return on equity while allowing investors to gain a deeper understanding of the reasons for this growth. Find out which parameters of the generating company's financial performance have or could have the greatest impact on its profitability. In particular, if the financial statement analysis shows a significant increase in ROE, it is possible to determine which component led to this increase: 1) whether the generating company achieved more profit per unit of energy sales; 2) whether it used more efficiently the assets that led to an increase in revenue; 3) whether the financial structure of capital has changed.

We carried modeled contingency calculations to illustrate the model's capabilities using "Territorial Generating Company No. 9" JSC (prior to its incorporation into T Plus PJSC) as an example. The investment appeal of this company's stocks was investigated, with the influence of possible positive changes in the quality of its corporate governance factored in. The results of these studies were published in [34].

In order to develop the model, it is planned to expand the mix of additional components when calculating numerical values of key financial indicators of generating companies using FINECOM. This will allow a more in-depth and objective assessment of the investment appeal of these companies, including a comparative analysis of their appeal to different groups of long-term investors.

3.4 Hierarchical modeling in expansion planning of electric power systems in the context of integration, deregulation, and renewable development

Key conceptual considerations. Traditionally, in the process of justification of decisions on the expansion of electric power systems, the latter were usually considered as engineering and economic in nature, represented by generating capacities/electrical plants, power grids/transmission lines, having their technical (installed and operating capacities of different types of power plants, redundancy, availability, minimum load, transmission line capacity, etc.) and economic (capital expenditures, fuel cost, operating cost, total cost, etc.) parameters. In the study of electric power systems (EPS) as engineering and economic systems, their organizational division into separate economic entities was usually not required.

In modern conditions, when planning the expansion of electric power systems, it is necessary to take into account new organizational factors [35]. This is caused by the fact that given deregulation and restructuring of the EPS there is an organizational unbundling of the latter into separate energy companies with their own objective functions of efficiency, although the physical and technological integrity of the EPS is preserved.

In addition, when planning the expansion of the EPS while taking into account the processes of cross-border power integration, despite the significant amount of work already done, one usually limits the scope to the study of the system efficiency of the cross-border power interconnection as a whole. However, in order for the cross-border power interconnection to take place and for each country to participate in it in the most effective way, the interests of individual countries should be taken into account. The proposed concept accounts for the organizational division into national electric power systems when justifying decisions on the development of cross-border power interconnections and cross-border electric connections.

Consideration of organizational factors (in addition to technical and economic factors) requires the use, along with conventional optimization approaches, of new equilibrium models that allow one to take into account the interests of many participants of the cross-border power interconnections or electric power markets (EPM) [35].

Besides, renewable energy sources are playing increasingly important role in modern electric power systems and need to be thoroughly considered while planning future power systems. Thus, renewables should be taken into account in the models of power systems expansion planning.

Thus, the elaborated concept of expansion planning of the electric power industry under modern conditions covers technical, economic, organizational aspects/factors takes into account electric power integration, deregulation, and renewable development as the most important trends taking place in the electric power industry of Russia and the world and offers mathematical optimization and equilibrium models as the main tools for research.

Elements of the methodology of hierarchical expansion planning of electric power systems in the context of their integration and deregulation. In its most comprehensive form, the general methodological framework of expansion planning of the electric power industry and EPS under the new conditions was formed at the MESI [8]. In terms of its structure, this framework includes a hierarchical sequence of stages. At each of these stages, one solves groups of certain general energy, system-wide, and facility-specific problems that deal with the electric power industry, specialized

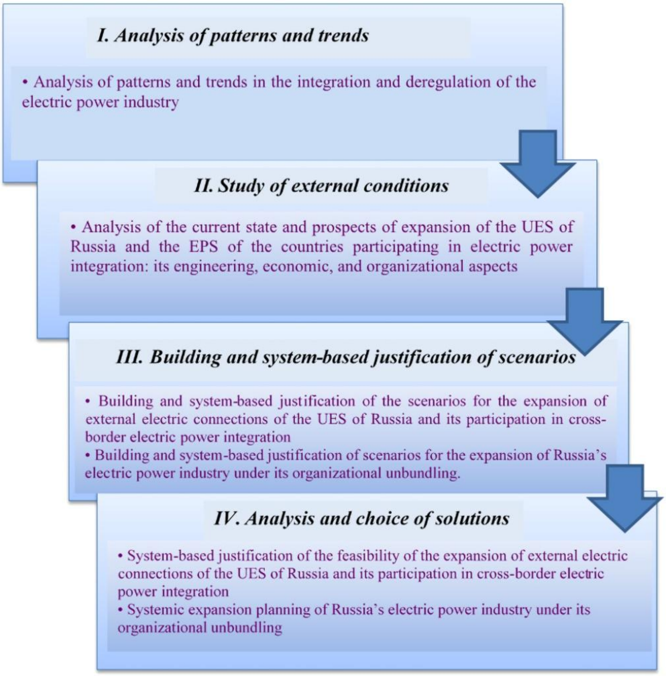


FIGURE 3.7 Multistage hierarchical methodological scheme for justifying the expansion of the electric power industry in Russia under integration and deregulation.

engineering and methodological aspects. This framework, being the most comprehensive, is taken as the basis for improvement in the directions indicated above. The ideological basis for improving the methodology is the conceptual considerations outlined above.

Fig. 3.7 presents a hierarchy of new problems of planning that supplement the problems formulated as part of the methodology [35], which are quite different and are present at all stages of the improved general methodological framework of justification.

The group of problems of *the first stage* is aimed *at analyzing the patterns and trends of integration, restructuring, and deregulation of the electric power industry*. These problems complement (but do not replace) the problems of the methodology developed at the MESI as presented at Stage 1 in terms of taking into account the new conditions. Analysis of integration, restructuring, and deregulation in different regions of the world, including Eurasia, where the Unified Energy System (UES) of Russia is located, allows one to identify global and regional patterns of the evolution of these processes, determine the main directions of their development and will contribute to the most relevant and appropriate development scenarios of

Russia's electric power industry and electric power integration of Russia in the Eurasian space.

When solving the problems of *the second stage*, one performs *the analysis of the current state and prospects of expansion of the UES of Russia and EPSs of related member states of electric power integration.* It considers different types of power plants (including thermal, hydraulic, nuclear power plants: TPP, HPP, NPP, distributed generation), consumer load, electrical networks, a wide range of their technical and economic performance indicators, including the possible volume and mix of generating capacity, assumed transmission capacity of cross-system electric connections, including cross-border ones, minimum load and availability factors of generating equipment of various types, capital expenditures, operating and fuel costs of power plants, capital expenditures and operating and fuel costs of power transmission lines, including cross-border ones, loss ratios for capacity/electricity transmission, daily limits on electricity generation at pumped storage plants (PSPs) and seasonal and annual limits on electricity generation at HPPs, electricity consumption and maximum electricity loads, etc., as well as the structural organization of the electric power industry (with division into generating companies).

The above indicators actually determine the external and internal conditions that should be taken into account when justifying the development of the electric power industry, and which will serve as input data for forming the development scenarios at the third stage and performing research calculations at the final stage.

At *Stage 3* we solve the problems of building and justifying in a system-based way the scenarios of expansion of the electric power industry, EPSs, and energy companies of Russia. In other words, these problems are formulated as the problem of forming scenarios for the development of external electric connections of the UES of Russia and its participation in cross-border electric power integration and the problem of development of Russia's electric power industry that takes into account its organizational division into separate power companies. It should be noted that the first problem also takes into account the organizational division of the electric power industry, albeit at a higher level of national electric power systems.

In the first problem, scenarios are formed not only for the development of the UES (Integrated Power Systems - IPSs) of Russia, but also for the EPS of adjacent countries, integration (or its strengthening) with which is supposed to be studied, i.e., actually for the entire cross-border power interconnection in question. This can be explained by the fact that, as was pointed out, in particular in [36], the parameters of the cross-border electric connections can be effectively determined by joint optimization of the development of electrically connected national EPSs (i.e., within the framework of the emerging cross-border power interconnection).

For the purpose of the problem of expansion planning of external electric connections of the UES of Russia and its participation in cross-border electric power integration, we consider the following fundamentally different: the scenario of no cross-border electric connection (reference case) and the scenario / scenarios of cross-border electric connection development and establishment of the cross-border power interconnection. In the latter case, there may be several scenarios for different perspectives for the development of the cross-border electric connection and cross-border power interconnection, as well as due to the uncertainty of future conditions and factors of this development. The baseline scenario serves as a kind of "reference point" against which other scenarios (with the development of the cross-border electric connection) are compared and their effectiveness is determined.

Two distinctly different types of scenarios are also built for the problem of expansion planning of Russia's electric power industry, taking into account its organizational division and the interests of individual power companies. As global and domestic experience shows, under the conditions of restructuring and deregulation of the electric power industry, imperfect electric power markets are formed where individual entities/energy companies are able to demonstrate their strategic behavior, i.e., make decisions that lead not to the achievement of the global optimum for the EPS, but maximize their objective functions of efficiency. Therefore, it is necessary to consider some baseline scenario (as a "reference point", as in the previous case), where the system-wide optimum would be achieved. Such a basic scenario is an idealized scenario with the consideration of perfect competition when the activity of each energy company is actually aimed at achieving the global optimum with respect to EPSs. The other type of scenario involves consideration of real imperfect competition. Their effectiveness (or rather ineffectiveness) is determined in comparison with the baseline scenario. The variety of scenarios is determined by different forms of organization of the electric power industry and the uncertainty of future conditions of its development and individual influencing factors.

Built and justified at the qualitative level, the scenarios are subjected to complex contingency studies at the next stage.

At *Stage 4*, we solve the problems of system-based justification of the feasibility of the development of external electric connections of the UES of Russia and its participation in the cross-border electric power integration, as well as the development of Russia's electric power industry while taking into account its organizational division and the interests of the participating entities. Special methodological provisions have been developed to solve the problems. They are a system of consistently applied hierarchically interrelated statements of problems of expansion planning of EPSs and power companies under modern conditions and that are set out below.

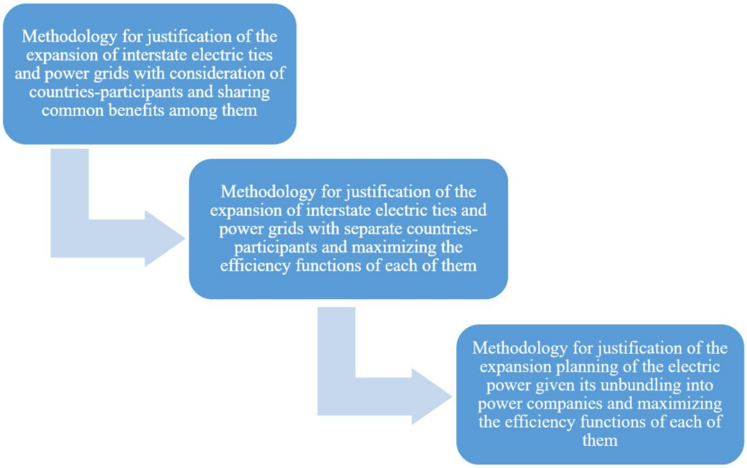


FIGURE 3.8 The hierarchical sequence of statements of problems of justification of electric power industry expansion with involved subjects specified.

Hierarchy of problem statements of expansion planning of the electric power industry that takes into account the organizational division and the interests of the entities involved.

Hierarchically co-subordinated statements of the problems of expansion planning of the electric power industry, taking into account the interests of individual entities, are shown in Fig. 3.8.

The first statement is designed to plan the expansion of external electric connections of Russia under multilateral electric power integration when Russia (along with other countries) is considered within the framework of the cross-border power interconnection. It involves the sequential solving of two subproblems.

Subproblem 1 is solved to determine the overall performance and effectiveness of the future cross-border multilateral interconnection, including the composition and preliminary parameters of the cross-border electric power system optimal from the standpoint of the entire interconnection. Based on the results obtained, the effectiveness of the cross-border power interconnection as a whole is evaluated. To solve subproblem 1, we perform rather complex optimization calculations for scenarios of the absence (scenario 1) and the establishment of a power interconnection (scenario 2) based on the system model of expansion and operating conditions of electric power systems CANOE [37]. The objective function of the model is the annualized costs for all EPSs, which are minimized for both scenarios:

$$Z_{sep}(X) \rightarrow min, \tag{3.53}$$

$$Z_{joint}(X) \rightarrow min, \tag{3.54}$$

where $Z_{sep}(X)$ is the objective function of the model for scenario 1; $Z_{joint}(X)$ is the objective function of the mode for scenario 2; X is the vector of CANOE model variables (covered in more detail in the next subsection).

The resulting optimal values of the objective function from (3.53) – (Z_{sep}) and (3.54) – (Z_{joint}) are compared with each other ($Z_{sep} \gtrless Z_{joint}$). If the costs in the second scenario are lower than in the first ($Z_{sep} > Z_{joint}$), then the cross-border power interconnection is feasible, otherwise it is not. The economic effect of the power interconnection is defined as the difference of costs (values of the objective functions) for the first and second scenarios:

$$\pm E_{total} = Z_{sep} - Z_{join}, \tag{3.55}$$

If the power interconnection is feasible, the effect will be positive ($+E_{total}$), if not, it will be negative (i.e., in fact, there will be no effect, but damage from establishing the interconnection) ($-E_{total}$).

The effect obtained and described above is integral. It includes the system effects produced by establishing the cross-border power interconnection and determined by the model: the power (E_{cap}) and fuel (E_{fuel}) effects.

In Subproblem 2, the integration system-wide effect obtained during the solving of the first subproblem is divided among the individual member countries σ ($\sigma \in \Sigma$ is the number of countries) [37,38]. So, the capacity effect for a given country is defined as the difference between the costs of development and operation of generating capacity (excluding the fuel component) in stand-alone and joint operation of the corresponding national EPS. Similarly, the fuel effect is determined when comparing the fuel costs for stand-alone and joint (as part of the cross-border interconnection) operation of some national EPS.

The effect of joining the cross-border interconnection for each country σ includes the capacity, fuel, and trade effects (the latter being an integral balance of revenues from exports and costs of electricity imports by the respective country in the calculation year and in general it can be both positive and negative) and takes into account the portion of costs of the cross-border interconnection attributable to the country (Z_{ISET_σ}, $\sigma \in \Sigma$):

$$E_{total_\sigma} = \pm E_{cap_\sigma} \pm E_{fuel_\sigma} \pm E_{trade_\sigma} - Z_{ISET_\sigma}, \ \sigma \in \Sigma. \tag{3.56}$$

The calculation of the trade effect makes use of the results of calculations not only of the primal CANOE model, such as the volumes of flows between nodes, but also the results obtained based on the dual model, namely, the dual variables (Lagrange multipliers). They characterize the value of electricity at the corresponding node for the producer and consumer and are adopted as the nodal price of electricity [38, etc.].

The sum E_{total_σ} over all countries $\sigma \in \Sigma$ will yield the integration effect obtained by solving subproblem 1.

The second statement, which clarifies and supplements the previous one, maximizes the efficiency of entering the cross-border electric connection / power interconnection project for each individual country.

The economic interest of the cross-border power interconnection participant is captured by the prices of "export" supply and "import" demand for electricity

$$p^{ex}_{\sigma j \sigma' j'},\ p^{im}_{\sigma' j' \sigma j},\ \ j,\ j' \in J_\sigma,\ \ j \neq j',\ \ \sigma,\ \sigma' \in \sum,\ \sigma \neq \sigma'.$$

These prices are the variables of the modified CANOE model discussed below. At the same time, prices depend on the volume of external ("export"/"import") power flows. Therefore, they can be represented as functions of these flows. These will be so-called inverse supply/demand functions. It is obvious that each member of the transnational interconnections seeks to maximize the export price and minimize the import price of electricity, which is formalized by the system of expressions (3.57).

$$\begin{cases} p^{ex}_{\sigma j \sigma' j'}\left(\sum\limits_{s \in S}\sum\limits_{t \in T} \tau_s x_{\sigma j \sigma' j' t s}\right) \rightarrow \max, \\ p^{im}_{\sigma' j' \sigma j}\left(\sum\limits_{s \in S}\sum\limits_{t \in T} \tau_s x_{\sigma' j' \sigma j t s}\right) \rightarrow \min \end{cases} \quad \begin{matrix} j,\ j' \in J_\sigma,\ \ j \neq j', \\ \sigma,\ \sigma' = \sum,\ \sigma \neq \sigma' \end{matrix} \tag{3.57}$$

The restraining factor in both the first and second cases is the opposing interests of the partners in electric power integration. These interests are formalized in the form of supply/demand functions (SF/DF). Overlaying the SF of one participant on the SF of another participant (or vice versa) at the point of their intersection gives a coordinated price (the maximum possible one for the exporter and the minimum attainable one for the importer) for both countries participating in the cross-border power interconnection:

$$p^{ex}_{\sigma j \sigma' j'} = p^{im}_{\sigma' j' \sigma j},\ \ j,\ j' \in J_\sigma,\ \ j \neq j',\ \ \sigma,\ \sigma' = \sum,\ \ \sigma \neq \sigma',$$

as well as the agreed volumes of power flows between them:

$$\sum_{s \in S}\sum_{t \in T} \tau_s x_{\sigma j \sigma' j' t s} = \sum_{s \in S}\sum_{t \in T} \tau_s x_{\sigma j \sigma' j' t s},$$
$$j,\ j' \in J_\sigma,\ \ j \neq j',\ \ \sigma,\ \sigma' = \sum,\ \ \sigma \neq \sigma'.$$

At the same time, the effective and coordinated transmission capacity of the cross-border electric connection between the considered participants of the cross-border power interconnection will also be provided, as well as other basic parameters of development of EPSs of member countries (volumes and mix of generating capacity by types of power plants, power output, structure and parameters of the main power grids, etc.).

The third statement of the problem of expansion planning of the electric power industry and the electric power system assumes their deeper organizational separation than it was performed in the two previous statements. Instead of countries, power-generating companies are considered as actors whose interests are taken into account when planning the expansion. The need to take into account this organizational division is caused by the fact that, as noted earlier, under the new conditions the decisions of energy companies, including development, may not lead to the achievement of a system-wide optimum. Therefore, it is necessary to assess to what consequences (from the point of view of development) the actions of energy companies can lead when motivated primarily by their commercial interests, although acting within a certain system of technical and regulatory standards and rules.

The problem is stated in the following way. Within an EPS, we consider several generating companies that own different types of generating capacities (TPP, HPP, NPP, etc.), and consumers that are represented by an aggregated demand function. The prospective time level for calculations is then set. Companies develop and operate their production facilities, and consumers build their long-term demand within a specified time period.

The behavior of generating companies is determined, on the one hand, by their desire to maximize their objective function of efficiency and, on the other hand, by the need to take into account the technical/technological (balance, operating conditions, and other) constraints of the EPS. To maximize the objective function, companies can commission new and load existing and newly commissioned generating capacity, as well as restrict the new capacity additions and the loading of their power plants. In the latter case, they demonstrate their strategic behavior by inflating long-term equilibrium electricity prices because, as noted earlier, imperfect electricity markets are formed under restructuring and deregulation.

We consider a single-product organizational structure when only one product (electricity) is traded, and a two-product organizational structure, when electricity and capacity are traded.

In formal terms, we state the problem of expansion planning of the electric power industry, given its organizational unbundling into power companies that are represented by the objective functions of efficiency, as a problem of maximizing these functions for each generating company:

$$f_l(Z) \to \max, \quad l \in L, \tag{3.58}$$

where f_l is the efficiency function of generating company l; L is the number of generating companies; Z is the vector of variables of the equilibrium model of development of the electric power industry and power companies (more details below).

The systems of optimization problems (3.58) are solved using a special equilibrium model of the development of the electric power industry and power companies, as presented below. The Cournot approach and the Nash equilibrium concept are used as the methodological basis for solving such a system of problems and for the model.

Hierarchical system of models of expansion planning of the electric power industry with the interests of the entities involved taken into account in the conditions of integration and deregulation. To solve the above-stated problems, we proposed a hierarchical information and computational system, including a family of mathematical models and information base as presented in Fig. 3.9 [35]. This system includes distinctly different but complementary mathematical models, including optimization (primal and dual) and equilibrium models. These types of models are usually applied separately for different classes of problems (not limited by the problems of development). In particular, equilibrium models were developed abroad mainly for the study of organizational and market structures in the electric power industry. In Russia, they currently receive undeservedly little attention (and not only when studying the development of the electric power industry). Combining these models into a single system and their joint application to the study and expansion planning of the electric power industry, EPSs, and energy companies, gives a new quality to the studies and the results obtained. Thus, this hierarchical system allows, for example, a comprehensive study of the electric power industry of Russia with the consideration of physical and process-related, technical and economic as well as organizational factors while taking into account the external electric connections of the UES of Russia and the interests of the electric power industry entities, supplementing the research conducted within the framework of the existing methodology of expansion planning of the electric power industry [35]. And both individual power companies and the country's electric power sector as a whole act as entities.

Accounting for the organizational division of the EPS into participating entities and their interests is carried out in the process of modeling in a sequential way, starting with the optimization of the common objective function of the participants, approaching step by step to the optimization of the objective function of a particular participant. We cover a total of three levels of consideration and modeling.

First, the first level of CANOE, the primal model for optimizing the expansion and operation modes of power systems, is used to optimize the interconnection as a whole with respect to a single objective function.

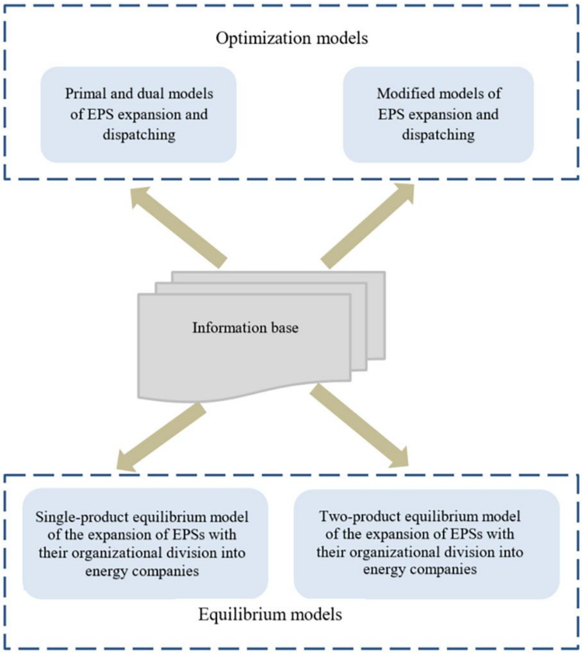


FIGURE 3.9 Hierarchical information and computing system of mathematical models to justify the expansion of the electric power industry under modern conditions.

Thus, it is assumed that the member countries of the EPS interconnection act so as to minimize system-wide costs. That is, in this case, the primary thing is to obtain a collective effect from the interaction of the entities involved. The resulting integral systemic effect of the association is shared between its participants/countries, thus taking into account their interests. To separate the effects, we apply special methodological provisions, which were mentioned above, and which use not only the results of solving the primal problem of the development and the operating conditions of the EPS, but also the long-term dual estimates (Lagrange multipliers, nodal prices) obtained by the dual model of development.

Then, at the second level, the modified CANOE optimization model considers individual entities/countries and optimizes their objective functions of effectiveness. In the modified model there is a pairwise consideration of the participating countries. At the same time, as is the case with the original CANOE model, captures fairly well the technical, economic, and technological features of the development and operation of the EPS.

Finally, at the third level, one uses so-called equilibrium models to optimize the objective functions of all available participants. In this case, it is possible to consider a concentrated EPS, which does not take into account the power grid infrastructure. This limitation is explained by the fact that, in general terms, achieving equilibrium in networks is currently not yet theoretically proven [39], although in some cases it can be implemented. In addition, equilibrium models assume the presence of a single interconnection, which is not always the case with cross-country interconnections. Therefore, equilibrium models are still used here to analyze the development of subsystems of the national EPSs that have a developed power grid infrastructure, which makes it possible to represent them as a single node in the model. At the same time, the technical, economic, and technological parameters of generating facilities are considered in equilibrium models with a sufficient degree of detail.

The CANOE model is actually the basis for the entire family of models presented in Fig. 3.9, because its technological structure in the form of balance, operating conditions, and other constraints is the basis for their construction. In addition, it should be noted that a number of constraints in equilibrium models are local to individual energy companies, while in optimization models they are system-wide. All models are solved in the GAMS system.

The closeness of the technological structure of these models and the similarity of the problems of prospective development also lead to the similarity of the composition of the input information for them. Although, of course, there are differences as well. Thus, in equilibrium models, technical and economic information on the development of certain types of power plants is further detailed with respect to power companies (including constraints on the development of different types of power plants, as already mentioned). Also, the equilibrium models do not require data on the development of electrical networks (because, as noted above, the latter are not considered in these models).

In connection with the above, to provide input data for the presented family of models one actually uses a common information base, which, however, is not a specialized database in the full sense of the word, as built on the basis of modern data storage and management technologies. Nevertheless, it meets the requirements for it by providing the necessary information to models for research calculations.

Below are the CANOE primal and dual models of the expansion and operating conditions of electric power systems [40–43]. The description of the dual model is limited to the presentation of dual estimates (Lagrange multipliers), which are formed by the constraints of the primal model and are solutions to the dual CANOE model.

The primal mathematical model of CANOE is developed on the basis of linear programming and has a large dimensionality. It allows calculating the optimal installed capacity X_{ij} for all considered types of power plants i ($i \in I$) (HPP, PSP, NPP, CPP, and CHPP using different fuels (gas, oil, coal), etc.; any specific power sources, e.g., export power plants) at each of the nodes j ($j \in J$), optimal values of throughput capacities of electric connections/cross-border power systems $X_{jj\prime}$ between the nodes j and $j\prime$ in the calculation year, as well as optimal operating capacities of power plants of the type i at the node j in the season s at the hour t on working days (x_{ijts}) and days off (y_{ijts}), pumping (charging) PSP capacity of the jth node within the interval t of the season s on working days (x_{ijts}^{charg}) and days off (y_{ijts}^{charg}); power flows along the lines/cross-border power system on days off within the hour range t in the season s from the node j to the node j' ($x_{jj'ts}^{h}$) and in the reverse direction ($x_{j'jts}^{h}$); power flows along the lines/cross-border power systems on working days within the hour range t in the season s from the node j to the node j' ($x_{jj'ts}^{w}$) and in the reverse direction ($x_{j'jts}^{w}$). The model considers daily load profiles of working and weekend days with hourly intervals t $(t \in T)$, $T = 24$ is the number of hours of working and weekend days (actual days) of each node / EPS j for each season of the year s $(s \in S)$, $S = 4$ is the number of seasons.

The objective function of the CANOE model is a function of the total costs reduced to the annual dimension (for the power interconnection as a whole, or by individual EPSs), and the optimal solution is determined by the minimum of these costs:

$$\sum_{j \in J} \sum_{i \in I} \sum_{s \in S} \sum_{t \in T} \tau_s^w c_{ij} x_{ijts} + \sum_{j \in J} \sum_{i \in I} \sum_{s \in S} \sum_{t \in T} \tau_s^h c_{ij} y_{ijts} + \tag{3.59}$$
$$+ \sum_{j \in J} \sum_{i \in I} k_{ij}(r + b_{ij}) X_{ij} + \sum_{j \in J} \sum_{\substack{j' \in J \\ j' \geq 2 \\ j' > j}} k_{jj'}(r + b_{jj'}) X_{jj'} \rightarrow min,$$

where τ_s^w is the given number of working days in the season s; τ_s^h is the given number of days off in the season s; c_{ij} is specific fuel costs of the power plants of the type i at the node j; k_{ij} is specific capital expenditures of the power plants of the type i at the node j; $k_{jj'}$ is specific capital expenditures of the transmission lines/cross-border electric connection between nodes j and j'; r is the discount rate; b_{ij} is fixed operational costs of power plants of the type i at the node j; $b_{jj'}$ is fixed operational costs of the lines between the nodes j and j'.

The first two summands of the objective function characterize the total annual fuel costs for the interconnection. The third summand includes investment and fixed operating costs of generating capacity. The fourth one represents the fixed operating costs of the lines, including the cross-border electric connection, as well as their investment costs.

In the process of optimization, it is necessary to provide a number of balance and operating conditions constraints, as presented below.

The capacity balance equations for determining the necessary additions of new power plants and increasing the capacity of transmission lines are as follows:

$$\sum_{i\in I} X_{ij} - \sum_{\substack{j\in J\\ j'\geq 2\\ j'\neq j}} x^{w}_{jj'ts} + \sum_{\substack{j\in J\\ j'\geq 2\\ j'\neq j}} x^{w}_{j'jts}\cdot(1-\pi_{j'j}) \geq P^{w}_{jts} + R_{jts}|\Psi_{jts}, \quad (3.60)$$

$$j\in J, \quad t\in T^{max}, \quad s\in S^{max},$$

where P^{w}_{jts} and R_{jts} is the consumers' load on a working day and the necessary capacity reserve at the power plants at the node j at the time interval t in the season s (only the seasons and hours of maximum loads are considered; the consumers' load is assumed for the working day as this is the period when it reaches its maximum); T^{max} is the set of time intervals in which the annual maximum loads occur; S^{max} is the set of seasons in which the annual maximum loads occur; $\pi_{j'j}$ is the coefficient of power loss in the line/cross-border electric connection between the nodes j and j'; Ψ_{jts} is a dual estimate characterizing the cost of the reserve of capacity at the node j in the season s and hour t.

Equations of hourly balances of actual power in daily load profiles are represented by the following relations:

$$\begin{cases} \sum_{i\in I} x_{ijts} - \sum_{\substack{j\in J\\ j'\geq 2\\ j'\neq j}} x^{w}_{jj'ts} + \sum_{\substack{j\in J\\ j'\geq 2\\ j'\neq j}} x^{w}_{j'jts}\cdot\left(1-\pi_{j'j}\right) = P^{w}_{jts} + x^{charg}_{ijts}\,\Big|\,\Theta^{w}_{jts} \\ \sum_{i\in I} y_{ijts} - \sum_{\substack{j\in J\\ j'\geq 2\\ j'\neq j}} x^{h}_{jj'ts} + \sum_{\substack{j\in J\\ j'\geq 2\\ j'\neq j}} x^{h}_{j'jts}\cdot\left(1-\pi_{j'j}\right) = P^{h}_{jts} + y^{charg}_{ijts}\,\Big|\,\Theta^{h}_{jts} \end{cases} \quad (3.61)$$

$$j\in J; \quad t\in T; \quad s\in S$$

where P^{h}_{jts} is the consumer load on the days off at the node j at the hour t in the season s; Θ^{w}_{jts} is the dual estimate characterizing the fuel component at the node j in the season s and hour t on working days; Θ^{h}_{jts} is the dual estimate characterizing the fuel component at the node j in the season s and hour t on days off.

Constraints.

Constraints on expansion of installed capacity of power plants:

$$N_{0ij} \leq X_{ij} \leq N_{Mij}|\xi_{jts}, i\in I; j\in J,$$

where N_{0ij} is initial installed capacity of power plants of the type i at the node j; N_{Mij} is maximum possible installed capacity of power plants of the type i at the node j by the end of the year under consideration; ξ_{jts} is dual estimate characterizing the cost of expansion of generating capacity of the type i at the node j.

Constraints on expansion of transfer capability of electrical connections (including interstate electric ties - ISETs):

$$\Pi_{0jj'} \leq X_{jj'} \leq \Pi_{Mjj'} | g_{jts}, \quad j, j\prime \in J \; j' \neq 1, \; j' > j, \tag{3.62}$$

where $\Pi_{0jj\prime}$ – initial transmission capacity of electrical connections between nodes j and j'; $\Pi_{Mjj'}$ – maximum possible transmission capacity of electrical connections between nodes j and j'; g_{jts} - dual estimate characterizing the cost of expansion of electrical connection between nodes j and j'.

Constraints on the actual power of power plants:

$$\begin{cases} a_{mijs} \cdot X_{ij} \leq x_{ijts} \leq a_{ijs} \cdot X_{ij}, \\ a_{mijs} \cdot X_{ij} \leq y_{ijts} \leq a_{ijs} \cdot X_{ij}, \end{cases} \tag{3.63}$$
$$i \in I, j \in J, t \in T, s \in S,$$

where a_{mijs} - the factor of minimum allowable capacity of power plants (operating and planned) of the type i at the node j during the season y; a_{ijs} - availability factor of power plants of the type i at the node j during the season s.

Constraints (3.63) characterize the adjustment range (range of changing actual power) of power plants, which may differ for different types of capacities. Besides, the right part of constraints (3.63) means that actual power x_{ijts} should not exceed the installed capacity X_{ij} taking into account the availability factor a_{ijs}.

Constraints on power flows through electrical connections (including ISETs):

$$\begin{cases} \Pi_{mjj'} \leq x^{w}_{jj'ts} \leq X_{jj'}, \\ \Pi_{mjj'} \leq x^{w}_{jj'ts} \leq X_{jj'}, \end{cases} \tag{3.64}$$
$$j, j' \in J, \quad j' \neq j, \quad t \in T, \quad s \in S,$$

where $\Pi_{mjj'}$ – the minimum permissible load of the electrical connection between nodes j and j' (can be equal to 0).

Hydro and pumped storage power plants.

For HPPs and PSPPs, special constraints are required, owing, in particular, to the limited availability of hydropower resources. PSPPs also operate in pumping/charging and generating/discharging modes.

Constraints on charge power of PSPPs:

$$0 \leq x^{charg}_{ijts} \leq a_{ijs} \cdot X_{ij}, \quad 0 \leq y^{charg}_{ijts} \leq a_{ijs} \cdot X_{ij}, \tag{3.65}$$
$$i = \{PSPP\}, \quad j \in J, \quad t \in T, \quad s \in S.$$

The constraints for the PSPPs on the power balances of charge and discharge are given in the expression (3.66) and for the total amount of electric power that can be stored in the PSPP reservoirs – in the ratio (3.67).

$$\sum_{t\in T} x_{ijts} - \eta_j^{PSPP} \sum_{t\in T} x_{ijts}^{charg} \leq 0, \quad \sum_{t\in T} y_{ijts} - \eta_j^{PSPP} \sum_{t\in T} y_{ijts}^{charg} \leq 0, \tag{3.66}$$

$$\sum_{t\in T} x_{ijts} + \sum_{t\in T} y_{ijts} \leq h_{ij} X_{ij} | \gamma_{js}^{PSPP}, \tag{3.67}$$

$$i = \{PSPP\}, \quad j \in J, \quad s \in S,$$

where η_j^{PSPP} – the efficiency of the "charge-discharge" cycle of the PSPP at the node j; h_{ij}, $i = \{PSPP\}$ – the maximum possible daily number of hours of utilizing the installed capacity of the PSPP of the node j, which characterizes the capacity of the PSPP reservoir (hours t of working and weekend days in each season s, during which the PSPPs are charged or discharged, are found in the course of the optimization process); γ_{js}^{PSPP} – a dual estimate that stands for the value of hydropower resources for the PSPP at the node j during the season s.

Depending on the water storage capacity, constraints are imposed on the total generation of HPPs for each season (3.68) or for the entire year (3.69):

$$\sum_{t\in T} (\tau_s^w x_{ijts}^w + \tau_s^h x_{ijts}^h) \leq h_{ijs} X_{ij} | \gamma_{js}^{HPP}, \tag{3.68}$$

$$i = \{HPP\}, \quad j \in J, \quad s \in S,$$

where h_{ijs}, $i = \{HPP\}$ – the maximum possible number of utilization hours of the installed capacity of the HPP at the node j during the season s; γ_{js}^{HPP} – a dual estimate that stands for the value of hydropower resources for the HPP of seasonal flow regulation at the jth node during the season s.

$$\sum_{s\in S} \sum_{t\in T} (\tau_s^w x_{ijts}^w + \tau_s^h x_{ijts}^h) \leq h_{ij} X_{ij} | \gamma_j^{HPP} \tag{3.69}$$

$$i = \{HPP\}, \quad j \in J,$$

where $h_{ij}, i = \{HPP\}$, - the maximum possible number of utilization hours of the installed capacity of the HPP at the node j in the target year; γ_j^{HPP}- a dual estimate that stands for the value of hydropower resources for the HPP of annual regulation flow at the jth node.

The constraints given in the right-hand sides of inequalities (3.68) and (3.69) are, respectively, the maximum seasonal and annual volumes of HPPs power generation, which reflect the volume of hydroelectric resources available to HPPs for the corresponding period.

The dual estimates formed by the constraints of the primal CANOE model (being the variables of the dual CANOE model) form an integral dual estimate, which is an indicator of the nodal price of electricity:

$$p_{jts} = \Psi_{jts} + \Theta^{w}_{jts} \cup \Theta^{h}_{jts} + \xi_{jts} + g_{jts} + \gamma^{PSPP}_{js} + \gamma^{HPP}_{js}, \quad j \in J, \; t \in T, \; s \in S. \tag{3.70}$$

The dual estimates derived from the model are long-term estimates that include investment components for the expansion of capacity reserve (Ψ_{jts}), power plants (ξ_{jts}) and lines/cross-border electric connections (g_{jts}), fuel components on working days and days off (Θ^{w}_{jts} and Θ^{h}_{jts}). The values γ^{PSPP}_{js} γ^{HPP}_{js} characterize the value of hydropower resources for PSPPs and HPPs, respectively.

Renewables.

Other renewable energy sources based on solar and wind energy are represented in the model by the installed capacity X_{ij}, $i = \{WPP, SPP\}$, $j \in J$ and actual power x_{ijts}, $i = \{WPP, SPP\}$, $j \in J$, $t \in T$, $s \in S$. The former is optimized independent variables, while the latter depends on the former and is determined in stages. First, it is calculated using the following equations:

$$\begin{aligned} x_{ijts} &= B_{ijts} \cdot X_{ij}, \; i = \{WPP\} \\ x_{ijts} &= C_{ijts} \cdot X_{ij}, \; i = \{SPP\}, \\ & j \in J, \; t \in T, \; s \in S, \end{aligned} \tag{3.71}$$

where B_{ijts}, $i = \{WPP\}$ and C_{ijts}, $i = \{SPP\}$ are sets of constants grouped by daily profiles formed based on available statistical information on the hourly dynamics of wind and solar intensity in the areas covered by the given EPSs/Cross-border power grid (CBPG) translated into power output of WPPs and SPPs as measured in relative units.

The actual power x_{ijts}, $i = \{WPP, SPP\}$, $j \in J$, $t \in T$, $s \in S$ obtained from (3.71) considers the availability of primary renewable energy resources (wind and solar).

To consider technical availability of SPPs and WPPs the obtained actual power should be also checked against the inequality (3.72), which is the right-hand side of the double inequality (3.63):

$$x_{ijts} \le a_{ijs} \cdot X_{ij}, \; i = \{WPP, SPP\}. \tag{3.72}$$

If the inequality (3.72) does not hold, x_{ijts} is assumed to be equal to $a_{ijs} \cdot X_{ij}$, $i = \{WPP, SPP\}$, otherwise x_{ijts} remains the same as was defined in (3.71).

Thus, actual power x_{ijts} takes into account both the availability of renewable energy resources and the technical availability of renewable power plants.

Hourly values of actual power x_{ijts}, $i = \{WPP, SPP\}$, $j \in J$, $t \in T$, $s \in S$ constitute daily profiles of power generation of WPPs and SPPs at the considered nodes for all seasons for optimal variables of installed capacity X_{ij}, $i = \{WPP, SPP\}$, $j \in J$ chosen by the model. Actual power for these types of capacity does not differentiate between for working days and holidays, and x_{ijts} is used to denote both x^{w}_{ijts} and x^{h}_{ijts}.

As pointed out above, renewable energy facilities are non-guaranteed sources of electricity, and they do not participate in the installed capacity balances (3.60). They do not substitute (save) the installed capacity of other power plants. In the meantime, renewables participate in electricity balances (Eqs. (3.61)) integrated for all days and seasons of the target year), saving fossil fuel of TPPs.

It should be noted that renewables are represented in the model as sources with variable but deterministic power output, while in reality, they generate power stochastically. A numerical experiment was conducted with the representation of renewable power generation as a set of values obtained by a random number generator [44]. Obtained in this way, new actual hourly power of renewable energy sources, grouped into daily power profiles for each season, factored in the stochastic generation of these sources. The total daily production of renewable energy sources, represented by random numbers, was assumed to be equal to that of a deterministic generation. The results of the computations showed that when a stochastic profile of renewable energy generation is used instead of a deterministic one, although the operating conditions of other types of power plants changed, the total cost for the power system/interconnection (the optimal value of the objective function) changed only by 0.1–0.2%, i.e., it was within the error range [45]. Therefore, the representation of renewable sources in the model by variable deterministic power output profiles can be considered quite acceptable. Nevertheless, the authors plan to represent renewables in the model in more detail in their future research, particularly with the consideration of their stochastic generation.

The modified CANOE model optimizes the development and operating conditions of each electric power cooperation participant separately, the latter being the country's EPS σ ($\sigma \in \Sigma$) [40–43]. The modified model determines for each national EPS the optimal coverage of its own load, as well as the optimal volumes of electricity output from the EPS (to the cross-border power interconnection) and input (from the cross-border power interconnection) to the EPS for the assumed calculation year.

The objective functions for all participants are the same and are described by the expression (3.73). This expression is a function of costs reduced to the annual dimension. Each member of the cross-border power interconnection minimizes their objective function, trying to reduce its costs of development and operation. The first three summands of the function are similar to those of the basic model (3.59). The fourth summand is the cost of the development of internal backbone networks of the σth member of the transnational power interconnection. The fifth summand is similar to the previous one in its structure and represents the costs borne by the σth member of the transnational interconnection.

$$\Lambda_\sigma = \sum_{j\in J}\sum_{i\in I}\sum_{s\in S}\sum_{t\in T}\tau_s^w c_{\sigma ij}x_{\sigma ijts} + \sum_{j\in J}\sum_{i\in I}\sum_{s\in S}\sum_{t\in T}\tau_s^h c_{\sigma ij}y_{\sigma ijts} +$$

$$+\sum_{j\in J}\sum_{i\in I}k_{\sigma ij}(r+b_{\sigma ij})X_{\sigma ij} + \sum_{j\in J}\sum_{\substack{j'\in J\\ j'\neq j}}k_{\sigma jj'}(r+b_{\sigma jj'})X_{\sigma jj'} + \tag{3.73}$$

$$+\varphi_\sigma \sum_{\sigma\in\Sigma}\sum_{j\in J}\sum_{\substack{\sigma'\in\Sigma\\ \sigma'\neq\sigma}}\sum_{j'\in J}k_{\sigma j\sigma' j'}(r+b_{\sigma j\sigma' j'})X_{\sigma j\sigma' j'} -$$

$$-\sum_{j\in J}\sum_{\substack{\sigma'\in\Sigma\\ \sigma'\neq\sigma}}\sum_{j'\in J}p^e_{\sigma j\sigma' j'}\sum_{s\in S}\sum_{t\in T}(\tau_s^w x^w_{\sigma j\sigma' j'ts} + \tau_s^h x^h_{\sigma j\sigma' j'ts}) +$$

$$+\sum_{j\in J}\sum_{\substack{s'\in S\\ s'\neq s}}\sum_{j'\in J}p^i_{\sigma j\sigma' j'}\sum_{s\in S}\sum_{t\in T}(\tau_s^w x^w_{\sigma j\sigma' j'ts} + \tau_s^h x^h_{\sigma j\sigma' j'ts}) \to min,$$

$$\sum_{\sigma\in\Sigma}\varphi_\sigma = 1,\ \varphi_\sigma > 0,\ \sigma\in\Sigma,$$

where Λ_σ is the costs of expansion and operation of the country's EPS σ taking into account the share of costs in the cross-border electric connection attributable to that country; φ_σ is the share of costs of the cross-border electric connection (measured in relative units), which the country σ bears (determined exogenously, outside the model); $p^e_{\sigma j\sigma' j'}$ and $p^i_{\sigma j\sigma' j'}$ are prices of electricity exported and imported by the country σ and the node j (these endogenous variables of the model).

The last two summands of the objective function (3.73) are new compared to the objective function of the basic model. The fifth summand takes into account the revenues received by the members of the transnational interconnection from electricity exports, and the sixth summand takes into account the costs of electricity imports.

The objective functions (3.73) are optimized by each member of the cross-border power interconnection with consideration of balance and operating conditions constraints on installed and operating capacities, constraints on the development of power plants and electric connections, on operating capacities and flows along lines, on the total annual output of the HPP and PSP for the entire interconnection, presented in the description of the base model of the CANOE.

The single-product equilibrium model of generating capacity expansion considers trade in one commodity, i.e., electricity [41–43]. The model considers a concentrated EPS without power grid infrastructure, which has already been explained above. At the same time, it can be assumed that, in the future, power grids can be developed to the extent that they do not create significant constraints on the transmission of electricity.

Each generating company $l \in L$ in the process of its development and operation maximizes the profit it receives, which is the objective function of the company l:

$$\begin{aligned} &\sum_{i\in I}\sum_{s\in S}\sum_{t\in T}\tau_s^w\,(p-c_{li})\,x_{list}+\sum_{i\in I}\sum_{s\in S}\sum_{t\in T}\tau_s^h\,(p-c_{li})\,y_{list}\\ &\quad - f\sum_{i\in I}k_{li}(z_{li}-z_{li}^0)-\sum_{i\in I}k_{li}b_{li}z_{li}\rightarrow \max\\ &\qquad\qquad l\in L, \end{aligned} \tag{3.74}$$

where p is the optimized variable of the average annual equilibrium price per unit of electricity; f is the financial return ratio; the index l denotes generating companies, the other parameters were explained earlier.

The first two summands of the objective function characterize the total annual fuel costs for the power interconnection. The third one is the cost of new generating capacity additions reduced to the annual dimension using the financial return ratio, and the fourth one is the annual fixed cost of operating generating capacity.

This model sets constraints on the development of installed generating capacity and modes of its use. However, they are not set for the power grid as a whole (as in the basic CANOE model), but rather for each power company $l \in L$. Additional operating conditions limits are set for power plant output during night hours (except for NPPs) and for seasonal output, as well as for the total annual output of TPPs and NPPs. They are required due to the specifics of the model to account for uneven electricity consumption.

It should be noted that capacity reserves are accounted for in the model in part by setting availability coefficients. Accounting for them in a more complete way within a single-product model is not possible. This requires an additional consideration of power trading, which is carried out in the two-product model presented below.

The equilibrium model (in contrast to the optimization models presented above) takes into account the response of electricity consumers to price levels by changing the volume of consumption. The electric power demand function for the model under consideration is represented by the following expression:

$$v\left[\sum_{s\in S}\sum_{t\in T}\tau_s^w\delta_{st}^w+\sum_{s\in S}\sum_{t\in T}\tau_s^h\delta_{st}^h\right]=d-qp, \tag{3.75}$$

where v, $0 \le v \le \hat{v}$ is the variable annual maximum load that takes into account the response of consumers to the price of electricity; $\hat{v} = \underset{s \in S, t \in T}{max} \{w_{st}\}$ is the upper limit on the annual maximum electric load s; $\delta_{st}^{w} = \frac{w_{st}}{\hat{v}}$, $\delta_{st}^{h} = \frac{h_{st}}{\hat{v}}$, $s \in S$, $t \in T$ is hourly loads of consumers for the working day w_{st} and the day off h_{st}, expressed in relative units with respect to the value of $\hat{v}$; p is the equilibrium price of electricity; d and q are coefficients of the demand function.

The operating capacity balance will be written as follows:

$$\begin{aligned} &\sum_{l \in L} \sum_{i \in I} x_{list}^{*}(p) = \delta_{st}^{w} v, \quad s \in S, \quad t \in T, \\ &\sum_{l \in L} \sum_{i \in I} y_{list}^{*}(p) = \delta_{st}^{h} v, \quad s \in S, \quad t \in T. \end{aligned} \tag{3.76}$$

Thus, the model consists of a system of linear programming problems (3.74), constraints on the development and operating conditions of power plants, the balance equations (3.76), and the equilibrium conditions (3.75). The problem to be solved is an inverse linear programming problem: to find the value $p^* \ge 0$ such that the optimal solutions satisfy the relation (3.76) given $p = p^*$. The Cournot method is used to find the equilibrium.

The two-product equilibrium model of generating capacity expansion takes into account electricity and capacity trading [43], so the model additionally includes the capacity price variable p^c. The variable of the electricity price is denoted by p^e. As a result, the objective function of the model is written as:

$$\begin{aligned} &\sum_{i \in I} \sum_{s \in S} \sum_{t \in T} \tau_s^w \left(p^e - C_{li}\right) x_{list} + \sum_{i \in I} \sum_{s \in S} \sum_{t \in T} \tau_s^h \left(p^e - C_{li}\right) y_{list} + \\ &+ \sum_{i \in I} \left(p^c - k_{li} b_{li}\right) z_{li} - f \sum_{i \in I} k_{li} \left(z_{li} - z_{li}^0\right) \to \max, \\ &\qquad l \in L. \end{aligned} \tag{3.77}$$

The two-product model has two demand functions: those for electricity and capacity. They are of the following form:

$$v \left[\sum_{s \in S} \sum_{t \in T} \tau_s^w \delta_{st}^w + \sum_{s \in S} \sum_{t \in T} \tau_s^h \delta_{st}^h \right] = d - q p^e, \tag{3.78}$$

$$1,2v = m - n p^c. \tag{3.79}$$

In the expression (3.79), the left side of the equality represents the capacity demand determined by the equilibrium annual maximum load v, taking into account the standardized value of redundancy.

As a result, the joint behavior of generating companies and consumers under conditions of electricity and capacity trade, in the long run, is modeled by a system of equations consisting of linear programming problems (3.77), balance equations (3.76) and equilibrium conditions (3.78), (3.79), supplemented with operating conditions constraints on generation by different types of power plants, which were mentioned when describing the one-product model. Furthermore, the model sets the constraint on variable costs to be recovered through the sale of electricity, and fixed operating and investment costs - through the sale of capacity. To find the equilibrium, just like with the single-product model, the Cournot method is used.

Thus, in line with the stated conceptual underpinning of the hierarchical expansion planning of the electric power industry, EPSs, and power companies under modern conditions, it is assumed to take into account the technical, economic, organizational aspects/factors, and integration and deregulation trends in the electric power industry. We propose a hierarchical system of mathematical optimization (primal and dual) and equilibrium models as the main tool for expansion planning.

The outlined elements of the hierarchical methodology for expansion planning of the electric power industry, EPS, and power companies implement the above conceptual underpinnings, mainly by taking into account the organizational division of the electric power industry into separate entities and the interests of these entities at different levels of the territorial and technological hierarchy of the electric power industry, including the hierarchical levels of the cross-border power interconnection, EPS/IPS, and power companies. The methodology is formalized as a multi-stage hierarchical methodological framework covering the problems of planning. Among other things, it includes a hierarchical system of successively solved interrelated methodological problems, supplementing those already formed earlier within the framework of the MESI methodology, for the solution of which special methodological statements have been developed.

In the first problem of expansion planning of external electric connections of Russia under conditions of multilateral electric power integration, we perform the maximization of the effectiveness of forming a cross-border power interconnection as a whole with the subsequent division of the integral system effect between all participating countries. This takes into account the interests of the member countries of the cross-border power interconnections and its organizational division into national EPSs. In the second problem that clarifies and complements the first one, the feasibility of each country's entry into the cross-border electric connection/interconnection is evaluated separately, followed by pairwise coordination and justification of the feasibility of electric power integration for both parties. Another problem involves maximizing the efficiency of individual power companies in their development within the EPS and imperfect EPMs.

To solve these methodological problems, in addition to the abovementioned methodological underpinnings, we have developed a hierarchical system of mathematical models. It includes distinctly different yet complementary models, including optimization (primal and dual) and equilibrium models. Combining these models into a single system and their joint application to the study and expansion planning of the electric power industry, EPSs, and power companies, gives a new quality to the results obtained. Thus, this system allows a comprehensive study of the electric power industry with the consideration of technical and economic as well as organizational factors, taking into account the external electric connections of the UES of Russia and the interests of the electric power industry entities, supplementing the research conducted within the framework of the existing MESI methodology of expansion planning of the electric power industry.

As part of the aforementioned system of models, we have developed a model for optimizing the development and operating conditions of the power grid. The model is employed to optimize the power grid as a whole with respect to a single objective function. To divide the total system effect obtained using this model between the countries participating in the interconnection, we use the dual model developed for optimizing the expansion and operating conditions of the EPS and the long-term dual estimates (Lagrange multipliers) obtained with its help are additionally used as part of the purpose-made methodology. We developed a modified model of the expansion and operating conditions of the EPS, which takes into account the organizational division of cross-border power interconnection into EPSs of individual countries, with optimization of their objective functions of efficiency. Single-product (with the trade in one commodity: electricity) and two-product (when the trade is in electricity and capacity) equilibrium models were developed so as to take into account the organizational division of the EPS into energy companies with optimization of the objective functions of the efficiency of each of them.

The study of large-scale expansion of renewables in potential cross-border electric power interconnection in North-East Asia [46]. Electric power integration is a global process that is being implemented through the construction of interstate electric ties and the creation of cross-border/interstate power grids (CBPG) [47]. It is consistent with the global trend of large-scale increase of the share renewable energy sources (RES). These tendencies are also evident in the case of North-East Asia (NEA). Besides, the interstate power grid expansion in the NEA will facilitate the large-scale development of intermittent green generation.

The study aims to research the prospective CBPI and CBPG expansion in North-East Asia with a particular emphasis on the expansion of renewable energy sources and environmental issues. It was assumed that solar and wind energy could be mainly developed in China, Mongolia (Gobitec project) and hydropower, including tidal energy, in Russia.

The study assumed that all countries of NEA (including China, Mongolia, Republic of Korea, Democratic People's Republic of Korea, Japan, and Russia) jointly impose a tax on CO_2 emissions as an economic incentive for the adoption and expansion of renewable energy sources, and other carbon-free (hydro and nuclear power plants) and low-carbon (gas thermal power plants) generating capacities in NEA. The study was conducted for the target year of 2040. The CANOE optimization model described above was used for performing the study.

The research evidenced that the formation of the NEA CBPG itself stimulates the additional growth of renewable and other carbon-free generating capacity (20.1 GW for wind and solar, 23.4 for hydro, and 11 GW for nuclear – the estimates are the difference between high and low values of the ranges given above). Formation of the CBPG accompanied by the introduction of CO_2 emissions tax has a significant impact on the expansion of pumped storage power plants. This results from the fact that the CBPG has a high ability to withstand irregular injection and withdrawal of RESs generation, which decreases the requirements to be met by power systems for storage capacity.

The share of renewable energy sources in the total CBPG installed capacity additions, given the introduction of CO_2 emission tax (in the amount of USD 60 per ton of CO_2), is quite high, being nearly 38% in the case of no interconnection and exceeding 40% in the case of interconnection.

Fig. 3.10 shows the change in capacity additions for all assumed levels of CO_2 emission tax for the scenario of power system interconnection. As seen, capacity additions respond differently to the tax introduction. Hydropower capacity changes steadily and quite moderately from 58.8 GW to 85.6 GW in the entire range of tax emission levels. Renewables react sharply even to a CO_2 emission tax of USD 30/ton. Both solar and wind capacity additions increase by two to three orders of magnitude (from 4.9 GW up to 180.8 GW and from 0.1 GW to 108.9 GW, respectively). Further growth of CO_2 emission tax results in a relatively steady increase in capacity additions of these types of power plants (to 226.9 GW and then to 242.8 GW – solar and to 136.7 and then to 144.3 – wind).

A tax of USD 30/ton affects nuclear expansion virtually in no way (increment of nuclear capacity addition with the tax introduced is just 0.1 GW). Nuclear power responds to the CO_2 emission tax introduction starting with the level of USD 60/ton. In this case, nuclear capacity additions increase by order of magnitude (from 13.6 GW up to 201.7 GW). Further tax rise does not cause an increase in the nuclear capacity because it reaches the upper constraint imposed on nuclear expansion in the model.

Capacity additions of thermal, particularly coal-fired power plants, decrease steadily and substantially with the introduction and further growth of CO_2 emission tax (from 348.4 GW down to 168.9 GW).

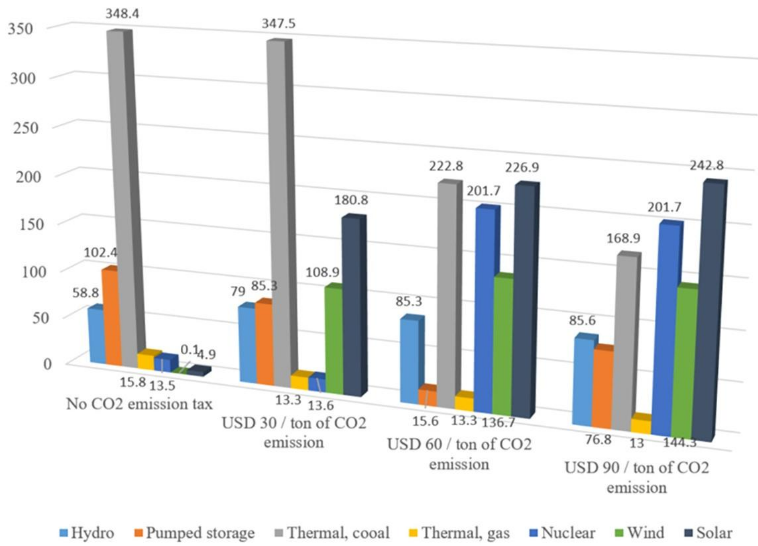


FIGURE 3.10 Capacity additions by type of power plants and level of CO_2 emission tax, the power system interconnection scenario. Source: calculated by the authors.

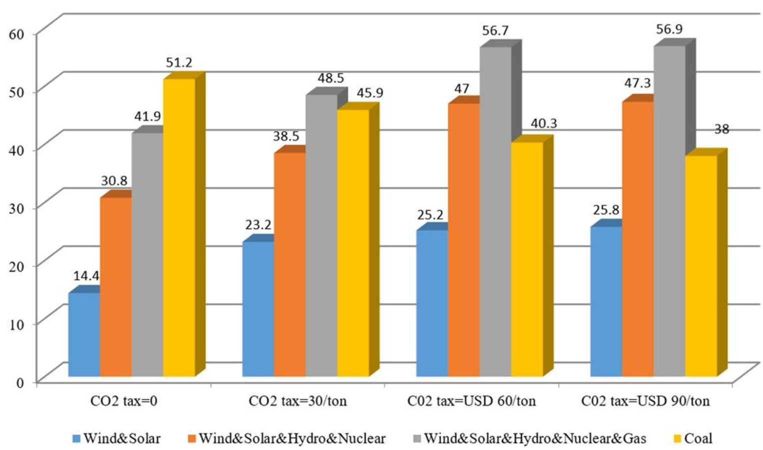


FIGURE 3.11 Shares of new renewables, all carbon-free sources, carbon-free, and low-carbon sources as well as high-carbon coal-fired power plants in the total capacity of the NEA power grid. Source: calculated by the authors.

Fig. 3.11 presents shares of optimal installed generating capacities, including new carbon-free (wind and solar), all carbon-free (wind, solar, hydro, nuclear), carbon-free and low-carbon (wind, solar, hydro, nuclear, gas), and high-carbon (coal) in the total CBPG capacity under all assumed levels of CO_2 emission tax.

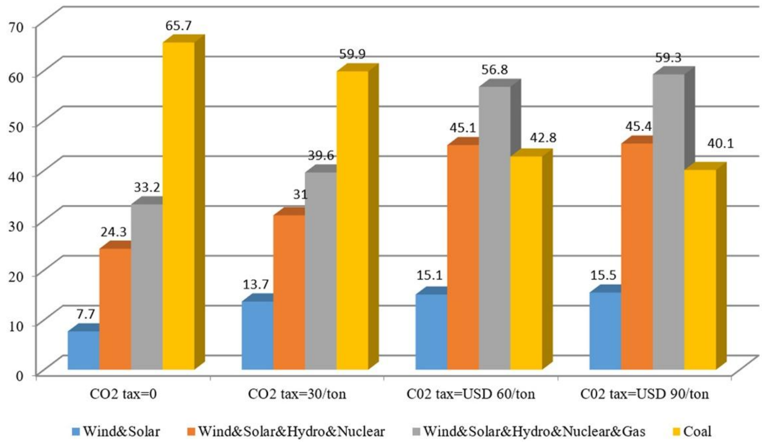


FIGURE 3.12 Shares of new renewables, all carbon-free sources, carbon-free and low-carbon sources as well as high-carbon coal power plants in the total power generation of the NEA power grid. Source: calculated by authors.

With no CO_2 emission tax, high-carbon coal-fired power plants predominate in the NEA CBPG mix, accounting for more than half the total installed capacity. However, even the introduction of USD 30 tax changes the picture. The share of carbon-free and low-carbon capacities exceeds that of coal capacity. With a further increase in the tax up to USD 60, the share of carbon-free capacity alone surpasses the coal capacity share. With a further rise in the tax, the trend toward an increasing role of carbon-free and low-carbon capacity strengthens, and, conversely, the influence of coal capacity weakens.

The introduction of CO_2 emission tax, even in the case of USD 30/ton, enhances renewable capacity considerably. In combination with other carbon-free and low-carbon capacities, they exceed the capacity of thermal coal-fired power plants. As for power generation, as noted above, the situation is different. The contribution of new renewables to the total power generation in NEA interconnection with no CO_2 emission tax is almost twice as less (Fig. 3.12) as their contribution to the total installed capacity (Fig. 3.11). All carbon-free and low-carbon environmentally friendly sources account for about one-third of the total NEA power interconnection generation. The other two-thirds are coal-fired power plants. The situation changes slightly with the introduction of the emission tax of USD 30. When the tax reaches USD 60, carbon-free and low-carbon sources start to predominate, accounting for more than half of power generation. With further growth in the tax to USD 90, their position becomes stronger. Coal-fired plants retain a share of about 40% in power generation (Fig. 3.11) and installed capacity (Fig. 3.12).

3.5 Hierarchical methodology for expansion planning of stand-alone electric power supply systems based on renewables

Introductory remarks. Stand-alone electricity supply systems (ESS) include systems of territories not covered by the centralized electricity supply and remote or separated by water barriers. For example, in the Russian Federation, areas of decentralized electric power supply occupy about 65% of the territory and are located mainly in the northern and northeastern parts of the country. In China, decentralized power supply from stand-alone electric power supply systems is typical for mountainous areas. In Greece, the power supply to the islands comes from stand-alone electricity supply systems. And so on.

The scale of stand-alone ESSs in terms of installed capacity of generation and distribution power grid differs quite significantly. The expansion planning of small stand-alone electric power supply systems presents virtually no methodological difficulties. Significant methodological problems arise when solving problems of the development of large stand-alone electric power supply systems, the distribution electrical networks of which include hundreds or more nodes and connections. Due to the notable specificity of the ESS, it is not possible to directly use the methodology developed for large EPSs at extra-high voltages to plan their expansion In this regard, the development of methodological foundations for the expansion planning of complex stand-alone ESSs is required [48–51, etc.].

This section presents a hierarchical methodology for expansion planning of complex stand-alone ESSs. We adopt the principles of the Benders decomposition method according to which the original complex problem is divided into a master problem and a set of subproblems. The methodological approach is illustrated by the example of the test ESS.

Basic premises. Currently, electric power supply systems are undergoing significant changes [3,4,50]. The increasing use of distributed power generation based on co-generation, as well as the use of renewable energy sources, leads to an increasing role of power distribution grids in supplying electricity to consumers. This radically changes their properties and requires reconsidering the problems of expansion planning and control of operating conditions of the ESS as based on new methodological foundations, reflecting, inter alia, the active participation of the ESS and consumers in the control of operating conditions, which defines the meaning of the concept of the active power supply system [3,4, etc.].

The active nature of the ESS implies the use of automatic means to control the configuration and parameters of the system in order to rationally (optimally) meet the requirements of economic efficiency of normal, repair, post-emergency, and other operating conditions (for example, minimum losses of active power), reliability of power supply to consumers (in terms of reducing power shortage and shortage of electricity to consumers in emergency situations), quality of power supplied to consumers (voltage levels, the presence of harmonics, etc.). Automatic means of controlling the reconfiguration of the power distribution network can be organized on the basis of reclosers. At the same time, one should ensure coordination of interaction between the active ESS and active consumers that have the ability to manage their own electricity consumption matching the pace of the process, using differentiated electricity tariffs or its current price on the electricity spot market.

Given the scale of complex ESSs, it is advisable to use a hierarchical approach to solving the problems of expansion planning of these systems in the form of two successive stages (see Fig. 3.13) [4]:

1. Comprehensive optimization of the structure and parameters of the ESS while taking into account the requirements for its activity, reliability, power quality, and economic performance of the development and operation of the system.
2. Study of operating conditions of the future ESSs based on a detailed analysis of its normal, emergency, post-emergency, and other operating conditions when meeting the increased requirements of consumers to the parameters of the operating conditions, the reliability of electricity supply to consumers, and the electric power quality while taking into account the specific means and measures to ensure the pro-activity of the ESS in the above sense.

It should be noted that the traditional technology of expansion planning of the ESS is limited to the first stage when taking into account the requirements for reliability of power supply, power quality, and efficiency of the system operation by appropriate constraints, reflecting the regulatory requirements established by numerous studies and design experience. The defining features of the current situation are that the digitalization and intellectualization of production processes at industrial consumers, in transport, services, households, etc., the dissemination of "fine" production technologies, increase drastically the requirements for the reliability of power supply and power quality. Relevant standards have not yet been developed, but even in the case of their appearance, the stage of the study of the conditions of operation of future ESSs should remain, given the tightening of consumer requirements, and the fact that the standardized values are akin to meaningless averages, and they cannot be worked out for all possible situations.

From the perspective of the problem in question, we are interested in what pro-active means and measures can be employed to achieve meeting the requirements for the reliability of electricity supply to consumers and the electric power quality while taking into account the economic feasibility of the ESS operation. Consequently, studies of the operating conditions

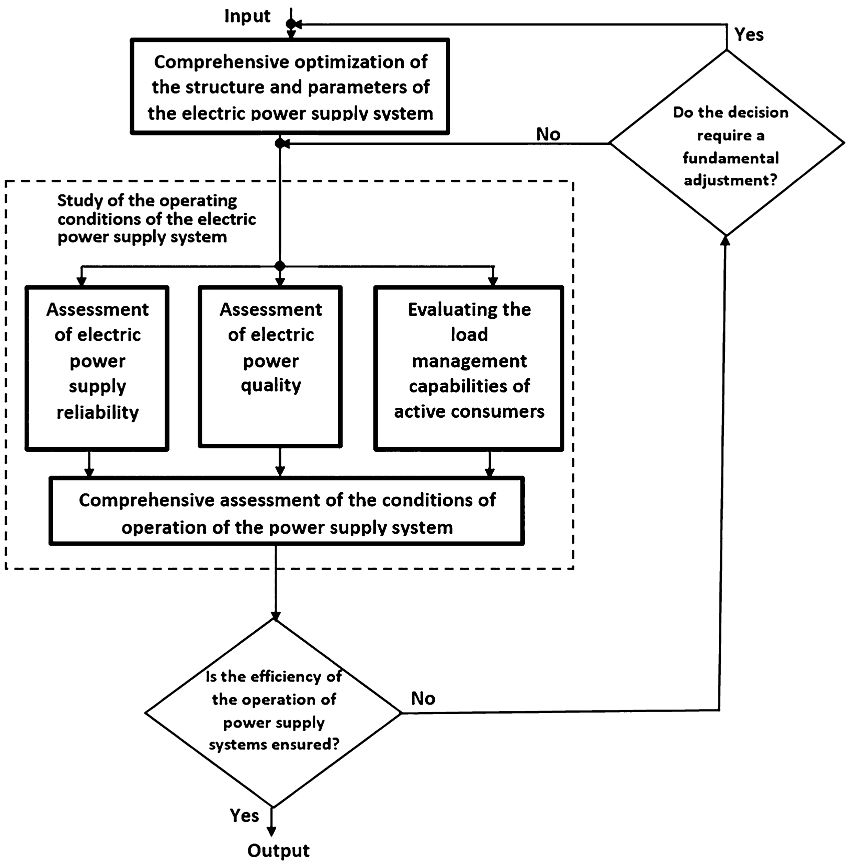


FIGURE 3.13 General scheme of expansion planning of active electric power supply systems.

of the future ESS at the second stage (see Fig. 3.13) include not only the assessment of reliability, quality, and efficiency metrics but also the selection of locations for the installation of reclosers, reactive and active power sources, including energy storage units and other devices to ensure the required voltage and frequency levels and meet other requirements for reliability, quality, and efficiency.

Fig. 3.13 shows that if the study of operating conditions in the presented form does not attest to the efficiency of the ESS operation, there is a return to the first stage and the adjustment of decisions on the development of the ESS.

An important point in the study of the problem of expansion planning of a stand-alone ESS is the timeframe assumed for its analysis. It seems appropriate in most cases to take a time period of 10 years for the following reasons. Consumers with a fairly short load projection horizon usually prevail in such ESSs. At the same time, many consumers, being raw materials extraction enterprises, have limitations on the time of their operations in terms of depletion of the field, changes in prices of raw materials, etc. There is also a tendency to build mobile modular mining and processing plants that can quickly increase or decrease their capacity in the event of changes in market conditions. Furthermore, the payback period of such production facilities is usually less than 10 years.

In view of the above circumstances, due to the possible significant variability of electricity consumption by such consumers from year to year, it is necessary to consider the development of the isolated ESS diachronically while taking into account the output/input of facilities with changes in load from year to year.

The considered features of the process of expansion planning of a standalone ESS are considered further in the formalization of the problem.

Formalizing the problem. The scheme of using the principles of the Benders decomposition method is shown in Fig. 3.14. As a master problem, in contrast to the generally accepted approach [6,7, etc.], we consider its interrelated components: optimization of generating capacity, including electric power storage, and optimization of the power grid.

Taking into account the above considerations in accordance with the principles of the Benders decomposition method [6,7], in its general form the problem in question is stated as a linear mixed-integer programming problem, namely:

$$\begin{gathered} (c^T x + d^T y) \rightarrow \min, \\ Ay \geq b, \\ Ex + Fy \geq h\ , \\ x \geq 0,\ \ y \in S\ , \end{gathered} \tag{3.80}$$

where $d^T y$ is the capital expenditures of commissioning new generating sources and new power lines of the distribution network and dismantling the decommissioned ones, commissioning of electricity storage units; y is a vector of integer variables corresponding to commissioning and dismantling of generating units and lines, commissioning of electricity storage units; $c^T x$ is current costs of fuel for power plants, maintenance and repairs of equipment, etc.; x is a vector of continuous variables corresponding to costs of fuel of power plants, maintenance and repairs of equipment, etc.; $Ay \geq b$ is a matrix equation of the balance of generated and consumed power of the PSS; $Ex + Fy \geq h$ is constraints on the loading of generating units in accordance with the load profile; $x \geq 0$, $y \in S$ is domains of continuous and integer variables.

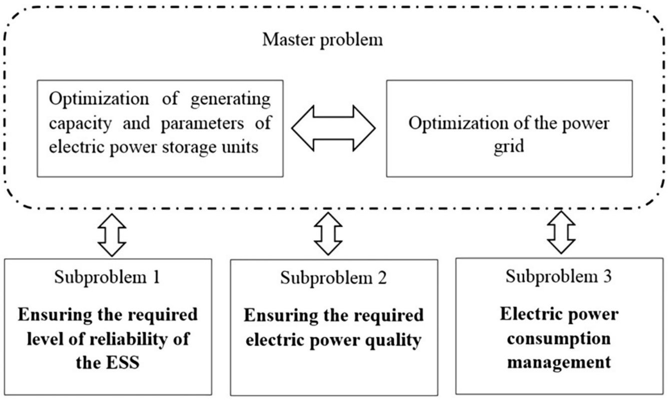


FIGURE 3.14 Schematic diagram of using the ideology of the Benders decomposition method.

If the integer values of y are fixed, then (3.80) is a linear programming problem with respect to x. Consequently, (3.80) can be written in the form

$$\left\{d^T y \,|\, Ay \geq b\right\} + \left\{c^T x \middle| (Ex \geq h - Fy),\ x > 0\right\} \to \min, \tag{3.81}$$

where $R = \{y|\ exists\ x \geq 0\ such\ that\ Ex \geq h - Fy,\ Ay \geq b,\ y \in S\}$.

The original problem can be broken down into a master problem and subproblems (see Fig. 3.14). According to [6,7] the master problem can be written as

$$\begin{gathered} Z^T_{lower} \to \min, \\ Z^T_{lower} \geq d^T y, \\ Ay \geq b, \\ y \in S, \end{gathered} \tag{3.82}$$

where $Z = c^T x + d^T y$; the *lower* index indicates the lower cutoff boundary according to the Benders algorithm.

The primal and dual subproblems are as follows:

$$\begin{gathered} c^T x \to \min\ , \\ Ex \geq b - F\hat{y}\ , \\ x \geq 0 \end{gathered} \tag{3.83}$$

$$\begin{gathered} (b - F\hat{y})^T u \to \min, \\ E^T u \leq c, \\ u \geq 0. \end{gathered} \tag{3.84}$$

In (3.83) and (3.84), $\hat{y}$ is the solution to the master problem; u is the solution to the dual subproblem.

To solve the problem in question, we employed the detailed algorithm presented in [51] for implementing the Benders decomposition method using formalization of the master problem and primal and dual subproblems, which gives the desired solution after several iterations.

A demonstration example. We consider the problem of expansion planning of a stand-alone active ESS of a mining and processing plant. We state the interrelated master problems of selecting the mix of generating units and electric power storage units, as well as the optimization of the active electric power grid. We have stated the subproblems of assessing and selecting means of ensuring the reliability of power supply to consumers using network reconfiguration, electric power quality, and consumer activity. In determining the generating capacity and parameters of electric power storage units, it is assumed that the storage units are charged only from sources based on renewable energy resources and that electric power generated as based on renewable energy resources has priority in covering the load profile. The stochastic nature of the power output of renewable energy sources (wind turbines and solar plants) is compensated by electricity storage units.

In the first iteration of solving the problem by implementing the generation optimization master problem, the following generating units and electric power storage units were identified:

- wind power units - 15 MW;
- solar power plants - 6 MW;
- diesel power plants - 24 MW;
- electric power storage units with a total capacity of 7 MW and a duration of operation of 5.5 hours.

Solving the master problem of selecting the electrical distribution network made it possible to determine the configuration and parameters of this network.

Further, we have solved the subproblems of assessing the reliability of electricity supply to consumers and the use of reconfiguration of the power grid to improve reliability, of determining the electric power quality, and of using the quality monitoring system for timely implementation of measures to ensure the necessary levels of electric power quality, as well as that of assessing the capacity of active consumers to equalize the daily load profile of the ESS.

As a result of solving the subproblem of optimizing the daily load profile of the active stand-alone ESS, the maximum total peak load capacity of consumers was 26.5 MW compared to the initial value of 31.98 MW (see Fig. 3.15).

In this regard, it became necessary to return to the master problems and adjust the capacity of generating units and parameters of electric power

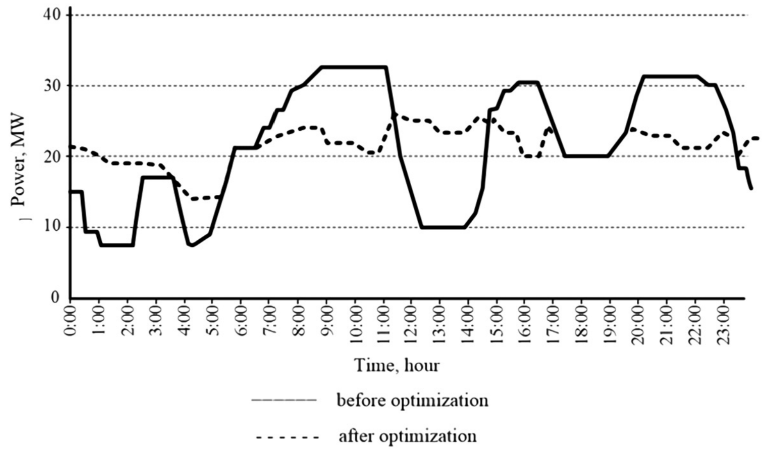


FIGURE 3.15 Generalized daily profile of active power of consumers of the electric power supply system before and after optimization.

storage facilities. Adjustments to the electrical network, as shown by the implementation of the network master problem, were not necessary. The subproblems of assessing and ensuring the reliability of electric power supply and power quality were also solved for the second time; the results of the solution showed the acceptability of the measures obtained in the first iteration of activities.

Taking into account the requirements for generation redundancy as well as the conditions for the use of renewable energy plants assumed initially, the optimal solution for the mix of the generating capacity would be as follows:

- diesel power plants - 18 MW;
- solar power plants - 6 MW;
- wind power plants - 15 MW;
- electricity storage facilities - 7 MW with a duration of operation of 5.5 hours.

Conclusions

The tasks of optimizing the prospective structure of generating capacities and developing the main electrical network are complex in mathematical terms and time-consuming in the process of solving. This is determined by the large dimension of the problem due to the significant number of described objects of the electric power industry and the need to take into account many different factors and conditions that determine the functioning of the designed electric power system. Also important is the ambiguity of the scenarios for the economic development of the regions under consideration, the presence of various ‘disturbances’ (social, economic, etc.) at different time intervals, as well as the development of scientific and technological progress, which determines the change in technologies for the production, transmission, and consumption of electricity (the appearance and active influence on the development of electric power systems of renewable energy sources, active consumers, increasing the flexibility of production capacities, etc.). Nevertheless, the existing set of mathematical models and research methods presented in this chapter makes it possible to predict with sufficient accuracy the development of electric power systems for a long-term period, based on various scenarios.

We propose an improved concept of feasibility of options for the expansion of the electric power industry in today’s context. It incorporates engineering, economic, organizational aspects/factors (with their subsequent detailed elaboration) and takes into account the main trends in the electric power industry in Russia and worldwide, such as integration, deregulation, and large-scale development of renewable energy sources. On the basis of this concept we develop a methodology that reifies the concept. Furthermore, we propose to use a system of optimization (primal and dual) and equilibrium mathematical models as the basic tool for arguing the feasibility of expansion planning options.

The set of tools developed by the authors was used to conduct optimization studies of the large-scale introduction of renewable energy sources into a potential cross-border power grid in Northeast Asia. Our studies attested to the possibility and feasibility of developing renewable energy sources to reduce greenhouse gas emissions within the above power system interconnection. A tax on CO_2 emissions served as an incentive mechanism for the introduction of renewable energy sources. The formation of the cross-border power grid also acts as a catalyst to stimulate the introduction of RES.

Acknowledgments

The research was carried out under State Assignment Project (no. FWEU-2021-0001) of the Fundamental Research Program of Russian Federation 2021-2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] R.N. Berdnikov, V.V. Bushuev, S.N. Vasiliev, N.I. Voropai, et al., in: V.E. Fortov, A.A. Makarov (Eds.), The Concept of the Intelligent Electric Power System of Russia with an Active and Adaptive Grid, Federal Grid Company of Unified Energy System JSC, Moscow, 2012, p. 219 (in Russian).

[2] M. Lu, Z.Y. Dong, T.K. Saha, A framework for transmission planning in a competitive electricity market, in: 2005 IEEE/PES Transmission and Distribution Conference and Expo: Asia and Pacific, Dalian, China, August 14–18, 2005, pp. 14–18, 6 p.

[3] J. McDonald, Adaptive intelligent power systems: active distribution networks, Energy Policy 36 (6) (2008) 89–99.

[4] N.I. Voropai, K.V. Suslov, Problems of expansion planning of active electric power supply systems, Promyshlennaya Energetika 1 (2018) 2–6 (in Russian).

[5] M. Shahidehpour, Yong Fu, Benders Decomposition in Restructured Power Systems, Tutorial, IEEE Press, New York, 2000, p. 55.

[6] A. Khodaei, S. Bahramirad, M. Shahidehpour, Microgrid planning under uncertainty, IEEE Transactions on Power Systems 10 (3) (2014) 362–371.

[7] M. Moradijoz, M.P. Moghaddam, M.-R. Haghifam, A flexible distribution system expansion planning model: a dynamic bi-level approach, IEEE Transactions on Smart Grid 9 (6) (2018) 5867–5877.

[8] N.I. Voropai, S.V. Podkovalnikov, V.V. Trufanov, et al., in: N.I. Voropai (Ed.), Expansion Planning of Electric Power Systems: Methodology, Models, Methods, and Their Application, Nauka, Novosibirsk, 2015, 448 p. (in Russian).

[9] N.I. Voropai, Multi-criteria decision making problems in hierarchical technology of electric power system expansion planning, in: Intelligent Computing and Optimization, Springer, Cham, Switzerland, 2019, pp. 362–368.

[10] N.I. Voropai, E. Yu, Ivanova methods for expansion planning of electric power systems and companies in the market economy environment, Izvestiya RAN, Energetika 3 (2006) 28–36 (in Russian).

[11] G. Owen, Game Theory, W.B. Sounders Comp., London, etc., 1968, p. 322.

[12] N.I. Voropai, E.Yu. Ivanova, Planning the expansion of electric power companies in the environment with divergent interests of the entities of relations, Izvestiya RAN, Energetika 6 (2006) 39–51 (in Russian).

[13] H. Moulin, Cooperative Decision-Making. Systems and Models, Mir, Moscow, 1991, p. 164 (in Russian).

[14] F.F. Wu, J. Contreras, Coalition formation in transmission expansion planning, IEEE Transactions on Power Systems 14 (3) (1999) 1144–1151.

[15] J. Von Neumann, O. Morgenstern, Theory of Games and Economic Behavior, Nauka, Moscow, 1970, p. 294 (in Russian).

[16] P. Fishburn, Utility Theory for Decision Making, Nauka, Moscow, 1978, p. 224 (in Russian).

[17] L.S. Belyaev, G.V. Voytsekhovskaya, V.A. Saveliev, et al., Systems Approach in Managing the Development of the Electric Power Industry, Nauka, Novosibirsk, 1980, p. 238 (in Russian).

[18] N.I. Voropai, V.V. Trufanov, Mathematical modeling of electric power systems development under current conditions, Elektrichestvo 10 (2000) 6–12 (in Russian).

[19] V.A. Khanaev, V.V. Trufanov, A.M. Trishechkin, Automation of system studies of the development of the Unified power system of the USSR, Elektronnoe Modelirovanie 8 (6) (1986) 59–64 (in Russian).

[20] G.M. Arbatsky, L.S. Belyaev, V.R. Takaishvili, et al., Software-and-information package for optimizing the structure of the Unified power systems, in: The Issues of Building the Automated Information Control System of the Development of the EPS. Issue 2. Structure and Principles of Stage I of Building the Automated Information Control System, MESI of the USSR, Irkutsk, 1975, pp. 67–95 (in Russian).

[21] V.A. Khanaev, Ways to Increase the Maneuverability of the Unified Power System of the USSR, Nauka, Novosibirsk, 1991, p. 136 (in Russian).

[22] V.V. Bushuev, N.I. Voropai, A.M. Mastepanov, et al., Energy Security of Russia, Nauka, Novosibirsk, 1998, p. 302 (in Russian).

[23] N.I. Voropai, E.Yu. Ivanova, V.V. Trufanov, The method of multi-criteria decision analysis for solving the problems of analysis of EPS development options, Izvestiya RAN, Energetika 6 (1998) 32–38 (in Russian).

[24] N.I. Voropai, V.V. Trufanov, V.V. Selifanov, G.I. Sheveleva, Toward an analysis of the efficiency of the Unified Power System of Russia, Elektrichestvo 5 (2000) 2–9 (in Russian).

[25] V.V. Khanaev, On comprehensive optimization of development of the electric power system and energy consumers, Energy systems studies, Contributions by the young scientists MESI, in: Energy Systems Studies, Contributions by the Young Scientists MESI, Iss. 29, Irkutsk, 1999, pp. 66–73 (in Russian).

[26] R.N. Holt, Fundamentals of Financial Management, Delo, Moscow, 1993, p. 128 (in Russian).

[27] Z. Bodie, R. Merton, Finance: Translated from the English Williams Publishing House, Moscow, 2004, p. 592 (in Russian).

[28] S.K. Dubinin, P.V. Goryunov (Eds.), Methodological Recommendations on Valuation and Development of Investment Projects and Business Plans in the Electric Power Industry at the Pre-Feasibility and Feasibility Study Stage (with Typical Examples), OAO RAO “UES of Russia”, OAO Scientific Centre of Applied Research, State University of Management, Moscow, 2008, p. 181.

[29] G.I. Sheveleva, Financial and economic model of an electric power company, Vestnik IrGTU 10 (2014) 265–269 (in Russian).

[30] V.I. Danilin, Operational and Financial Planning in the Corporation (Methods and Models), Nauka, Moscow, 2006, p. 334 (in Russian).

[31] M.V. Lychagin, N.B. Mironosetsky, Modeling the Financial Activity of an Enterprise, Nauka, Novosibirsk, 1986, p. 295 (in Russian).

[32] V.V. Titov, Optimization of the Operation of an Industrial Enterprise: Issues of Methodology and Modeling, Nauka, Novosibirsk, 1987, p. 250 (in Russian).

[33] V.V. Titov, V.D. Markova (Eds.), Improvement of Institutional Mechanisms of Governance in Industrial Corporations: a Collection of Scientific and Engineering Contributions, Novosibirsk, 2013, p. 352 (in Russian).

[34] G.I. Sheveleva, Corporate governance and investment appeal of electric power companies, Vestnik IrGTU 7 (2013) 225–229 (in Russian).

[35] S.V. Podkovalnikov, Improving the methodology of expansion planning of the electric power industry in Russia under integration and deregulation, Habilitation thesis submitted for the degree of D.Sc. in Engineering Sciences: 05.14.01, Irkutsk, 2020, p. 292 (in Russian).

[36] E.P. Volkov, V.A. Barinov, A.S. Manevich, Planning Methodology and Prospects for the Expansion of Russia’s Electric Power Industry, Energoatomizdat, Moscow, 2010, p. 556 (in Russian).

[37] L.S. Belyaev, S.V. Podkovalnikov, V.A. Savelyev, L.Yu. Chudinova, Efficiency of Cross-Border Electric Connections, Nauka, Novosibirsk, 2008, p. 239 (in Russian).

[38] S.V. Podkovalnikov, V.A. Savelyev, O.V. Khamisov, L.Yu. Chudinova, Justification of the feasibility of cross-border power interconnections with the sharing of effects between the participants, Avtomatika i Telemekhanika 10 (2018) 26–38 (in Russian).

[39] X.-P. Zhang, Restructured Electric Power Systems. Analysis of Electricity Markets with Equilibrium Models, Wiley-IEEE Press, 2010, p. 307.

[40] P.V. Kostenko, S.V. Podkovalnikov, O.V. Khamisov, Modeling and study of the development of cross-border electricity markets in Northeast Asia, Izvestiya RAN, Energetika 3 (2006) 146–153 (in Russian).

[41] S.V. Podkovalnikov, O.V. Khamisov, Imperfect electric power markets: modeling and study of generating capacity development, Izvestiya RAN, Energetika 2 (2011) 66–86.

[42] S. Podkovalnikov, L. Chudinova, I.L. Trofimov, L. Trofimov, Structural and operating features of the creation of an interstate electric power interconnection in North-East Asia with large-scale penetration of renewables, Energies 15 (10) (2022) 3647, https://doi.org/10.3390/en15103647.

[43] S.V. Podkovalnikov, K.A. Semyonov, O.V. Khamisov, Development of generating capacities under different organizational structures of electric power markets, Izvestiya RAN, Energetika 4 (2014) 3–14 (in Russian).

[44] I.L. Trofimov, L.N. Trofimov, S.V. Podkovalnikov, L.Y. Chudinova, L.S. Belyaev, V.A. Savel'ev, The computing and information system for research of prospective electric power grids expansion, Yugoslav Journal of Operations Research 29 (2019) 465–481, https://doi.org/10.2298/YJOR181115021T.

[45] L.N. Trofimov, I.L. Trofimov, The assessment of integration effects accounting the stochasticity of wind and solar power plants generation in the Asian Power Grid, E3S Web of Conferences 139 (2019) 3–7, https://doi.org/10.1051/e3sconf/201913901068.

[46] S. Podkovalnikov, L. Chudinova, I. Trofimov, L. Trofimov, Structural and operating features of the creation of an interstate electric power interconnection in North-East Asia with large-scale penetration of renewables, Energies 15 (10) (2022) 3647, https://doi.org/10.3390/en15103647.

[47] N. Voropai, S. Podkovalnikov, L. Chudinova, The evolution of interstate power grid formation, Global Energy Interconnection 4 (4) (2021) 335–353, https://doi.org/10.1016/j.gloei.2021.09.008.

[48] G. Gelli, E. Giani, G.G. Soma, F. Pilo, Planning of reliable active distribution systems, CIGRE 2012 Session, Paris, France, August 26–30, 2012, p. 7.

[49] P.S. Georgilakis, N.D. Hatziargyriou, A review of power distribution planning in the modern power systems era: models, methods and future research, Electric Power Systems Research 21 (2) (2015) 501–510.

[50] N.I. Voropai, Electric power system transformations. A review of main prospects and challenges, Energies 13 (2020) 5639, p. 15, https://doi.org/10.3390/en13215639.

[51] C.A.G. MacRae, A.T. Ernst, M. Ozlen, Benders decomposition approach to transmission expansion planning considering energy storage, Energy 112 (2016) 795–803.

This page intentionally left blank

CHAPTER

4

Hierarchical modeling principles for operation and control of electric power systems

N.I. Voropai[†], *A.V. Domyshev*, *D.N. Efimov*, *I.N. Kolosok*, *E.S. Korkina*, *V.G. Kurbatsky*, *A.B. Osak*, *D.A. Panasetsky*, *N.V. Tomin*, *V.A. Shakirov*, *D.N. Sidorov*, *A.N. Kozlov*, *and E.V. Popova*

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

4.1 Introduction

Problems related to the study of electric power systems (EPS) operating conditions and their control in normal, emergency, post-emergency, repair, and other situations are of great variety and considerable complexity. In this regard, the issues to be faced are determined by key features of the problems to solve within the investigated time frame as related to the need for detailed consideration of the structure of EPSs in question, their states and processes occurring in them at different levels of territorial, temporal, and situational hierarchies of the problems of analyzing the system states, monitoring its operating conditions, and development of supervisory and automatic control actions. Given these circumstances, it is quite relevant to consider the ideology of hierarchical modeling as a methodological basis for solving the problems of research and monitoring of the operating conditions of EPSs and control over their operating conditions.

[†]Deceased.

Hierarchical Modeling of Energy Systems
https://doi.org/10.1016/B978-0-44-313917-8.00013-4

This chapter presents the results of the application of hierarchical modeling to solving some problems (that are typical in a certain sense) of analysis and optimization of operating conditions of electric power systems and control over operating conditions of these systems. At the same time, the hierarchical ideology of modeling complex EPSs is used not only to solve hierarchically presented sets of problems but also as a means of effective formalization of some labor-intensive problems in order to accelerate the process of solving them given the huge variety of conditions that require consideration.

4.2 Hierarchical control of electric power systems operation

Hierarchical problems of investigating and controlling electric power operation conditions have a rich history and go back to the works of G. Kron [1,2], V.A. Venikov, and O.A. Sukhanov [3,4]. The methods developed by the above authors provide for a preliminary division (decomposition) of the original model of the EPS into subsystems. Solving the problem is first performed independently for individual subsystems. This solution is then supplemented by adjustment procedures, taking into account the links between subsystems. The iterative process for these two successive steps results in the desired solution for the system as a whole.

In the G. Kron's diakoptics method, the solutions obtained at the first step for subsystems are used to determine the parameters of equivalents representing subsystems in a chain of intersections, which includes branches connecting subsystems. Then, using the calculation of the operating conditions in the chain of intersections, the operating conditions at the boundaries of the subsystems are determined. The last step is to calculate the components in terms of the currents (or voltages) of the subsystems that are to be determined as caused by the action of energy sources in other subsystems.

The development of this approach in the works of V.A. Venikov and O.A. Sukhanov was the introduction of the so-called functional characteristics of subsystems, which allows us to generalize the considered approach to the nonlinear problems of calculation and optimization of operating conditions, EPS state estimation, and studies of transients in the EPS [4,5].

It should be noted that the hierarchical approach to solving the problems of supervisory and automatic emergency control was adopted for the Unified Energy System (UES) of the USSR back in the early 1960s. In general, the hierarchical ideology of control of normal and emergency operating conditions of the UES of the USSR was formed by the 1980s [6,7, etc.] and with minor adjustments has been preserved since the 1990s [8] to the present [9], having proved its effectiveness under conditions of a large electric power interconnection. The main tenets of this ideology are as follows.

The system of supervisory control of the operating conditions of the UES of Russia, its constituent integrated and regional EPSs, and stand-alone EPSs includes a nomenclature of problems of temporal and territorial control hierarchies. Temporal hierarchy of problems considers problems of long-term operating conditions planning (ranging from a month to a year, and, in the case of HPPs with multi-year watercourse control, to several years), short-term operating conditions planning (ranging from a day to a week), operational (within a day) and automatic (matching the pace of the process) operating conditions control. The territorial hierarchy of supervisory control problems for the UES of Russia subsumes three levels: the level of the power interconnection as a whole, the cross-regional, and regional levels. The basic principle of interaction between different levels of both temporal and territorial hierarchies of supervisory control of the operating conditions is the principle of subordination of control problems of the lower level in relation to the upper level: when solving control problems at the lower level, the results of solving problems of the upper level of the hierarchy are to be taken into account.

The automatic emergency control system for the prevention of instability of the UES of Russia and stand-alone EPSs has a pronounced hierarchical structure [9,10, etc.]. The lower level of this system consists of devices of emergency automatics, which implement control actions to ensure the stability of the EPS. The middle level coordinates the actions of the lower-level devices using fairly simple algorithms for calculating the current operating conditions. The upper level solves the problems of coordination of the middle-level subsystems, with the use of sufficiently detailed models of the operating conditions of the EPS.

Decades of use of the hierarchical ideology of supervisory and automatic emergency control of operating conditions of the UES and stand-alone EPSs in Russia have proven its effectiveness.

Recently, a number of studies on solving conventional and new problems of control of operating conditions of large EPSs on the basis of the hierarchical approach have been carried out. Each of such statements of control problems is based on the corresponding hierarchy of EPS models and the control system under consideration. Let us briefly review the developments made in this direction.

In [11], the authors state the problem of optimizing the load flow in a large AC power grid using a modified Benders decomposition algorithm. The master problem is the optimization of the number and composition of subsystems from the standpoint of minimizing the time to solve the problem as a whole given parallel optimization of the load flow in subsystems, which represents a set of subproblems in the Benders method. The optimization criterion in each subsystem (subproblem) is a minimum of active power losses, and the solution is sought by the method of internal points.

The study [12] considers a hierarchical approach using the Benders decomposition method when solving the problem of restoration of consumer power supply to ensure the resilience of the EPS, which means the ability of the system to resist disturbances, "absorb" their consequences for the EPS and consumers and quickly restore the normal operating conditions or the ones close to it. The information base of the problem is provided by the synchrophasor technology. Optimization of the volume and placement of the restorable load is considered as a master problem. As a subproblem, the authors state an assessment of the reliability of the AC power grid at each recovery step while ensuring the balance of generation and consumption capacities, taking into account the network constraints and, if necessary, adjusting the operating conditions so as to make them fall within the admissible range. The subproblem is started if the specified constraints on operating conditions parameters are not met.

Recently, the hierarchical approach to the study of the operating conditions of the EPS and their control based on the system of systems concept has been quite common [13–16, etc.]. This concept reflects the real situation of two-level interaction of the type "microgrid - distribution company (DISCO) [13,15], "DISCO - independent system operator (ISO)" [14], "microgrid - multiple microgrids" [16] through the appropriate two-level operating conditions control system.

The direction of hierarchical decentralized control of EPS operating conditions that makes use of multi-agent technology is also undergoing development [17–19, etc.]. The study [17] gives a conceptual view of the architecture of operating conditions control of multiple microgrids using its hierarchical multi-agent representation. Three levels of control are introduced. At the lower level, local control actions are implemented. The middle level is represented by the control systems of each of the microsystems. The upper level deals exclusively with managing the interaction of microsystems to ensure acceptable normal and stable emergency operating conditions of the entire set of microsystems. The presented concept is to a large extent similar to the hierarchical system of emergency control of the UES of Russia, the main underpinnings of which are outlined above. In [18], the authors consider a hierarchical multi-agent approach to the analysis of operating conditions reliability of the EPS as a cyber-physical system based on calculations of its dynamic stability under cyber attacks. Each agent (the upper level of the hierarchy) represents a group of coherent oscillators (the lower level of the hierarchy), the coherence of motion of oscillators is evaluated by methods of modal analysis. To reduce communication, the interaction between agents is implemented through a dedicated protocol. The study [19] presents a hierarchical three-level multi-agent technology for decentralized control to ensure the stability of the EPS with respect to angles and voltages. At the lower level, the groups of coherent oscillators of the system are determined by methods of modal analysis. The middle level is represented by the problem of ensuring the stability of the EPS with respect to angles as applied to oscillations between coherent groups of generators, which is solved using the method of Lyapunov functions, with FACTS devices being considered as control means. At the upper level, the same means are used to dampen voltage fluctuation and to avoid situations with loss of voltage stability as achieved by the action of an appropriate multi-agent control subsystem.

In [20], the authors consider a hierarchical and distributed stochastic system for analyzing and controlling the operating conditions of an electric distribution network with a large share of electric energy storage. The lower level solves the stochastic problem of controlling individual storage facilities to minimize costs based on a Markov decision-making process. At the upper level, the optimal operating conditions of the distribution network are determined by the minimum of losses, taking into account the constraints on the voltage levels at the nodes. In [21], the authors present a four-level strategy for supervisory control of active load flow in the EPS with a predictive model when integrating a cluster of wind turbines (wind farm) into the system (daily and current supervisory control, cluster optimization, wind farm management). In [22], a fully distributed hierarchical control methodology for coordinating the operation of renewable energy sources in an active electrical distribution network is outlined. Four levels are considered: automatic power control of generating units, primary and secondary frequency control, and supervisory optimization of the operating conditions of the system. The coordination of the control of individual renewable energy plants is done using an infinite-time discrete consensus algorithm. The study [23] discusses a strategy for bilevel optimization of the distribution of various types of energy by energy hubs, the totality of which forms the Internet of Energy: the lower level represents the optimal supervisory control in each energy hub for individual energy resource flows; the upper level coordinates the optimal load flow between hubs.

A review article [24] gives a comprehensive view of the hierarchical control of DC microsystems. Hierarchical control of microsystems is considered at three levels: primary control (load distribution between distributed generation units in accordance with their load characteristics); secondary control (control of voltage levels and control of microsystem synchronization with external EPSs); tertiary control (load distribution between distributed generation units, on the one hand, and the external EPS, on the other); control of microsystem operating conditions in coordination with the distribution electrical network system operator. Approaches to solving problems of the primary and secondary levels of control are discussed in detail, with the analysis of centralized, decentralized, and mixed control configurations as applied at the secondary level.

The study [25] presents the results of testing the existing micro-system of the Illinois Institute of Technology, USA, and considers the problems of cost-effective operation of the microsystem given its joint operation with the external EPS, isolation of the micro-system for stand-alone operation, restoration of joint operation of the microsystem with the external EPS. To solve these problems, hierarchical control principles are proposed and investigated. The study [26] investigates the problem of calculating the probabilistic load flow and analyzing its variants by the method of hierarchical adaptive polynomial chaos.

The above concise review gives an idea of the directions and findings of research on the use of the hierarchical methodology for solving various problems of controlling the operating conditions of the EPS.

4.3 Hierarchical modeling in state estimation of electric power systems

Introductory remarks. The ongoing processes of integration of EPSs into large power interconnections and the creation of international electric power markets lead to the need to develop and improve algorithms and information-and-computing technologies used to solve problems of calculation, planning, and management of electric power operating conditions.

Management of such large synchronously operating power connections, such as the UES of Russia, can only be carried out using a computational information model of the system. Further in this section, when required, the UES of Russia will serve as an illustration of the fundamental considerations behind the formation of a computational information model of a complex EPS (using state estimation methods) that are otherwise generic in their meaning.

In order to solve the problems of managing the electric power system in Russia, a multi-level hierarchical system of operational supervisory control has been created, including the following: System Operator of the Unified Energy System (SO UES); seven territorial integrated supervisory control offices, branches of SO UES; in each of the seven energy systems - regional supervisory control offices in each region; control points of power plants and electric grid companies, repair crews.

The effective hierarchical system of supervisory and automatic control of the UES of Russia operating conditions, which has been established by now, is provided with detailed current measurement information received from traditional measuring instruments and measuring tools of SCADA (Supervisory Control and Data Acquisition) systems and WAMS (Wide-Area Measurement System) phasor measurement units (PMU).

Based on the data obtained, a unified computational model of the UES/ES is formed, which includes several thousand nodes, more than 10,000 branches, and most fully reflects the topology and operating conditions of the UES. One of the priority activities of the SO UES is the creation of a hierarchical system for the formation of operating conditions of the UES of Russia, in which the problem of state estimation of the EPS has an important place [27].

State estimation (SE) is one of the main problems of the subsystem of operational and emergency control of ESP operating conditions. It is used to form a computational model of the current operating conditions of the EPS based on the operational information obtained from the SCADA system and the WAMS.

The SE procedure for the EPS includes sequential solving of the following problems: 1) formation of the current equivalent circuit of the EPS based on supervisory signal indication data; 2) analysis of observability and introduction of pseudo-measurements; 3) detection of gross errors in telemetry measurements, i.e., bad data detection; 4) calculation of state vector estimates, including absolute values of U and voltage phases at nodes, and estimated values of operating conditions parameters.

Thus, the problem of state estimation functionally represents a sequence of solving several subproblems, and for solving it, it is required to perform calculations for a large-dimension EPS consisting of parallel working subsystems, and an important factor is the requirement of high speed of employed algorithms and programs, providing a solution at the pace matching that of the technological process.

An effective method for solving these problems is to solve the SE problem in line with the principle of hierarchical modeling, based on a hierarchical description of the investigated system and the processes occurring in it. As applied to models of complex engineering systems, the works [28,29] highlighted two directions for a hierarchy: 1) vertical hierarchy, in which models are divided into levels depending on the structural and functional features of the system; 2) horizontal hierarchy, in which models are divided into levels depending on the methods of their study.

Similar approaches were proposed in the works of the Melentiev ESI, SB RAS, when developing a multi-agent approach to solving the problem of the SE of the large-dimension EPS [30,31]. In the process of SE, vertical hierarchy is performed based on the breakdown of the equivalent circuit of large dimension into subsystems (structural decomposition), and horizontal hierarchy - based on functional decomposition in accordance with the list of problems solved during the state estimation (*network topology analysis*; *observability analysis*; *bad data analysis*; *calculation of estimates and steady-state operating conditions*).

The problem of hierarchical modeling using SE problem decomposition is treated in a large number of works. In the 1970s-80s of the last century, the decomposition of the SE problem was relevant because of limited computing resources, and the processing of large complex circuits using them was very long. Such a decomposition is the subject of [32,33] and other studies. Nowadays, the need to decompose the SE problem is dictated by the very structure of the supervisory control of the UES of Russia built on a hierarchical principle. This decomposition is described in [27,34,35] and other studies. Decomposition of the SE problem is also widely covered in the works of authors from other countries [36–38, etc.].

Let us consider in more detail the approaches to hierarchical modeling using decomposition methods in solving the SE problem that were developed at the Melentiev Energy Systems Institute SB RAS.

The problem of state estimation of the EPS and methods for solving it. The problem of the EPS SE is to find such estimated values of the measured variables that are closest to the measurements themselves in the sense of the criterion:

$$J(y) = \left(\overline{y} - \hat{y}\right)^T R_y^{-1} \left(\overline{y} - \hat{y}\right), \tag{4.1}$$

while satisfying the equations of the electric circuit

$$w(y, z) = 0, \tag{4.2}$$

linking measured and unmeasured z operating conditions variables (R_y-covariance matrix of measurement errors). As measurements in solving the SE problem, we use remote measurements received from SCADA systems: absolute values of nodal voltages U_i, generation of active P_i and reactive Q_i powers at nodes, power flows in transformers and lines P_{ij}, Q_{ij}, and, less commonly, currents at nodes and lines $I_i,\ I_{ij}$, as well as measurements of complex electrical quantities of nodal voltages $\{U, \delta\}$ and currents $\{I, \varphi\}$ from PMUs, i.e., WAMS measurement equipment. Accordingly, the measurement vector is as follows:

$$\overline{y} = \left\{P_i, Q_i,\ P_{ij}, Q_{ij}, U_i,\ \delta_i,\ I_i,\ I_{ij}, \varphi_{ij}\right\} \qquad \overline{y} = \{P_i, Q_i\}$$

SCADA telemetry measurements are received by the supervisory control centers at 5-second intervals; at present, the main power grids and 750-220 kV electric power facilities are fully equipped with telemetry sensors.

Development of the WAMS in Russia is carried out at a rapid pace: with less than 100 PMUs were installed at 25 power facilities in 2005-2009, at the beginning of 2020 there were 829 PMUs at 128 power facilities already put into operation, mostly those manufactured within the country itself [39]. Currently, it is mandatory to install PMUs at power plants with an installed capacity of 500 MW or more, as well as at substations of 330 kV and above. The PMUs record measurements of operating conditions parameters with high accuracy and frequency (50 measurements per second), the average delivery time of phasor measurements data to the supervisory control centers is 150 ms, which enables their application in the tasks of automatic and emergency control.

When solving the SE problem, we usually introduce the state vector $x = (\delta, U)$ of the dimension $(2n - 1)$, where n is the number of nodes, including the absolute values U and angles δ of the nodal voltages for all nodes of the EPS except for the phase of the base node. Such a state vector uniquely determines all other operating condition variables and makes it possible to use explicit dependencies of measured and unmeasured variables of x as the electric circuit equations (4.2) and solve the SE problem in state vector coordinates.

A significantly different statement was proposed at the MESI SB RAS [40]. It consists in the use of so-called test equations (TE). Test equations are electrical circuit equations that include only the measured operating conditions variables y:

$$w_k(y) = 0 \tag{4.3}$$

The test equations can be derived from the system of steady-state equations (SSE) after excluding unmeasured variables. First proposed for the verification of telemetry, the test equations then began to be used to solve almost all of the above problems that are part of the SE complex in real-time.

Large residuals of the test equations

$$\left| w_{ki}(\overline{y}_i) \; > d_i \right| \quad , \tag{4.4}$$

where d_i is the threshold determined by the statistical properties of normal measurement errors, indicate the presence of gross errors among the components of the measurement vector $\overline{y}_i$, included in the ith test equation. To test hypotheses about the presence of bad data, including errors in the network topology, algorithms for logical analysis of the information included in the test equations have been developed.

In this statement, the SE problem is solved in coordinates of measured variables and is reduced to minimization of the criterion (4.1) under constraints in the form of a system of test equations (4.3). This approach does not require a transition to the state vector x, allows us to take into account the exact measurements (given $r_{ij} = 0$ the corresponding y_i is not included into (4.1), but appears in (4.4) as a constant).

If it is necessary to calculate unmeasured parameters, the basic system of measurements y_b is chosen, and the system of equations is solved

$$y_b(x) - \hat{y}_b = 0. \tag{4.5}$$

The system (4.5) is solved by the Gaussian method, where at the first iteration the triangular factorization of the matrix and selection of the basis are performed simultaneously, and at all subsequent iterations, only the reverse Gaussian procedure is performed.

In contrast to conventional SE methods, the method of test equations allows us to fix the values of measured variables by assigning zero variances to them. This provides advantages both in solving the SE problem for both the complete circuit and in the case of decomposition of the equivalent circuit.

Despite the fast-paced development of information collection and processing systems in the EPS, when solving the problem of SE there is still a problem related to the insufficient volume and low quality of measurement information in networks with voltages below 220 kV. This leads to errors in the formation of the equivalent circuit, the appearance of unobservable areas, critical measurements and critical groups that cannot be detected, the effect of "smearing" of gross errors, and, as a consequence, the distortion of the results of SE and the low accuracy of the estimates obtained.

In large-dimension EPSs consisting of subsystems operating in parallel, there are also problems associated with the heterogeneity of the equivalent circuit, large volume and heterogeneity of measurement information, poor synchronization of data at the boundaries of subsystems, etc. Distributed data processing in SE problem decomposition is an effective method for solving these problems, improving the quality of results and reliability of the computational procedure of the SE of EPSs.

Hierarchical distributed SE algorithms using decomposition and aggregation. The distributed OS approach using decomposition and aggregation procedures involves performing the following steps:

1. At the decomposition stage, break down the equivalent circuit into subsystems by one method or another.
2. Perform SE for each subsystem.
3. Solve the coordination problem, which consists of calculating boundary variables and checking the boundary conditions. If the conditions are not satisfied, then the calculation is repeated by subsystems with new values of the boundary variables.
4. At the aggregation stage, combining the solutions obtained for individual subsystems, and the solution of the coordination problem, form a common solution for the complete circuit.

A large number of structural decomposition methods are currently used in solving the SE problem, the main ones are [41,42], etc.:

1. decomposition according to the geographical principle or according to the administrative division of the territory covered by the EPS;
2. decomposition with boundary branches, with cross-system links being most often used as the latter;
3. decomposition with boundary nodes;
4. decomposition based on the structure of matrices used in solving the SE problem, etc.

Decomposition according to the geographical principle or according to the administrative division of the territory does not require the use of special algorithms and is usually carried out in accordance with the structure

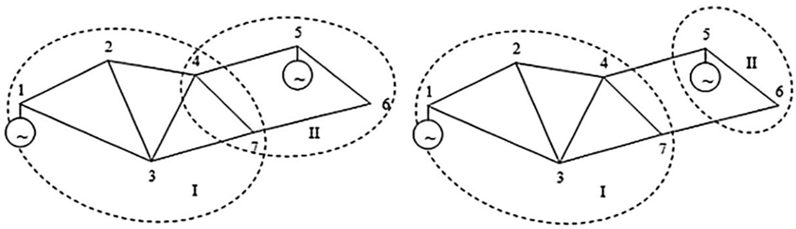


FIGURE 4.1 *Left*: circuit decomposition by boundary nodes. *Right*: circuit decomposition by boundary branches.

of supervisory control of a large EPS. The basic algorithms of SE problem decomposition involve the breakdown of the equivalent circuit into subsystems, the boundaries of which can be nodes (Fig. 4.1 - left) or branches (Fig. 4.1 - right).

When decomposing the circuit by boundary nodes, the requirement of equality of the absolute values of voltage and phase angles at all boundary nodes acts as boundary conditions:

$$U_i = U_j = \cdots = U_k, \tag{4.6}$$

$$\delta_i = \delta_j = \cdots = \delta_k. \tag{4.7}$$

Also, at all boundary nodes, the balance ratios of active and reactive power must be observed. For example, for the boundary node l, which is common to i, j, ..., kth subsystems

$$P_{load_l} - P_{gen_l} + \sum_{s=i,j,\ldots,k} \sum_{m\in\omega_s} P_{lm}(U_l, \delta_l, U_m, \delta_m) = 0, \tag{4.8}$$

$$Q_{\mathrm{load}_l} - Q_{gen_l} + \sum_{s=i,j,\ldots,k} \sum_{m\in\omega_s} Q_{lm}(U_l, \delta_l, U_m, \delta_m) = 0, \tag{4.9}$$

where P_{load_l}, Q_{load_l}, P_{gen_l}, Q_{gen_l} active and reactive power of load and generation at the node l; the set of nodes of the sth subsystem, incident to the lth node.

When decomposing the circuit by boundary branches, the requirement of equality of active P_{ij} and reactive Q_{ij} power flows from the ith subsystem to the jth subsystem acts as boundary conditions:

$$P_{ij} = -P_{ji} + \Delta P_{ij}, \tag{4.10}$$

$$Q_{ij} = -Q_{ji} + \Delta Q_{ij}, \tag{4.11}$$

For each boundary branch, the following equations must hold:

$$U_m^2 = \left(U_l - \frac{P_{ml}r_{ml} + Q_{ml}x_{ml}}{U_m}\right)^2 - \left(\frac{P_{ml}x_{ml} + Q_{ml}r_{ml}}{U_m}\right)^2 = 0, \tag{4.12}$$

$$\delta_m - \delta_l - arctg\frac{P_{ml}x_{ml} - Q_{ml}r_{ml}}{P_{ml}r_{ml} + Q_{ml}x} = 0. \tag{4.13}$$

Circuit decomposition by boundary branches is employed in calculations more often than decomposition by boundary nodes.

Decomposition of the SE problem when solving it by the TE method [40]. When using the TE method for each of the subsystems the problem of state estimation is solved, i.e., we search for the minimum of the objective function

$$\varphi_v = \left(\overline{y}_v - y_v\right)^T R_{yv}^{-1}\left(\overline{y}_v - y_v\right), \tag{4.14}$$

subject to the constraints in the form of a system of test equations

$$w_k\left(y_v, y_b\right) = 0, \tag{4.15}$$

where: ν - number of the subsystem, y_b - boundary measured variables.

The obtained estimates of the boundary variables are passed to the upper level, where the coordination problem is solved, which consists in the minimization:

$$\varphi_b = \left(\overline{y}_b - y_b\right)^T R_{yb}^{-1}\left(\overline{y}_b - y_b\right), \tag{4.16}$$

subject to the constraints in the form of test equations including only measured boundary variables:

$$w_k\left(y_b\right) = 0. \tag{4.17}$$

The problems (4.14), (4.15) and (4.16), (4.17) are solved iteratively until the necessary accuracy of the estimates is achieved. This technique does not require modification of the state estimation algorithms and can be implemented using existing software [43], but coordination of the solution of individual subsystems requires performing 3 to 4 iterations.

The use of phasor measurements in a distributed SE using decomposition. The Wide Area Measurement System (WAMS) of the UES of Russia is a distributed hierarchical information and measurement system, covering the facility level, the regional level, and the main level.

At the facility level, phasor measurement units (PMUs) and/or software and hardware packages (SHP) of the WAMS are installed, including PMUs and local phasor vector concentrator (PDC). Stand-alone PMUs and WAMS SHPs installed at the facility level shall provide measurement, processing, storage of phasor measurement data and their transfer to the regional PDCs.

At the regional level, in integrated supervisory control offices and regional supervisory control offices, regional PDCs are installed so as to ensure the collection of phasor measurement data from the stand-alone PMUs and WAMS SHP of electric power facilities, data exchange with other regional PDCs, processing and storage of phasor measurement data, and its transfer to the main PDC.

At the main level, in the central supervisory control office, the main PDC is installed so as to ensure the collection of phasor measurement data from the regional PDCs, their processing and storage.

The function of transmitting phasor measurement data to the regional PDC installed at the supervisory control center must be implemented from one local PDC. At the same time, redundancy of this local PDC must be provided in the WAMS SHP of the power plants.

The task of EPS SE is solved at all levels of the hierarchy of the power system of Russia. Equipping each level with the PMUs, as follows from the SO UES Standard STO 59012820.29.020.001-2019, allows one to provide for the use of phasor measurement in SE algorithms of any level of the hierarchy.

Using phasor measurements to coordinate the solutions of individual subsystems in the decomposition of the SE problem. When the equivalent circuit is broken down into subsystems (*those of structural decomposition*), the installation of the PMUs at the boundary nodes allows the boundary variables and to be fixed also at the values measured with high accuracy. In this case, when decomposing with boundary nodes, the boundary conditions (4.6), (4.7) are fulfilled automatically, and the solution of the coordination problem consists in calculating the nodal injections at the boundary nodes as per (4.8), (4.9), using estimates of power flows in the lines as obtained during the calculation of individual subsystems. In this case, the operating conditions of individual subsystems can be calculated independently of each other, iterative calculations by subsystems are not required. The disadvantage of this approach is the impossibility to obtain estimates of injections at relay nodes with accuracy = 0, so if the boundary nodes are relay nodes, then decomposition with boundary branches is used.

When partitioning into subsystems with boundary branches, the PMU is installed at one of the nodes of the boundary branch. Then at the other end of the branch a "calculated phasor measurement" can be obtained [44], i.e., the voltage absolute value and phase value calculated through measurements of the physical phasor measurement actually installed at the adjacent node.

$$U_j^{calc} = \sqrt{U_1^2 - 2U_i I_{ij}(r_{ij}\ cos\varphi_i + x_{ij}\sin\varphi_i) + I_{ij}^2(r_{ij}^2 + x_{ij}^2)}$$

$$\delta_j^{cals} = \delta_l - arctg\frac{I_{ij}\ (x_{ij}cos\varphi_{ij} - r_{ij}\sin\varphi_{ij})}{U_i - I_{ij}\ (r_{ij}cos\varphi_{ij} + x_{ij}\sin\varphi_{ij})}.$$

Installation of the PMU at one of the nodes of the boundary branch in combination with measurements from the "calculated phasor measurement" at the neighboring node ensure fulfillment of the boundary conditions (4.12), (4.13) in the boundary connection. Since the PMU installed at the node allows receiving or calculating measurements (pseudo-measurements) of power flows at all branches outgoing from the node, the boundary conditions (4.10), (4.11) will also be met when partitioning with boundary branches. In this case, the operating conditions of individual subsystems can also be calculated independently of each other, iterative calculations by subsystems are not required.

To synchronize (coordinate) the phase angles of the voltages obtained when solving the SE problem by subsystems, each subsystem uses the phase angle measurement from one of the installed PMUs. These nodes are taken as the base nodes of the subsystems. The PMU measurements (phasor measurements) coordinate the results of the SE of the individual subsystems. When partitioning into subsystems with boundary nodes, it is reasonable to use common boundary nodes for several subsystems as nodes to install PMUs. Such an arrangement of PMUs simultaneously with the coordination of the phase angles of the voltages by subsystems simplifies solving the coordination problem.

When partitioning into subsystems with boundary branches, the boundary branch node where the real, rather than the "calculated" phasor measurement is detected should be chosen as the base node.

The placement of PMUs at the boundary nodes of the subsystems. A simple, but not optimal solution to this problem is to place PMUs at all boundary nodes. With an optimal combination of physical and "calculated" phasor measurements at all subsystem boundary nodes, the voltage absolute values and phases required to coordinate the solutions of the individual subsystems can be determined.

To minimize the number of PMUs, not only the list of boundary nodes is analyzed, but also a list of internal lines of subsystems that are incident to these nodes. It may turn out that boundary nodes belonging to the same subsystem bound the same line. Then it is enough to install the PMU at one end of the line and get the "calculated" phasor measurement at the other end. To select the optimal placement of the PMU, we developed an algorithm that implements the annealing simulation method [45].

As calculations show, the number of PMUs installed during circuit decomposition is significantly less than the total number of boundary nodes.

Using phasor measurements to improve the quality of the SE in the boundary areas of subsystems. Detection of gross errors (bad data) in the remote data, or the verification of telemetry measurements, is one of the most important problems in the EPS SE. When calculating subsystems working in parallel that have their own means of collecting and processing remote data, due to inaccurate synchronization of data across subsystems in the boundary areas of subsystems, interacting and oftentimes coordinated bad data can occur, which significantly complicates the processing procedure and can affect the convergence of state estimation. Precisely synchronized measurements from PMUs installed at the boundary nodes can significantly improve the bad data detection efficiency in the boundary regions and the accuracy of the resulting estimates.

In the works on the decomposition of the SE problem [46], it is proposed to use information from the neighboring EPS to increase data redundancy and the efficiency of the bad data detection and state estimation procedure. Installation of PMUs at the boundary nodes of the neighboring EPSs allows one to fix the boundary variables of the state vector at the values measured with high accuracy. With an optimal combination of physical and "calculated" phasor measurements at all boundary nodes of the EPS we can determine U and δ, which are necessary to coordinate the solutions of individual systems. At the same time, the operating conditions of individual EPSs can be calculated independently of each other.

To improve the efficiency of the bad data detection algorithms and the accuracy of estimates in the boundary areas of synchronously operating subsystems of the EPS connected by electric power lines, the following algorithm for phasor measurement processing is proposed:

1. Installation of phasor measurements at the boundary nodes of the subsystems that have connections via power transmission lines with neighboring subsystems, according to the algorithm [46].
2. Allocation of local boundary regions observed from the phasor measurements for each subsystem.
3. The accumulation of the phasor measurements on servers acting as a phasor data concentrator (PDC) and belonging to separate subsystems.
4. Backing up the phasor measurements on a remote server acting as a virtual PMU.
5. Formation of TE using the Crout's method [47], which allows one to detect critical measurements and critical groups that represent the greatest "danger" to the SE algorithm in terms of gross errors.
6. Analysis of measurements, which received during verification the attributes of "doubtful" and "erroneous data". Replacement of such measurements with pseudo-measurements P_{ij}, Q_{ij} calculated from real phasor measurements, or with backup phasor measurements from virtual PMUs.
7. The use of similar measurements of neighboring subsystems, mutual verification of their validity.
8. The solution of the SE problem for the boundary areas of subsystems.

Fig. 4.2 shows the workflow of cooperation of the EPS I with neighboring independent power systems II and III. The locations of the actual PMU are indicated by black circles and those of "calculated" ones by uncolored circles. Important cross-system lines are 1-21, 3-22, 12-23, 12-31. Note that one of the facilities of the EPS I (node 12) is unobservable with respect to phasor measurements, but due to this fact it is invulnerable to cyber attacks on the WAMS. For mutual monitoring tasks, it is preferable to use

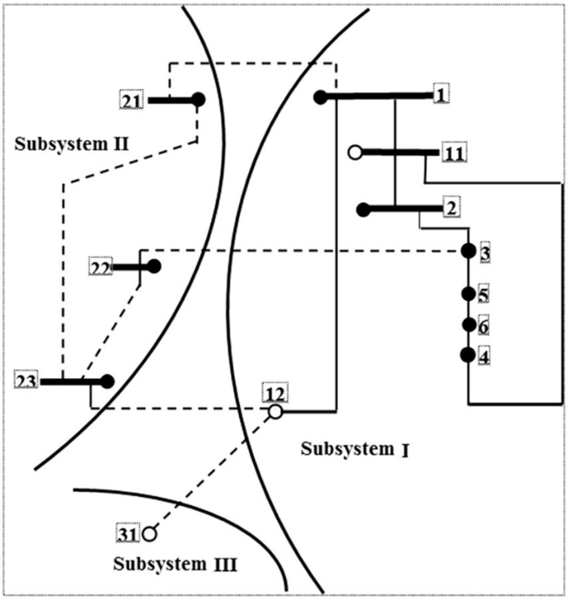


FIGURE 4.2 PMU placement at the boundary nodes of neighboring EPSs.

only actually installed phasor measurement units (PMUs) so as not to accumulate errors in pseudo-measurements of "computed" PMUs obtained from real cyber-attacked devices.

The use of phasor measurements of complex electrical quantities of high accuracy, coming from PMUs, allows one to solve a number of problems arising in the decomposition of the SE problem:

1. installation of PMUs at the boundary nodes of the subsystems allows one to simplify solving of the coordination problem and does not require iterative calculations for the subsystems,
2. setting nodes with phasor measurements as base nodes of subsystems provides coordination of phase angles of voltages during calculation by subsystems,
3. measurements from PMUs installed near the boundary nodes can significantly improve the bad data detection efficiency in the boundary regions and the accuracy of the resulting estimates.

A two-level structural decomposition algorithm. Because of the insufficient availability of devices for the phasor measurements of networks of all voltage classes, the installation of phasor measurements at the boundary nodes can actually be used only when the circuit is divided into sufficiently large subsystems with a small number of boundary nodes and

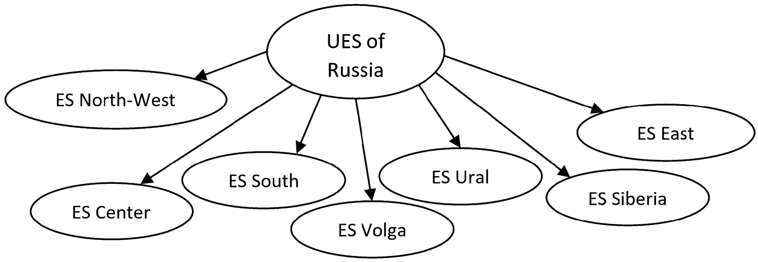


FIGURE 4.3 Schematic diagram of the UES of Russia.

branches, but this does not solve the problem of heterogeneity of the circuit.

To calculate large heterogeneous circuits, the study [48] proposed a method of dividing the equivalent circuit into subsystems by voltage levels, which allows one to significantly reduce the negative effect of heterogeneity of the equivalent circuit and telemetry information when calculating subsystems of the same voltage class, but for complex closed-loop configurations, this inevitably leads to a large number of boundary nodes. The installation of phasor measurements at all of these nodes is not possible at the current level of development of the WAMS in Russia. As a result, a two-step algorithm for breaking down the equivalent circuit into subsystems was developed that makes use of the advantages of both approaches.

At the first stage, the circuit is divided into large enough subsystems with a minimum number of cross-system links and boundary nodes. Such decomposition can be performed on the basis of administrative division of, for example, the complete circuit of the UES of Russia into running in parallel integrated EPSs (ESs) of large regions of the country (Fig. 4.3), or artificially, when the complete circuit is divided into separate fragments using dedicated algorithms. Devices for measuring complex electrical quantities are installed at the boundary nodes of the subsystems.

At the second stage of decomposition, the equivalent circuit of each subsystem is, in turn, divided into areas or fragments corresponding to the levels of nodal voltages. The calculation starts with the highest voltage level (750-500 kV). As a rule, this part of the circuit is well provided with high precision telemetry and contains the base node of the complete circuit. Then the other fragments of the circuit, ranked by voltage levels (220 kV, 110 kV, etc.), are calculated sequentially, each time a node bordering with the area of higher voltage level is selected as a base node. The method of test equations used herein allows the boundary parameters to be fixed.

After completing the calculation of the lower-level fragments of all large subsystems, the coordination problem is solved, which in this case consists in the calculation of nodal injections at the boundary nodes according to the estimates of power flows obtained by the subsystems, or in the calculation of flows at the boundary branches.

Functional decomposition of the problem of state estimation of the EPS. The idea of *functional decomposition* of the state estimation problem is to divide this problem into subproblems [48,49], the main of which are the following ones: *network topology analysis*; *observability analysis*; *bad data analysis*; *calculation of estimates and steady-state operating conditions*.

Solving the first two subproblems in the general SE procedure can be performed in each of the subsystems independently because their results do not affect each other. The functional decomposition considers two subproblems of state estimation: analysis of bad data and calculation of estimates. The bad data detection is performed a priori by the TE method. *The choice of method for EPS SE* is made depending on the solution of the problem of a priori bad data detection. If bad data are detected or absent, the weighted least squares criterion is selected, and if it is impossible to identify bad data, the robust SE criterion with bases enumeration, based on the genetic algorithm [50], is selected, which allows one to detect and reject erroneous telemetry simultaneously with obtaining estimations.

A multi-agent system for implementing a two-level hierarchical SE algorithm. The multi-agent approach [42] was used to implement the SE problem-solving algorithm developed. The multi-agent system (MAS) architecture for distributed SE is shown in Fig. 4.4. Types of agents in this system:

1. MAS_0 is a general multi-agent system containing all subsystems and all agents.
   a. A_{DE} is a partitioning agent that breaks down the equivalent circuit into large subsystems, and these, in turn, are broken down into areas by voltage level;
   b. A_K is a coordinating agent, it coordinates calculations of large subsystems, calculates boundary variables (active and reactive powers at boundary nodes; power flows at boundary branches);
   c. A_{AG} is an aggregation agent that, if necessary, performs the aggregation of data received by the coordinating agent from individual subsystems, i.e., forms the operating conditions for the complete circuit;
2. $MAS_{1,2\dots N}$ are multi-agent systems containing subsystems of the first level of decomposition, which include areas by voltage levels;
3. MAS_{IJ} is an agent of the i-th subsystem of the j-th voltage level, it transmits to the lower level the values of voltage and phase angle of its boundary nodes. It contains a local multi-agent system consisting of three agents:
   a. A_{BD} is a bad data detection agent that performs bad data detection and, depending on the results of its work, triggers the agent A_{SQ} or the agent A_R;

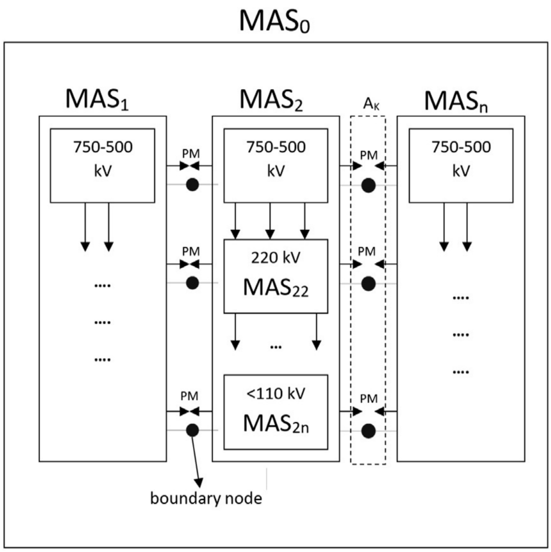


FIGURE 4.4 The architecture of the multi-agent system for state estimation of the EPS.

b. A_{SQ} is a SE measure as per the weighted least squares method, it is triggered by the A_{BD} agent in case all bad data or no data is detected;

c. A_R is a robust criterion SE agent, it is triggered by the A_{BD} agent if all bad data cannot be identified.

d. A_k is the coordinating agent of the voltage level areas, it calculates the active and reactive powers at the boundary nodes of the areas.

The application of multi-agent technologies in the decomposition of the EPS SE problem allows the following:

1. Arranging a flexible selection of the method for solving this or that SE problem for each subsystem.
2. Integrating artificial intelligence methods and numerical methods for problem-solving.
3. Coordinating the interaction between problems at different levels.
4. Performing parallel data processing at different voltage levels for local subsystems of significantly lower dimensionality.
5. Quickly exchanging data between problems solved at different levels and distributed geographically with the help of mobile agents.
6. Speeding up the process of telemetry processing and, therefore, reducing the time of state estimation of the system.

Decomposition of the SE problem as a method of increasing cyber resilience of the EPS. The process of digitalization of the EPS, the use of intelligent technologies, sophisticated engineering, information, and communication equipment have increased the cyber-security risks of the EPS [51,52]. The modern electric power system and its facilities are complex systems consisting of two closely interconnected layers: physical (process) and information-and-communication subsystems. Hardware and software tools of SCADA systems and WAMS and the problem of state estimation, designed to support the actions of supervisory control personnel in the course of the operational and emergency control of the EPS, are the components of the information-and-communication subsystem that are critical and at the same time most vulnerable to cyber attacks [53]. In the studies performed at the Melentiev ESI, SB RAS, along with engineering and organizational measures aimed at improving the cyber-security of EPS facilities, to analyze the vulnerability of the information-and-communication subsystem and mitigate the impact of cyberattacks on the quality of physical subsystem control it is proposed to employ statistical methods of processing of measurement information coming from SCADA and WAMS systems. First of all, these are methods of static and dynamic state estimation and measurement verification [54], wavelet analysis, methods of fuzzy logic [55,56], and other methods of processing information used in the control of EPSs.

Another approach to solving the problem of cyber-security of the EPS that is built on the decomposition of the equivalent circuit into areas on the basis of belonging of measurements to the data acquisition system of either SCADA or WAMS, was proposed in [57]. This approach also reduces *measurement heterogeneity*, which positively affects the convergence of the SE computational process.

Cyber attacks on power plants are not always aimed at destroying them completely. Attempts to penetrate the information subsystem to distort the values of certain state parameters are aimed at getting some economic gains. Any cyber attack is a sudden intrusion into the information system of an electric power facility. The SE procedure is one of the first among the operational management tasks, which receives distorted information due to cyber-attacks and becomes a barrier to malicious intrusion [58]. Once it is discovered that the original information is distorted or lost in the EPS, the source of a possible cyber attack must be located, and to do this, each server and the local sensors connected to it must be analyzed.

Thus, a new decomposition approach to solving the SE problem under cyber-threats is proposed: the network is divided into domains (previously formed areas), in the center of which is the SCADA server and the Wide Area Measurement System (WAMS) concentrator (see Fig. 4.5).

The number of phasor measurements in the circuit can be artificially increased by arranging the "calculated" phasor measurements, in this case, it is preferable to install them at the nodes where there are SCADA measurements so as to quickly detect the fact of data mismatch. The calculation

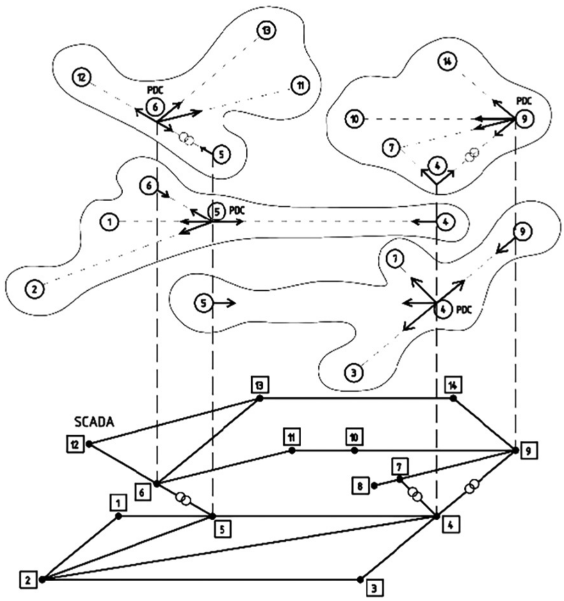


FIGURE 4.5 Partitioning of the IEEE 14 bust test system by the origin of measurements: a SCADA server or WAMS concentrator (PDC).

of the SE problem is carried out simultaneously in those areas where both types of measurements are present. The creation of such connected regions in the equivalent diagram is performed using the spanning tree algorithm [59], in this case, a double spanning tree: it forms connected graphs only in those regions where nodes with two kinds of measurements are located.

The SE decomposition algorithm for detecting and locating cyber attacks works as follows:

1. In the equivalent circuits, local domains observed by the PMU are formed, each of which belongs to the corresponding PDC. The boundary nodes in this approach are nodes belonging to both systems (SCADA and WAMS) at the same time. 2. Before calculating the estimates in each area, a bad data detection procedure is performed using the test equation method. As a rule, this procedure reliably detects individual bad data when measurement redundancy is high enough. Modern cyber attack techniques allow the generation of sets of erroneous measurements that are not separately identifiable by the bad data detection methods used, such as the TE method [54,60] or methods of analysis of residuals of estimation [61,62]. If any questionable groups of data are detected in this way, it indicates a possible cyber attack in the monitored area. If the method of TE failed to detect them before the SE, then it can be done by methods of a posteriori analysis (-test, analysis of the estimate residuals). 3. According to the results of the SE, the value of the objective function is checked for each

calculation at the decision point, i.e., the -test is checked:

$$\varphi\left(\hat{y}\right) < x^2 \tag{4.18}$$

Given $v => 30$ the objective function $\varphi\left(\hat{y}\right)$ has a normal distribution with v degrees of freedom and variance equal to $2v$. In this case, the normalized value of the objective function $\tau = \left(\varphi\left(\hat{y}\right) - v\right)/\sqrt{2v}$ is calculated and compared to the quantile of the normalized normal distribution γ_a corresponding to the given probability of error of the 1st kind, i.e., the following condition is checked:

$$\gamma < \gamma_a \tag{4.19}$$

4. When solving the SE problem in each local area (linear SE for PDC areas and non-linear SE in SCADA areas) 4 values of the objective function are archived: total value, the value with respect active power measurements $\varphi_P\left(\hat{y}\right)$, the value with respect to reactive power measurements $\varphi_Q\left(\hat{y}\right)$, and the value with respect to voltage $\varphi_U\left(\hat{y}\right)$. At the same time, the archive stores estimates of voltages at the most sensitive nodes of the circuit, as well as the values of absolute values and phases of voltages at all boundary nodes. This backup allows one to monitor the behavior of the values listed in items 2 and 3. "Outlier" values of the general objective function indicate a sharp change in the composition of measurements or failure of the data network (physical damage of a network component or the introduction of uncertain remote signals).

Algorithm testing. For each subsystem three x^2 tests are performed according to the results of the SE, including verification of the conditions (4.18), (4.19) given the same synchronized SCADA and PMU measurements:

1. Test 1 is for the complete circuit with SCADA measurements;
2. Test 2 is for the complete circuit with SCADA and PMU measurements;
3. Test 3 is performed in two steps: first, linear SE is performed for the domains by means of PMU measurements sent to a single PDC device, then, if necessary (when the complete circuit is not observable by PMUs), SE is performed for the complete circuit involving SCADA measurements.

For Test 3, the conditions (4.18) or (4.19) are checked separately for the areas corresponding to each PDC measurement and for the entire circuit after the coordination problem is solved. Depending on the test results presented in Table 4.1, conclusions are drawn about possible cyber attacks on SCADA and WAMS systems.

As follows from Table 4.1, a negative answer (No) when checking the conditions (4.18) or (4.19) indicates a possible cyber attack for the relevant data acquisition system (SCADA or WAMS) or for its part. In this case, the residuals of the estimate are analyzed to detect distorted measurements.

TABLE 4.1 The results of test: Are condition (4.18) or (4.19) met?

Case	Test 1	Test 2	Test 3	Expert conclusion
1	Yes	Yes	Yes	No cyber attack
2	No	Yes	Yes	No cyber attack on WAMS No cyber attack on SCADA measurements in the coordination task Cyber attack on SCADA measurements that are not involved in the coordination task
3	Yes	No	No	Cyber attack on WAMS: to localize a cyber attack, check which PDC Condition (4.18) or (4.19) is not met
4	No	No	Yes	No cyber attack on WAMS Cyber attack on SCADA, distorted SCADA measurements that are not involved in the coordination task

The algorithm of decomposition of the state estimation problem on the basis of whether the measurements belong to the SCADA or WAMS systems is effective in terms of detecting malicious attacks on the EPS. This resolves several issues:

1. Data heterogeneity is eliminated (SCADA and WAMS measurements are processed separately);

2. A decomposition by voltage class has been made since WAMS sensors are now mainly installed at high and extra-high voltage facilities;

3. Verification algorithms work faster and more efficiently with smaller amounts of information. The results of wrong data detection using two independent data collection and processing systems and a combination of a priori and a posteriori wrong data detection allow us to conclude that there is a malicious cyber attack on the electric power facility in question;

4. Calculation of the SE problem is performed in parallel by SCADA measurements and by PMU measurements within the same domain: in case of a cyber attack on a single server or concentrator (and its failure) it becomes obvious in which domain the SE procedure failed to work. At the end of the computational cycle, the matching problem for all domains is solved to calculate the complete circuit.

5. An analysis of the results of the coordination task allows conclusions to be drawn about the fact of the cyber attack, its location, and its possible target. Information about the location of a cyber attack is transmitted to the personnel of the corresponding control center of the system or EPS facility.

Thus, in modern conditions of operation and management of the EPS, one requires the creation of a calculation model based on state estimation methods for high-dimensional circuits consisting of subsystems operating in parallel. This leads to a large heterogeneity of equivalent circuits, increases the loading with respect to computing resources in the supervisory control centers, and increases the calculation time. An effective method for solving these problems is to solve the SE problem in line with the principle of hierarchical modeling, based on a hierarchical description of the investigated system and the processes occurring in it.

The algorithms developed for state estimation of the EPS by the method of test equations are based on the structural and functional decomposition of the problem using phasor measurements. These algorithms allow the following:

1. performing parallel data processing in subsystems of smaller size than the original circuit;
2. reducing the negative effect of circuit heterogeneity on the calculation results;
3. simplifying the solution of the coordination problem;
4. avoiding the performance of iterative calculations by subsystems;
5. increasing the efficiency of bad data detection methods;
6. speeding up the processing of telemetry.

To implement the developed algorithms of SE problem decomposition, a multi-agent approach is used. The application of multi-agent technologies in the decomposition of the EPS SE problem allows the following:

1. Arranging a flexible selection of the method for solving this or that SE problem for each subsystem.
2. Integrating artificial intelligence methods and numerical methods for problem-solving.
3. Coordinating the interaction between problems at different levels.
4. Quickly exchanging data between problems solved at different levels and distributed geographically with the help of mobile agents.

All of these advantages allow one to reduce markedly the state estimation time for the complete circuit and increase the accuracy of the resulting estimates.

To improve the cyber resilience of modern EPSs, analyze the vulnerabilities of SCADA and WAMS facilities to cyber attacks and reduce the impact of cyber attacks on the quality of EPS control, an algorithm is proposed for decomposition of the SE problem on the basis of belonging of measurements to SCADA and WAMS systems.

4.4 Multi-agent systems for hierarchical intelligent control of electric power systems

Basic premises. Multi-agent systems (MAS) are a promising approach to the implementation of hierarchical intelligent control of EPS operating conditions with effective distribution of functions between the levels of the hierarchy of the created control system. The main reasons for the particular relevance of MAC in this regard are the following:

1. the problems to be solved, the models used for this purpose, and, hence, the systems to be developed are heterogeneous and distributed: - in space, - in functional terms;
2. the complexity of the EPS operating conditions control increases;
3. the EPS control system should provide for opportunities and means to adapt to changes in the environment, including those by modifying its structure and parameters directly in the course of its operation;
4. the evolution of software is towards its development on the basis of autonomous, specialized, interacting modules;
5. when all information and processing resources are distributed across different network nodes, the concept of distributed and parallel computing is adopted.

MAS intelligent agents are active, autonomous, communicative, and motivated objects, operating in complex, dynamic environments, carrying out distributed solving of complex problems based on intelligent information analysis in the operating conditions of real operation of the controlled system.

As an illustration, the following diagram of three-level control, which actually formalizes on the basis of the agent-based approach the three-level subsystem of the instability prevention automatics (IPA) of the emergency control system of the EPS.

At the first level, there are agents that have access to local information resources related to a particular energy facility. The functional purpose of these agents is local control of operating conditions parameters (controlling and constraining operating conditions parameters, implementing specific control actions, etc.).

"Supervisors" in relation to the first-level agents ("helpers") are the second-level agents that determine the control setpoints based on the forecasting of the state of the power grid, transmission capacity, load of power plant generators, etc.

Level 3 agents ("coordinators") can coordinate the algorithms of Level 2 agents:

1. frequency control in the system;
2. satisfaction of operational requests and performance of switching operations;
3. control of EPS operating conditions in critical and emergency situations;
4. provision of generator active power reserves for the real-time market;
5. analysis of reliability, cost-efficiency of operation, etc.

Agents of different levels independently access the information resources specified for them.

The intelligent agent can process data and transmit the results of its work over the network. At the same time, "helper" agents can communicate with the "supervisor" and pass the required information to each other.

Real-time MASs can be used both for automatic control and for operator decision support.

In some cases, agents can be made to work by using off-the-shelf basic solutions, i.e., agent platforms. There are now many platforms, both commercial and open-source. The most commonly used platform is Jade. This platform and its extensions provide various means to enable agents to function within the Semantic Web paradigm.

Considering agents in the context of the Semantic Web leads to the need to integrate MASs with web applications, in particular the creation of a web interface for agents. There are several ready-made approaches that provide a solution to this problem. For example, Jade Gateway provides the interaction between the external application and the Jade platform. Jade 4 Spring provides easy integration of Jade agent containers and the Spring framework. This approach allows the effective use of agents in the context of a web application. Visualization of ontological models is proposed to be performed using Flare Prefuse. Flare is an Action Script library for creating visualizations that run in Adobe Flash Player.

Principles of building multi-agent systems. Multi-agent systems can have different architectures. The simplest architecture is *the reactive architecture*, based on a simple stimulus-response mechanism triggered by information received from the sensors. This architecture is characterized by a fast but not very meaningful reaction to disturbances. Agents in the MAS with a reactive architecture are quite simple to implement. Many of the devices that control the operation of the EPS can be considered as agents with the simplest reactive structure. Such devices include, for example, devices of protection equipment (PE), automatic excitation control (AEC) of generators, various local automation devices, etc. The fact that each individual agent in a reactive architecture has a rather limited set of knowledge about the other agents is the reason for the lack of agent coordination.

Another type of the MAS architecture is *layered architecture*, which in addition to reactive interaction includes deliberative behavior of agents.

This implements another important component of the MSA, that of the principle of communication. If agents interact to coordinate their actions, they must exchange messages using some language. Currently, the most popular language for inter-agent interaction is FIPA (The Foundation for Intelligent Physical Agents) [63–66].

The FIPA standard requires that messages exchanged by agents must contain a set of mandatory fields: "sender", "recipient", "communicative intent", "message content", "language", "ontology", and a number of fields used for control. Ontology is a dictionary of symbols and their meanings. For effective communication, both sender and receiver must understand the meaning of the symbols in the message. Ontology can include various elements: agent actions (which can be performed by them), terms, concepts, etc. Terms are expressions that define objects (abstract or concrete) that "exist in the world".

Coordination of agents can be established by applying different approaches, for example, *organizational structuring* or *distributed multi-agent planning*.

Organizational structuring provides coordination by defining roles, channels of communication, and authority. Organizational structuring is an easy way to resolve conflicts between agents in order to ensure their coordinated behavior. The system of centralized emergency control is an example of organizational structuring: there is a control center agent, which has some set of knowledge about the current and prospective states of the system and sets the rules of behavior for the other agents in accordance with the hierarchical structure of the MAS. However, such timely centralized management is difficult to implement in cases where there is a shortage of time to gather information and make control actions.

Distributed multi-agent planning is based on a different way to eliminate the uncoordinated and conflicting behavior of agents. To do this, a plan is built, which describes all the different actions and interactions of agents necessary to achieve a common global goal. In the process of operation, agents interact to amend their individual plans until all conflicts have been resolved.

A possible implementation of the multi-agent approach is considered below, using the example of voltage avalanche prevention [65–68].

Example of coordination of agents when preventing a voltage avalanche. An MAS that can be used to prevent a voltage avalanche must have a layered architecture and use distributed multi-agent planning [69,70, etc.]. To control the post-emergency operating conditions in order to prevent a voltage avalanche in the EPS, an emergency control system (ECS) will be required, which should detect the critical situation and coordinate the operation of various devices.

Parameters are indicators of the critical situation. Various studies have suggested using a significant voltage drop and a significant increase in reactive power generation by synchronous machines (unacceptable increase in excitation current) as indicators of a critical situation preceding a voltage avalanche. Thus, these two criteria can be used to identify a critical situation and trigger the emergency automatics (EA).

Control actions. Analysis of large system accidents has shown that rapid load shedding (LS) is often the only way to prevent the collapse of the entire EPS [71,72, etc.]. On the one hand, load shedding should be done as quickly as possible, on the other hand, it should be optimal. It is quite difficult to perform optimization calculations for all kinds of emergency situations in advance, so some of the calculations are performed directly during the emergency and post-emergency operating conditions of the EPS. The amount of data about the state of the system that must be collected to perform the optimization procedure is usually large. The state estimation alone may take a few minutes, but the load shedding procedure under post-emergency operating conditions should work much faster. Therefore, less complicated principles of automatics are considered. A set of simple control actions (CA) to control the post-emergency operating conditions of the EPS operation is given below:

1. UV1 – Fast change of transformer ratios of the transmission part of the network and the head transformers of the distribution part of the network.
2. UV2 – Voltage increase at a number of synchronous compensators and hydro generators.
3. UV3 – Fast change of the transformation ratio of some generator transformers.
4. UV4 – Load shedding at some substations in case the voltage level at these substations is lower than allowed or if load shedding is necessary to reduce the current load of the network components.
5. UV5 – Redistribution of active power of generators, restoration of power supply to some consumers.

UV1-UV3 have approximately the same execution time. Their main purpose is to prevent a sharp increase in reactive power losses, increase the generation of charging power by power transmission lines, and prevent the operation of on-load tap changing (OLTC) devices of the distribution transformers of the network. The load shedding procedure (UV4) is performed after UV1-UV3. This sequence of actions is designed to reduce the amount of load that can be shed. UV5 implies the execution of the optimization procedure. Optimization of the post-failure operating conditions takes much more time compared to the time required to perform UV1-UV4.

Thus, UV1-UV4 provide fast control to eliminate the effects of the first disturbance and prevent a voltage avalanche. UV5 performs post-failure operating conditions optimization. In terms of the hierarchical approach, a hierarchy of control actions over time is implemented here.

An example of a MAS ECS for controlling the reactive power of generators. The following is a discussion of the ECS MAS, which provides reactive power control, prevents emergency tripping of generators, and keeps the voltage on the load buses within acceptable limits.

The considered MAS consists of agents of two types: Load Agents and Generator Agents. Any agent at any time has access to the following set of local data:

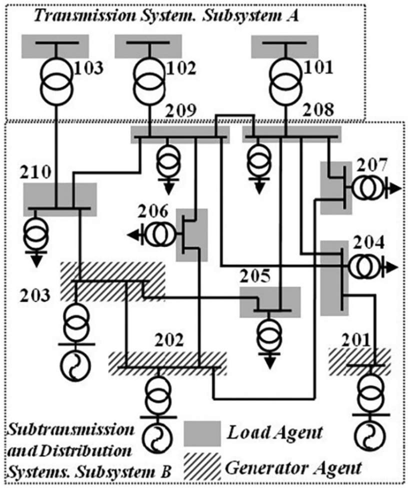


FIGURE 4.6 Part of the modified IEEE One Area RTS-96 system.

1. local operating conditions parameters (primary and secondary voltage, active power flows, etc.).
2. equipment operating conditions characteristics (generator output voltage, transformer OLTC tap number, generator excitation current, etc.).

Any agent at any one time has two goals:

1. local – maintenance of local operating conditions parameters and characteristics of local equipment operation within permissible limits,
2. global – preventing a voltage avalanche.

To ensure that the different parts of the MAS work independently, each agent must have knowledge of only those agents that have the maximum impact on its work. For example, (see Fig. 4.6), the Load Agents installed in Subsystem A must have sufficient knowledge of the agents installed in Subsystem B, because these agents can have a significant impact on their work. On the other hand, although the agents in Subsystem B must have sufficient knowledge of each other, they only must know about the three agents in Subsystem A, the Load Agents, since only these agents can affect their work. With this distribution of agent information, the distribution part of the EPS has minimal impact on the transmission part of the EPS.

The following simple *Voltage Control Ontology* can be proposed for the purposes of the MAS being developed:

1. *Actions of agents:*
   - Increase reactive power.
   - Stop increasing reactive power.
   - Start load shedding.

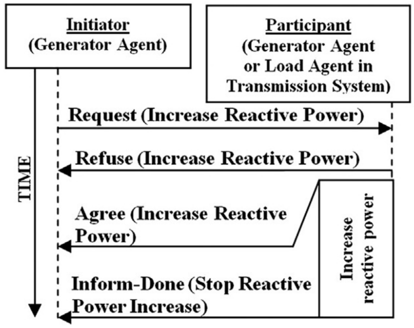


FIGURE 4.7 Request Interaction Protocol.

2. *Terms:*
   - Owner.
   - Voltage level.

The Generator Agent receives local information about the magnitude of the excitation current, the primary and secondary voltages on the substation buses, the active power flows, and the number of the generator transformer OLTC tap. If the excitation current exceeds the maximum allowable value, the Generator Agent tries to rule out the possibility of a generator tripping due to overload. To do this, it sends messages to other agents who are able to reduce the reactive power shortage in the affected region. The action sequence diagram for the *Request Interaction* protocol used by the Generator Agent is shown in Fig. 4.7.

The Generator Agent can use some set of rules that would allow it to decide whether to send a message to one agent or another. The Generator Agent always knows when the reactive power increase process in its subsystem is over. If the process of reactive power increase is over, but the Generator Agent is still in the overexcited state, it starts the procedure of shedding the consumer load.

The FIPA standard *Contract-Net Interaction protocol* is used to perform the load shedding procedure. The initiator agent of this protocol seeks to optimize some function that characterizes the load shedding process. To that end, it:

1. sends n requests of the *Call For Proposal* type (the request contains the voltage level value on the primary side of the substation of the Load Agent) to various Load Agents and receives from them m proposals and k refusals (Fig. 4.8).
2. accepts j proposals and sends j *Accept Proposal* messages to the Load Agents with the lowest voltage levels.

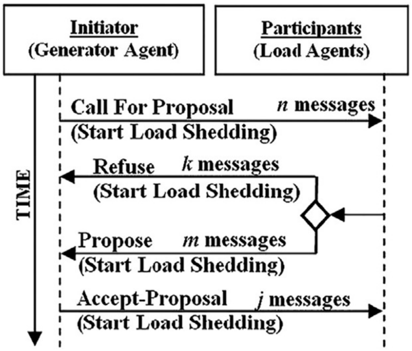


FIGURE 4.8 Contract-Net Interaction protocol.

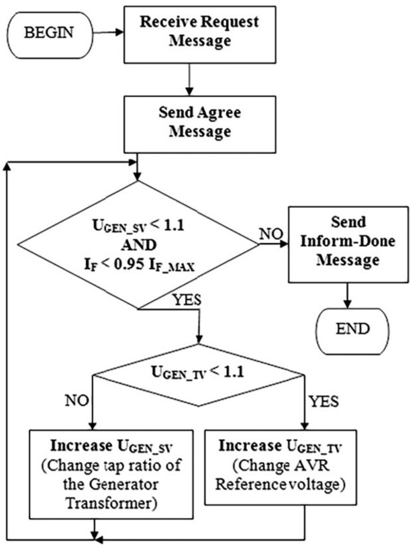


FIGURE 4.9 Algorithm of increasing the reactive power generation: $U_{GEN\ SV}$ - secondary generator voltage, $U_{GEN\ TV}$ - voltage at the generator terminals, I_F - excitation current, $I_{F\ MAX}$ - maximum allowable continuous excitation current.

The Generator Agent is also able to receive a request to increase reactive power generation and analyze the operating conditions of the generator. The algorithm for increasing the reactive power generation is shown in Fig. 4.9.

The Load Agent receives local information about the primary and secondary voltages on the substation buses, about active power flows, and about the tap-off number of the load transformer. The Load Agent participates in the load shedding procedure: having received an *Accept Proposal*

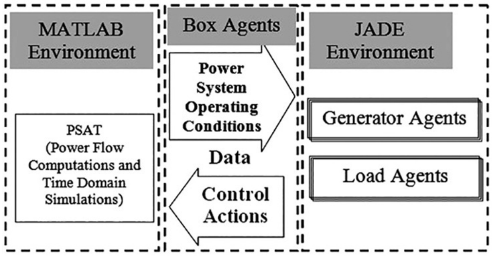


FIGURE 4.10 Software implementation of the MAS.

type message, it starts to shed the load on its substation buses until the primary voltage rises to a certain preset level. It can also shed the load independently in the event of a critical voltage drop on its substation buses. If the Load Agent is located at the substation where the transformer of the transmission part of the network is installed, it can take part in the reactive power control (Fig. 4.9). In this case, the Load Agent changes the OLTC tap of the transmission transformer until the primary voltage drops (or the secondary voltage rises) to some set value. When changing the OLC tap of a transformer, the Load Agent must coordinate its actions with the Generator Agents of the transmitting part of the network.

The software implementation of the MAS. Almost any programming language can be used to program agents, but object-oriented languages are the most suitable because the concept of an agent is very similar to that of an object.

The computer model of the considered MAS was implemented in the JADE agent development framework [69] and uses the capabilities of the JAVA language. Agents developed for the JADE platform consist of three main layers: the *message handling layer*, the *behavioral layer*, and the *functional layer*. The message handling layer is responsible for sending and receiving messages. The behavior layer provides control over the order in which the agent's behaviors are executed. The functional layer is responsible for the actions that the agent can perform. JADE provides a complete set of the following features: full compliance with FIPA specifications; efficient asynchronous message transport; simple agent lifecycle management procedure; library of interaction protocols, etc.

The necessary calculations of steady-state operating conditions and continuous transients were performed in the Matlab®/PSAT environment [70]. The capabilities of the JAVA language were used to perform communication between the Matlab/PSAT and JADE environments (Fig. 4.10).

The connection between the Matlab environment and the JADE agent environment was achieved by means of *Box Agents*. Box Agents are JAVA objects that contain different data structures. In the continuous transient calculation cycle, the Box Agents transfer information about the state of the system at each integration step from the Matlab environment to the JADE environment. Then, the agents in the JADE environment process the information received from the Box Agents and, if necessary, generate some set of CAs, put the CA information into the Box Agents, and pass the Box Agents back to the Matlab environment. Thus, all calculations are performed within the computer's RAM and do not require the use of a hard disk. This approach greatly speeds up the modeling process. The proposed software implementation of the MAS allows us to use the capabilities of the Matlab environment and simulate the complex behavior of agents.

4.5 Hierarchical modeling and emergency control of electric power systems

Unique features of the problem. In complex EPSs, hundreds of thousands of disturbances of different nature occur throughout the year, which in the vast majority of cases are eliminated by protection equipment (PE) and emergency automatics (EA), as well as by emergency actions of personnel, without any consequences for the system and consumers. Some emergencies "break through" the barrier of emergency control as a result of failures of PE and EC systems, errors of the supervisory control and operating personnel, and beyond-design (in extremis) emergency conditions, resulting in a cascading development of the emergency process, which is interrupted and eliminated by the next stage of the EC. Such emergencies with a cascading development of the emergency process, but without noticeable consequences for the system and consumers, occur in dozens annually in large power interconnections, such as the UES of Russia or the U.S. and Canadian power interconnections. In isolated cases, this next stage of the EC fails to cope with the emergency situation, the cascading development of which becomes uncontrollable, and a major system accident with severe, often catastrophic, consequences for the system and consumers occurs. The most unique cases are widely known and are actively discussed by experts [71,72, etc.]. Severe system accidents of the cascade type are usually associated with problems of survivability [73] or vulnerability [74] of EPSs, and their nature is objectively determined by the dynamic properties of the systems [75].

Such system accidents in complex EPSs include two main stages: development of the emergency process and system recovery. At both stages, the EPS is represented as a high-dimensional nonlinear dynamic system with discrete changes in parameters within a certain time interval.

Modeling the development of an emergency process and the choice of controls for its interruption are complex, labor-intensive problems that are characterized, in addition to the high dimensionality of the models, by the multiplicity of initial states of the system and possible ways of development of the accident. The EPS recovery process is also quite difficult to model due to the diversity of intermediate states of the system and controls, as well as the need to find the most rational strategy for its implementation [76].

To reduce the labor intensity of research, we consider an approach based on the principles of hierarchical modeling, which is characterized by the integrated use of a set of models, allowing us to consistently reduce the dimensionality of the description of the system, the set of its states and paths of development of accidents and recovery of the EPS.

Overview of the models. In a generalized form, mathematical models to study the development of emergency processes and recovery of the EPS are systems of nonlinear ordinary differential and algebraic equations of the form

$$\begin{aligned} \frac{dx}{dt} &= f(x, y, a, t); \quad x(t_o) = x_o; \\ 0 &= g(x, y, a, t); \quad y(t_o) = y_o; \\ a &= a(t_1, t_2, \ldots, t_m). \end{aligned} \tag{4.20}$$

Here, the vector x represents the dynamic state variables of generators, turbines, and boilers of power plant units with their control systems, synchronous and asynchronous motors, control systems of DC lines and links, FACTS devices, etc. The vector y includes, first of all, the state variables of the electrical network (voltages, currents, etc.), as well as some variables of the mentioned dynamic components that link them to the network. The parameters of the EPS are represented in (4.20) by the set a. Some of them change discretely in the process of accident development and recovery of the system during the implementation of the control actions of EA and personnel that are related to switching off and on of the components of the generation, power grid, and consumers.

The initial values of the state variables x_o, y_o in (4.20) represent the pre-emergency conditions in the EPS, which change during the operation of the system in accordance with the load profiles of electricity consumers, the load of generators, the load flow in the power grid. Usually, when studying the stability of the EPS and the cascade development of emergency processes, a set of the most dangerous operating conditions $Z = \{z_1, \ldots, z_L\}$ is considered, which is determined by characteristic points of load profiles (e.g., daily maximum load), the most severe levels of loading of generators and lines. Thus, x_o, $y_o \in Z$ and, for complex systems, the set Z has high dimensionality.

The vector x in (4.20) includes variables of different levels of change described on different timescales. Their influence may differ at different stages of the transition process. Taking this into account, the structure of the mathematical model (4.20) should be flexible and is formed on the basis of methods of separation of motions (singular disturbances). For example, at the initial stage, when the task is to check the stability of the EPS, the most significant are the mutual oscillations of the rotors of generators, and the slower processes in the turbines and boilers of the power plant units are not yet manifested and can be assumed not changing in time. At subsequent stages, the mutual oscillations of the rotors of the generators are attenuated and may not be taken into account in the model as dynamic state variables of the system. On the contrary, the processes in the turbines and boilers of the power plant units, as well as the dynamics of the total frequency in the EPS become significant in (4.20) [76–78].

Along with a detailed model of EPS dynamics of the form (4.20), in what follows we will use a simplified model in the hierarchical research technology, in its general form written as

$$\frac{d_x}{d_t} = f\left(x, a, t\right),\ x\left(t_o\right),\ a = a\left(t_1,\ t_2, \ldots t_m\right). \tag{4.21}$$

The simplifications in (4.21) are associated with not taking into account the dynamics of generator speed controllers, simplified consideration of the excitation control effect, and modeling the loads with constant conductivities. As a result of the latter assumption, the electrical network becomes passive, which allows one to exclude the network nodes, for example, by the transformations known from electrical engineering, such as "star-delta" and "delta-star". As a result, we obtain a simplified model of the electrical network in (4.21) in the form of a complete polygon of intrinsic and mutual conductivities with respect to the nodes of the application of the generators' electromotive force. In physical terms, the model (4.21) is written in the form (4.22)

$$\frac{d^2\delta_i}{dt^2} = \frac{1}{T_{Ji}}(P_{Ti} - E_i^2 g_{ii} - \sum_{\substack{j=1 \\ j \neq i}} E_i E_j b_{ij} \sin\left(\delta_i - \delta_j\right),\quad i = \overline{1, n}. \tag{4.22}$$

Here P_{Ti} - turbine power, δ_i - rotor angle of the generator i in relation to the conditional synchronous axis, E_i - generator electromotive force, g_{ii} and b_{ij} - intrinsic active and mutual reactive conductivity in relation to the nodes of the application of generators' electromotive force, T_{Ji} - generator inertia constant, n - number of generators in EPS.

Thus, at each stage of the process, depending on the research objectives, a different mathematical model of the dynamics of the EPS can be used while taking into account the factors that are significant for this stage. Excluding unimportant variables simplifies the model, but one needs to monitor for calculation errors. Additional simplification of the model (4.22), reducing its dimensionality, is possible by taking into account the heterogeneity of the structure of the complex EPS. Tightly coupled oscillators make coherent (coordinated) motion in the transient and can be replaced by a single equivalent oscillator [79,80].

The listed characteristics of power plant dynamics models allow applying the technology of hierarchical modeling [81] in the study of the occurrence and development of cascade accidents and recovery of the system after them.

Hierarchical modeling problems. Let us consider the hierarchical principles of modeling as applied to the two following problems.

A) *The first problem* is related to the assessment of conditions under which the cascade development of accidents in the considered EPS given its specified circuit is possible. The solution to this problem is based on performing a series of successive stages, using at each successive stage an increasingly detailed mathematical model of the EPS while reducing the set of conditions affecting the result.

Let $Z = \{z_1, \dots, z_L\}$ be the set of dangerous operating conditions of the system, and $V = \{v_1, \dots, v_K\}$ be the set of disturbances (short circuits in lines, emergency shutdowns of generators, lines, consumers, etc.), which can be superimposed on each state $z_l \epsilon Z$. In some combinations of $\{z_l, v_k\}$, where $l = \overline{1, L}$; $k = \overline{1, K}$, the stability of the EPS is preserved, in others it is disrupted. Cases of system instability are dangerous from the point of view of cascading accident development.
At the first stage of the study, the so-called design conditions are determined, which are a set of combinations of $\{z_l, v_k\}$ in which the stability of the EPS can be compromised. Since for a complex system the number of such combinations is quite large, we use the simplest mathematical model of the dynamics of mutual oscillations of pairs of oscillators, which is easily obtained on the basis of the model (4.22) with certain assumptions about the motion of other oscillators [80–82]. This allows one to form a square matrix of the metrics $\{w_{ij}\}$; $i, \ j = \overline{1, n}$, where n is the number of generators in the system, reflecting the dynamics of their interaction under the conditions in question.

The analysis of the matrix $\{w_{ij}\}$ enables the following:

1. identify the combinations $\{z_l, v_k\}$ that are not dangerous from the point of view of the stability of the EPS, and that are unnecessary to analyze in the future;
2. combine the remaining combinations of $\{z_l, v_k\}$ into clusters based on the proximity of the system response, so that for a cluster combining pairs $\{z_s, v_p\}$...$\{z_r, v_q\}$, where $(s, r) \epsilon L$; $(p, q) \in K$, the relation $E(w_{ijsp} \approx E(w_{ijrq})$; $i, j = \overline{1, n}$ is valid, where E is some operator. Let us denote the resulting cluster as $G_d, \ d \epsilon D, \ D$ - a set of clusters. Here, w_{ijsp}, w_{ijrq} are the values of the matrix of metrics $\{w_{ij}\}$; $i, j = \overline{1, n}$, for the combination of conditions $\{z_s, \ v_p\}$ $\{z_r, v_q\}$, respectively. The operator E represents,

for example, the Euclidean norm of the matrix $\{w_{ij}\}$; $i, j = \overline{1,n}$ or some other similar estimate;

3. select for each cluster a representative combination of $\{z_{ld},\ v_{kd}\}$, the set of which forms the design conditions for which a more detailed analysis of the dynamics of the EPS is required. As a representative combination of $\{z_{ld},\ v_{kd}\}$, for the cluster it is reasonable to choose E that is the worst one in the sense of the estimates of the operator. The results, which will be obtained at the second step for the worst combination $\{z_{ld},\ v_{kd}\}$ will be known to be true for other combinations $\{z_l,\ v_k\}$ of the cluster.

The second stage is associated with studies of the transients of the EPS given a set of design conditions in order to determine the stability of the system and the choice of control actions to ensure stability. At this stage, a mathematical model of the dynamics of the EPS at short time intervals within a few seconds of a transient process of the form (4.22) is used [82]. As a result, the set of design conditions is significantly reduced to $D^* \subset D$, where D^* is combinations of design conditions that are dangerous from the point of view of cascading emergency process.

At the third stage, the conditions of cascading emergency processes given possible failures of EC devices, errors of supervisory control personnel, unique combinations of design conditions $\{z_{ld^*},\ v_{kd^*}\}$ $d^* \epsilon D^*$ are investigated [80,82]. In this case, one uses a mathematical model of continuous transients in the EPS (one of the varieties of the model of the type (6.20)) with a representation of dynamic characteristics of system components at intervals of up to several minutes or dozens of minutes, with shutting down of power plants and consumers, division of EPSs into isolated subsystems when acted upon by EA devices. The purpose of this stage is to determine the control actions of the EA that interrupt the cascade development of the accident at its early stages.

B) *The second problem* is related to the recovery of the EPS after severe system accidents, where the need for hierarchical modeling arises when analyzing the feasibility of the next recovery step, assessing the risk of failure of this process, and choosing the most rational strategy for its implementation [83,84].

When restoring a complex EPS from a severe post-emergency condition, the following measures can be used: introduction of a fast power reserve, connection of consumers disconnected during the development of the accident, synchronization of power plants with the system and individual subsystems with each other, loading of power plants, etc. At each successive recovery step i for the state S_i, the EPS stability reserves must be met in order to guarantee the transition to this state from the previous one S_{i-1} and not to allow the recovery process to fail.

Assessment of the feasibility of the EPS state S_i can be performed in three steps. The first stage is similar to the corresponding stage of the previous problem, but with a certain simplification, because in this case for one current state S_i we consider only one condition z_i, and the set of disturbances $V = \{v_1, \ldots, v_K\}$ remains the same. The second stage is also similar to the corresponding stage of the previous problem with the difference that in this case the control actions of the EA means are already set, and the fulfillment of the condition of the stability of the EPS can be achieved only by changing the state variables (load of power plants and the load flow in the network). The third stage is related to the analysis of the risk of recovery failure in case of sudden disturbances at the step i, failures of emergency control means, etc., and is performed by modeling the emergency process over a long time interval.

The rational strategy of EPS recovery can be determined using mathematical models at two levels: analysis of possible ways of recovery (with a relatively simple model), the study of the chosen rational strategy (on the basis of a detailed model of the long-term dynamics of the EPS).

Procedures for selecting control actions in both problems can be formulated in terms of optimal control methods. However, such formalization may require oversimplification of the model of the dynamics of the EPS. To avoid this, one can use the method of directed simulation based on factorial design of experiments to estimate the gradient of the objective function and choose the direction of change of the factorial design toward the optimum.

In its formalized form this problem is represented as a search for an extremum of the objective function

$$\text{extr } F(u) \tag{4.23}$$

subject to the constraints given in the form of systems of equations, equalities, and inequalities,

$$f_i(u) \leq 0, \quad i \in I, \tag{4.24}$$

and constraints verified by simulations of transients in the EPS,

$$f_j(u) \leq 0, \quad j \in J, \tag{4.25}$$

In (4.23)–(4.25), either parameters a or initial values of state variables x_0, y_0 of the models (4.20), (4.21) act as the optimized variable u.

The movement to the optimum when changing the gradient of the objective function is performed according to the expression

$$u^{s+1} = u^s - \frac{h\partial F(u^s)}{\partial u}, \tag{4.26}$$

where $s = 0, 1, 2, \ldots$ - the steps of directed simulation, h - the constant that determines the magnitude of the shift of the factorial design of experiments towards the extremum of the function $F(u)$.

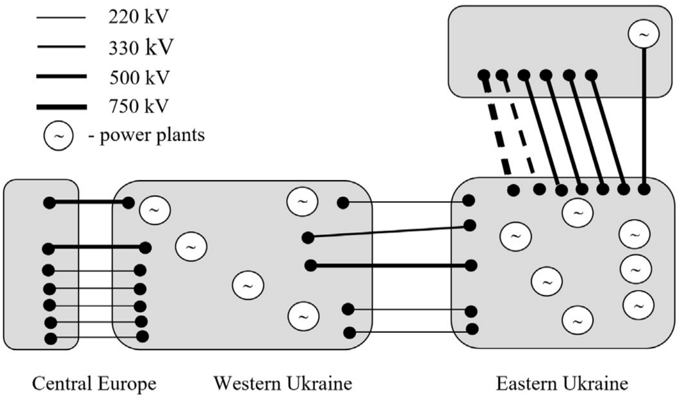


FIGURE 4.11 The structural diagram of the power interconnection.

The rational structure of the algorithm is achieved by using saturated factorial designs of experiments and a simplified model of the dynamics of the EPS while moving toward an optimum with a transition to a more detailed model near it [84].

A demonstration example. Using the case study of the Ukrainian power interconnection (Fig. 4.11), let us consider the unique features of the processes of development of a complex hypothetical emergency situation and recovery of the system afterward (Fig. 4.12) [84]. The hypothetical emergency scenario was as follows.

Due to the emergency overloading of transmission lines from the Central European EPS, the power interconnection is divided along these lines with the failure of the EA, which disconnects the excess generation, and the emergence of a large excess capacity in the western part of the Ukrainian power interconnection. Overloading of transmission lines between the western and eastern parts of the power interconnection leads to division along these lines after a long asynchronous run due to the failure of the asynchronous operation elimination automatics. In this case, due to a long asynchronous run, two units of the South Ukraine NPP are shut down by process protections.

In the thus separated western part of the power interconnection, two nuclear power plants, Rivne and Khmelnitsky NPPs, are shut down because of a rapid increase in frequency, after which the frequency is restored almost to the rated value.

In the eastern part of the power interconnection, three units at the Zaporizhzhya NPP are shut down during out-of-step conditions and this part of the system is separated from the ES Center of Russia due to overloading of the transmission lines. The frequency is reduced to 46,5 Hz, automatic frequency unloading is operating, as a result of which the frequency increases to an acceptable level.

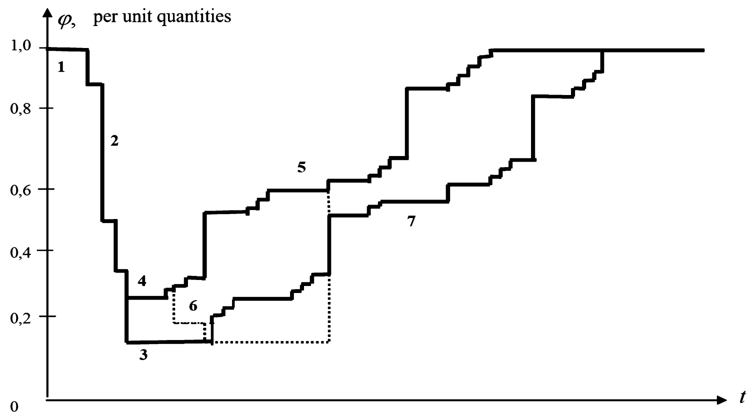


FIGURE 4.12 Processes of the accident development and recovery of the power interconnection of Ukraine (1 - pre-fault state; 2 - accident development; 3 - post-fault operating conditions of the western part of the power interconnection; 4 - the same for the eastern part; 5 - recovery of the eastern part; 6 - failure of recovery of the eastern part; 7 - recovery of the western part; $\varphi = P_n\,|f - f_0|\,/\,P_{nf}\,f_0$; and P_{n0} - load capacities, current and during the pre-fault operating conditions; f_n and f_0 frequency in the system, current and during the pre-fault operating conditions; t - time).

The analysis of the recovery process of the power interconnection revealed a weakness in its eastern part in the post-emergency condition due to the overloading of some transmission lines in the direction of the IPS of the Central federal district of the Russian Federation, which could lead to a breakdown of the recovery process and aggravate the consequences of the accident (Fig. 4.12). Therefore, it was necessary to correct the post-fault condition of the eastern part of Ukraine's power interconnection in order to eliminate this weakness and guarantee the implementation of a rational strategy to restore the EPS (Fig. 4.12).

Thus, due to the growing scale and complexity of the EPS, the relevance of research on severe system accidents of cascade nature and system recovery after them increases. The unique features and complexity of the behavior of the EPS give rise to problems of modeling states and processes in the system, which are effectively solved on the basis of hierarchical modeling principles.

4.6 Automatic hierarchical volt/var control of electric power systems under normal and post-emergency conditions

Introductory remarks. In this section, the principles of building a system of automatic voltage control in the power grid are considered using the case study of the real design of the voltage and reactive power control system as implemented for the Magadan EPS.

In the Magadan EPS, the main generation is concentrated hydro generation, represented by Kolyma and Ust-Srednekanskaya HPPs, located at a distance of about 100 km from each other. Such concentrated generation creates difficulties with optimal control of voltage in the network. If it is possible to set a certain level of voltage on the buses of the HPP in the normal circuit, depending on the time of the year and overall load, so that this will be optimal for the EPS, then in repair operating conditions there will be situations in which in one part of the power plant voltage will be below the rated value, and in the other - that close to the maximum allowable value. Under such conditions, the centralized voltage control in the Magadan EPS achieved by changing the HPP reactive power generation alone proves ineffective.

In fact, the only effective way of voltage control in the Magadan EPS is the use of existing and installation of additional reactive power sources (RPS), which, being produced in a controlled version, are already components of an active-and-adaptive electrical network.

Given that voltage problems often occur during accidents, which are random and not predictable events, it is necessary to provide automatic control of the RPSs in order to avoid situations of static stability disruption.

At present, the Magadan EPS is already using "battery of static capacitors - controlled shunt reactor" packages. Additional reactive power control devices may be installed in the future. In general terms, when considering the voltage control problem, we can distinguish two ways to place and control reactive power sources:

Method 1 is redundant, that is when RPSs with a large control reserve in terms of generation and reactive power consumption are installed at important nodal substations. With reactive power reserves, it is possible to ensure a fixed voltage level at a given point in the network under any operating conditions. The control algorithm, in this case, is local, i.e., according to the local voltage measurement at the substation, the selection of the composition of RPS components included in operation (capacitors, controlled and uncontrolled reactors) is performed. The disadvantage of this method is the need to install a redundant array of RPS elements at several nodal substations. Given that the cost of the RPS includes not only the cost of capacitors and reactors but also the cost of cells (220, 110, 35, 10 kV), this drawback is significant.

Method 2 is a coordinated one, i.e., when RPSs are installed at important nodal substations with minimum control reserve in terms of generation and reactive power consumption. Maintaining the voltage within the optimal range is done by coordinated control of the RPSs at different facilities, combined with coordinated control of the voltage on the HPP buses. In comparison with Method 1, a more complex system of distributed control

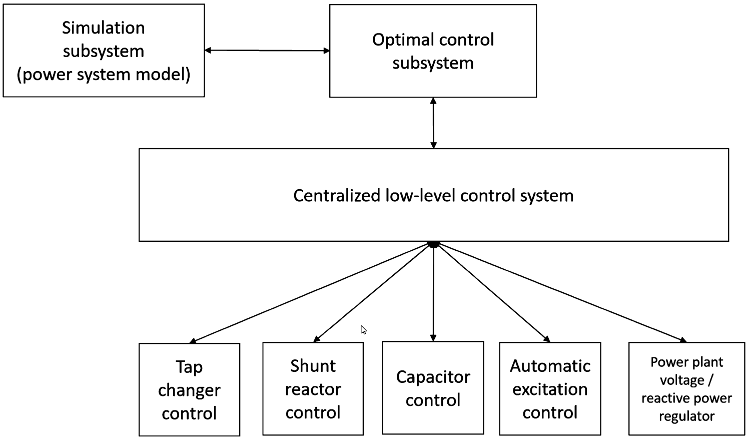


FIGURE 4.13 Generalized structure of the voltage control complex.

is required here, which calls for communication channels, but the requirements to the volume of primary equipment of RPSs are significantly reduced, which is especially significant taking into account that in Method 2 power reserves of RPSs are determined given possible repairs of elements of RPSs.

The most promising and at the same time more feasible, from an economic point of view, is Method 2.

System architecture. To ensure reliable and error-free control, the automatic voltage and reactive power control system is divided into several functional systems. The structure of the complex is shown in Fig. 4.13. At the lower level of the complex, there are local controllers of control devices and the centralized coordinating system of operating conditions automatics. At the upper level, there is the optimal voltage control system.

Functions of the centralized coordinating system of operating conditions automatics:

1. Interaction with and monitoring of control devices.
2. Transmission of status information of local controllers to the optimum control system via a standard protocol (IEC 60870-5-104 or IEC 61850).
3. Processing of the control task from the optimal control system.
4. Transmission of control actions to local controllers. Conversion of control actions into the form required for a particular type of controller.
5. Control of process constraints and consistency of constraints.
6. Registration and archiving of information, including incoming commands from the optimal control subsystem.

The optimal voltage and reactive power control system cyclically performs the following tasks:

1. Collection of information about the current state of the system.
2. Formation and updating of the nodes/branches model.
3. State estimation.
4. Operating conditions prediction.
5. Formation of constraints for optimization.
6. Dynamic optimization with constraints.
7. Analysis of optimization results.
8. Formation of control actions and their transmission to the coordinating system.

Failure of computationally intensive mathematical algorithms of the optimal control subsystem does not lead to failure of the whole system but transfers the system to operate as governed by local control algorithms that provide less optimal, but acceptable control. In addition, the optimal control system itself provides redundancy for each of the computational algorithms. Thus, the dynamic state estimation algorithm is backed up by a less accurate but more reliable static state estimation algorithm. Predictions using machine learning algorithms are backed up by coarser but more reliable approximation algorithms. Dynamic optimization is backed up by static optimization.

State estimation. The task of state estimation is to obtain the steady-state operating conditions that would be closest to the available measurements:

$$\overline{v}-v(x)\rightarrow 0, \tag{4.27}$$

where $\overline{v}$ are measured operating conditions parameters, $v(x)$ are operating conditions parameters calculated by values of the system state vector x.

We have developed an original state estimation method using the classical algorithm [85,86] together with the algorithm for dynamic state estimation based on the sigma-point Kalman filter [87]. A flowchart of the combined algorithm is shown in Fig. 4.14.

State estimation is performed based on the node/branch model generated by the topological processor of the ANARES software package [88]. Input data for the topological processor are a graphical single-line diagram of the electrical network and the state of switching devices.

To solve the static state estimation problem, the weighted least squares method is used, which is based on minimizing the following objective function:

$$J=[\overline{v}-v(x)]^T R_v^{-1} [\overline{v}-v(x)] \tag{4.28}$$

where $\overline{v}$ are measured operating conditions parameters, $v(x)$ are operating conditions parameters calculated by values of the system state vector x. The matrix R_v is a covariance matrix, which is a diagonal matrix of measurement variance $R_v=diag\left\{\sigma_{v1}^2,\sigma_{v2}^2,\ldots,\sigma_{vm}^2\right\}$ if there is no correlation between the different measurements, m is the number of measurements.

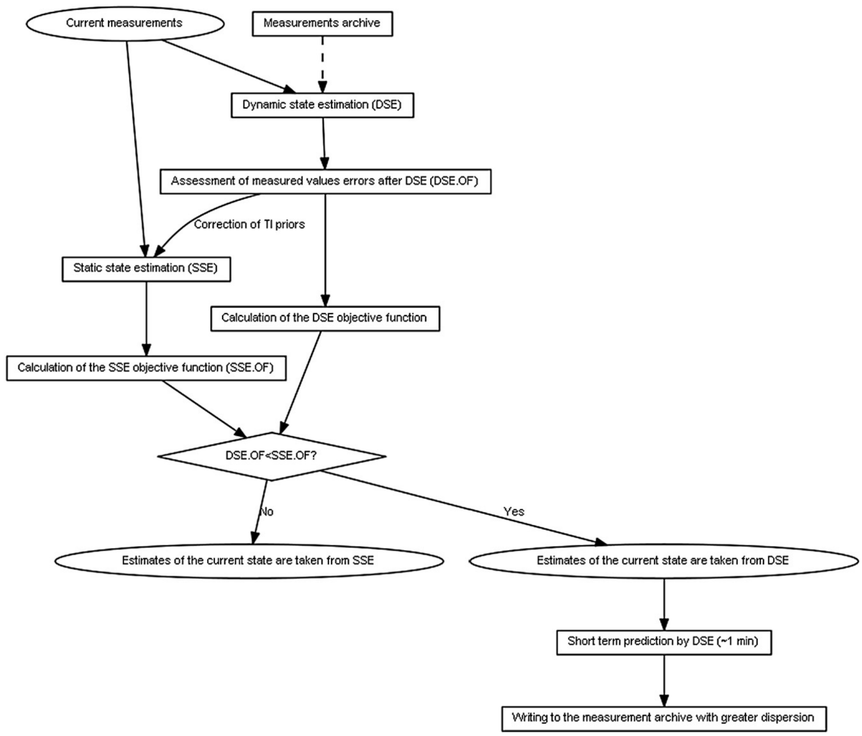


FIGURE 4.14 State estimation algorithm.

The result of the state evaluation is the state vector $\hat{x} = \left[\hat{U}_1, \hat{U}_2, \ldots, \hat{U}_n, \widehat{\delta}_1, \widehat{\delta}_2, \ldots, \widehat{\delta}_n\right]^T$, which contains the estimated values of voltage absolute values and phases for each node, n is the total number of nodes in the electrical network.

The problem of dynamic state estimation, as noted above, is solved using a sigma-point Kalman filter [87]. The prediction horizon can range from a few seconds to a few minutes, which corresponds to the interval between obtaining measurements at the moment of time k and at the moment of time $k+1$.

The method under consideration implies the selection by a special method of a set of sigma-points in the parameter space, which characterize the statistical characteristics of the desired function with sufficient accuracy.

Prediction of operating conditions. Prediction of operating conditions in the optimal operating conditions and reactive power control subsystem is performed by a combined algorithm that uses prediction based on load

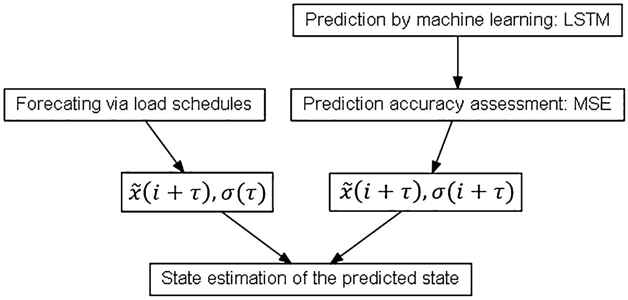


FIGURE 4.15 Generalized prediction algorithm.

profiles and machine learning using ANNs. A generalized flowchart of the prediction algorithm is shown in Fig. 4.15. The prediction depth is up to one day.

The deep LSTM (Long Short Term Memory) network is adopted as the ANN architecture used for the refined prediction algorithm [89]. The use of recurrent LSTM networks for load forecasting allows one to obtain results not inferior to FCRBM networks [90]. At the same time, on the basis of LSTM networks, it is possible to build deep networks, which in turn allows one to identify more complex dependencies in the original data. As for the choice of a particular type of recurrent network cells, then the choice in favor of the LSTM is backed by the work [91] that analyzed different variants of deep neural networks (in particular, LSTM and GRU) and found out that LSTM with dropout technology gives the best result on all tests.

Formation of constraints. The next stage of optimal control is the formation of constraints, such as: allowable voltages, constraints on the delivery of reactive power, allowable currents and power flows at the branches of the electrical network.

The constraints can be set manually in advance for each option of the topological state of the electrical network, as well as calculated by the weighting method. To select the current set of constraints, it is necessary to classify the current or predicted state of the EPS: normal, emergency, repair, etc. Given the different topological states of the electrical network, there can be several dozen sets of constraints.

Classification of the EPS operating conditions is performed using the random forest method [92–94], which is a development of the decision tree method. An important advantage of decision trees is that they not only classify the operating conditions but also allow one to justify numerically the selected option.

Dynamic optimization. The optimum voltage and reactive power control subsystem uses a dynamic optimization algorithm to obtain optimum control actions for a given depth. Input data for dynamic optimization are

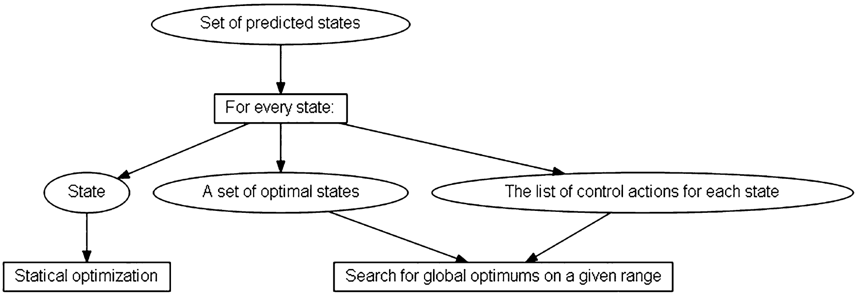


FIGURE 4.16 Generalized optimization algorithm.

the current estimated operating conditions; a set of predicted operating conditions; a list of possible control actions.

The proposed solution takes into account the cost of control actions, which depends not only on the vector of the system state but also on time. As a result of optimization, the whole time range under consideration is divided into several subranges, each of which finds the optimal solution for the given subrange. The complete objective function of the optimization problem can be written as follows:

$$f_d = \sum_{j}^{p} \left(\sum_{i=b_p}^{e_p} f_i\left(X_i\right) + C\left(\xi_j - \xi_{j-1}, i\right) \right), \tag{4.29}$$

where ξ_j=argmin$\sum_{i=b_p}^{e_p} f_i\left(X_i\right)$ - vector of optimal control parameters within the subrange; b_p and e_p - indices of the beginning and the end of the subrange in the time slice; C - cost function of actions, which depends on the cost of each specific action, taking into account the time specified by the index i; ξ_0 is taken equal to the initial value of control parameters X_0; f_i - objective function of each optimization subproblem including active power losses; deviations from the acceptable voltage ranges; violations of operating conditions constraints.

The cost of controlling C this or that equipment depends on such factors as the remaining service life of the equipment; the priority of using the CA; the minimum allowable time between switching actions of the same device.

A method based on the L-BFGS-B algorithm is used as a method for finding the local optimum in the dynamic optimization process [95–97]. This method is quasi-Newtonian and takes into account the constraints on the control parameters.

The dynamic optimization algorithm in its generalized form is shown in Fig. 4.16.

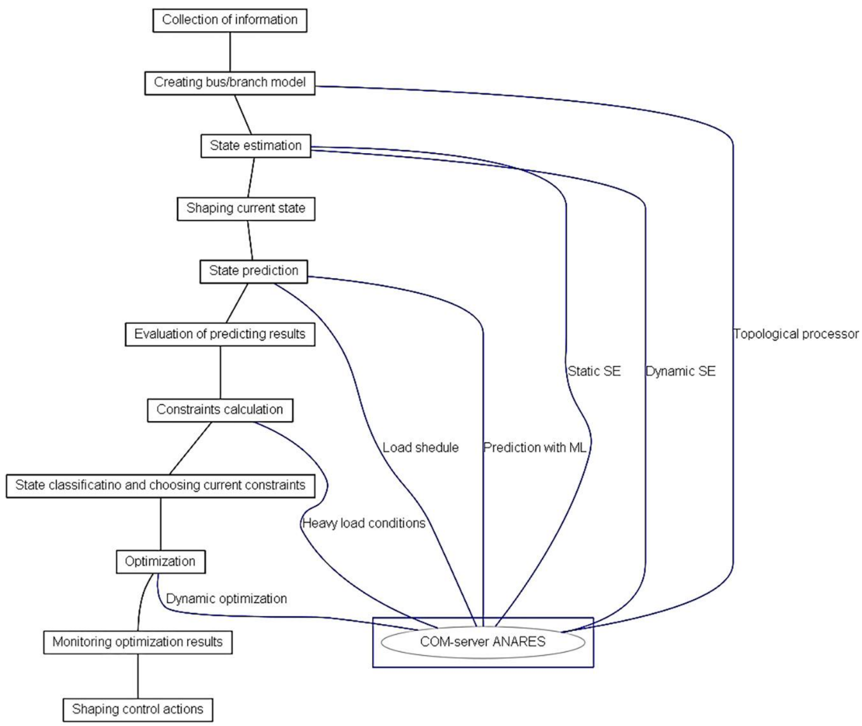


FIGURE 4.17 Embedded version of the system of optimal control of voltage and reactive power in the electrical network.

This statement of the dynamic optimization problem makes it possible to obtain the optimal value for the entire period of time under consideration. The search for the global optimum over the entire prediction range is carried out taking into account the cost of the CA factored in the overall objective function.

Software implementation. A subsystem for optimal control of voltage and reactive power of the EPS is developed on the basis of the ANARES software package [88]. This subsystem can be used as part of the automatic voltage control system, as well as for other similar tasks.

For operating systems of the Windows family, the embedded version is implemented as a COM-server (Fig. 4.17). For Linux, it is possible to implement an embedded version of the optimal control subsystem as a RESTful web server communicating with the target system in the JSON format.

The proposed approach to the construction of a hierarchical complex of automatic voltage control allows combining modern methods of machine learning with conventional computational methods, which provides high control reliability. The presented system has an industrial implementation and can be used not only for voltage control but also for other tasks of optimal control of electrical operating conditions.

4.7 Hierarchical modeling for increasing the flexibility of electric power systems with renewable energy resources

Introductory remarks. Modern electric power systems (EPS) are some of the most complex man-made spatially distributed engineering facilities that rely on innovative technologies for the production, transmission, distribution, storage, and consumption of electricity. EPSs are constantly evolving under the influence of many objective factors that determine the electricity demand on the part of economic sectors and the social sector. In the process of development of the EPS, their structure and properties change under the influence of new technologies and facilities. There is a need to study these new properties, new problems in the operation of systems, and, accordingly, the need to use new means to ensure the normal operation of the EPS.

This section considers the definition of a new property of flexibility of the EPS, analyzes the factors that reduce the level of system flexibility, formulates measures to increase the flexibility of modern and, especially, future EPSs, covers the methods developed to justify these measures based on hierarchical modeling when optimizing the measures under consideration. This way we pursue the main goals of the joint Russian-German project, supported by the Russian Science Foundation (RSF), Project No. 19-49-04108, and by Deutsche Forschungsgemeinschaft (DFG), Project No. RE 2930/24.

Definition of the flexibility property of the EPS. Due to the relatively short period of interest in the property of flexibility of systems, its definition has not yet been established and there are several similar versions [98–101, etc.]. By way of illustration, let us present a few definitions of the property of flexibility.

- An engineering system is flexible if its design parameters are defined in such a way that, taking into account the use of the control subsystem, the system meets all requirements and constraints at every moment of its operation subject to the impact of any uncertain factors [98].

- Flexibility of operation - the ability of the EPS to respond to change in electricity consumption and production - is a characteristic of all systems operating in conjunction with the main EPS, with a high level of variable renewable energy sources [99].

- Operational flexibility is the ability of the EPS to absorb disturbances in order to maintain a safe state of operation. Localized flexibility is operational flexibility at a given node of the EPS [100].

- The mass adoption of variable renewable energy sources significantly increases the uncertainty of electricity generation and consumption. This requires that the EPS has the ability to adapt to changes in its state in the required time and at minimum cost [101].

Summarizing the above and other concepts, we can propose the following definition of the flexibility property of the EPS: flexibility of the EPS is its ability to maintain a normal or close to normal state under the influence of internal (sudden changes and fluctuations in load, flows through the lines and generation) and external (sudden disturbances of different origin) random (uncertain) factors.

Sudden changes in loads can occur due to random irregular fluctuations in electricity consumption as determined by the classic case of variability in the power consumption of many current-using equipment items (e.g., determined by the operating conditions of many machines in a machine manufacturing plant), the uncertainty of the spot (balancing) electricity market (arising from the random electricity pricing in this market and the dependency on this random nature of obligations under contracts for the purchase and sale of electricity), the activity of consumers controlling their own power consumption in real-time (from the perspective of the EPS supervisory control personnel it appears as a random process of power consumption by an active consumer).

Random fluctuations in generation are characteristic of generating units based on renewable energy resources (wind turbines, photovoltaic panels, small hydropower plants). The random fluctuations of generation contribute (even if to a lesser extent) to the insensitivity zones of the automatic speed controllers of conventional generating units: inside the insensitivity zone, the unit load is uncertain.

As a consequence, the superposition of random load fluctuations and generation of the specified origin forms a random process of flow fluctuations along the lines.

Accidental disturbances include the influence of external (short circuits, emergency shutdowns of lines, transformers, bus sections at substations, etc.) and internal (operation of protection and automation devices, failures of these devices, erroneous actions of personnel, etc.) factors.

Thus, in addition to the conventional factors that cause random fluctuations of EPS operating conditions variables, to which the system adapts thanks to its internal properties of self-adaptation due to the influence of static load and generation characteristics, as well as the action of control and automation systems (see below for details), nowadays we have to consider the factors whose influence is stronger, as determined by the introduction of new energy technologies, which generates new problems that require further research.

It is of interest to compare the concept of flexibility of the EPS with the known property of security of systems. In accordance with [102], security is defined as the property of the EPS to preserve the specified operating conditions under changing conditions, component failures, and sudden disturbances. Abroad, the term "security" in this context is construed as the level of risk in the realization of the system's ability to withstand sudden disturbances [103]. The above definitions show that the concepts of flexibility and security are very close in meaning. At the same time, the property of flexibility of the EPS, among other aspects considered, reflects the "internal pro-active nature" of the system, which is emphasized by taking into account the ability of its self-adaptation to influencing factors, as well as the use of a number of "active" measures to ensure the flexibility of the EPS. In this respect, security is akin to an "external", "passive" assessment of the system's capabilities in the above sense.

Trends in the flexibility changes of the EPS. Modern EPSs using conventional power and electrical engineering technologies and controls are characterized by a sufficiently high level of flexibility due to the presence of internal properties of self-adaptation, self-stabilization of systems, and control of their operating conditions. Self-adaptation of the EPS, its ability to dampen internal and external destabilizing factors, is determined by the presence of frequency and voltage regulation effects of load, the frequency characteristics of synchronous generators, as well as the inertia of rotating masses of synchronous machine rotors and the action of control, protection and automation systems. Due to the ability to self-adapt, the EPS adapts to sudden operating conditions changes and disturbances within the permissible (design) range of their values, and when operating conditions change and disturbances go beyond the permissible limits, the emergency control system is triggered, counteracting the cascading emergency situation by its containment and elimination [104].

Electric power systems of the 21st century are undergoing radical changes in their internal structure and properties due to the active use of innovative technologies in the production, transport, distribution, storage, and consumption of electricity. These changes significantly reduce the ability of future EPSs to self-adapt and self-stabilize and, as a consequence, reduce their level of flexibility. The internal factors leading to the above consequences are related to the massive use of power electronics and rectifier-inverter systems to connect high-speed gas turbine and gas-gen sets, wind turbines, photovoltaic systems, electricity storage units, DC lines and links, and variable speed electric motors of load to the EPS.

Many local current-using equipment items, including household current-using equipment, are equipped with their own rectifier devices to communicate with the EPS. At this level, local DC microsystems are actively implemented using rectifier-inverter units for communication with the EPS [105].

The growth in the use of these technologies and devices in the EPS significantly reduces the frequency and voltage load regulation effects noted above, the frequency control characteristics of generators, the inertial capabilities of the system, and, as a consequence, reduces the level of its flexibility [104].

On the other hand, the growing share of randomly fluctuating generation from renewable energy resources (wind turbines, solar photovoltaic panels, small hydropower plants) leads to a significant negative impact of fluctuations in the generated power on the self-adaptation and self-stabilization capabilities of the system, i.e., on the flexibility of the EPS. There is a new problem of damping power imbalances resulting from these random fluctuations, for the solution of which it is advisable to use energy storage based on rapidly developing innovative technologies. In general, the control systems of many devices using power electronics (FACTS, electric power storage units, DC lines and links) have high control and stabilization efficiency. The widespread use of these devices in future EPSs will provide a radical increase in the controllability of EPSs, and consequently in the flexibility, stability, and survivability of these systems [104].

Thus, a comprehensive study of the impact of new factors on the level of flexibility of future EPSs and the role of various means and measures to increase the flexibility of these systems is necessary.

Measures and means to increase the flexibility of future EPSs. To ensure the flexibility of the EPS, one should consider opportunities to increase the flexibility of generation, the power grid, and loads, as well as ensuring flexibility through protection and control systems, and to assess the effects of the integrated use of various means at these levels. These possibilities are as follows [106,107].

1. As noted above, the frequency characteristics of speed and frequency control systems of conventional synchronous generators play an important role in ensuring the flexibility of the EPS, increasing the possibility of self-adaptation and self-stabilization of these systems to mitigate the negative effects of internal and external factors. In addition to this, increasing the speed of loading and unloading of these units, increasing the depth of their unloading, maintaining the necessary level of rotating and operating reserves of active generating capacity, and increasing the reliability of fuel supply to power plants contribute to increasing the flexibility of generating units [99–101].
2. The flexibility of transmission and distribution networks can be increased by eliminating weaknesses in the network, reducing the capacity constraints of weak sections, and increasing the efficiency of utilizing the capacity of weak links. An effective measure in this regard is the use of FACTS devices [108], the control systems of which enable the stabilization of the EPS operating conditions variables and the maintenance of the required reserves of link capacities under normal, emergency and post-emergency operating conditions. Increasing

the flexibility of active transmission and distribution networks can be achieved by automatically reconfiguring the network topology [108, etc.]

3. Load flexibility is provided by the frequency and voltage regulation effects noted above, as well as real-time load control exercised automatically or by active consumers, the use of local electric power storage facilities and distributed generation units at consumers (prosumers) [100,101, etc.].
4. Integrated multi-energy systems provide additional opportunities to increase the flexibility of the EPS by using devices that produce the required type of energy at the expense of using another type of energy (for example, heat pumps, electric boilers, etc.) [109, etc.]. Innovative gas supply systems as part of integrated energy systems provide additional opportunities to increase the flexibility of power generation through the use of highly efficient gas technologies, especially in combined heat and power generation [110, etc.].
5. Efficient protection, automation, and control systems play a key role in ensuring the flexibility of the EPS [111,112, etc.]. The efficiency of these systems can be significantly increased by using intelligent technologies by increasing the accuracy of predictions of the state variables of the EPS, reducing the time for preparing control actions, and increasing the specificity of their implementation [99–101, etc.].
6. It is worth mentioning the very detailed review article [113] (393 references cited). The authors analyze the following measures to increase the flexibility of EPS: load management of active consumers; various service measures (reserves of various kinds, restoration of power plants "from scratch," etc.); energy storage, primarily that for electricity; flexibility on the generation side (maneuverability of power plant units, combined cycle gas turbines, etc.); innovative technologies of power generation by using some other type of energy (electric heating, heat pumps, electric vehicles as energy storage, etc.); measures to increase the flexibility of the electrical network, in particular, automatic configuration of the network circuit, etc.
7. It is important to use market mechanisms to effectively stimulate the use of measures to increase the flexibility of the EPS [114]. For example, in the long term, it is advisable for owners of generating assets to minimize short- and long-term costs and maximize return on capital, taking into account additional investments in the implementation of measures to increase the flexibility of the EPS, if the latter lead to improved system reliability and, consequently, reduce the risk of economic losses.

As follows from the above list of means and measures to increase the flexibility of the EPS, those of them that are specific in nature can be used either at large power plants and in the high voltage transmission electric network (in the production and transport subsystem), or in the low voltage distribution electric network and directly at consumers (in the electricity supply subsystem). In this case, the implementation of measures to increase flexibility, for example, in the subsystem of electricity supply can cause problems in the production and transport subsystem, and vice versa. Therefore, it is necessary to consider both subsystems together when studying the flexibility of the EPS.

Some key findings. In the current research practice, given the need to consider both the production and transport subsystem, as well as the electricity subsystem, two general approaches to modeling the EPS dominate when analyzing their flexibility: "top-down" and "bottom-up".

The "bottom-up" approach is local in nature and usually considers distributed means of increasing the flexibility of the electric distribution network. A case in point is the problem of optimizing the load flow in the electricity supply subsystem taking into account measures to increase the flexibility of the distribution network [114,115, etc.]. In this case, the production and transport subsystem is considered in an aggregated manner. Simplified load flow models are often used, such as linearized, partitioned models but taking into account local power grid constraints [116] as well as conditions for participation in electric power markets [117,118].

Analysis of the capabilities of the "bottom-up" approach shows [115–119, etc.] that it in principle makes it possible to obtain an estimate of the expected level of flexibility of the EPS depending on the recommended solutions for increasing flexibility as obtained by using one or another optimization method. Having said that, the result of the study remains local and isolated. For example, the result of the study may be aimed at compensating for a local fluctuation.

In the case of considering network constraints, the "bottom-up" approach involves analyzing a fragment of the electric distribution network. This approach usually does not provide a direct quantitative assessment of the level of flexibility of the EPS, but it is possible to indirectly measure the available level of flexibility by assessing its impact on the relevant components of the objective function in the optimization problem (e.g., market revenue, the level of undesirable voltage and current deviations, etc.).

The opposite approach to modeling ("top-down") is used when analyzing the prospects for the development of the production and transport subsystem, its participation in the wholesale electricity market, or the growth of electricity generation from renewable energy sources in the whole system, etc. [120,121, etc.]. In this approach, the flexibility of a large number of facilities is usually combined into a kind of virtual flexibility potential. The total flexibility potential is further modeled as the sum of available generation or load (at a certain point in time), or as the total energy amount (over a certain period of time), within which it is allowed to consider the impact of measures to increase the flexibility of the EPS. Accordingly, system flexibility is defined as the power or/and energy delivered to the EPS due to the influence of measures to increase flexibility (e.g., from powerful system energy storage facilities comparable in capacity with pumped-storage power plants).

Due to the high level of detail of the production-and-transport subsystem model, they can be used to analyze system-wide interdependencies between the various sources of EPS flexibility (distributed flexibility enhancements or high-capacity electricity storage systems) together with conventional power plants and the transmission network. Typical problems arising from this are related to the required development of the transmission grid [121], the need for large amounts of electricity storage due to the high share of renewable energy sources, etc. Most studies either reflect the role of flexibility measures for the EPS as a whole, or attempt to pinpoint actual levels of flexibility. Having said that, most studies using the "top-down" approach fail to consider the impact of distributed flexibility enhancements on electric distribution networks. Therefore, an estimate of the amount of distributed flexibility means in these cases may be overestimated due to the failure to take into account the distribution network constraints.

Thus, the analysis of the current state of research shows that two different levels (the production-and-transport subsystem and the electricity supply subsystem) use two different approaches to justify the potential of the means to ensure the flexibility of the EPS. However, the application of these incompatible approaches leads to strong limitations in the use of each of them. Thus, the results of the "bottom-up" approach are only applicable to an individual part of the system. On the one hand, if distributed flexibility means are used within the distribution network, there is little impact on the transmission network, where additional flexibility means will be needed. On the other hand, the application of distributed flexibility means at the transmission network level will generally affect the distribution grid in terms of link capacity constraints and the need for local flexibility means.

Therefore, in order to avoid modeling ambiguity, the development of a consistent EPS model is required to investigate distributed means of increasing its flexibility. The issue formulated in the joint Russian-German project is related to the development of a comprehensive unified approach to the modeling and optimization of the production-and-transport subsystem and the electric power supply subsystem to study and justify distributed means to increase the flexibility of the EPS in both subsystems. The integrated unified approach developed is based on the principles of hierarchical modeling.

Hierarchical modeling of EPS in the study of their flexibility. Due to the active development of distribution subsystems, the complexity of the problem of calculating steady-state operating conditions increases. The transmission system can no longer be analyzed in isolation from the distribution system, but their joint calculation involves a number of difficulties.

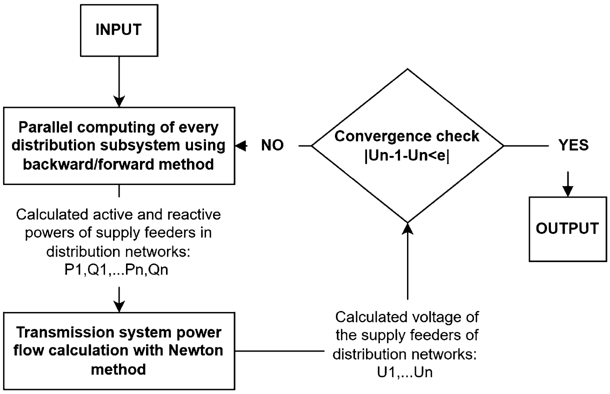


FIGURE 4.18 Flowchart of the procedure for finding a common steady-state solution for a hierarchical EPS (k is the number of iterations).

First, the conventional methods used to calculate the transmission system are not effective in the calculation of distribution networks, and second, the joint calculation in a common cycle can lead to significant time delays, which may be longer than the time of one control cycle [122], which is unacceptable. Thus, the analysis of operating conditions of hierarchical EPSs requires the implementation of the following approaches:

1. Application of different mathematical methods for the transmission and distribution parts of the network. Various modifications of the backward/forward method [123], which are used for radial networks and provide a better calculation speed and convergence in comparison with Newton's method, are most often used as a calculation algorithm for a distribution network.
2. Implementation of parallel computing for the transmission and distribution subsystems, which can significantly reduce the calculation time.

Obviously, the use of parallel computing requires the implementation of a procedure to find a common solution. As an example, Fig. 4.18 shows a flowchart for finding a common steady-state solution for a hierarchical EPS containing a common transmission part as well as an arbitrary number of distribution subsystems.

Next, we will elaborate on the optimization of hierarchical EPSs. Research published in recent years on the subject of a comprehensive analysis of the flexibility of EPSs at different levels shows that bilevel programming can be an effective mathematical tool for solving this problem. This approach is a special kind of optimization, where one problem is embedded (nested) into another. The external optimization problem is usually presented as an upper-level optimization problem and the internal one as a lower-level optimization problem [124]. The initial bilevel programming problem is stated as follows:

$$
\begin{aligned}
f_1(x_1, x_2) &\to \min_{x_1}, \\
g_1(x_1, x_2) &\le 0, \\
f_2(x_1, x_2) &\to \min_{x_2} \\
g_2(x_1, x_2) &\le 0,
\end{aligned}
\tag{4.30}
$$

where f_1, f_2 - objective functions, and g_1, g_2 - constraint functions at each level.

Bilevel optimization problems are directly related to game theory and can be equivalently described as a hierarchical Stackelberg game [125], where the upper-level optimizer is the leader and the lower-level optimizer is the follower, and the solution of the bilevel optimization problem is a Stackelberg equilibrium. In a Stackelberg game, players of the game compete with each other in such a way that the follower responds optimally to the leader's action only after the latter has made the first move. This type of hierarchical game is asymmetrical, i.e., the leader and follower cannot be swapped. This game approach differs from the classic Nash equilibrium statement, where those strategies in which everyone tries to do better for themselves by doing better for others are more optimal. As a result, in bilevel programming, the leader optimization problem contains a nested optimization problem, i.e., the follower optimization problem. The Stackelberg equilibrium occurs when the follower chooses the best response to the leader's strategy.

Most of the research on the application of bilevel optimization for joint analysis of the flexibility of the transmission and distribution systems is reduced to the so-called problem of the optimal exchange of power between these levels of the EPS. For example, in [126] the bilevel optimization problem is represented as a sequential Stackelberg game involving several leaders (distribution system operators, DSO) and one follower (system operator, SO). In such an arrangement of interaction, there are separate local markets, each of which has a DSO operating there. Flexibility resources (renewables, demand systems, electric vehicles, etc.) of electric distribution networks can be offered by DSO in the SO power transmission network, but only after the DSO has optimized and activated these resources to eliminate local imbalances. The SO is responsible for the operation of its own balancing market, where both resources from the transmission network and resources from the distribution networks can participate. Thus, the SO optimizes the activation of the active power reserve at each node of the transmission network and its decision variables are stored in the vector u_{SO}. The DSO, in turn, optimizes the activation of active power reserve, reactive power injection/consumption, and voltage at each node of the distribution network. The DSO solution variables in the local mar-

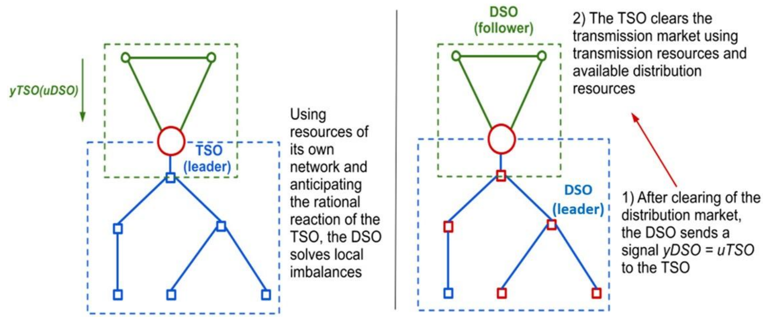


FIGURE 4.19 Graphical representation of the hierarchical SO-DSO coordination modeling arrangement by means of bilevel optimization. On the left side of the figure, the DSO expects the function of the rational response on the part of the SO, calculating y_{SO} (u_{DSO}) backwards. The waiting process takes place before the Stackelberg game. The Stackelberg game involving the DSO and SO begins in the right part of the figure. *Left* - the DSO sends the signal $u_{DSO} = i_{SO}$ to the SO, which *Right* responds rationally by activating the transmission power resources and possibly the distribution network resources if they are available. The DSO guarantees the stated power reserves sent to the SO.

ket $k \in N$ are represented by the vector u_{DSO}. The general arrangement of hierarchical modeling of SO-DSO coordination by means of bilevel optimization is presented in Fig. 4.19.

In Stackelberg's game settings, however, the consumers at the lower level of the EPS do not always act as leaders. In [127], the authors proposed a stochastic bilevel model to develop an optimal energy exchange strategy between the generating company (GenCO) and the electric vehicle load aggregator (EVLA) in the electricity and ancillary services market. Here the GenCO is set as a leader that owns companies of conventional and wind generation, and also is a party to coordination with the EVLA, which acts as a follower. Electric vehicle owners are connected to the EVLA so as to participate in the market indirectly. The stochastic intra-hour problem was that the generating company's expected profit maximization at the top level depended on the state of electric vehicle charging, and at the bottom level - on the market equilibrium of the balancing market and the day-ahead market, when the EVLA maximizes total charge (or its available energy) to encourage electric vehicle owners. The bilevel problem itself was transformed into a mixed-integer linear programming problem (MILP) using Karush-Kuhn-Tucker optimality conditions and strong duality. This allowed a Stackelberg equilibrium to be found, resulting in increased profitability for the GenCO, minimizing costs for consumers with electric vehicles, and offsetting the uncertainty associated with wind generation and active consumers.

Here it is important to note that there is no single generally accepted solution concept for bilevel optimization problems. The most popular are the optimistic and guaranteed (pessimistic) solutions. As a result of intensive research on bilevel optimization problems, many search methods have been proposed by various researchers. A promising solution is the reduction of the bilevel problem to a series of bilevel optimization problems with an optimistic solution. The latter are reduced to a series of one-level optimization problems using the penalty method and Karush-Kuhn-Tucker conditions for the (convex) lower-level problem. A more standard and simpler optimization algorithm [128] can be used to numerically solve the obtained one-level problems, which turn out to be nonconvex.

A demonstration example. Let us consider a typical problem of increasing the flexibility of the EPS, that of demand management of the active consumer as a bilevel optimization problem of interaction between energy companies and consumers themselves, who are willing and able to manage their energy consumption. Energy companies and consumers seek to maximize their income and/or reduce costs. Let $\mathcal{K} = \{1, 2, \ldots, K\}$ be a set of energy companies, $\mathcal{N} = \{1, 2, \ldots, N\}$ - set of active consumers, and $\mathcal{T} = \{1, 2, \ldots, T\}$ - finite set of time intervals. Let us state a static Stackelberg game between companies (leaders) and their consumers (followers) to find the income that maximizes prices and optimal demand. Thus, we obtain the statement of the problem in the form of bilevel optimization.

In Stackelberg games, the leader(s) first announces their decisions to the follower(s), and then the follower responds. In our problem (game), the leaders send price signals to the consumers, who respond optimally, given their demands. To capture the market competition between companies we provide for the opportunity to play the Nash game of price selection. The equilibrium point in such a game is what companies announce to their consumers.

Each active energy consumer $n \in \mathcal{N}$ receives all price signals from each energy company $k \in \mathcal{K}$ at each time interval $t \in \mathcal{T}$ and seeks to select their utility-maximizing demand for each time interval from each company, taking into account budgetary and energy needs. Let us denote the price of company k at the time t by $p_k(t)$. Let $B_n \geq 0$ and $E_n^{min} \geq 0$ denote, respectively, the budget of the consumer n and the minimum energy demand for the entire time horizon.

The utility for the consumer n is defined as

$$U_{c,\ n} = \gamma_n \sum_{k \in \mathcal{K}} \sum_{t \in \mathcal{T}} \ln(\xi_n + d_{n,k}\,(t))$$

The consumer n aims to achieve the maximum gain when reaching the threshold of the minimum amount of energy and not exceeding a certain budget. Therefore, optimization on the consumer side is stated as follows:

$$U_{c,\ n} \to \max,$$

$$\sum_{k \in \mathcal{K}} \sum_{t \in \mathcal{T}} p_k\,(t) d_{n,k}\,(t) \leq B_n,$$

$$\sum_{k\in\mathcal{K}}\sum_{t\in\mathcal{T}} d_{n,k}(t) \geq E_n^{min},$$
$$t \in \mathcal{T}\ ,\ k \in \mathcal{K}$$

Denoting the prices set by other companies as p_{-K}, the total income for a particular energy company k is defined as

$$U_{e,\ k} = \sum_{k\in\mathcal{K}} p_k(t) \sum_{n\in\mathcal{N}} d_{n,k}(p_k, p_{-k}, t)$$

Given the availability of capacity at the company k in the period t, denoted by $G_k(t)$, and for the fixed price p_{-K}, the optimization problem for the company k is to

$$U_{e,\ k} \rightarrow max$$
$$\sum_{n\in\mathcal{N}} d_{n,k}(p_k, p_{-k}, t) \leq G_k(t)$$
$$p_k(t) > 0$$
$$t \in \mathcal{T}$$

The goal of every energy company is to maximize its income and, therefore, its profits. In addition, due to competition in the market, prices announced by other energy companies also affect the determination of the price in the company k. Thus, the energy company k's price choice is actually a response to what other competitors in the market have announced; this response is also limited by the availability of energy. In this statement, we have the Nash game among energy companies.

Let us illustrate this approach by the case study of the Danish island of Bornholm, where a large-scale project to increase the flexibility of the power grids is being implemented (Fig. 4.20). The appeal of this example is the availability of complete information about the problem, including the estimates made by the company, with which we will compare the results obtained by the proposed method of bilevel optimization.

Over 50% of the considered EPS is based on RESs, including a combination of sources of distributed generation (wind, solar, biomass, biogas, and CHPP) and energy storage (heat pumps, district heating, electric vehicles), and its data are freely available for own computational experiments. Out of 28,000 consumers, 2,000 participate in flexible electricity demand management. They are equipped with demand response devices with smart controllers so as to respond to prices in real time.

As can be seen from the charts (Fig. 4.21), the solution based on the Stackelberg game yields a better result in terms of optimizing the price per kW of power than the solution by the Danish project EcoGrid EU, which implements innovations to increase flexibility in the Bornholm EPS.

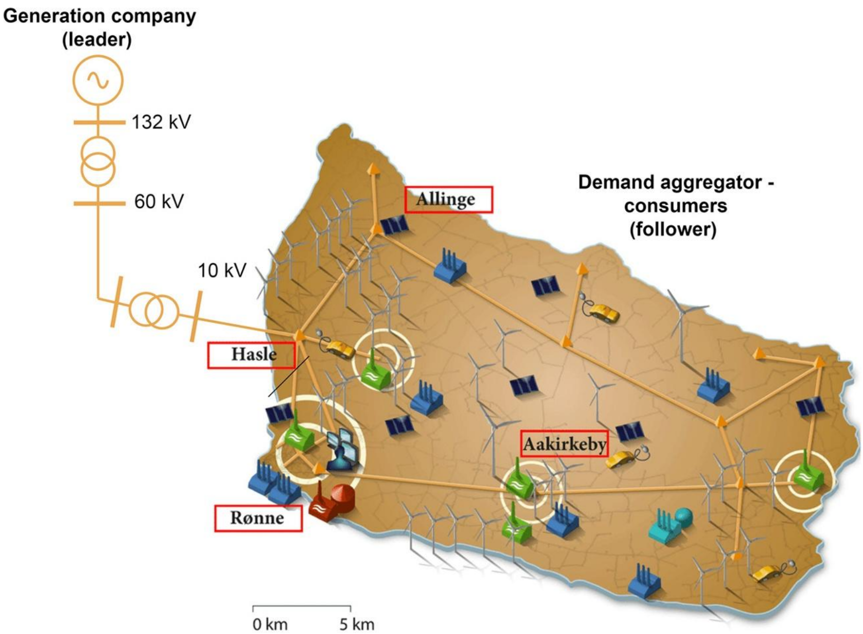


FIGURE 4.20 Simplified circuit of the Bornholm EPS, representing two levels of the EPS: the upper level - the high-voltage network (generating company) and the lower level - the low-voltage network with distributed flexibility elements.

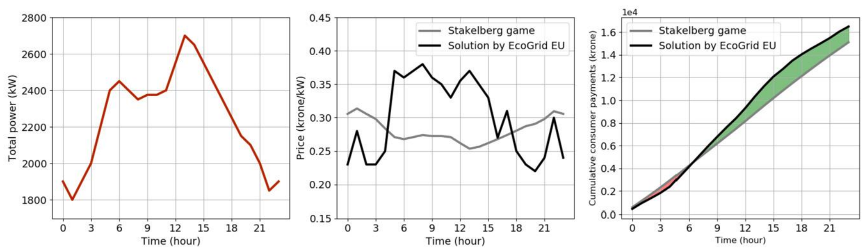


FIGURE 4.21 The results of the bilevel optimization solution of the interaction between the power company and the load aggregator: a) total load capacity per day; b) the solution obtained on the basis of the Stackelberg game and the solution by the EcoGrid EU company.

As expected, both sides benefit from the bilevel optimization model:

1. The electricity supplier, by providing economic incentives for the consumer to purchase energy during peak generation hours, engages renewable sources (judging by peak hours, it is solar generation) rather than conventional expensive fuel resources, thereby maximizing their income;

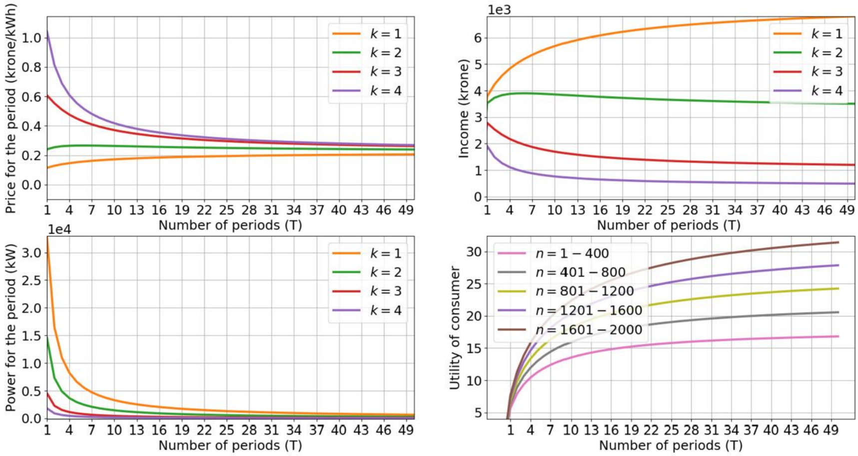


FIGURE 4.22 Results of hierarchical modeling of the interaction of several competing energy companies with active consumers.

2. The consumer, in turn, changes their profile of energy consumption in accordance with changes in the cost of electricity, thus minimizing their costs.

Let us consider the more complex case when we have not one but several competing companies at the top level of the EPS ($k = 4$). Our task will be to study the effects of hierarchical modeling of the interaction of several energy companies ($k = 1, 2, 3, 4$) with active consumers managing demand for different time periods ($T_{max} = 48$). Let us assume that energy companies have different levels of capacity available, and different numbers of active consumers have different budgets. The results of the modeling are shown in Fig. 4.22.

Based on the graphs in Fig. 4.22 we can see that the first generating company, which has more capacity ($k = 1$), can make sufficient profit by setting prices lower than those of its competitors who do not have such capacity. In this case, such a company receives more income (due to the volume of sales). Over time, the market price of electricity from different companies evens out, as the seller, who set the price below the market price, increases it because they see that the buyer is ready to buy energy at a higher price, and the seller, who inflates the price, reduces it, hoping for an increase in demand.

The utility of consumers increases as their budget grows because by engaging a greater number of active flexible consumers the aggregator increases its ability to change the consumption of electricity at a given point in time and thus increases the flexibility of the distribution network. Since we consider the problem of hierarchical modeling as based on bilevel optimization, increasing the flexibility at the lower level (low-voltage electrical

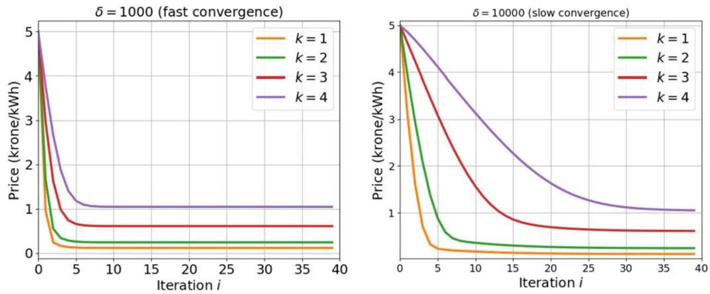


FIGURE 4.23 A study of the convergence of a bilevel optimization algorithm using the example of the Bornholm EPS.

network) leads indirectly to increasing the flexibility at the upper level (high-voltage electrical network).

The next goal of our demonstration example is to investigate the convergence of the bilevel optimization algorithm as illustrated by the case study of the Bornholm EPS. For each iteration of the algorithm $i \in \{0, 1, \ldots\}$ we denote the demand on the part of the consumer n at the time t from the company k by $d_{n,k}^{(i)}(t)$, and the price announced by the company k at the time t as $p_k^{(i)}(t)$. In our algorithm, $p_k^{(1)}(t)$ is chosen arbitrarily for each company $k \in \mathcal{K}$ and time $t \in \mathcal{T}$. Based on the initial price selection, the values of $d_{n,k}^{(1)}(t)$ are calculated. Prices are then sequentially updated using the following update rule:

$$p_k^{(i+1)}(t) = p_k^{(i)}(t) + \frac{\left(\sum_{n\in N} d_{n,k}^{(i)}(t) - G_k^{(i)}(t)\right) * p_k^{(i)}(t)}{G_k^{(i)}(t) + N + \delta * p_k^{(i)}(t)}. \tag{4.31}$$

As can be seen from the obtained charts in Fig. 4.23 and the expression (4.31) the speed of setting the market price depends on the value of δ, because for each iteration the step of change in the cost of electricity is inversely dependent on the value of $p_k^{(i+1)}(t)$.

Thus, in the example considered, the bilevel optimization model allows one to solve the problem of demand management in the EPS achieving favorable results for both parties: for the buyer - costs are minimized, for the generating company - revenues are maximized.

At the same time, competition in the market leads to the fact that the prices announced by other energy companies also affect the pricing in a particular company. The equilibrium price in the market is formed on the basis of the prices announced by each of the companies, and the price of energy of a particular company depends on the availability of its generating capacity. The company that sets the price below the market price, noticing that the consumer is willing to buy energy at a higher price as well, increases it in order to increase its income, and vice versa. The speed at which the market price is set, in turn, depends on the step at which energy companies change the cost of their services.

It is important to note that an increase in the number of active consumers and their budgets leads to an increase in the possibility of adjustment and, consequently, an increase in the flexibility of the distribution grid, as the constraints in solving the problem of reducing consumer costs change. In this case, the buyer can buy energy at a higher price, which will facilitate solving the problem of maximizing the seller's profit.

Prospects for using agent-based approach and machine learning in multilevel research of EPS flexibility. The formation of bilevel optimization models is greatly influenced by the issues with a large number of variables and the presence of probabilistic data, which significantly increases computation time and notably complicates the search for the desired equilibrium. In recent years, approaches based on artificial intelligence (AI) methods, which focus on the methodology of agent-based systems and machine learning algorithms, have been proposed to solve the problems of multilevel flexibility analysis of the EPS. Their application makes it possible to bypass two key limitations of the classical statement of the multilevel optimization problem: computational complexity and nonconvexity of the solution. Such limitations are due to the fact that the assessment of flexibility potential is not only related to the identification of available means of flexibility but also to the need to take into account a number of stochastic factors (for example, the behavior of electric vehicle consumers, the uncertainty in electricity markets, the need for heating for the CHPP and heat pumps, the probabilistic nature of RES, etc.).

The trend in the published research of recent years attests to the fact that effective solutions can be found by using reinforcement learning techniques [129–135]. These methods allow combining the optimization of EPS flexibility options with probabilistic hierarchical modeling of its behavior when considering power transmission and distribution systems together. The advantage of the reinforcement learning method is that the created virtual Markov environment (e.g., an EPS model with various flexibility components) can go through an infinite number of repetitions and scenarios in order to train the agents, who remember all the situations established and the ways to exit them that gave the maximum reward. This approach allows one to significantly reduce the computational cost (since the optimization takes place offline), especially when the dimensionality of the EPS is high, and the problem is multilevel since a trained agent or agents with knowledge of most of the optimal solutions can be used to control the EPS flexibility means in real-time.

It can be assumed that a promising approach for multilevel flexibility analysis of real complex EPSs can be the approach of agent-based bilevel cooperative reinforcement learning. In this case, the mathematical statement of the bilevel optimization based on reinforcement learning implies combining it with the so-called Markov game, x_i in the expression (4.30), which will correspond to the agent's strategy π_i, the function f_i - to its cumulative reward, and g_i - to the action space constraint [133]. A Markov game is defined by the tuple $\langle S_i, A_i, P, R_i, \gamma \rangle$ [135], where S_i - state space, A_i - action space of the agent, and A - joint action space, $P : S \times A \to P(S)$- transition function, $R_i : S \times A \to R$ - reward function, and γ - discount factor. Agents in each state perform actions simultaneously, following their strategy $\pi_i : S \to P(A_i)$. The goal of the i the agent is to maximize its discounted total reward $\sum_t \gamma^t r_i^t$, where r_i^t is the reward of the i-th agent at the time t. Assuming Agent 1 is the leader and Agent 2 is the follower, the problem is stated as:

$$\begin{gathered}
\mathbb{E}_{r_1^1 r_1^2 \cdots \sim \pi_1, \pi_2} \sum_{t=1}^{\infty} \gamma^t \, r_1^t \;\to \max_{\pi_1} \\
\pi_1 \in \Pi_1 \\
\mathbb{E}_{r_2^1 r_2^2 \cdots \sim \pi_1, \pi_2} \sum_{t=1}^{\infty} \gamma^t \, r_2^t \to \max_{\pi_2} \\
\pi_2 \in \Pi_2
\end{gathered} \tag{4.32}$$

Such statement can be considered as a version of the Stackelberg game with several states, which extends the standard bilevel optimization problem in two dimensions: 1) the objective function is represented by the summation of discounted rewards in successive states; 2) the form of the objective function is unknown and can only be studied through interactions with the environment (i.e., EPS models at different levels). In this case, we can formally define the level of cooperation in a Markov game with two players as the ratio between the aggregate reward of the agents:

$$CL = \frac{\sum_{\overrightarrow{\pi}} (V_1^{\overrightarrow{\pi}} - \overline{V}_1)(V_2^{\overrightarrow{\pi}} - \overline{V}_2)}{\sqrt{(V_1^{\overrightarrow{\pi}} - \overline{V}_1)^2 \sum_{\overrightarrow{\pi}} (V_2^{\overrightarrow{\pi}} - \overline{V}_2)}} \tag{4.33}$$

where $V_i^{\overrightarrow{\pi}}$ is an abbreviation of $V_i^{\overrightarrow{\pi}}(s_0)$ that denotes the average discounted total reward for the agent from the initial state s_0 according to the joint strategy of $\overrightarrow{\pi}$ and $\overline{V}_i = \frac{1}{\overrightarrow{\pi}} \sum_{\overrightarrow{\pi}} V_i^{\overrightarrow{\pi}}$. According to this definition, the levels of cooperation in cooperative and zero-sum games are equal to 1 and -1, respectively.

Computational experiments run on complex modeled examples of multilevel problems have demonstrated the effectiveness of the agent-based bilevel cooperative learning approach for finding Stackelberg solutions, which significantly outperforms the modern conventional approaches, including classical bilevel optimization [133].

4.8 Hierarchical modeling and control of renewable energy communities based on advanced optimization and machine learning methods

The energy industry is currently undergoing the biggest transformation since Thomas Edison. "Smart" technologies and new energy practices such as the Internet of Energy, blockchain, machine learning, digital twins, energy communities, virtual power plants, etc. are spreading at an incredible pace. A key element of the new energy industry, which is due to the large share of renewable energy sources (RES) in the energy mix, will be energy flexibility, the value of which has already increased significantly during the pandemic in many countries, and given the challenges of the "energy transition" it will become extremely important. Energy communities can provide significant benefits to power systems as a new aggregate source of distributed flexibility, and new technologies can have significant economic and environmental effect on such communities.

Based on definitions from [135–137], with additions from discussions presented in [138–140], this study relies on the following definition of the energy community (EC): "An EC, from the engineering standpoint, is a group of microgrids or facilities (e.g., interconnected loads and distributed energy resources) within clearly defined electrical boundaries that act as a single managed entity in relation to an external power grid. An EC can be connected to or disconnected from an external grid to be able to operate both in grid-connected mode and in isolated mode. Such a community is usually based on open and voluntary membership. It is controlled by shareholders or members in a more or less autonomous and effective way, with such shareholders and members located in close proximity to the location of RES projects that are owned and developed by the same legal entity." Shareholders or members here refer to individuals, small and medium-sized businesses, or local governments, including municipalities.

Research published in recent years on the subject of EC captures many important aspects, such as factors driving the emergence and development of ECs, the supporting institutional environment [141], barriers to the implementation of the energy community model and business models for their implementation [142], approaches to EC design and management [143,144], modeling behavior of EC members [145], concepts of cooperative community-based energy consumption [146].

A number of factors complicate the implementation of a successful EC project. First of all, when creating ECs and managing their operation, several objectives are pursued, aimed at improving economic performance, minimizing environmental impact, ensuring top engineering specifications. These goals are in most cases contradictory, and ensuring high scores on some criteria is achieved at the expense of compromising the others. In addition, the stages of design and subsequent optimal management of the EC are interrelated and the decisions made during the design of the configuration influence the efficacy of the management of such a system afterwards. Moreover, the problem of multi-criteria choice of EC configuration is complicated by the uncertainty of the preferences of a decision maker or a group of decision makers. This is due to the extended duration of the life cycle of the project and multiple scenarios for the development of external conditions. The subsequent task of managing such a community with multiple performance criteria is complicated by the problem of convergence and high computational complexity of optimization models. In fact, there is a non-trivial task of forming a fair local electricity market within the EC, where it is required to reconcile the personal interests of individual members with the maximization of the public welfare of the entire community to maintain the long-term aggregation of such an energy structure.

Approaches to multi-criteria choice of microgrid configurations and microgrid communities are presented in recent studies, e.g., [147–149]. However, the uncertainty factor is taken into account only in some of them [150,151] and only in the design of individual microgrids. Research on multi-criteria management of ECs considers the distribution of heat, cold energy, and electricity, as well as demand response management to achieve economic, environmental and technical effects [143,152]. However, little attention has been paid to optimizing the mutual exchange of energy among community members so as to take into account both their interests and those of the community as a whole.

New energy practices for building ECs. To improve the economics and reliability of power supply to facilities within local smart grid systems, as well as to increase the efficiency of their interaction with external large power systems, ECs consisting of several heterogeneous local power systems are increasingly being used. Such ECs can share local energy resources for mutual benefit, develop related production facilities, and bring significant economic benefits to external power systems if there is an electrical interconnection with them. To date, many concepts for building such communities have been developed and the search continues for the most effective solutions in terms of their architecture and engineering.

The active development of local smart grid systems in the EU, the USA, and Australia in the EC format has led to the development of new practices that implement advanced, both economic and social, principles of building local interconnections. For example, the so-called "co-assembly" principle implements platform management of aggregated sets of distributed energy facilities [153]. This practice can be used both at the local level within microgrids (where such platforms form an EC being co-assembled) as well as at the national and even regional levels of large power systems. In this case, platform-based solutions are used for creation of virtual power plants and integration into wholesale energy storage and controllable load markets.

A similar principle is actively implemented in Great Britain, where several projects are being developed to create local energy markets: markets for electricity and flexibility [154]. For example, on the Orkney Islands that are part of Scotland, where more than 10% of the residents have their own energy sources, an EC is organized with two pilot projects run at once: TraDER and ReFLEX. The TraDER project implements the ideas of a local real-time energy marketplace, where RES and sources of flexibility, which are energy storage, controllable load, and local flexible generation, are to be traded among themselves. The purpose of the market is to ensure the highest possible utilization rate of RES in the local power system through the services of flexibility providers. The ReFLEX project, in contrast to the local energy market, involves the creation of a centralized system of intelligent management of local RES and sources of flexibility, which are the charging stations for electric cars and housing and utilities systems [155]. The project focuses on ways to motivate the local community to invest in these RES and sources of flexibility. The project introduces a "green" energy tariff, which is when paid enables consumers to financially support local renewable energy owners and allows renewable energy prosumers themselves to sell electricity to the grid.

In another project [156], Western Power Distribution (WPD) in Cornwall offers a business model of energy consultants to support local ECs. In their geographic region there are 97 ECs with a total installed generation capacity of more than 100 MW, for which WPD performs continuous monitoring, analysis, and planning of their activities, launches online analytical services, manages project assets, and conducts consulting and educational activities. These services allow the region's ECs to have an economic effect in the form of reduced costs for their energy supply. Local Energy Oxfordshire (LEO), another project to create a county-wide local EC, has also entered the implementation phase [157]. The project is expected to deploy the PicloFlex Flex Marketplace, connecting all prosumers and owners of the county's flexibility sources to it. Its objectives include establishing a common approach to the rapid connection of new consumers and distributed generation, developing new approaches to long-term expansion planning of power energy systems in the context of the existence of ECs, and the study of new options for the architecture of the energy market in a situation where distributed energy prevails over centralized energy.

In Australia, due to the unique features of its geographical location, for the most part a different type of EC is being developed: local power systems with a single control circuit, which are created to supply power to island ECs. On islands, the main task of microgrids is to reduce the consumption of imported diesel fuel through the use of RES, while it is necessary that the electricity supply becomes both more self-sufficient, cheaper, and more environmentally friendly [158]. The islands have ongoing projects that use various combinations of multiple elements of varying capacity in microgrids, including diesel generators, PV panels, wind turbines, and energy storage units. One example of such a microgrid is the EC on King Island near Tasmania [159], which includes biofuel diesel generators, PV panels, wind turbines, electricity storage systems (batteries with a 1.5 MWh capacity), and flywheel energy storage for frequency control. The most unusual of Australia's "island" energy communities is the underground town of Coober Pedy, the opal mining capital of the world. For its power supply, instead of the existing diesel generation, a microgrid is being built, which consists of wind generation, PV panels, battery storage with a certain capacity, flywheels, and dynamic balancing load [160]. Diesel generators will be used only as backup power sources up to 70% of the time.

One example of the construction of an island EC in Europe (Culatra Island, Portugal) [161] demonstrates another principle of co-development that presupposes a more advanced level of cooperative behavior, leading not only to immediate results, but also to the achievement of long-term effects associated with the increasing complexity of the set of interacting facilities and to solving new problems. Practical examples in [162] show how the community is able to adapt new technological solutions for the green transition to the specific needs of the island as expressed by the islanders themselves, including batteries, electric vehicles, home retrofits, or heat pumps, which in combination can lay the foundation for a RES-based EC and leverage the associated socioeconomic benefits. Nevertheless, [145] notes that having just 25% of enthusiastic members is sufficient in such communities to achieve certain benefits, including a significant reduction in net energy exchange with the external power grid.

Other examples of ECs implementing the principle of co-development are the eco-settlements in the Netherlands that use digital solutions created by Spectral and Metabolic. For example, a settlement of the future is offered by the environmentally-minded EC "Earth Ships" (Aardehuizen) built around the idea of maximum efficiency of resource use and autonomy [163]. Houses in the settlement are equipped with 80 kW PV panels, there is a 35 kW micro CHPP, which runs on biofuel from wood chips, a 10 kW heat pump, a 100 kW energy storage system and charging stations for electric cars with a total capacity of 580 kW, as well as a connection to the power grid. Formed from these energy sources and flexibility inherent in them, the microgrid is controlled by Metabolic's Smart Integrated Decentralised Energy (SIDE) system. SIDE, in addition to optimal control, provides a peer-to-peer electricity trading function between microgrid facilities owned by different owners amounting to an average of 11.5 MWh per year.

The U.S. market for microgrids, including community microgrids, is one of the largest in the world. There the ECs of the Pacific States and the American South are creating "backup" microgrids, whose main purpose is to provide power in the face of regular natural disasters. In California, such microgrids serve as an environmentally friendly and technologically advanced alternative to the installation of backup diesel generators to be switched on during preventive grid outages regularly used to prevent wildfires [164]. For example, the Smart Neighborhood project in Alabama, which involves PV panels, lithium-ion storage, a gas microturbine, and air conditioning and ventilation systems at consumers. All assets are owned by the EC and managed centrally by SCEISMIC, a system developed by Oak Ridge National Laboratory. An important feature of this EC is the ability to run for 12 hours on battery power alone, in case of a power outage during Alabama's not infrequent seasonal hurricanes. The microgrid on Ocracoke Island, North Carolina, features diesel generators, a 1 MWh energy storage unit, PV panels, thermostats, and remote-controlled electric water heaters. If necessary, the autonomous power supply of the island can be implemented for up to 3 days [165].

Prospects for the development of ECs in Russia. It is important to emphasize that to date there is actually no uniquely Russian concept of designing different types of ECs: for farms, commercial and non-commercial enterprises, island states, isolated and non-isolated territories However, the theories of architecture of their design and operation that have been elaborated abroad are also applicable in Russia. Noteworthy are the domestic microgrids that are being developed so as to match the characteristics and needs of the territories that are to be integrated into communities.

In general, the creation of microgrids and their integration into ECs is of significant practical importance for consumers who are part of these microgrids, as they make it possible to address the issue of rising electricity prices. A particularly attractive solution for Russia is the creation of microgrids for power supply to commercial and industrial consumers. Commercial and industrial microgrids, supplementing the power supply from the power grid, make it possible to provide their consumers with a significant effect of reducing their electricity costs and meet the requirements for "carbon-free" energy consumption, power supply reliability, and power quality, that are often more stringent than those met by centralized power supply.

A regulatory framework is being drawn up in Russia for the development of this business practice of industrial microgrids. The first step was the emergence of the concept of industrial ECs - active energy complexes (AEC) in internal power supply systems of industrial enterprises [169] (Fig. 4.24). AEC in this case refers to commercial microgrids connected to the UES, which include generation not participating in the wholesale market and having a capacity of up to 25 MW.

In the conditions faced by the Russian hinterland in small microgrids [170–173], in order to provide electricity and heating for agricultural and other purposes, original methods were proposed for using gasification-based plants (GP), capable of running both on conventional motor fuel

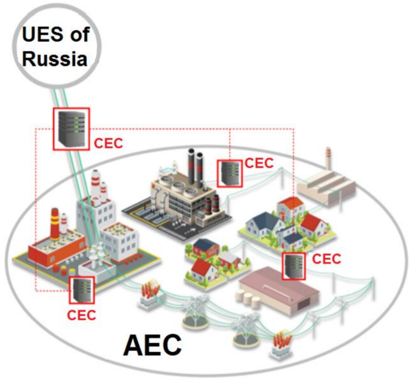


FIGURE 4.24 Illustration of an AEC architecture with controlled intelligent connections (CAI).

and on alternative fuels obtained by burning agricultural waste: waste produced by livestock complexes when using methane as biogas, crop residues that come in the form of straw and chaff, and wood processing residues. Study [174] proposed a technology of combustion of municipal solid waste and degassing of landfills to obtain biogas, which in addition to heating of the nearby residential area, is also intended to solve the urgent global environmental problem of pollution of air and environment.

The GPs have an increased efficiency of operation (75-78%), as they allow one not only to generate electricity while utilizing MSW and agricultural waste, but also to obtain thermal energy used for process purposes, such as heating of water for watering animals on farms, washing of process equipment, as well as heating of nearby settlements. A more even loading of the equipment available in such a local power system is necessary in order to sell excessive biogas in case of a decline in consumed capacity as well as to cover peak loads when there is a shortage of biogas. This allows for smoothing out of generation and consumption profiles, as well as trading electricity with the shared power grids at established tariffs [173], if there is an electrical connection with them.

A similar problem, that of smoothing out load and generation profiles is mainly solved by using different types of energy storage in isolated local power systems with no connection to the unified power system of the country. For example, in remote Russian regions of the Arctic, the Russian Far North and the Russian Far East [166–168]. Such regions are characterized by a limited number of large generating facilities and consumer groups, whose core are mining and processing plants, seaports, hydrocarbon deposits, oil platforms, etc.

Multi-criteria analysis in the design and management of EC. Designing EC of microgrids and managing their operation pursues a set of goals, covering economic, environmental, and social aspects of development. Multi-criteria analysis in decision-making on the development of micro-grid communities has been theoretically elaborated and put into practice.

Fraunhofer University, together with Metabolic and Spectral, conducted a detailed feasibility study of microgrids in Dutch ECs, and, as claimed in [165,167], made a revolutionary discovery in the field of RES by "increasing flexibility from the bottom up." The technical and economic performance of 9 different scenarios derived for four energy community options were considered and compared: Aardehuizen - a self-sufficient eco-village consisting of 23 households built by their owners themselves from environmentally friendly materials; DeCeuvel - a former shipyard site with houseboats upcycled into buildings; Schoonschip - floating barge houses; Republica Papaverweg - a mixed area development in the former industrial area of North Amsterdam. Assessment of modeling results was performed by determining 4 key performance indicators (KPIs), varying from 0 to 10: the ratio of energy production to consumption; self-sufficiency (what percentage of energy consumed is produced locally); capital investment; payback period (how long it takes for the system to become cheaper than a conventional system). All scenarios considered the intelligent SIDE system (developed by Metabolic and Spectral), which is based on the MILP optimizer module that decides when to switch on/off each of the flexible loads to optimize energy flows based on energy consumption and economic costs. Optimization was to be carried out in two stages: first at the level of individual consumers (households), then at the level of the entire EC.

The results of the study identified a number of best practices (scenarios) that can be used for the future development of operational management systems of ECs. Some of the scenarios in the study included various green solutions, such as the environmentally friendly materials used for construction in the Republica Papaverweg and De Ceuvel settlements. Some of these solutions correlated with social factors, such as in the Schoonschip settlement where the study accounted for the need to maintain biodiversity and human health at the local level by creating a special biosphere. This included the use of vacuum toilets, wastewater delivered to a biogas treatment plant, and houses having green roofs. In the case deemed optimal from the economic standpoint (one of the options for the environmental community Aardehuizen), the scenario involved the additional installation of a micro-CHPP to provide heating and electricity in winter, running on wood chips. District heating by a heat pump from an external CHPP plant was also provided, as well as charging stations for electric vehicles. In the end, this scenario leads to a technically feasible system that is almost entirely (89%) self-sufficient and most economical in the long run, breaking even in 8.5 years instead of 11.6 years compared to a conventional gas-fired energy system.

The results obtained in [164] also pointed out that each microgrid and each EC are unique and the efficiency of their operational management system (in this particular study, the SIDE system) depends strongly on a wide range of conditions and factors: equipment mix, nature of its operation, geographical conditions, presence of local production facilities, and so on. For example, extremely expensive hydrogen storage facilities are efficient and break even only in the case of completely isolated energy communities.

In [175], an analysis of seven case studies of EC pilots in Belgium, Spain, the Netherlands, and Greece was conducted based on a multi-actor multi-criteria analysis approach. The focus was on the issues of stakeholder identification, EC options, compliance with local requirements, and preferences among stakeholders. The main goals at all study sites were to reduce emissions and maintain the functionality of the power system while respecting socioeconomic criteria. All EC options included a higher share of renewable energy generation. The study revealed the existence of great heterogeneity in EC options, the multiplicity of goals and decision makers.

The importance of considering environmental and social criteria was reflected in [176], where the development of a microgrid community was considered within the boundaries of a conservation area. This imposed a restriction on the mix of the generating sources. The authors proposed a comprehensive approach to planning and management of ECs, taking into account social, environmental, and economic benefits of the specific location of such a community. An approach of this kind makes it possible to implement the full cycle of a project study: from assessing the feasibility of creating a microgrid community in a particular area (city, remote area, industrial zone, etc.) to the development of intelligent tools for optimal control of operation of the already established EC. Numerical results obtained using a real-world test case implemented in three settlements in the Baikal tourist and recreation area show that the proposed structure proves effective for improving the welfare of EC members, who receive from 20 to 40% reduction in operating costs by decreasing the LCOE value while increasing the reliability of power supply in these settlements.

Multi-criteria approaches to design and management of ECs have been proposed in a number of studies. Study [143] focused on the analysis of three different configurations of energy communities with consumers of electricity and heat. A unique feature of the study was that the ECs were presented as prosumers. A demand response tool with two strategies was used to improve community configurations. The first strategy was a price-based demand response program, and the second strategy was a new DSM model that adapts EC electricity demand to capabilities of local renewable energy sources. Multi-criteria optimization aimed to improve the economic performance of the community while minimizing CO_2 emissions and striving to meet energy demand from own energy sources.

Studies [148,149] considered a novel type of distributed energy system that combined several energy storage units (heat, cold, and electricity storage). Three modes of operation of the power system WERE proposed to take full advantage of the benefits of multi-energy storage. A two-stage method was proposed to optimize the configuration of the distributed energy system and manage its operation. The multi-objective optimization model took into account the annual CO_2 emissions, the annual total costs, and the energy self-sufficiency metric in the EC. The installed capacities in the community were optimized in two steps using the genetic algorithm of non-dominated sorting and the TOPSIS method. The results of the distributed energy system approach attested to the attainability of reducing annual CO_2 emissions and dependence on an external grid.

In a study by Rehmanetal [177] different configurations of energy systems combined in an EC were designed and compared. The energy systems included photovoltaic panels, wind turbines, and energy storage units. The energy systems were modeled in the TRNSYS software environment, and multi-criteria optimization was performed using a genetic algorithm of non-dominated sorting. The optimization goal was to minimize two variables: imported electricity and life cycle cost. The proposed approach made it possible to form efficient configurations and determine the main directions of improving their technical and economic performance. Study [178] proposed a multi-criteria approach to the development of a distributed energy system with photovoltaic panels, internal combustion engines, heat pumps, gas boilers, electric and thermal energy storage. The entropy method and the TOPSIS method were combined for multi-criteria optimization of the energy system. The study considered a new approach to supplying energy to settlements with near-zero energy consumption under various scenarios. Optimization was carried out with three objectives aimed at minimizing costs and energy imports, while maximizing the share of solar energy.

Individual studies considered approaches that deal only with multi-criteria management of ECs. For example, in studies [148,149,177], the authors proposed an approach to providing flexibility in a microgrid community through demand response programs [152]. In the incentive-based model, it was the responsibility of the microgrid community aggregator to provide flexibility. The goal of the aggregator was to minimize the cost of managing flexibility, which included incentives paid to residential users for changing requirements and penalty payments to the community operator for breach of contractual obligations. Optimization was carried out in two stages. At the first stage a two-objective optimization is performed to determine the solution area close to the optimal one, and at the second stage a single-criteria optimization by the gradient descent method was performed to refine the solution.

Study [179] proposed collaborative multi-purpose energy management for a microgrid community. The criteria for management were costs, greenhouse gas emissions, energy losses, and voltage drop in the microgrid community. Stochastic multi-objective optimization was performed by compromise programming, which was used to combine heterogeneous objective functions. In [180] models of the market operator and distribution network operator were designed for a microgrid community with non-dispatchable RES taking into account multiple objectives. It was necessary for the power system to maximize the net profit received from the sale of electricity. For the microgrid, it was desirable to maximize the net profit received from energy consumption. Finally, it was necessary for the independent system operator to maximize the level of energy stored to ensure the reliability of power supply. Caoetal in [181] proposed a three-level multi-microgrid management structure aimed at minimizing the cost of system operation and improving the use of RES. At the upper level of the hierarchy, the global operating costs of the microgrid community were minimized, and at the lower level, the operating costs of individual microgrids were minimized. The novelty of the approach was the medium level introduced to further adjust source control and efficiently distribute energy between microgrids.

A review of research on the development of multi-criteria approaches to the creation and management of ECs showed that only a few of the works addressed both problems. The stage of determining the structure of the EC in most studies is not represented comprehensively enough in terms of deciding on the mix of equipment and taking into account the uncertainty of the importance of the criteria. Meanwhile, the solution to this problem largely determines the effectiveness of EC management and the attainability of high scores on the criteria. In the case of multi-criteria optimization at the stage of management, the studies considered above took into account a limited set of 2 to 3 criteria. Only some of the studies dealt with the issues of formation of a fair local electricity market within the EC, where it was necessary to reconcile the personal interests of individual participants with the maximization of the public welfare of the entire community.

Multi-criteria methodology for EC planning and operation. Researchers at the Melentiev Energy Systems Institute, SB RAS developed a multi-criteria approach to the creation and management of EC operation, the overall flow chart of which is shown in Fig. 4.25. Planning of ECs begins with outlining of the existing and prospective socio-economic conditions of development of the area. Based on the results of the analysis, the list of existing and prospective consumers is compiled, and electrical loads are calculated for each microgrid of a potential EC. An analysis of energy resources, including renewable resources, is conducted to determine the mix of possible microgrid generating facilities. Based on the information obtained, scenarios for the development of the energy system are formed to ensure that the goals deemed important for decision makers are achieved.

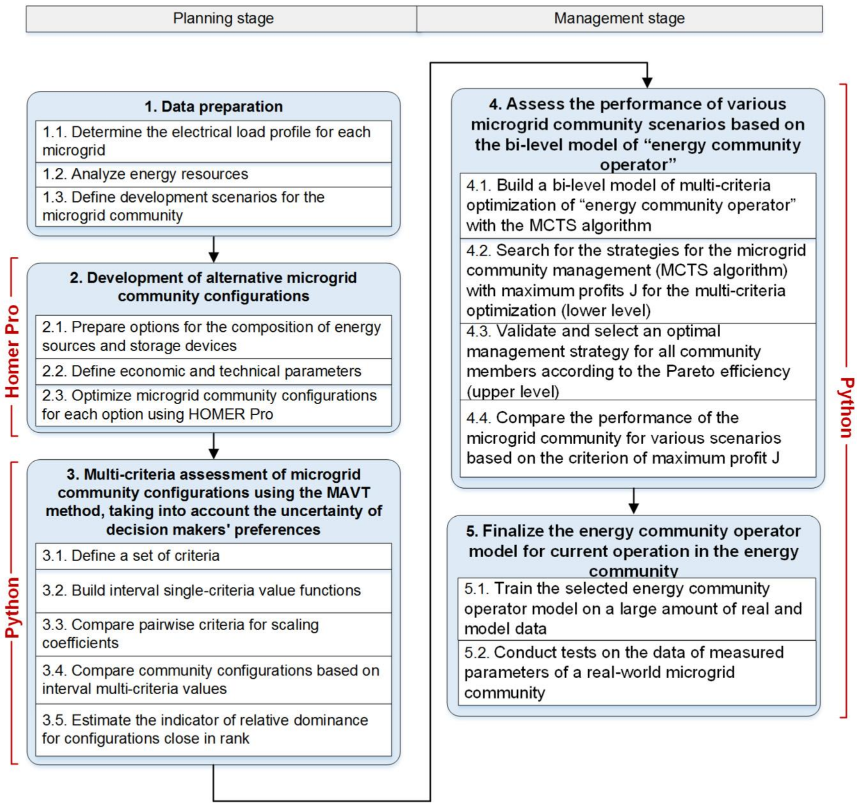


FIGURE 4.25 Overall algorithm of the proposed multi-criteria planning and management of EC operation.

The second step in creating an EC configuration is to develop alternative configurations of the microgrid community [182]. The software products HOMER, iHOGA, RETScreen, Hybrid2, INSEL, TRNSYS, and others [183] are used in many studies to solve the problem of determining microgrid configurations. HOMER is the most frequently used software, which is due to the wide range of power plants available for research, the possibility of specifying technical parameters of the plants, and the convenience of preparing input data [184,185]. Therefore, in this study, the second step determines the configuration for combining microgrids using HOMER. The profile of electrical loads of the EC is made up of the profiles of all the microgrids. A diversity of configurations is ensured by specifying different sets of available power plants.

Because HOMER performs single-criteria optimization, many studies have proposed multi-criteria approaches to solving the problem using TOPSIS, VIKOR, AHP, COPRAS [186,187], and other software products.

The vast majority of multi-criteria studies are performed assuming certainty with respect to preferences and criterion estimates. There are only few papers that use fuzzy multi-criteria methods for multi-criteria comparison, such as Fuzzy-AHP, Fuzzy-TOPSIS, e.g., [188,189]. Under high uncertainty of EC development ESO development, factoring in this uncertainty is crucial. Therefore, in this study, the third step is a multi-criteria evaluation of the configurations, which takes into account the uncertainty of the decision maker's preferences regarding the importance of the criteria in each of the scenarios under consideration. A modified method of multi-criteria value theory (MAVT) is used to evaluate the configurations. Various modifications of the MAVT to account for uncertainty have been proposed to date [190,191]. The proposed approach is different in how it constructs interval value functions and interval scaling coefficients. The final choice of alternatives is based on the analysis of interval multi-criteria estimates. If such estimates overlap, the procedure for determining the relative dominance indicator is used. Multi-criteria interval estimates serve as the basis for determining the EC configurations that best fit the scenarios taken into consideration.

At the fourth stage, the bilevel CommunityEMS model of the "energy community operator" is used to evaluate the feasibility of the selected EC scenarios. The model was developed earlier in the Python software environment using open-source libraries for optimization (Pyomo) and reinforcement learning (Tensorflow, gym) [192]. A modification introduced into the CommunityEMS model by the present study is the consideration of more criteria (economic, environmental) in the lower level objective function, which is minimized by the agent of the multi-criteria version of the Monte Carlo Tree Search (MCTS) algorithm [193]. The MCTS agent is actually the LocalEMS local management system that attempts to find the optimal microgrid management strategy (as part of the EC or as a standalone system) with respect to multiple criteria to maximize public welfare. The lower level solves the problem of finding a market equilibrium by determining the optimal volumes of capacity exchange, prices, and peak capacity in the EC. The upper level is necessary for the realization of social justice, when it is the strategy that yields gives a fair distribution of profits among community members that is chosen from the set of possible strategies of the lower level, according to the Pareto efficiency condition. In fact, at the lower level, the CommunityEMS model tries to take into account economic (maximum profit) and environmental (minimum CO_2 emissions) criteria, and at the upper level - social criteria, by organizing a fair local market to stimulate long-term participation in the EC.

It should be noted that in the proposed bilevel statement, the lower-level problem is a linear programming problem statement that does not depend on the variables of the upper-level problem solution and is solved by reinforcement learning based on the MCTS algorithm [194]. Moreover, given a fixed solution of the lower-level problem, the upper-level problem is also a linear programming problem. This means that if the solution to the lower-level problem is unique, the bilevel model can be solved very efficiently as a cascade of two linear programming problem statements, one corresponding to the lower level and the other to the upper level. The uniqueness of the solution of the lower-level problem can be checked a priori with standard linear programming tools [195]. If the lower-level solution is not unique, the bilevel problem can be solved by transforming it into a single non-linear optimization program [196].

Based on the results of performance evaluations at the end of the fourth stage, the optimal scenario for the creation of an EC is selected. For this scenario, the fifth stage finalizes the implemented bilevel "energy community operator" model with the aim of its practical implementation as part of the current operation. For this purpose, the CommunityEMS MCTS agents this time are trained on a large amount of real-world data, including various actual measurements from sensors and smart meters installed in the EC microgrids.

The proposed approach is applied to 3 settlements on the coast of the Sea of Japan, with the settlements located in close proximity and, at the same time, far removed from the electric power system. Diesel generators, which have high wear and tear and low efficiency, are used to power them. The analysis of energy resources performed revealed the availability of resources of wood chips as a result of ongoing logging. The global horizontal irradiance in the area is 1,282.5 kWh/m^2. The average wind speed on the coast at a height of 10 m is 3.6 m/s. The area under consideration is characterized by the availability of the potential for economic growth. On the other hand, the nature of the area is unique and has the potential for ecotourism development.

Therefore, the study of the quality of solutions obtained using a two-stage multi-criteria approach was conducted for the design and management of the EC of the three localities under three scenarios.

1. The economic scenario aims to build an energy EC with the highest technical and economic performance.
2. The environmental scenario aims to ensure minimal impact on the environment while ensuring technical performance.
3. The balanced scenario assumes focus on all aspects of EC development.

At the planning stage, the application of a modified MAVT method and calculation of the relative dominance index allowed us to choose the best configurations for the three scenarios, taking into account the interval-valued preferences of decision-makers. Comparison of EC configurations (see Fig. 4.26)) with those of isolated microgrids showed the advantage of the former. They have better values of LCOE, CO2 emissions, renewable penetration. The results obtained during the optimization of operation

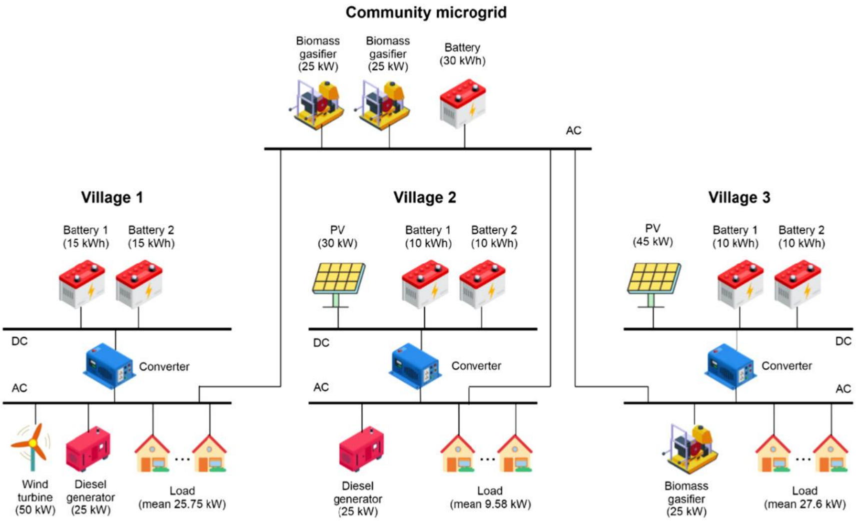


FIGURE 4.26 Example of an EC configuration for a scenario of minimum CO_2 emissions.

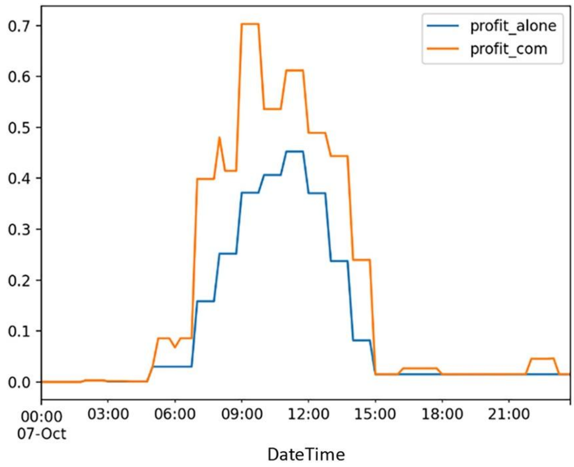


FIGURE 4.27 Results of EC operation for Village 2 at minimum CO_2: a) microgrid profits compared to the scenario where they operate on their own ($); b) electricity price in the EC when exchanging power ($/kWh).

show that, thanks to the multi-criteria approach, microgrids manage to achieve a significant benefit from connecting to the EC: from 10 to 60% additional profit (Fig. 4.27, 4.28). In addition, as a result of cooperation through the proposed CommunityEMS platform, end users in the local energy market can significantly reduce their overall energy bill.

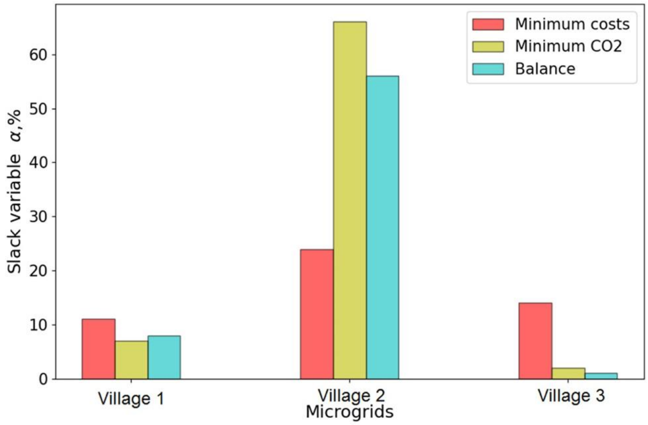


FIGURE 4.28 The additional amount of profit (expressed in terms of percentage) that microgrids make when they participate in an EC, according to the Pareto efficiency condition.

4.9 Conclusion

The above analysis of the state of research in this subject area attests to the availability of elaborate developments in hierarchical modeling principles for operation and control of electric power systems. At the same time, the hierarchical ideology of modeling complex EPSs is used not only to solve hierarchically presented sets of problems but also as a means of effective formalization of some labor-intensive problems in order to accelerate the process of solving them given the huge variety of conditions that require consideration.

At the same time, the quality of the findings that apply to individual directions and various electric power systems varies. All this requires revitalizing and incorporating basic research into the problems of intelligent energy systems and ways of solving them.

Acknowledgments

The research was carried out under State Assignment Project (no. FWEU-2021-0001) of the Fundamental Research Program of Russian Federation 2021-2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] G. Kron, Diakoptics: the Piecewise Solution of Large-Scale Systems, Nauka, Moscow, 1972, p. 544 (in Russian).

[2] G. Kron, Tensor Analysis of Networks, translated from the English, Sov. Radio, Moscow, 1978 (in Russian).

[3] O.A. Sukhanov, A.M. Sednev, Hierarchical structures in cybernetic modeling of complex electrical systems, Izvestiya Vuzov. Energetika 2 (1977) 3–8 (in Russian).
[4] V.A. Venikov, O.A. Sukhanov, Cybernetic Models of Electrical Systems, Energoizdat, Moscow, 1982, p. 328 (in Russian).
[5] O.A. Sukhanov, Yu. Sharov, Hierarchical Models in the Analysis and Control of Operating Conditions of Electric Power Systems, Publishing House of Moscow Power Engineering Institute, Moscow, 2007, p. 312 (in Russian).
[6] S.A. Sovalov, Operating Conditions of the Unified Energy System, Energoatomizdat, Moscow, 1983, p. 384 (in Russian).
[7] N.I. Voropai, V.V. Ershevich, Ya.N. Luginsky, et al., Control of High-Powered Power Interconnections, Energoatomizdat, Moscow, 1986, p. 296 (in Russian).
[8] N.V. Lisitsin, F.Y. Morozov, A.A. Okin, V.A. Semyonov, The Unified Energy System of Russia, Publishing House of Moscow Power Engineering Institute, Moscow, 1999 (in Russian).
[9] S.N. Vasilyev, N.I. Voropai, I.N. Kolosok, V.G. Kurbatsky, et al., Theoretical Foundations, Methods, and Models of the Control of Large Electric Power Systems, Federal Grid Company of Unified Energy System PJSC, Moscow, 2015, p. 188 (in Russian).
[10] S.A. Sovalov, V.A. Semyonov, Emergency Control in Power Systems, Energoatomizdat, Moscow, 1988, p. 416 (in Russian).
[11] Y. Zhao, M.R. Hesamzadeh, A modified Benders decomposition algorithm to solve second-order cone AC optimal power flow, IEEE Transactions on Smart Grid 10 (2) (2019) 1713–1724.
[12] A. Gholami, F. Aminifar, A hierarchical response-based approach to the load restoration problem, IEEE Transactions on Smart Grid 8 (4) (2017) 1700–1709.
[13] A.K. Marvasti, Y. Fu, S. DorMohammadi, M. Rais-Rohani, Optimal operation of active distribution grids: a system of systems framework, IEEE Transactions on Smart Grid 5 (3) (2014) 1228–1237.
[14] A. Kargarian, Y. Fu, H. Wu, Chance-constrained system of systems based operation of power systems, IEEE Transactions on Power Systems 31 (5) (2015) 3404–3423.
[15] M.S. Mahmoud, M.S.U. Rahman, M.A.L.-S. Fouad, Review of microgrid architectures – a system of systems perspective, IET Renewable Power Generation 9 (8) (2015) 1064–1078.
[16] Zhao Bo, Wang Xiangjin, Lin Da, M.M. Calvin, et al., Energy management of multiple microgrids based on a system of systems architecture, IEEE Transactions on Power Systems 33 (6) (2018) 6410–6421.
[17] S. Suryanarayanan, J. Mitra, S. Biswas, A conceptual framework of a hierarchically networked agent-based microgrid architecture, in: IEEE PES Transmission and Distribution Conference, New Orleans, Louisiana, USA, April 22–29, 2010, p. 5.
[18] Jin Wei, D. Kundur, Two-tier hierarchical cyber-physical security analysis framework for smart grid, in: IEEE PES General Meeting, San Diego, California, USA, July 22–27, 2012, p. 5.
[19] S. Shukla, L. Mili, Hierarchical decentralized control for enhanced rotor angle and voltage stability of large-scale power systems, IEEE Transactions on Power Systems 32 (6) (2017) 4783–4793.
[20] Zhuang Peng, Liang Hao, Hierarchical and decentralized stochastic energy management for smart distribution system with high BESS penetration, IEEE Transactions on Smart Grid 10 (6) (2019) 6516–6527.
[21] Lin Ye, Cihang Zhang, Yong Tang, et al., Hierarchical model predictive control strategy based on dynamic active power dispatch for wind power cluster integration, IEEE Transactions on Power Systems 14 (6) (2019) 4617–4629.
[22] Shiwei Xia, Sigi Bu, Can Wan, et al., A fully distributed hierarchical control framework for coordinated operation of DERs in active distribution power networks, IEEE Transactions on Power Systems 14 (6) (2019) 5184–5197.

[23] Hui Guo, Fei Wang, Lijun Zhang, Jian Luo, A hierarchical optimization strategy of the energy router-based energy internet, IEEE Transactions on Power Systems 14 (6) (2019) 4177–4185.

[24] C.N. Papadimitriou, E.I. Zountouridou, N.D. Hatziargyriou, Review of hierarchical control in DC microgrids, Electric Power Systems Research 122 (1) (2015) 159–167.

[25] Liang Che, M. Shahidehpour, DC microgrids: economic operation and enhancement of resilience by hierarchical control, IEEE Transactions on Smart Grid 5 (5) (2014) 2517–2526.

[26] Yijun Xu, L. Mili, Junbo Zhao, Probabilistic power flow calculation and variance analysis based on hierarchical adaptive polynomial chaos – ANOVA method, IEEE Transactions on Power Systems 14 (5) (2019) 3316–3325.

[27] B.I. Ayuyev, A.T. Demchuk, V.L. Prikhno, Hierarchical system for calculating the current operating conditions of the Unified Energy System based on telemetry data, Energetik 5 (2004) 9–12 (in Russian).

[28] T.I. Aliyev, Complex systems research based on the combined approach, in: I All-Russian Scientific and Practical Conference IMMOD, St.Petersburg, 2003, pp. 50–55 (in Russian).

[29] M.A. Duel', A.V. Prikhod'ko, Decomposition of hierarchical multilevel control systems of complex power facilities, Eastern-European Journal of Enterprise Technologies 6/3 (54) (2011) 49–55 (in Russian).

[30] A.Z. Gamm, I.N. Kolosok, A.S. Paltsev, Methods of decomposition of EPS state estimation problem when solving it on the basis of multi-agent technologies, in: Proc. of the "Riga Technical University 48th International Scientific Conference", Riga, 2007, pp. 205–214.

[31] I.N. Kolosok, A.S. Paltsev, Development of a multi-agent system for distributed state estimation of the electric power system, in: Methodological Problems of Investigating the Reliability of Large Power Systems. Issue 59. Methodological and Practical Problems of Reliability of Liberalized Energy Systems, Melentiev ESI, SB RAS, Irkutsk, 2009, pp. 234–240 (in Russian).

[32] A.Z. Gamm, Yu. Grishin, Distributed information processing in automated supervisory control systems of power systems, in: Proceedings of V International Seminar "Distributed Information Processing", Novosibirsk, 1995, pp. 243–247 (in Russian).

[33] D.L. Kroshko, D.A. Novitsky, O.A. Sukhanov, Hierarchical algorithms for solving state estimation problems in electric power systems, Elektronnoe Modelirovanie, Kyiv, 2007.

[34] V.L. Prikhno, Hierarchical principles of formation of steady-state operating conditions models based on telemetry information, Tekhniceskaya Elektrodinamika, Kyiv, Special issue Part 1 (2006) 22–27 (in Russian).

[35] D.M. Maksimenko, E.V. Mashalov, V.G. Neuimin, State estimation based on optimization algorithm in the RastrWin3 software package, Izvestiya NTTs Edinoy Energeticheskoy Sistemy 2 (69) (2013) 36–44 (in Russian).

[36] W. Jang, V. Vittal, G.T. Heydt, Diakoptic state estimation using Phasor measurements units, IEEE Transactions on Power Systems 23 (4) (2008) 1580–1589.

[37] A. Primadianto, C.N. Lu, A review on distribution system state estimation, IEEE Transactions on Power Systems 32 (5) (2017) 3875–3883.

[38] K. Dehghanpour, Z. Wang, J. Wang, et al., A survey on state estimation techniques and challenges in smart distribution systems, IEEE Transactions on Smart Grid 10 (2) (2019) 2312–2322.

[39] WAMS of the UES of Russia, https://www.smpr.technology/ (in Russian).

[40] A.Z. Gamm, L.N. Gerasimov, I.N. Kolosok, et al., State Estimation in the Electric Power Industry, Nauka, Moscow, 1983, p. 320 (in Russian).

[41] A.Z. Gamm, Decomposition algorithms for solving the EPS state estimation problem, Elektronnoe Modelirovanie 3 (1983) 63–68 (in Russian).

[42] A.S. Paltsev, Application of multi-agent technologies to hierarchical EPS state estimation, in: Liberalization and Modernization of Power Systems: Risk Assessment and Optimization for Asset Management, Int. Workshop Proc., Irkutsk, Russia, August 18–23, 2006, pp. 187–192.
[43] A. Grishin, I.N. Kolosok, E.S. Korkina, L.V. Em, V.G. Ornov, N.N. Shelukhin, Software package “Otsenka” [Estimation] for the Real-Time Estimation of the EPS State, Elektrichestvo 2 (1999) 8–16 (in Russian).
[44] R.F. Nuqui, A.G. Phadke, Phasor measurement unit placement techniques for complete and incomplete observability, IEEE Transactions on Power Delivery 20 (4) (2005) 2381–2388.
[45] E.S. Korkina, Placement of PMUs on the EPS circuit by means of the annealing method, in: Proceedings of the XIV Baikal International School/Workshop “Optimization Methods and Their Applications”, Irkutsk-Severobaikalsk, July 2–8, 2008, pp. 63–72 (in Russian).
[46] I.N. Kolosok, E.S. Korkina, Development of a state estimation methodology to improve the quality of control of the boundary areas of the neighboring smart transmission grids, in: Proceeding Workshop on CTDSG’16, Prague, Czech Republic, October 11–13, 2016, pp. 461–466.
[47] I. Kolosok, E. Korkina, E. Buchinsky, The test equation method for linear state estimation based on PMU data, in: Proc. of the 18th Intern. Power System Computation Conference (PSCC-2014), Poland, Wroclaw, Aug. 18–22, 2014, ID 76.
[48] I.N. Kolosok, A.S. Paltsev, Application of the multi-agent approach to the decomposition of the EPS SE problem, in: Proc. of III International Scientific-Practical Conference, October 13–16, 2008, Ekaterinburg, 2008, pp. 350–355 (in Russian).
[49] I.N. Kolosok, E.S. Korkina, O.A. Sukhanov, Algorithms of distributed state estimation of large power systems, Elektrichestvo 4 (2011) 27–36 (in Russian).
[50] A.Z. Gamm, I.N. Kolosok, R.A. Zaika, Robust methods of electric power system state estimation and their implementation with the help of genetic algorithms, Elektrichestvo 10 (2005) 2–8 (in Russian).
[51] L.V. Massel, The use of modern information technology in the Smart Grid as a threat to cybersecurity of energy systems in Russia, Information Technology and Security 1 (3) (2013) 56–65, Institute of Special Communication and Information Security, National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, Kyiv, Ukraine (in Russian).
[52] N.I. Voropai, I.N. Kolosok, E.S. Korkina, A.B. Osak, Issues of cybersecurity in electric power systems, in: Electric Power Industry in National Projects, The Publishing House of the Moscow Power Engineering Institute, Moscow, ISBN 978-5-7046-2348-9, 2020, pp. 67–88 (in Russian).
[53] N.I. Voropai, I.N. Kolosok, E.S. Korkina, A.B. Osak, Issues of vulnerability and survivability of cyber-physical electric power systems, Energeticheskaya Politika 5 (2018) 53–61 (in Russian).
[54] A.Z. Gamm, I.N. Kolosok, Gross Error Detection of Telemetry in Electric Power Systems, Nauka, Novosibirsk, 2000, p. 152 (in Russian).
[55] I.N. Kolosok, L.A. Gurina, Improving the reliability of information flows of phasor measurement data, in: Power System Protection 2017, Proceedings of the International Scientific and Technical Conference, 2017, pp. 915–921 (in Russian).
[56] I.N. Kolosok, L.A. Gurina, Assessment of SCADA and WAMS data quality in cyber attacks on EPS information and communication infrastructure, Informacionnye i Matematicheskie Tekhnologii v Nauke i Upravlenii 1 (17) (2020) 68–78 (in Russian).
[57] I.N. Kolosok, E.S. Korkina, Decomposition of power system state estimation problem as a method to tackle cyberattacks, in: The 1st IEEE Industrial Cyber-Physical Systems, ICPS 2018, St.Petersburg, May 15–18, 2018, pp. 398–403.

[58] I.N. Kolosok, L.A. Gurina, Determination of the index of vulnerability to cyber attacks for the problem of state estimation using SCADA data and phasor measurements, Elektrotekhnika 1 (2017) 52–59 (in Russian).
[59] R.L. Graham, P. Hell, On the history of the minimum spanning tree problem, Annals of the History of Computing 7 (1) (1985) 43–57.
[60] A.Z. Gamm, A.M. Glazunova, Y.A. Grishin, I.N. Kolosok, E.S. Korkina, Development of algorithms of electric power system state estimation, Elektrichestvo 6 (2009) 2–9 (in Russian).
[61] Y. Liu, M.K. Reiter, P. Ning, False data injection attacks against state estimation in electric power grids, in: 16th ACM Conf. on Computer and Communications Security, 2009, pp. 21–32.
[62] M.V. Khokhlov, Vulnerability of EPS state assessment to cyber attacks, in: Methodological Problems of Investigating the Reliability of Large Energy Systems: Relevant Problems of Reliability of Energy Systems, Rudenko International Scientific Seminar, 2015, pp. 557–566 (in Russian).
[63] The current set of standard FIPA specifications (Electronic publication), http://www.fipa.org/repository/standardspccs.html (free access).
[64] F. Bellifemine, G. Caire, D. Greenwood, Developing Multi-Agent Systems with JADE, Wiley, London, 2007, p. 336.
[65] S.D.J. McArthur, E.M. Davidson, V.M. Catterson, et al., Multiagent systems for power engineering applications. Part I, IEEE Transactions on Power Systems 22 (4) (2007) 1743–1752.
[66] S.D.J. McArthur, E.M. Davidson, V.M. Catterson, et al., Multiagent systems for power engineering applications. Part II, IEEE Transactions on Power Systems 22 (4) (2007) 1753–1759.
[67] Defense plan against extreme contingencies, CIGRE Task Force, C2.02.24, 2007, p. 38.
[68] W.R. Lachs, A new horizon for system protection schemes, IEEE Transactions on Power Systems 18 (1) (2003) 334–338.
[69] F. Bellifemine, G. Caire, T. Trucco, G. Rimassa, JADE programmer's guide (Electronic publication), CSELT and University of Parma, http://www.jade.tilab.com/doc, 2000 (free access).
[70] F. Milano, An open source power system analysis toolbox, IEEE Transactions on Power Systems 20 (3) (2005) 1199–1206.
[71] W. Taylor, D.C. Erickson, Recording and analyzing the July 2 cascading outage, IEEE Computer Applications in Power 10 (1) (1997) 18–25.
[72] N. Grudinin, I. Roytelman, Heading of emergencies in large electric grids, IEEE Spectrum 4 (1997) 15–16.
[73] N.I. Voropai, Survivability of electric power systems: methodological foundations and research methods, Izvestiya AN SSSR. Energetika i Transport 6 (1991) 33–39 (in Russian).
[74] A.A. Fouad, Qin Shou, V. Vittal, System vulnerability as a concept to assess power system dynamic security, IEEE Transactions on Power Systems 9 (2) (1994) 291–298.
[75] N.I. Voropai, G.V. Shutov, Dynamic properties of bulk power interconnections, Electrical Power and Energy Systems 18 (3) (1996) 56–61.
[76] N.I. Voropai, Modeling of long-term transients in electric power systems: state of the art, Elektronnoe Modelirovanie 7 (6) (2005) 33–41 (in Russian).
[77] X. Xu, R.M. Mathur, J. Jiang, et al., Modeling of generators and their controls in power system simulations using singular perturbations, IEEE Transactions on Power Systems 13 (1) (1998) 66–77.
[78] J.R. Winkelman, J.H. Chow, B. Avramovic, et al., An analysis of interarea dynamics of multimachine systems, IEEE Transactions on Power Apparatus and Systems 10 (2) (1981) 81–92.

[79] N.I. Voropai, Simplification of the mathematical models of power systems in the dynamic processes of different length, in: 8th Power System Computation Conference, Helsinki, Finland, August 25–29, 1984, p. 6.
[80] O.A. Agarkov, N.I. Voropai, D.N. Efimov, et al., Structural and hierarchical modeling in studying the processes in electric power systems, in: International AMSE Conference "Applied Modeling and Simulation", Lviv, Ukraine, September 30 – October 2, 1993, p. 5.
[81] N.A. Abramenkova, N.I. Voropai, T.B. Zaslavskaya, Structural Analysis of Electric Power Systems (in the Tasks of Modeling and Synthesis), Nauka, Novosibirsk, 1990, p. 226 (in Russian).
[82] O.A. Agarkov, V.P. Kychakov, N.I. Voropai, Transient stability studies of bulk power systems using simplified and detailed mathematical models, in: 9th Power System Computation Conference, Cascais, Portugal, August 30 – September 4, 1987, p. 6.
[83] N.I. Voropai, A.M. Krol', V.V. Novorussky, Development of intellectual decision support tools for restoration of power interconnections after accidents, Izvestiya RAN. Energetika 1 (1996) 25–33.
[84] N.I. Voropai, Hierarchical modeling and artificial intelligence in studies of complex electric power systems and their control in the event of major accidents, Izvestiya RAN. Teoriya i Sistemy Upravleniya 1 (2005) 152–158 (in Russian).
[85] A. Monticelli, State Estimation in Electric Power Systems: a Generalized Approach, Springer Science & Business Media, 2012, p. 394.
[86] A.Z. Gamm, Statistical Methods for State Estimation of Electric Power Systems, Nauka, Moscow, 1976, p. 22 (in Russian).
[87] G. Valverde, V. Terzija, Unscented Kalman filter for power system dynamic state estimation, IET Generation, Transmission & Distribution 5 (1) (2011) 29–37.
[88] Software package for power system modeling, [Online]. Available in Russian: http://anares.ru/software.
[89] D.L. Marino, K. Amarasinghe, M. Manic, Building energy load forecasting using deep neural networks, in: Industrial Electronics Society, IECON 2016 - 42nd Annual Conference of the IEEE, IEEE, 2016, pp. 7046–7051.
[90] R. Jozefowicz, W. Zaremba, I. Sutskever, An empirical exploration of recurrent network architectures, in: International Conference on Machine Learning, 2015, pp. 2342–2350.
[91] A. Graves, Practical variational inference for neural networks, in: Advances in Neural Information Processing Systems, 2011, pp. 2348–2356.
[92] T.K. Ho, Random decision forests, in: Proceedings of 3rd International Conference on Document Analysis and Recognition, vol. 1, IEEE, 1995, pp. 278–282.
[93] L. Breiman, Random forests, Machine Learning 45 (1) (2001) 5–32.
[94] E.M. Kleinberg, On the algorithmic implementation of stochastic discrimination, IEEE Transactions on Pattern Analysis and Machine Intelligence 22 (51) (2000) 473–490.
[95] A. Domyshev, et al., Optimal power flow calculation using BFGS-based optimisation scheme, in: IEEE Conference on Energy Internet and Energy System Integration (EI2), IEEE, 2018, p. 6.
[96] R.H. Byrd, et al., A limited memory algorithm for bound constrained optimization, SIAM Journal on Scientific Computing 16 (5) (1995) 1190–1208.
[97] P. Armand, P. Segalat, A limited memory algorithm for inequality constrained minimization, Technical Report 2003-08, University of Limoges, France, 2003, pp. 1–15.
[98] Y.M. Volin, G.M. Ostrovsky, Flexibility analysis of complex engineering systems under uncertainty, Avtomatika i Telemekhanika 7 (2002) 92–106.
[99] J. Cochran, M. Miller, O. Zinaman, M. Milligan, et al., Flexibility in 21st century power systems, in: 21st Century Power Partnership, Denver, USA, Clean Energy Ministerial, 2014, pp. 1–14.
[100] M.A. Bucher, S. Delicaraoglou, K. Heussen, P. Pinson, G. Andersson, On quantification of flexibility in power systems, in: IEEE Power Tech, Eindhoven, Netherlands, June 29 – July 2, 2015, p. 6.

[101] J. Zhao, T. Zheng, E. Litvinov, A unified framework for defining and measuring flexibility in power system, IEEE Transactions on Power Systems 31 (1) (2016) 329–341.
[102] N.I. Voropai (Ed.), Reliability of Energy Systems (Collection of Recommended Terms), Energiya Publishing and Analytical Center, Moscow, 2007, p. 192 (in Russian).
[103] R.J. Marceau, J. Endrenyi, R. Allan, F.L. Alvarado, et al., Power system security assessment: a position paper, Electra 175 (1997) 49–77.
[104] N.I. Voropai, A.B. Osak, Electric power systems of the future, Energeticheskaya Politika 5 (2014) 22–29 (in Russian).
[105] N. Hatziargyriou (Ed.), Microgrids: Architectures and Control, IEEE Press – Wiley, New York, 2014, p. 325.
[106] N. Voropai, Ch. Rehtanz, Flexibility and resiliency of electric power systems: analysis of definitions and content, in: EPJ Web of Conferences, International Workshop on Flexibility and Resiliency of Electric Power Systems, FREPS 2019, 217, 01018, Irkutsk, Russia, August 26–30, 2019, 2019, p. 6.
[107] X.P. Zhang, Ch. Rehtanz, B. Pal, Flexible AC Transmission Systems: Modeling and Control, Springer, Berlin, e.a., 2006, p. 383.
[108] Hongbo Sun, Wang Yishen, D. Nikovski, Jinyun Zhang, Flex grid: a dynamic and adaptive configurable power distribution system, in: IEEE Power Tech, Eindhoven, Netherlands, June 29 – July 2, 2015, p. 6.
[109] Xinyu Chen, Chongquing Kang, M. O'Maley, Quing Xia, et al., Increasing the flexibility of combined heat and power for wind power integration in China: modeling and implication, IEEE Transactions on Power Systems 30 (4) (2015) 1838–1847.
[110] G. Koeppel, G. Andersson, The influence of combined power, gas and thermal networks on the reliability of supply, in: 6th World Energy System Conference, Torino, Italy, July 10–12, 2006, p. 7.
[111] N.I. Voropai, D.N. Efimov, I.N. Kolosok, et al., Intelligent control and protection in the Russian electric power system, in: Application of Smart Grid Technologies, Elsevier – Academic Press, London, 2018, pp. 61–140.
[112] R. Roofegari nejad Sun Wei, A. Golshani, Distributed restoration for integrated transmission and distribution systems with DFRs, IEEE Transactions on Power Systems 34 (6) (2019) 4964–4973.
[113] P.D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renewable & Sustainable Energy Reviews 45 (2015) 785–807.
[114] J.E. Bistline, Turn down for what? The economic value of operational flexibility in electricity markets, IEEE Transactions on Power Systems 34 (1) (2019) 527–534.
[115] A. Soliman, A.-H. Mantawy, Modern Optimization Techniques with Applications in Electric Power Systems, Springer, New York, 2012, p. 392.
[116] T. Sansawatt, L. Ochoa, G.P. Harrison, Smart decentralized control of DG for voltage and thermal constraint management, IEEE Transactions on Power Systems 27 (3) (2012) 672–683.
[117] S. Kippelt, J. von Haebler, M. Westermann, C. Rehtanz, Assessment of capacity management approaches in distribution grids, in: IEEE International Energy Conference (ENERGYCON), Leuven, Belgium, October 5–9, 2016, p. 7.
[118] J. Hu, S. You, M. Lind, J. Ostrgaard, Coordinated charging of electric vehicles for congestion prevention in the distribution grid, IEEE Transactions on Smart Grid 5 (2) (2014) 703–711.
[119] P.M. Sotkiewicz, J.M. Vignolo, Nodal pricing for distribution networks: efficient pricing for efficiency enhancing DG, IEEE Transactions on Power Systems 21 (2) (2006) 301–311.
[120] H.C. Gils, Assessment of the theoretical demand response potential in Europe, Energy 67 (2014) 1–18.

[121] C. Spieker, J. Schwippe, D. Klein, C. Rehtanz, Transmission system congestion analysis based on an European electricity market and network simulation framework, in: Power System Computation Conference (PSCC), Wroclaw, Poland, August 18–22, 2014, p. 6.

[122] P. Lieberherr, Parallel power flow algorithm for large – scale distribution network topologies, Master's Thesis, Zurich, January 2017, p. 96.

[123] E. Bompard, E. Carpaneto, G. Chicco, R. Napoli, Convergence of the backward/forward sweep method for the load-flow analysis of radial distribution systems, International Journal of Electrical Power & Energy Systems 22 (7) (2000) 521–530, https://doi.org/10.1016/S0142-0615(00)00009-0.

[124] J. Bard, Practical Bilevel Optimization: Algorithms and Applications, Kluwer Acad. Publ., Dordrecht, 1998, p. 336.

[125] H. von Stackelberg, Market Structure and Equilibrium, Bazin, Urch and Hill, Springer, 2011, p. 134, XIV.

[126] H.L. Cadre, et al., A game-theoretic analysis of transmission-distribution system operator coordination, European Journal of Operational Research 274 (1) (2019) 317–339.

[127] A. Tavakoli, et al., Self-scheduling of a generating company with an electric vehicle load aggregator under an energy exchange strategy, IEEE Transactions on Smart Grid 10 (4) (2019) 4253–4264.

[128] S. Dempe, S. Franke, Solution of bilevel optimization problems using the KKT approach, Optimization 68 (8) (2019) 1471–1489, https://doi.org/10.1080/02331934.2019.1581192.

[129] Ch. Zhangyu, et al., Research on distributed renewable energy transaction decision-making based on multi-agent bilevel cooperative reinforcement learning, in: CIRED Conference Proceedings, Madrid, Spain, August 28–31, 2019, p. 6.

[130] D. Sidorov, D. Panasetsky, N. Tomin, et al., Toward zero-emission hybrid AC/DC power systems with renewable energy sources and storages: a case study from lake Baikal region, Energies 13 (2020) 12–26.

[131] Y. Shang, W. Wu, J. Guo, Z. Lv, Z. Ma, W. Sheng, R. Chen, Stochastic dispatch of energy storage in microgrids: a reinforcement learning approach incorporated with MCTS, CoRR, October 2019, arXiv:1910.04541 [abs], 2019, p. 7 (open access).

[132] D. Zhang, R.C. Qiu, Deep reinforcement learning for power system applications: an overview, CSEE Journal of Power and Energy Systems 6 (1) (2020) 213–225.

[133] H. Zhang, et al., Bi-level actor-critic for multi-agent coordination, arXiv:1909.03510, 2019, p. 8, https://doi.org/10.48550/arXiv.1909.03510.

[134] M.L. Littman, Markov games as a framework for multi-agent reinforcement learning, in: Machine Learning Proceedings, Elsevier, 1994, pp. 157–163.

[135] V.Z. Gjorgievski, S. Cundeva, G.E. Georghiou, Social arrangements, technical designs and impacts of energy communities: a review, Renewable Energy 169 (2021) 1138–1156, https://doi.org/10.1016/j.renene.2021.01.078.

[136] D.T. Ton, M.A. Smith, The U.S. Department of energy's microgrid initiative, The Electricity Journal 25 (2012) 84–94.

[137] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001, 2019. (Accessed 21 December 2018).

[138] G. Walker, P. Devine-Wright, Community renewable energy: what should it mean?, Energy Policy 36 (2008) 497–500.

[139] M. Warneryd, M. Håkansson, K. Karltorp, Unpacking the complexity of community microgrids: a review of institutions' roles for development of microgrids, Renewable & Sustainable Energy Reviews 121 (2020) 109690, https://doi.org/10.1016/j.rser.2019.109690.

[140] B. Fina, H. Auer, Economic viability of renewable energy communities under the framework of the renewable energy directive transposed to Austrian law, Energies 13 (2020) 5743, https://doi.org/10.3390/en13215743.

[141] M.L. Lode, G. te Boveldt, T. Coosemans, L. Ramirez Camargo, A transition perspective on Energy Communities: a systematic literature review and research agenda, Renewable & Sustainable Energy Reviews 163 (2022) 112479, https://doi.org/10.1016/j.rser.2022.112479.

[142] G. Iazzolino, N. Sorrentino, D. Menniti, A. Pinnarelli, M. De Carolis, L. Mendicino, Energy communities and key features emerged from business models review, Energy Policy 165 (2022) 112929, https://doi.org/10.1016/j.enpol.2022.112929.

[143] E. Dal Cin, G. Carraro, G. Volpato, A. Lazzaretto, P. Danieli, A multi-criteria approach to optimize the design-operation of Energy Communities considering economic-environmental objectives and demand side management, Energy Conversion and Management 63 (2022) 115677, https://doi.org/10.1016/j.enconman.2022.115677.

[144] H.R. Bokkisam, M.P. Selvan, Effective community energy management through transactive energy marketplace, Computers & Electrical Engineering 93 (2021) 107312, https://doi.org/10.1016/j.compeleceng.2021.107312.

[145] M.S. Simoiu, I. Fagarasan, S. Ploix, V. Calofir, Modeling the energy community members' willingness to change their behaviour with multi-agent systems: a stochastic approach, Renewable Energy 194 (2022) 1233–1246, https://doi.org/10.1016/j.renene.2022.06.004.

[146] G. Di Lorenzo, S. Rotondo, R. Araneo, G. Petrone, L. Martirano, Innovative power-sharing model for buildings and energy communities, Renewable Energy 172 (2021) 1087–1102, https://doi.org/10.1016/j.renene.2021.03.063.

[147] M.S. Javed, T. Ma, J. Jurasz, J. Mikulik, A hybrid method for scenario-based techno-economic-environmental analysis of off-grid renewable energy systems, Renewable & Sustainable Energy Reviews 139 (2021) 110725, https://doi.org/10.1016/j.rser.2021.110725.

[148] Z. Liu, J. Guo, D. Wu, G. Fan, S. Zhang, X. Yang, H. Ge, Two-phase collaborative optimization and operation strategy for a new distributed energy system that combines multi-energy storage for a nearly zero energy community, Energy Conversion and Management 230 (2021) 113800, https://doi.org/10.1016/j.enconman.2020.113800.

[149] Z. Liu, G. Fan, D. Sun, D. Wu, J. Guo, S. Zhang, X. Yang, X. Lin, L. Ai, A novel distributed energy system combining hybrid energy storage and a multi-objective optimization method for nearly zero-energy communities and buildings, Energy 239 (2022) 122577, https://doi.org/10.1016/j.energy.2021.122577.

[150] Z. Ullah, M.R. Elkadeem, K.M. Kotb, I.B.M. Taha, S. Wang, Multi-criteria decision-making model for optimal planning of on/off grid hybrid solar, wind, hydro, biomass clean electricity supply, Renewable Energy 179 (2021) 885–910.

[151] V. Shakirov, A. Kozlov, Multicriteria assessment of biomass gasification-based hybrid energy systems in remote areas, Biofuels, Bioproducts and Biorefining 17 (2) (2023) 380–388, https://doi.org/10.1002/bbb.2377.

[152] M.J. Rana, K.H. Rahi, T. Ray, R. Sarker, An efficient optimization approach for flexibility provisioning in community microgrids with an incentive-based demand response scheme, Sustainable Cities and Society 74 (2021) 103218, https://doi.org/10.1016/j.scs.2021.103218.

[153] D. Kholkin, I. Chausov, A new formula for the energy transition [Electronic document], Energy Policy, https://energypolicy.ru/d-holkin-i-chausov-novaya-formula-energeticheskogo-perehoda/energoperehod/2020/13/20/, 2020. (Accessed 20 December 2020).

[154] O. Valarezo, T. Gómez, J.P. Chaves-Avila, L. Lind, M. Correa, D. Ulrich Ziegler, R. Escobar, Analysis of new flexibility market models in Europe, Energies 14 (12) (2021) 3521, https://doi.org/10.3390/en14123521.

[155] S. Schreiber, Ch. Zöphel, Ch. Fraunholz, U. Reiter, A. Herbst, T. Fleiter, D. Möst, Experience curves in energy models—lessons learned from the REFLEX project, in: Martin Junginger (Ed.), AtseLouwen, Technological Learning in the Transition to a Low-Carbon Energy System, Academic Press, 2020, pp. 259–279, https://doi.org/10.1016/B978-0-12-818762-3.00014-5.
[156] C. Walker, P. Devine-Wright, M. Rohse, L. Gooding, H. Devine-Wright, R. Gupta, What is 'local' about smart local energy systems? Emerging stakeholder geographies of decentralised energy in the United Kingdom, Energy Research & Social Science 80 (2021) 102182, https://doi.org/10.1016/j.erss.2021.102182.
[157] T. Schittekatte, L. Meeus, Flexibility markets: Q&A with project pioneers, Utilities Policy 63 (2020) 101017, https://doi.org/10.1016/j.jup.2020.101017.
[158] W. Craft, L. Ding, D. Prasad, Understanding decision-making in regenerative precinct developments, Journal of Cleaner Production 338 (2022) 130672, https://doi.org/10.1016/j.jclepro.2022.130672.
[159] M. Negnevitsky, J. Hamilton, S. Lyden, X. Wang, Achieving high renewable energy penetration in off-grid systems via low load diesel integration: a case study of King Island, Australia, in: Proceedings of CIGRE 2018, Paris, France, 2018, pp. 1–12.
[160] EPS storage system being commissioned in Australian microgrid, Fuel Cells Bulletin 2 (2017) 7–8, https://doi.org/10.1016/S1464-2859(17)30084-6, 2017. (Accessed 2 March 2017).
[161] A. Pacheco, J. Monteiro, J. Santos, C. Sequeira, J. Nunes, Energy transition process and community engagement on geographic islands: the case of Culatra Island (Ria Formosa, Portugal), Renewable Energy 184 (2022) 700–711, https://doi.org/10.1016/j.renene.2021.11.115.
[162] B. Homan, G. Hoogsteen, S. Nebiolo, J.L. Hurink, G.J.M. Smit, Maximizing the degree of autarky of a 16 house neighbourhood by locally produced energy and smart control, Sustainable Energy, Grids and Networks 20 (2019), https://doi.org/10.1016/j.segan.2019.100270.
[163] W. Yang, S.N. Sparrow, M. Ashtine, D. Wallom, T. Morstyn, Resilient by design: preventing wildfires and blackouts with microgrids, Applied Energy 313 (2022) 118793, https://doi.org/10.1016/j.apenergy.2022.118793.
[164] The Microgrid Case Studies: Community Resilience for Natural Disasters, https://sepapower.org/resource/the-microgrid-case-studies-community-resilience-for-natural-disasters/, 2020.
[165] V.Yu. Kononenko, O.V. Veshunov, V.P. Bilashenko, D.O. Smolentsev, Effects of the use of energy storage in isolated energy systems of Russia, Arctic: Ecology and Economics 2 (14) (2014) (in Russian).
[166] D.N. Karamov, Optimization of the composition of the equipment of autonomous energy complexes using renewable sources and energy storage devices, PhD. Thesis, Irkutsk, 2016, 152 p. (in Russian).
[167] N.I. Voropai, K.V. Suslov, T.V. Sokolnikova, Z.A. Styczynski, P. Lombardi, Development of power supply to isolated territories in Russia on the bases of microgrid concept, in: 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 2012, pp. 1–5, https://doi.org/10.1109/PESGM.2012.6344612.
[168] B.V. Lukutin, O.A. Surzhikova, E.B. Shandarova, Renewable Energy in Decentralized Power Supply, Energoatomizdat, Moscow, 2008, p. 231 (in Russian).
[169] Active energy complexes are the first step towards industrial microgrids in Russia, Expert-analytical report, NTI Energynet, Moscow, 2020, p. 58 (in Russian).
[170] A.N. Zazulya, A.V. Kobelev, S.V. Kochergin, N.A. Khrebtov, The use of biogas plants in the power supply of agricultural enterprises in the Tambov region, Science in Central Russia 4 (2013) 66–71 (in Russian).
[171] Patent 2258535 Russian Federation, IPC A 61 L 11/00, B 09 B 1/00, Device for extracting biogas for neutralization of landfills for storing municipal solid waste, Marinenko E.E.,

Efremova T.V., Perfilov E.V., Cherkasov A.V., Gorbunova M.E.; applicant and patent holder State educational institution of higher professional education Volgograd State University of Architecture and Civil Engineering (VolgGASU) - 2003125540/15; statement 2003.08.18, published 2005.08.20, Bulletin No. 16, p. 6 (in Russian).

[172] Gas generators for the generation of electricity from natural gas, https://lucheeotoplenie.ru/tipy-otopleniya/elektricheskoe/gazogeneratory-dlya-vyrabotki-elektroenergii-na-prirodnom-gaze.html. (Accessed 1 April 2022) (in Russian).

[173] F.A. Kipriyanov, The use of a gas generator in conjunction with a power plant, Sovremennaya Tekhnika i Tekhnologii 3 (2017), https://technology.snauka.ru/2017/03/12525, 2017. (Accessed 19 April 2021) (in Russian).

[174] D. Graaf, New strategies for Smart Integrated Decentralised Energy Systems, Report, https://www.metabolic.nl/publications/side-systems-pdf/, 2018. (Accessed 2 June 2019).

[175] M.L. Lode, S. Heuninckx, G. teBoveldt, C. Macharis, T. Coosemans, Designing successful energy communities: a comparison of seven pilots in Europe applying the Multi-Actor Multi-Criteria Analysis, Energy Research & Social Science 90 (2022) 102671, https://doi.org/10.1016/j.erss.2022.102671.

[176] N. Tomin, V. Shakirov, A. Kozlov, D. Sidorov, V. Kurbatsky, C. Rehtanz, E.E.S. Lora, Design and optimal energy management of community microgrids with flexible renewable energy sources, Renewable Energy 183 (2022) 903–921, https://doi.org/10.1016/j.renene.2021.11.024.

[177] H. ur Rehman, F. Reda, S. Paiho, A. Hasan, Towards positive energy communities at high latitudes, Energy Conversion and Management 196 (2019) 175–195, https://doi.org/10.1016/j.enconman.2019.06.005.

[178] J. Guo, P. Zhang, D. Wu, Z. Liu, X. Liu, S. Zhang, X. Yang, H. Ge, Multi-objective optimization design and multi-attribute decision-making method of a distributed energy system based on nearly zero-energy community load forecasting, Energy 239 (2022) 122124, https://doi.org/10.1016/j.energy.2021.122124.

[179] H. Karimi, S. Jadid, Optimal energy management for multi-microgrid considering demand response programs: a stochastic multi-objective framework, Energy 195 (2020) 116992, https://doi.org/10.1016/j.energy.2020.116992.

[180] W.Y. Chiu, H. Sun, H.V. Poor, A multi objective approach to multi microgrid system design, IEEE Transactions on Smart Grid 6 (5) (2015) 2263–2272.

[181] Y. Cao, B. Zhou, S.W. Or, K.W. Chan, N. Liu, K. Zhang, An interactive tri-level multi-energy management strategy for heterogeneous multi-microgrids, Journal of Cleaner Production 319 (2021) 128716, https://doi.org/10.1016/j.jclepro.2021.128716.

[182] N. Tomin, V. Shakirov, V. Kurbatsky, R. Muzychuk, E. Popova, D. Sidorov, A. Kozlov, D. Yang, A multi-criteria approach to designing and managing a renewable energy community, Renewable Energy 199 (2022) 1153–1175, https://doi.org/10.1016/j.renene.2022.08.151.

[183] K. Ram, P.K. Swain, R. Vallabhaneni, A. Kumar, Critical assessment on application of software for designing hybrid energy systems, Materials Today: Proceedings 49 (2022) 425–432, https://doi.org/10.1016/j.matpr.2021.02.452.

[184] D. Ribó-Pérez, Á. Herraiz-Cañete, D. Alfonso-Solar, C. Vargas-Salgado, T. Gómez-Navarro, Modelling biomass gasifiers in hybrid renewable energy microgrids; a complete procedure for enabling gasifiers simulation in HOMER, Renewable Energy 174 (2021) 501–512, https://doi.org/10.1016/j.renene.2021.04.083.

[185] S. Sinha, S.S. Chandel, Review of software tools for hybrid renewable energy systems, Renewable & Sustainable Energy Reviews 32 (2014) 192–205, https://doi.org/10.1016/j.rser.2014.01.035.

[186] O.M. Babatunde, J.L. Munda, Y. Hamam, Hybridized off-grid fuel cell/wind/solar PV /battery for energy generation in a small household: a multi-criteria perspective, International Journal of Hydrogen Energy 47 (2022) 6437–6452, https://doi.org/10.1016/j.ijhydene.2021.12.018.

[187] F. Odoi-Yorke, J.J. Owusu, L. Atepor, Composite decision-making algorithms for optimisation of hybrid renewable energy systems: Port of Takoradi as a case study, Energy Reports 8 (2022) 2131–2150, https://doi.org/10.1016/j.egyr.2022.01.118.

[188] J. Vishnupriyan, D. Arumugam, N.M. Kumar, S.S. Chopra, P. Partheeban, Multi-criteria decision analysis for optimal planning of desalination plant feasibility in different urban cities in India, Journal of Cleaner Production 315 (2021) 128146, https://doi.org/10.1016/j.jclepro.2021.128146.

[189] H.T. Nguyen, U. Safder, X.Q. Nhu Nguyen, C. Yoo, Multi-objective decision-making and optimal sizing of a hybrid renewable energy system to meet the dynamic energy demands of a wastewater treatment plant, Energy 191 (2020) 116570, https://doi.org/10.1016/j.energy.2019.116570.

[190] E.A. Aguayo, A. Mateos, A. Jiménez, A new dominance intensity method to deal with ordinal information about a DM's preferences within MAVT, Knowledge-Based Systems 69 (2014) 159–169, https://doi.org/10.1016/j.knosys.2014.05.017.

[191] B. Yatsalo, A. Korobov, L. Martínez, Fuzzy multi-criteria acceptability analysis: a new approach to multi-criteria decision analysis under fuzzy environment, Expert Systems with Applications 84 (2017) 262–271, https://doi.org/10.1016/j.eswa.2017.05.005.

[192] N. Tomin, V. Shakirov, A. Kozlov, D. Sidorov, V. Kurbatsky, C. Rehtanz, E.E.S. Lora, Design and optimal energy management of community microgrids with flexible renewable energy sources, Renewable Energy 183 (2022) 903–921, https://doi.org/10.1016/j.renene.2021.11.024.

[193] D. Perez, S. Samothrakis, S. Lucas, Online and offline learning in multi-objective Monte Carlo Tree Search, in: 2013 IEEE Conference on Computational Intelligence in Games (CIG), 2013, pp. 1–8, https://doi.org/10.1109/CIG.2013.6633621.

[194] S. Totaro, I. Boukas, A. Jonsson, B. Cornélusse, Lifelong control of off-grid microgrid with model-based reinforcement learning, Energy 232 (2021) 121035, https://doi.org/10.1016/j.energy.2021.121035.

[195] O.L. Mangasarian, Uniqueness of solution in linear programming, Linear Algebra and Its Applications 25 (1979) 151–162.

[196] B. Cornelusse, I. Savelli, S. Paoletti, A. Giannitrapani, A. Vicino, A community microgrid architecture with an internal local market, Applied Energy 242 (2019) 547–560, https://doi.org/10.1016/j.apenergy.2019.03.109.

CHAPTER

5

Hierarchical modeling for development of pipeline energy systems, coal supply systems, and integrated energy systems

V.A. Stennikov, E.A. Barakhtenko, N.I. Voropai, T.V. Dzyubina, O.A. Edeleva, N.I. Ilkevich, Zh.V. Kalinina, A.D. Sokolov, D.V. Sokolov, L.N. Takaishvily, and O.N. Voitov

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

The first section focuses on the hierarchical modeling technology for the spatio-temporal planning of heating systems at the levels of a country, a region, and a city. The second section of the chapter reviews the experience of using hierarchical modeling methods to solve a complex problem of optimal development and reconstruction of district heating systems, as the most common representatives of pipeline systems. The third section presents new results obtained using the optimization methodology for gas supply systems as pipeline systems of a complex network structure. The fourth section deals with original methods of hierarchical modeling for coal supply systems, and the fifth section provides information and computational tools for managing their development. The sixth section discusses intelligent integrated energy systems and the principles of their construction, architecture, models, and methods for their creation and operation management in the context of the energy transition.

Hierarchical Modeling of Energy Systems
https://doi.org/10.1016/B978-0-44-313917-8.00014-6

Abbreviations

HS – Heating System
THC – Theory of hydraulic circuits
HS – Heat Source
HN – Heat Network
DP – Dynamic Programming
MLO – Multi-Loop Optimization
DISIGR – The name of a software package
SB RAS – Siberian Branch of the Russian Academy of Sciences
SOSNA – The name of a software package
GSS – Gas Supply System
UGSS – Unified Gas Supply System
RF – Russian Federation
MESI – Melentiev Energy Systems Institute
PJSC – Public Joint Stock Company
PRNG – Pseudo-Random Number Generation
MGP – Main Gas Pipeline
CS – Compressor Station
GPU – Gas Pumping Unit
GCF – Gas Condensate Field
LP – line part
CSS – Coal Supply System
NEMS – National Energy Modeling System
IMSP – Information and Modeling Software Package
CHPP – Combined Heat and Power Plant
IIES – Intelligent Integrated Energy System
RES – Renewable Energy Source

5.1 Spatial and temporal hierarchy of the expansion planning of heating systems

Hierarchical levels of heating studies. Modern heating systems (HSS) are engineering structures unique in scale and complexity and are of increasing importance in all areas of the life of the country and society. The geographically dispersed nature of heating systems and their integration at the level of regions and the country as a whole, on the one hand, and the need to make decisions on the expansion of heating systems at different time levels (1, 5, 10, 15 years), on the other hand, predetermine the application of the hierarchical principle for the analysis of heating. This approach makes it possible to study the prospects of the development of geographically heterogeneous heating systems both as a whole and with the isolation of individual aspects, linking them to the adopted scheme of planning the expansion of systems [1,2].

These considerations are implemented on the basis of the multilevel decision-making workflow the fundamental idea behind which is to decompose one complex problem into a number of simple problems of lesser complexity and to align the resulting solutions.

The integrating basis for solving the above array of problems is the methodological principle based on the unity of the energy, environmental, and economic aspects that are focused on the study of heating systems.

The theoretical foundation for solving problems of design and control over the operation of pipeline systems of various types and serving various purposes is the theory of hydraulic circuits (THC) originally proposed at the MESI and successfully undergoing further development there, which is the basis for modeling, calculation, evaluation, and optimization of pipeline and hydraulic systems of various types [3,4].

At the "Country" level, we make projections of the directions of development of the country's heating system in the future. The level of detail is low, it is mainly the average technical and economic performance metrics that are used here.

The mathematical statement of the problem of optimal expansion of the heating system at the country level, together with the justification of the directions of its expansion at the regional level, can be presented in the following form:

$$C_{HSS} = \sum_{t=1}^{T} (C^t_{HS}(x^t) + C^t_{HN}(x^t)) \rightarrow \min, \tag{5.1}$$

where C_{HSS} is total discounted costs of the expansion of the heating system of the country; C^t_{HS} is discounted costs of reconstruction, modernization of existing or construction of new heat sources (HS) during the period t; C^t_{HN} is discounted costs of reconstruction, modernization of existing or laying of new heat networks (HN) during the period t; x^t is heat delivery (transfer) by the HN from the HS to the consumer during the period t; T is considered time period of heating system expansion, divided into equal time periods $t = (1, \ldots, T)$.

The system of constraints includes:

Balance ratios of heat production and consumption:

$$\sum_{t=1}^{T} x^t \geq \sum_{t=1}^{T} Q^t_{HS}, \qquad t \in T, \tag{5.2}$$

$$\sum_{t=1}^{T} Q^t_{HS} = \sum_{t=1}^{T} Q^t_{C}, \qquad t \in T, \tag{5.3}$$

where Q^t_C is the amount of heat consumed in the country as a whole in the time period t.

Balance ratios of electricity production and consumption:

$$\sum_{t=1}^{T} W^t_{HS} \leq \sum_{t=1}^{T} W^t_{C}, \qquad t \in T, \tag{5.4}$$

$$W_{HS}^{t}=f(Q_{HS}^{t}), \qquad t\in T, \tag{5.5}$$

where W_C^t is the amount of electricity consumed in the country as a whole in the time period t.

The most promising direction for the expansion of the heating system is currently the co-generation, which represents the combined generation of heat and electricity. The ratio (5.5) shows that the volume of electricity generation depends on the volume of heat production during their combined production.

Constraints on the volume of fuel consumption of different types:

$$B_{\tau}^{t}\le B_{\tau\,\max}^{t}, \qquad t\in T, \tag{5.6}$$

$$Q_{HS}^{t}=f(B_{\tau}^{t}), \qquad t\in T, \tag{5.7}$$

where B_τ^t is the volume of fuel of the τth type consumed in the country over the period of time t; $B_{\tau\,\max}^t$ is the maximum volume of fuel of the τth type produced in the country over the period of time t.

Constraints on the amount of emissions of harmful substances into the environment from heating system:

$$F_{\tau}^{t}\le F_{\tau\,\max}^{t}, \qquad t\in T, \tag{5.8}$$

$$F_{\tau}^{t}=f(B_{\tau}^{t}), \qquad t\in T, \tag{5.9}$$

where F_τ^t is the volume of emissions of harmful substances from combustion of the fuel of the τth type in the time period t; $B_{\tau\,\max}^t$ is the maximum permissible volume of emissions of harmful substances, which is set in the country in the time period t.

Among the main issues/problems solved here we address the following ones: analysis of general patterns in the development of systems; projections of energy production and consumption; determining the rational scale of implementation of promising heat sources; their optimal mix, etc. Methods for statistical information processing, regression analysis, linear programming, etc. are used here as methodological tools.

At the "Region" level it is supposed to consider in more detail the promising technologies used for the production, consumption, and transmission of energy. A financial assessment of scenarios for the development of the region's heating is made. The statement of the problem as a whole corresponds to that of (5.1)–(5.9) described above, with the only difference that the scale of the area is changed and the level of detail of consideration of energy facilities is increased.

Consideration of external relations at the levels described above ensures the mutual alignment of the tasks facing the heating industry with the long-term expansion plans of the electric power system and the conditions of the fuel supply of the country and the region. This approach of searching for the optimal path of the technological and spatial evolution of the heating system seems relatively simple and clear and makes it possible to conduct research, on the one hand, independent of the consideration of system-wide issues of the energy sector, yet in conjunction with them, and, on the other hand, fits well into the structure of its general model.

At the "Settlement" level, one should work out specific decisions on the structure and parameters of heating systems and heat sources while taking into account the specific characteristics of the local energy industry and local conditions [1]. On the basis of incentive mechanisms and legal regulation, a unified state policy in the heating industry is carried out.

The conceptual statement of the problem consists in the search for effective directions of transformation of the system structure in terms of selection of optimal locations of new heat sources, their type, performance, area of operation; reconstruction of existing and laying of new routes of heat networks, their flow diagram and parameters; flow diagrams and types of connecting heat consumers; replacement of obsolete technologies and equipment with new energy-efficient solutions; ensuring requirements of reliability of heating and system controllability [5,6].

The solutions should meet the physical and technical conditions of the heating system operation, the constraints on the parameters of operating conditions, and be aligned with the minimum costs of the development and operation of the system.

The mathematical statement of the problem can be written in the following form.

Find the minimum of the objective function in the form of present (discounted) costs:

$$\min(C_{HS}(x, \delta t) + C_{HN}(x, h, H) + C_{El}(x, \delta t)), \tag{5.10}$$

where $C_{HS}(x, \delta t)$, $C_{HN}(x, h, H)$ is discounted costs of heat sources and heat networks; $C_{El}(x, \delta t)$ are costs of supplementary electricity.

In the expression (5.10), $C_{HS}(x, \delta t)$ and $C_{HN}(x, h, H)$ includes costs of the existing and new components of the system, as well as those of the reconstruction of existing heat networks and sources. The value of $C_{El}(x, \delta t)$ ensures that the options under consideration are brought to the same energy effect.

The system of conditions and constraints includes:

- material balances at the nodes (Kirchhoff's first law)

$$Ax = Q, \tag{5.11}$$

where $A = \{a_{ji}\}$ is a connection matrix for linearly independent nodes of dimension $(m-1) \times n$; x is a vector of costs for network sections; Q is a vector of costs at nodes;

- equality of effective pressure heads and pressure losses for independent loops (second Kirchhoff's law)

$$BH = Bh, \tag{5.12}$$

where $B = b_{ri}\}$ is the matrix of loops or coincidences of the selected basic system of loops and branches; h, H are vectors of losses and effective pressures.

- the constitute relation as a function of the head loss (pressure difference) at the section

$$h_i = f(x_i, d_i, l_i) = P_j - P_{j+1} - H_i, \quad j \in J, \quad i \in I, \tag{5.13}$$

where d_i, l_i is diameter, length of the ith section of the network;

- constraints on the flow rate of the heat transfer fluid in the network sections x_i

$$0 \le x_i \le \overline{x}_i, \quad i \in I, \tag{5.14}$$

- constraints on the node pressure P_j

$$\underline{P}_j \le P_j \le \overline{P}_j, \quad j \in J, \tag{5.15}$$

- constraints on the available head at consumers Δh_j

$$\Delta h_j \ge \Delta \underline{h}_j, \quad \Delta h_j = P_j^{(S)} - P_j^{(R)}, \quad j \in J_1, \tag{5.16}$$

where the indices S and R denote the supply and return pipes;

- constraints on the rate of flow of the heat transfer fluid through sections of the network W_i

$$W_i(x_i, d_i) \le \overline{W}_i, \quad i \in I, \tag{5.17}$$

- constraints imposed by reliability requirements, which are defined by standardized values:

the availability factor at all consumer nodes

$$K_j^{(1)} \ge K_N^{(1)}, \quad j \in J_1, \tag{5.18}$$

probabilities of failure-free operation for all consumer nodes

$$R_j^{(2)} \ge R_N^{(2)}, \quad j \in J_1, \tag{5.19}$$

- discrete sets of pipe schedules

heat sources G

$$g_i \in G_i \subset G, \quad i \in I_{m+1}, \tag{5.20}$$

pipeline diameters D

$$d_i \in D_i \subset D, \quad i \in I, \tag{5.21}$$

pumping stations T

$$H_i \in T_i \subset T, \quad i \in I, \tag{5.22}$$

- acceptable methods of reconstruction and logical conditions for their choice for:

operating heat sources $\nu(G)$

$$\nu(g_i) \in \nu(G_i) \subset \nu(G), \quad i \in I_{m+1}, \tag{5.23}$$

existing sections of the heat network $\nu(D)$

$$\nu(d_i) \in \nu(D_i) \subset \nu(D), \quad \in I_1, \tag{5.24}$$

pumping stations $\nu(H)$

$$\nu(H_i) \in \nu(T_i) \subset \nu(T), \quad j \in I_1, \tag{5.25}$$

the temperature profile of the heat transfer fluid (t) in the supply and return lines and their difference (δt):

$$\delta t = t_i^{(S)} - t_i^{(R)}, \quad i \in I_{m+1}. \tag{5.26}$$

Here J_1, J_2, J_3, J_4 is a subset of consumer nodes, source nodes, branch nodes, and source nodes with fixed capacities; I_1, I_2 is subsets of existing and newly designed network sections; I_3, I_4 is a subset of sections with existing and new pumping units; I_{m+1} is a subset of dummy links connecting source nodes with the dummy node $j = m + 1$.

The need to take into account the existing state and reliability requirements complicates the problem considerably. Solutions for the flow diagrams change from the branched (dead-end) type to the multi-loop (ring) type. The requirements for reliability and controllability of systems lead to the need of introducing structural and parametric redundancy in them. The continuous nature of the objective function becomes discrete with additional local minima. The hydraulic and economic characteristics of the system components are nonlinear. A certain difficulty in solving the problem in question is due to the highly distributed nature of heat networks, the dispersion of heat sources and consumers, the continuous development over time.

The general mathematical model of nonconvex programming stated above cannot in principle be fully formalized and solved by a single universal method and is decomposed into an array of separate relatively independent problems with their further linking within a single computational process. This allows one to spread it out over time, intervene in its course and make adjustments to the solution, taking into account the individual characteristics of the systems.

In the general problem of optimal development of the heating system, it is relatively easy to separate interrelated problems of optimization of flow diagram structure and flow diagram parameters, analysis and reliability of the system, assessment of the system performance under the planned operating conditions, etc.

Optimization of the flow diagram structure of the system involves selecting the number, type, location, and capacity of sources, including determining the feasibility of expanding or, conversely, excluding existing sources from the flow diagram; finding the optimal flow diagram of the heat network with its division into parts that redundant and non-redundant parts.

The mathematical statement of the problem includes an objective function in the form of the expression (5.10), a system of conditions and constraints in the form of the equations, inequalities, and logical conditions (5.11)–(5.16), (5.20), (5.22), (5.23), (5.25).

The stated problem is reduced to the problem of the most profitable load flow in a given "redundant" network flow diagram and consists in minimization of the nonlinear function (5.10) subject to the above-described constraints. The optimal solution is on the boundaries of the admissible area defined by the system of balance equations (5.11)–(5.13) and corresponds to one of the trees connecting consumption nodes with heat sources. Its search is carried out by the method of directed limited enumeration of options of the trees of the "redundant" flow diagram, first applied to heating systems in [7] and developed in subsequent works [8,9].

The model part concerning heat sources takes into account their capacity limitations (both for existing and newly designed sources), as well as the conditions of equipment discreteness. Algorithms for calculating sources of different types (CHPPs and fossil and nuclear fuel-fired boiler houses) were developed. Calculations are made taking into account the existing and newly designed heat sources, their standard schedules, optimal loading of the main equipment during the year, annual profiles of heat loads duration (Rossander profiles), and some other features of systems operation.

Optimization of the flow diagram parameters of the system is aimed at identifying bottlenecks in the system and selecting techniques for their reconstruction; determining diameters of new and reconstructed sections; selecting locations and parameters of pumping units; determining flow rates in sections of the multi-loop network and pressures at its nodes, including the available pressures at the headers of heat sources.

The optimization criterion is a minimum of discounted costs, expressed by the function (5.10), and including the cost of construction and operation of heating pipelines and pumping stations, the cost of electricity consumed for pumping heat transfer fluid, and the cost of heat losses. Optimization with respect to heat sources is not done here, so their costs are not included in the criterion. The system of conditions and constraints consists of the subsystems (5.11)–(5.17), (5.21), (5.22), (5.24), (5.25), defining the area of admissible solutions, physical-and-engineering, and other requirements describing the features of heating systems and their individual components. The complexity of this problem, unlike optimization of systems having a tree-shaped structure, is caused by the following: multi-loop flow diagrams with a number of loops; unknown variables of the flow rate vector x in sections; the objective function being non-convex with respect to x; necessity to include the entire model of load flow (5.11)–(5.13) and its calculation in the optimization process.

The dynamic programming (DP) method [8] is used for solving the problems of optimization of parameters of tree-shaped flow diagrams, and the multi-loop optimization (MLO) method was proposed at the ESI for multi-loop systems [10,11].

The use of the DP method allows one to take into account individual features of the system and its components, the existing state, technical limitations, and logical conditions when selecting parameters. Load flow analysis ensures the feasibility of the decisions made and the operability of the system during its operation.

Evaluating the performance of the system by load flow analysis (hydraulic analysis) for various operating conditions. This problem, on the one hand, has the importance of its own for the calculation and analysis of operating conditions of systems, and, on the other hand, is applied in the multistage process of their optimization and describes the range of admissible solutions in optimization models.

This is the name given to the problem of calculating the parameters of hydraulic states of pipeline systems, which include the heat transfer fluid flow rates in the sections and its pressure at the nodes of the network flow diagram. Distribution of flow rates and pressures in the system is described by a system of linear (counterparts of the first and second Kirchhoff laws for an electric circuit) and non-linear (relationship between flow rates and pressure losses in network sections) equations (5.11)–(5.13).

Another important purpose of these problems in the multilevel process of optimization of development and reconstruction of heating systems is to check and evaluate their performance, the ability to implement the expected modes of operation, satisfying the required profile of heat demand, etc. To solve these problems, the methods of nodal pressures, loop flow rate, etc. are applied. They are the basis for the creation of dialog systems of hydraulic calculations like DISIGR and others. [12].

Analysis and assurance of the reliability of providing heating to consumers involve consideration of two levels of reliability, assessed by the availability factor $K_j^{(1)}$ (the first - design - level) and the probability of failure-free operation $R_j^{(2)}$ (the second - reduced or emergency - level) [13].

Calculation of metrics of reliability of providing heating to consumers when solving the problem of transformation of heating systems is carried out according to the following dependencies:

$$K_j^{(1)} = (T_{HSeason} - \sum_{i \in I_j} Z_i)/T_{HSeason}, \tag{5.27}$$

$$Z_j^1 = T_{HSeason}(1 - K_j^{(1)}), \tag{5.28}$$

$$R_j^{(2)} = \prod_{n=1}^{N} exp\left[-\sum_{i \in I_j} \omega_i (\Delta t_n - t_{pj}^{(2)}) exp\ (-t_{pj}^{(2)}/\hat{\tau}_{\mathrm{b}i})\right], \tag{5.29}$$

$$a_j^{(2)} = -lnR_j^{(2)}, \tag{5.30}$$

where ω_i, $\hat{\tau}_{\mathrm{b}i}$ is the parameter of failure flow (1/h) and the average recovery time of the ith component of the heat network (Z); I_j is the set of components at the branch to the jth consumer and in the ring part of the network that hydraulically connected to it; Δt_n is the duration of the nth time interval, into which the heating season is divided $\Delta t_n = \frac{T_{HSeason}}{N}$; $t_{pj}^{(2)}$, $t_{pk}^{(2)}$ is the amount of the temporary reserve of the jth consumer relative to the reduced level of reliability for components of the heat network.

On the basis of probabilistic assessments of the considered levels of reliability, one distinguishes between redundant and non-redundant parts of the heat network [14]. The parameters of the redundant part of the network are chosen so that if any of the sections of this part of the network fails, consumers will receive some, usually a reduced amount of heat, called the standardized value of reserve heating ϕ_j, $j \in J_1$.

The value of the first level metric ($K_j^{(1)}$) depends equally on the reliability of all components [of redundant and non-redundant parts] of the network, since failures of this level occur almost always in case of failures of all its components. $K_j^{(1)}$ determines the allowable total length of the non-redundant branch to the node j and of the redundant network hydraulically connected to it.

The second level metric ($R_j^{(2)}$) depends, to a greater extent, on the reliability of the components of the non-redundant branch. This metric defines the permissible length of a non-redundant branch to a node, i.e., the point at which the network is divided into redundant and non-redundant parts. The value of this metric determines the need for network redundancy.

The presented set of models, methods of computational tools, is versatile enough, it allows one to describe practically any type and structure of heating systems and to consider the full range of problems of their expansion.

The process of forming the solutions is carried out in accordance with the multilevel workflow of its preparation, the main idea of which is that the proposals formed by the lower level should be summarized and transmitted to the upper level, where, taking into account the interests of the state, the main directions of development of the heating industry of the country and its regions are formed. Thus, iterative linking of lower and upper-level solutions is carried out.

5.2 Hierarchical modeling in the design of heating systems

Workflow of solving the problems of designing heating systems. The distinctive feature of the problem of optimal heating system design is that it involves the building of its algorithm from a different mix of subproblems unique to the set of heating systems under consideration and taking into account their specific characteristics. As a rule, it is a complex iterative computational process during which subproblems for various heating systems can be solved in different orders and by employing different methods depending on the predefined goal. One of the possible workflows for solving the problem of optimal heating system design is shown in Fig. 5.1.

The above problems are solved for the heating systems of large scale and complexity which is due to their multi-ring structure, availability of multiple active components (pumping stations, control devices), and a large number of pipelines. As a result, the analysis of such heating systems proves unfeasible within a reasonable amount of time. The means of overcoming the above-mentioned difficulties is the application of approaches based on the decomposition of heating system equivalent diagrams or the decomposition of problems that are to be solved into simpler subproblems. Decomposition is a part of the multilevel modeling methodology, which assumes transition from an original complex problem to a hierarchically connected set of problems of lower dimensionality and complexity when solving problems of high dimensionality. This methodology has been successfully applied at the Melentiev Energy Systems Institute, SB RAS, to solving problems of analysis and design of heating systems [15–18].

Abroad, methods based on the decomposition of equivalent models of heating systems and other energy systems have been widely adopted [19–21]. The high dimensionality of heating systems, as well as the high complexity of the problems to be solved, are successfully overcome by applying approaches based on aggregation [22–24] and hierarchical modeling [23–27].

Fundamental principles of multilevel heating system modeling. Mathematical and computer modeling of the heating system begins with the

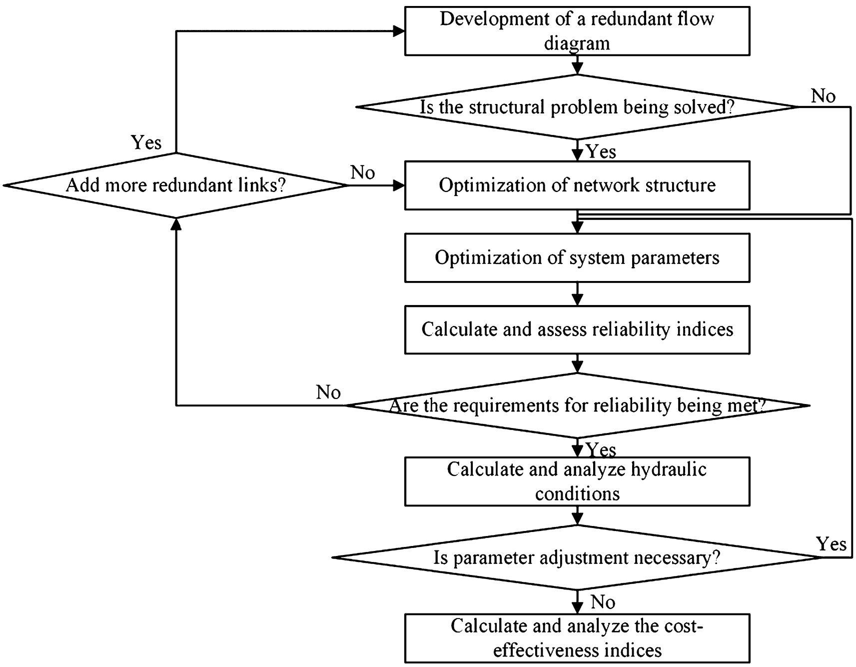


FIGURE 5.1 An aggregated flowchart of solving the problem of optimal design of the heating system.

construction of its model, which describes the configuration of the heating system, the composition of its equipment and its characteristics, the state of components and their properties (technical specifications, hydraulic parameters, and boundary conditions). Heating systems of different types have common structural-and-topological properties and physical laws of the flow of the transported medium [3], which allows us to formulate the following general considerations characteristic of the methodology of their computer and mathematical modeling:

1. All heating systems can be modeled as a graph whose vertices correspond to the nodes (sources, connecting nodes, consumers) while the edges correspond to the branches (pipelines, active branches with pumping stations, pressure or flow control devices).
2. The problems of mathematical modeling of the heating system share their conceptual and mathematical statements, while the methods, algorithms, and dedicated software used to solve them can be versatile in their nature (that is, they do not depend on the type of the heating system).
3. A computer model of the heating system of a certain type can be represented as the array of a graph describing the configuration of this

system and a set of graphical and mathematical models describing the properties of its elements.

4. Modern heating systems of different types, as a rule, are constructed as per the hierarchical principle that allows constructing hierarchical mathematical models of these systems and to solve the problems by applying multilevel modeling.

In the case of multilevel modeling the unified model of the heating system is considered as a set of hierarchically connected subsystems according to the following aspects related to the features inherent in their construction and operation:

1. Performed energy functions:
   - generation,
   - transport,
   - storage,
   - consumption.
2. Sectioning of heating systems according to territorial and geographical criteria.
3. The structure of the transport subsystem in the heating system:
   - main networks,
   - distribution networks,
   - internal consumer networks.
4. Delimiting individual subsystems within a unified system, such as pumping and compressor stations in the network, source pumping equipment systems, supply and return main lines of heat networks, individual branches of pipelines, individual consumer systems, the distribution system of the heat transfer medium, etc.
5. Structural-and-topological architecture of the transport subsystem in the heating system:
   - ring-shaped subnetworks,
   - tree-shaped branches.

The application of multilevel modeling allows moving from an initial complex problem to a hierarchically connected set of subproblems, each of which has lower dimensionality and complexity if compared to the initial problem.

Methods for solving the problem of determining the optimal parameters of the heating system. To solve the problem under consideration, efficient methods for determining the optimal parameters of pipeline systems of various types and purposes have been developed as part of the theory of hydraulic circuits [3,5,6]. For branched networks (those having a tree-shaped configuration in a single-line representation), a method of

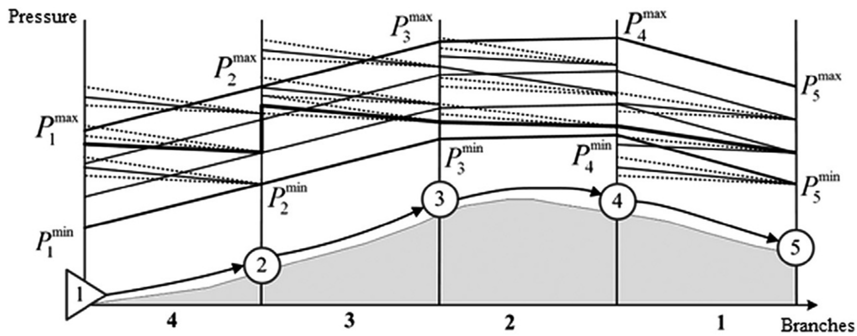


FIGURE 5.2 Illustration of the process of solving a problem using the dynamic programming method.

step-by-step optimization based on dynamic programming has been developed [3,6]. For ring-shaped networks (having the ring-shaped configuration in a single-line representation), a multi-loop optimization method based on sequential solution improvement has been developed [10,28]. An important feature of the above methods is that they allow us to fully take into account the specifics of the equipment used, the ways of its construction and operation, as well as the complexity of nonlinear mathematical models, and flexibly adjust the computational procedure to the mathematical models of the array of equipment used.

Dynamic programming method. The additive objective function (5.1) makes it possible to apply the DP method to solve the problem of determining the optimal parameters of branched heating systems: for networks of this type, the flow rates at the branches x are uniquely determined by the tree-shaped structure and the nodal flow rates Q. The computational procedure based on DP consists in a multistep process of determining the parameters of network elements (branches and nodes) by their sequential selection proceeding in the direction from consumers to the source [7]. The solution search area (Fig. 5.2), formed between the upper ($P_j^{\max}$, $j \in J$) and lower ($P_j^{\min}$, $j \in J$) pressure constraints, is divided into n intervals (by the number of branches), which are divided into μ cells (they define the solution accuracy). The problem is solved in three stages:

1) "the forward pass", during which all cells are sequentially filled in and a set of provisionally optimal options is formed;

2) choosing the lowest cost option for the entire network;

3) "the backward pass", during which the parameters and cost components corresponding to the selected option are restored.

If there are several sources, the source with the highest performance is taken as the main source and all solutions are pulled toward it.

Mathematically, the process of determining the provisionally optimal option in the cell z ($z = 1, \ldots, \mu$) at the step i is described by a recurrence equation:

$$Z_i^*(\tilde{P}_{jz}) = \min_{\substack{d_i^u \in D_i \\ k=1,\ldots,\mu}} \left[Z_i^{\mathrm{PN}}(d_i^u) + Z_i^{\mathrm{PS}}(\tilde{\tilde{P}}_{jk} - \tilde{P}_{jz}) + Z_{i-1}^*(P_{j+1,k}) \right], \tag{5.31}$$

where Z_i^{PN} are pipeline costs, including the cost of construction, operation, electricity consumption and heat loss; d_i^u is the diameter of pipeline; $\tilde{P}_{jz}$ and $\tilde{\tilde{P}}_{jk}$ are pressures upstream of the pumping station and downstream of it in the cells z and k, respectively; Z_i^{PS} is costs of the pumping stations with the head $\tilde{\tilde{P}}_{jk} - \tilde{P}_{jz} = H_{iz}$; $Z_{i-1}^*(P_{j+1,k})$ is the amount of costs at the step $i-1$ in the cell k; Z_i^* is the amount of costs for the selected provisionally optimal option.

Multi-loop optimization method. The idea behind the MLO method is to decompose the complex problem of determining the optimal parameters of a ring-shaped heating system into two less complex subproblems [10,28]:

1. calculation of the flow distribution in the network (flow rates at the network branches x and pressures P at its nodes) given fixed pipeline diameters d and heads H;
2. determination of the optimal parameters (pipeline diameters d and heads H) of the selected network tree by the DP method given fixed flow rates of the heat transfer fluid x.

The MLO method involves setting up an iterative computational procedure for sequential improvement of network parameters, during which the above subproblems are alternately solved until a solution is obtained that can no longer be improved by the iterative process. The criterion for the termination of the computational procedure is the cessation of the decrease of the objective function.

The problem of calculating the flow distribution in the heating system is reduced to solving systems of linear and nonlinear algebraic equations. It is common to distinguish between two basic forms of notating such systems: nodal and loop models of flow distribution [3]. The problem statement in the case of a nodal flow distribution model is as follows. The given are: the incidence matrix $\boldsymbol{A}$, the vector Q of nodal inflows and outflows of the heat transfer fluid, the vector of heads H, the vector-function of hydraulic characteristics $f(x, s)$, and the pressure P'_m at the node m. It is necessary to determine the vectors of heat transfer fluid flow rates at the network branches $\boldsymbol{x}$ and pressures at its nodes P, satisfying the system of Eqs. (5.11)–(5.13). The nodal pressure method is used to solve this problem [3,6]. In the case of stating the problem in its loop form, the method of loop flow rates is used to solve it [3,6].

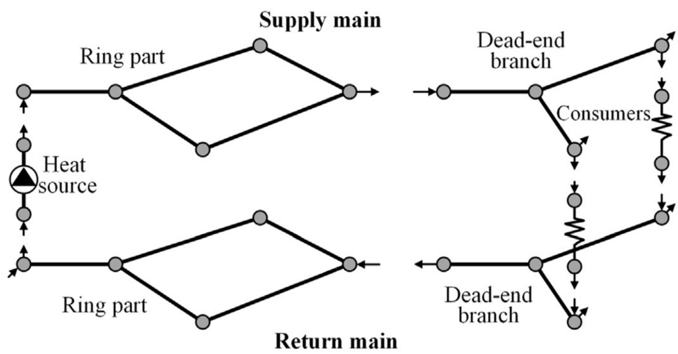


FIGURE 5.3 Levels of a hierarchical model of the heating system.

The methodology of multilevel modeling and problem solving. The new methodology developed by the authors for determining the optimal parameters of the heating system allows one, with the help of multilevel modeling of the heat network, to move from the original complex problem to a hierarchically related set of subproblems, each of which has lower dimensionality and complexity compared to the original problem. The methodology includes:

1) principles of multilevel decomposition of the heating system model and construction of its hierarchical model;

2) principles of coordination ("linking") of solutions between the levels of the hierarchical model of the heat network in the process of determining the optimal parameters of the heating system;

3) a computational procedure for determining the optimal parameters of the heating system focused on solving the problem, taking into account the hierarchical construction of the heating system model;

4) an algorithm based on the application of the MLO and DP methods that are adapted to solving the problem for the hierarchical model of the heat network.

The hierarchical model of the heating system when solving the problem of determining the optimal network parameters using multilevel modeling allows the following levels to be considered separately (Fig. 5.3):

1) the heating system as a whole;

2) supply and return main lines;

3) ring and tree-shaped parts (dead-end branches) of the supply and return main lines;

4) individual heating system components (heat sources, consumers, pipelines, pumping stations, etc.).

The flow distribution model for each level of the heating system hierarchical model is described by Eqs. (5.11)–(5.13). The flow distribution in the tree-shaped part of the network is unambiguously determined by the tree-shaped structure and nodal outflows (inflows) at the consumers' end. Dedicated algorithms (Section 5.1) based on efficient mathematical methods have been developed to solve the problem of flow distribution in multi-loop systems [29,30]. The application of methods of multilevel modeling together with these algorithms allows solving problems of real-life dimensionality when studying heating systems.

The flow distribution model for each level of the heating system hierarchical model is described by Eqs. (5.11)–(5.13). The flow distribution in the tree-shaped part of the network is unambiguously determined by the tree-shaped structure and nodal outflows (inflows) at the consumers' end. Dedicated algorithms (Section 5.1) based on efficient mathematical methods have been developed to solve the problem of flow distribution in multi-loop systems [29,30]. The application of methods of multilevel modeling together with these algorithms allows solving problems of real-life dimensionality when studying heating systems.

The search for the optimal flow diagram and parameters of the components of the heating system poses rather complex problems, the solution of which is impossible without hierarchical modeling. The computational procedure for solving the parametric problem is deemed impossible without applying multilevel modeling and includes the following main stages [6,28].

1. Multilevel decomposition of the heating system equivalent flow diagram and construction of its hierarchical model.
2. Determination of the optimal parameters of the return main line using an algorithm based on the MLO method.
3. Defining constraints on pressure at the consumers' end at the nodes of the supply main line taking into account the obtained pressure values at the nodes of the return main line to ensure the necessary heads at the consumers' end (see the expressions (5.15-5.16).
4. Determination of the optimal parameters of the supply main line using an algorithm based on the MLO method.
5. Calculation of total costs and capital expenditures for the heating system as per the parameters obtained during optimization.

To solve the problem of determining optimal parameters of supply and return main lines an algorithm is developed as based on the application of the MLO method and with the emphasis on the calculation that takes into account hierarchical construction of a model of the heating system. This algorithm consists of the following steps:

1. Defining set J_L of nodes of the flow diagram, which have incident areas belonging to both ring part and dead-end branches of the network.
2. Calculating initial flow distribution in the ring part of the network and at dead-end branches.

3. Performing the "forward pass" of the DP method for the determination of provisionally optimal options of parameter values of all dead-end branches.
4. Transferring pressure and cost values of provisionally optimal options obtained at the level of dead-end branches to the level of ring-shaped networks for all nodes $j \in J_L$.
5. Performing the "forward pass" of the DP method for determination of suboptimal variants of parameters of the ring part of the heating system, in doing so pressure and cost values of the ring part and dead-end branches are "linked" at nodes $j \in J_L$.
6. Selecting the option corresponding to the solution with the lowest cost at the source with the highest performance.
7. Performing the "backward pass" of the DP method to restore the parameters and cost components of the ring and dead-end parts of the network.
8. Calculating flow distribution in the ring part of the network and at dead-end branches.
9. If the criteria of terminating the computational process are not met, the transition to step 5 is performed.

Provisionally optimal solutions obtained at the nodes connecting dead-end branches to the ring part of the network, are "reconciled" with the results for the ring part during the computational process as per the MLO method. In doing so, the following principle is used. If the node j is the initial node both for the branches of the ring part and for the dead-end branches, then the "linking" of pressure values and summing up of cost values take place in the cells of this node. Let $J^{(i)}$ denote a set of nodes where it is required to "link" the pressure values at the node j at the step i of the computational process. "Linking" the pressure values is done as per the expression

$$P_{jz} = \max_{k \in J^{(i)}} \tilde{P}_{kz}, z = 1, \ldots, \mu. \tag{5.32}$$

Let $I^{(i)}$ denote a set of all branches outcoming from node j, the costs of which should be taken into account at the step i of the computational process. The costs are summed up as per the expression

$$Z^*_{iz} = \sum_{r \in I^{(i)}} Z^*_{rz}, z = 1, \ldots, \mu. \tag{5.33}$$

Fig. 5.4 presents a fragment of the hierarchical model of a heat network. After calculating Section 5.5, one has to determine the parameters of Section 5.6. Prior to its calculation, pressure and cost values are "linked" between the levels of the hierarchical model of the heat network.

The main feature of the proposed algorithm is that for dead-end branches the "forward pass" of the DP is performed only once, and pa-

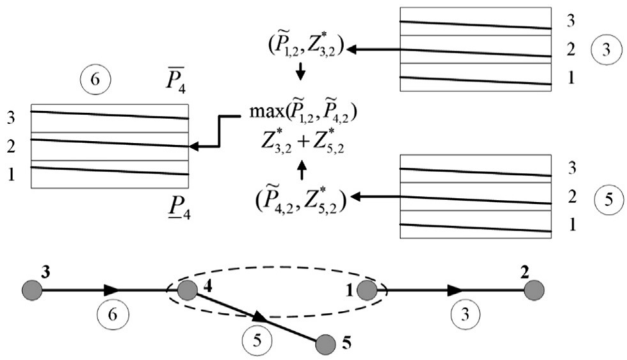


FIGURE 5.4 Model for "linking" results between hierarchical levels.

rameter determination is performed only for the ring part of the network during the iterative process of the MLO method. To this end the solutions of the ring part and the dead-end branches are "linked" according to the principles indicated above.

Computational tools. Due to the large size of real-life heating systems and the complexity of mathematical calculations in solving the problems of expansion and reconstruction of heating systems, the relevant software packages are in demand. At the MESI the authors have been developing an instrumentation platform as a unified versatile basis for building software packages tailored to the special aspects of solving applied problems and modeled heating systems [6,28]. This platform is a set of software components that implement models, methods, and algorithms of the hydraulic circuit theory.

Methodological support is implemented in the form of basic software components of the instrumentation platform. To ensure the versatility of these components, the principles of their construction have been proposed [18,31].

On the basis of the proposed platform and the proprietary software components, we have developed the software package SOSNA (Synthesis of Optimal Systems with Consideration of Reliability) designed to determine the optimal parameters of the heating system [6,32]. This software package allows one to determine: locations with insufficient throughput capacity; methods for the reconstruction of existing pipelines; pipeline diameters of new and reconstructed pipelines; locations of installation and parameters of pumping stations. The workflow of solving the problem of determining the heating system parameters in the software package SOSNA is shown in Fig. 5.5.

The new logical organization of algorithms proposed here that is focused on the multilevel modeling of the heating system has been implemented in the software package SOSNA. New efficient data structures,

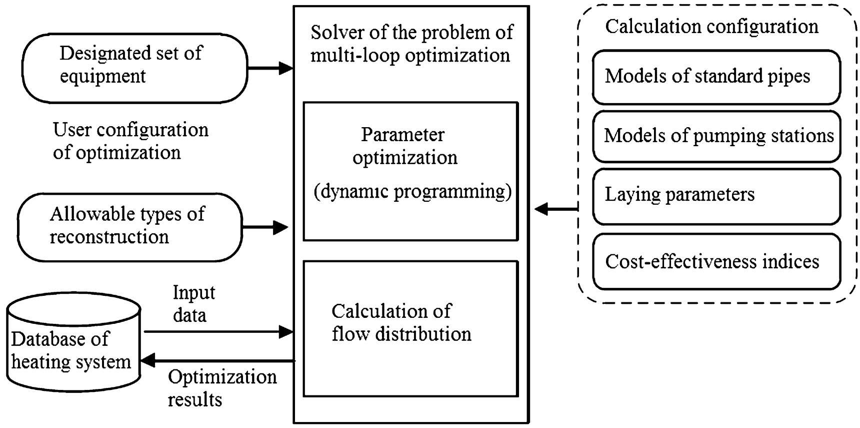


FIGURE 5.5 Workflow of solving the problem of determining the parameters of the heating system using the software package SOSNA.

including compact storage schemes for sparse matrices, have been applied in the process of software implementation.

Practical application of multilevel modeling. The proposed algorithms implemented in the SOSNA software package are used in practice to solve real-life problems of optimal heating system reconstruction. The calculations of the heating system of the Tsentralny and Admiralteysky districts of St. Petersburg, the city of Bratsk, and the urban locality of Magistralny attested to the effectiveness of multilevel modeling of heating systems and the possibility of obtaining hierarchically related solutions to practical problems of their optimal design.

Fig. 5.6 shows an aggregated flow diagram of the heating system of a Russian city. In terms of hierarchical construction, it reflects the level of heat sources and main heat networks, usually considered in the predesign document "Heating system flow diagram". District heating of this system is carried out from four heat sources: GDB.2, GDB.1, ICHPP-2, and ICHPP-1. The equivalent flow diagram of the heating network contains 632 branches and 613 nodes.

As a result of the calculations, we have determined branches with insufficient throughput capacity, for which it is necessary to increase the diameter of pipelines, the required operating heads of pumping stations, the rational available heads at consumers, optimal flow distribution, distribution of zones of heat sources, etc. Table 5.1 shows the parameters of these branches (pipeline length values (L_i), specific pressure loss values (h_i), heat transfer fluid flow rate values (x_i), heat transfer fluid velocity values (v_i), pipeline diameters (d_i)) as measures before and after reconstruction.

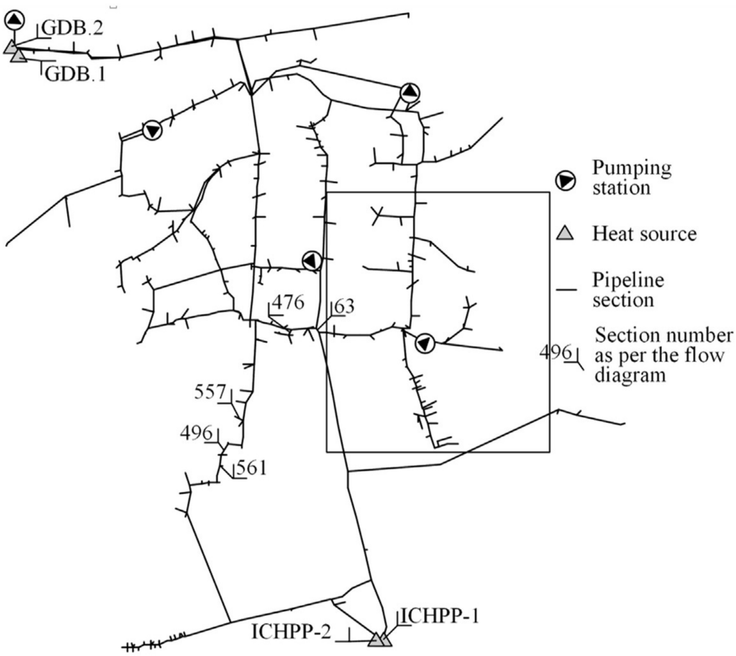


FIGURE 5.6 Flow diagram of the heating system of the city.

TABLE 5.1 Parameters of branches before and after the reconstruction.

Branch number	L_i m	Before the reconstruction				After the reconstruction			
		h_i mm/m	x_i t/h	v_i m/s	d_i mm	h_i mm/m	x_i t/h	v_i m/s	d_i mm
63	12.0	61.9	1,461.8	2.0	517	6.1	1,473.6	1.4	616
496	10.0	8.4	85.0	2.4	359	1.6	85.0	1.8	414
557	11.0	5.4	48.1	1.4	359	4.8	48.1	1.4	414
561	10.0	12.1	126.6	1.4	359	3.4	126.6	0.7	414
476	10.5	13.7	68.0	2.3	69	7.9	68.0	1.5	100

The algorithms implemented as part of the SOSNA software package that take into account multilevel decomposition of the model of the heat network provided a solution to the problem in 4 seconds. Applying parallel computations in combination with multilevel decomposition of the network model allowed us to obtain the solution in 1.5 seconds. The SOSNA software package, which had been earlier used at the MESI for the determination of optimal heating system parameters arrived at the solution to the problem in 166 seconds.

The performed comparative analysis of the results of calculations obtained with the aid of the SOSNA software package of the previous and

TABLE 5.2 Costs and capital expenditures of the heating network.

Main pipe	Discounted costs, mln. rubles / year	Capital expenditures, mln. rubles
SOSNA software package		
Return	424.24	34.9
Supply	396.11	34.9
Total	820.35	69.8
SOSNA software package (new version)		
Return	424.24	34.9
Supply	396.11	34.9
Total	820.35	69.8

new versions are given in Table 5.2. It presents the values of the discounted costs of the heating system and the capital expenditures required for the reconstruction of the heating network. The values of the objective function of discounted total costs of the system for the software package of the previous and new versions prove consistent with each other, thus decomposition of the equivalent flow diagram does not lead to compromising the quality of the obtained result.

The methodology and algorithms developed allow us solving practical problems for complex multi-loop heating systems of large (real-life) dimensionality and are applied to solving practical problems of their optimal expansion and reconstruction. The proposed methodological backing for solving the considered problems is focused on the multilevel modeling of heating systems, which provides a reduction in the dimensionality of the original problem by obtaining subproblems of lower dimensionality and a reduction of the total time for solving the original problem.

The application of the developed methodological backing and software allows one to obtain recommendations on expanding complex heating systems, increasing the efficiency of their operation, and the quality of supplying heat to consumers.

5.3 Hierarchical modeling in the expansion planning of gas supply systems

Special aspects of modeling the gas supply system. Gas supply systems (GSS), including gas producing and gas transporting components, are topologically and technically complex facilities and their study is impossible without the application of hierarchical modeling and principles of aggregation of equivalent flow diagrams in an aggregated form. The aggregated flow diagram, faithful to the actual GSS, is expanded by adding new production centers, transport links, and consumption nodes planned for implementation. As a result, a redundant aggregated flow diagram is

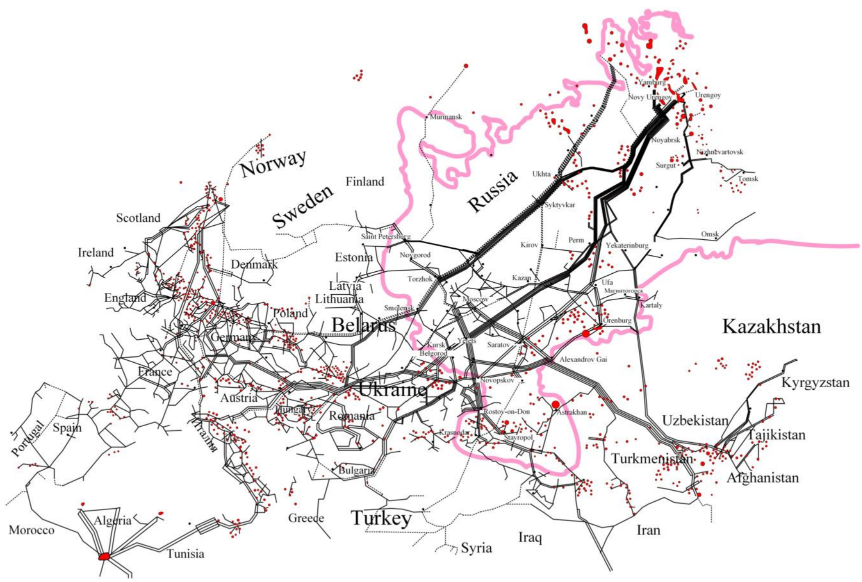


FIGURE 5.7 Unified gas supply system of the Russian Federation as part of the European gas supply system.

formed, and this flow diagram captures the dynamics of the system expansion within the timeframe considered. The process of the transformation of the actual flow diagram into the equivalent model is shown as illustrated by the Unified Gas Supply System (UGSS) of Russia in Fig. 5.7 (the actual flow diagram of the UGSS of the RF) and Fig. 5.8 (redundant aggregated equivalent flow diagram of the UGSS) [33].

The equivalent flow diagrams thus obtained allow studying rational growth rates and proportions in the development of the gas supply of individual regions and the country as a whole taking into account interaction of all systems that are part of the energy sector, while touching upon general energy, economic, environmental, and other cross-disciplinary issues.

The information base that provides hierarchical modeling of the prospective expansion of gas supply systems (for example, the UGSS of Russia) for the future [33–37] includes the demand for gas at the nodes of the flow diagram in dynamics; export supplies; constraints on production and transport, technical and economic performance metrics of gas production and gas transmission systems; gas consumption to cover auxiliary needs and gas leaks, etc. The methodological developments proposed at the MESI allow one to state and solve complex problems of optimal expansion of gas supply systems in the future [33].

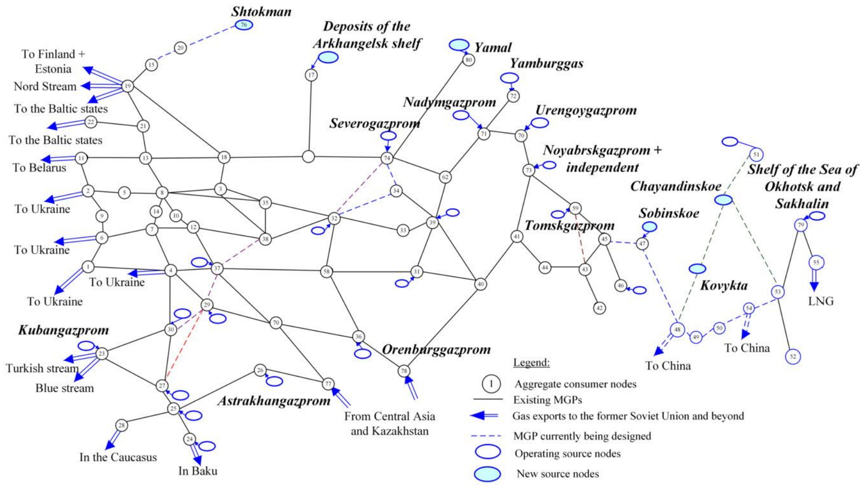


FIGURE 5.8 Redundant aggregated equivalent flow diagram of the GSS of the Russian Federation.

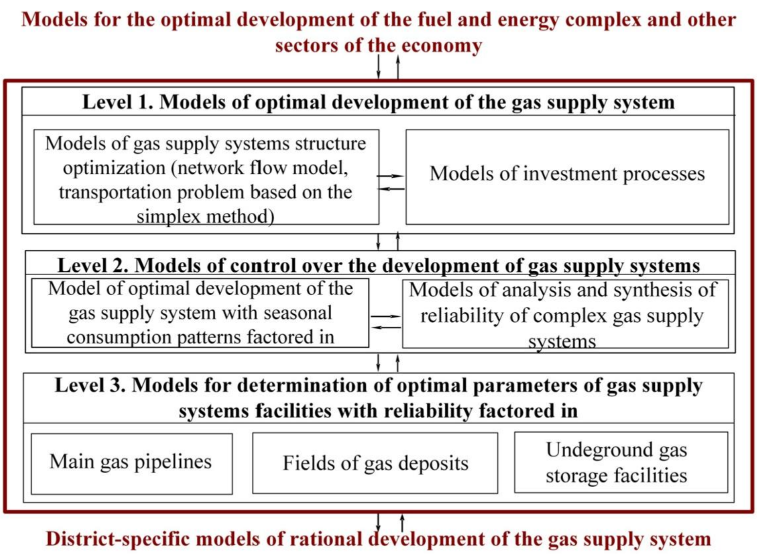


FIGURE 5.9 Models for solving problems of optimal development of gas supply systems.

Fig. 5.9 shows the structure of the models developed for solving the problems of optimal expansion of gas supply systems and their interaction at three hierarchical levels of consideration.

Models for overall development of GSSs of the first hierarchical level. The model for optimizing the structure of the gas supply system is presented by a flow model that allows finding a gas supply plan that ensures minimum costs of gas production, transport, and delivery to consumers when gas demand is fixed.

The generalized problem of flow modeling is written down in the following form:

$$\sum_{(i,j)} \left(c_{ij}x_{ij} + k_{ij}y_{ij}\right) \to \min \tag{5.34}$$

$$\sum_i \lambda_{ij}x_{ij} - \sum_i x_{ij} = \begin{cases} -v, & j = s \\ 0, & j \neq s, t \\ w, & j = t \end{cases} \tag{5.35}$$

$$l_{ij} \leq x_{ij} \leq d_{ij} + y_{ij}, \quad (i, j) \in U, \tag{5.36}$$

$$0 \leq y_{ij} \leq g_{ij}, \quad (i, j) \in U, \tag{5.37}$$

where x_{ij}, y_{ij} are gas flows along the existing and new edges; d_{ij}, g_{ij} are throughput capacities and increments of edges; c_{ij}, k_{ij} are "prices" of gas transport along the existing and new edges; λ_{ij} is the edge factor, which takes into account changes in gas flow as it passes through the edge. Additional nodes s and t are introduced: the common inflow and outflow. U is the set of all nodes; v and w are the total flows from the node s and to the node t, respectively.

Here, the optimality criterion is the minimum cost of gas production, transport, and delivery to consumers, while the constraints are production capacity of existing and new companies and requirements to meet the minimum demand by consumers (5.36), (5.37) provided that the balance of gas supply and withdrawal at the network nodes is maintained (5.35).

This is a well-known minimum cost flow problem, which belongs to the class of linear programming problems and is solved by a modified Busacker–Gowen algorithm [33,38].

Backed by these developments and by way of presenting a demonstration example, we have performed studies that were to determine the optimal volumes of production and transport of gas flows for the averaged scenario of consumption in Russia and exports for 2020, 2025, and 2030. The results of the studies at the 2030 level are shown in Fig. 5.10. When summarizing them, we have obtained interval estimates of metrics characterizing gas consumption, exports, consumption for auxiliary needs, and leakages [33].

The dotted line in Fig. 5.10 outlines the flow diagram of gas supply to the Northwestern Federal District. Using this flow diagram as an example, in what follows we will show the details of solving the problems of lower levels of consideration.

Models of investment processes allow planning of investments (directions, volumes, and terms of their financing) so that the resulting discounted

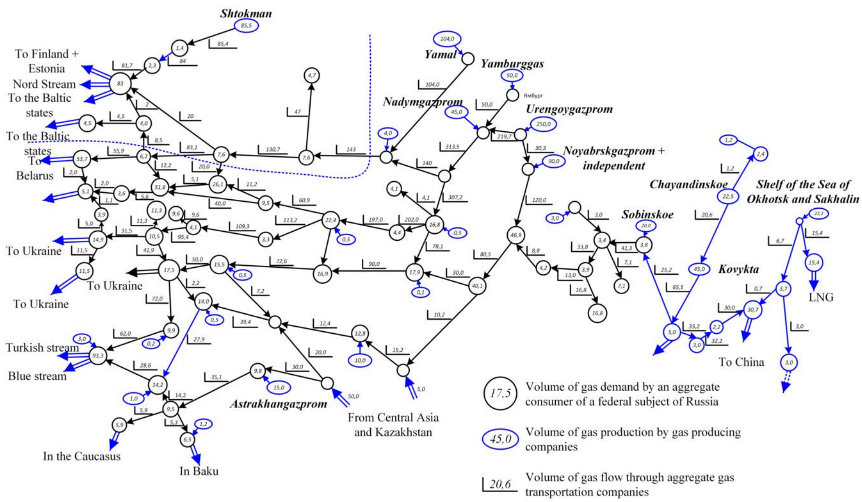


FIGURE 5.10 Optimal gas production and transportation volume for the averaged scenario of consumption in the Russian Federation and exports in 2030, bcm/year.

effect satisfied the interests of all entities of relations to the greatest extent [33,39].

The mathematical *model of investment planning* is written as follows:

$$\sum_{i=1}^{N} [AC_i \cdot x_i] \rightarrow \min, \tag{5.38}$$

$$\sum_{i=1}^{N} [BP_{Di} \cdot x_i] \rightarrow \max, \tag{5.39}$$

$$\sum_{i=1}^{N} [(TR_{Di} - TC_{Di}) \cdot x_i] \rightarrow \max, \tag{5.40}$$

$$\sum_{i=1}^{N} K_{it} \cdot x_i \leq B_t \quad (t = 1, 2, ..., T), \tag{5.41}$$

$$\sum_{i=1}^{N} f_{jti} \cdot x_i \leq F_{jt} \quad (j = 1, 2, \ldots, J; t = 1, 2, \ldots, T), \tag{5.42}$$

$$\sum_{i=1}^{N} Q_{i,t} \cdot x_i \geq Q_{\min t} \quad (t = 1, 2, ..., T). \tag{5.43}$$

Here: x_i is the share of the total cost of implementation of the ith investment option (in the case of interchangeability of investment objects given integer values of $x_i = [0; 1]$); K_{it} is the cost of investment in the ith option, invested in the tth interval of the investment period; T is the number of intervals in the investment period; B_t is the planned amount of financial resources in the tth interval; f_{jti} is total costs of the jth production factor used in the ith option (for example, wages, fixed production assets, costs of construction, transport, etc.); F_{jt} is the capacity of the jth production factor in the tth interval; Q_{it} is the volume of gas supply to consumers in accordance with the ith option in the tth time interval; $Q_{\min t}$ is the minimum necessary volume of gas supply to consumers in the tth interval; N is the total number of acceptable options of investment projects; AC_i is average costs of the ith investment option; BP_{Di} is the amount of fiscal charges of the ith option discounted to the beginning of the investment period; TR_{Di}, TC_{Di} are discounted inflows of funds and payments, respectively.

The criterion (5.38) represents the minimum average cost and is used when it is necessary to maximize the national economic interest. Criterion (5.39) maximizes fiscal charges and is of national interest. Criterion (5.40), corresponds to the maximum profit of the owners. The constraints stand for the following: (5.41) - funding opportunities; (5.42) - capacity in terms of financial resources; (5.43) - conditions of gas supply to consumers.

The problem is of a multi-criteria nature, and it is solved using the method of successive trade-offs. The result is a matrix that represents the amount of financial resources by a source of funding for each interval of the investment period.

The model for determining the mix of *funding sources* by minimum specific costs is used to find the optimal mix of funding sources from the range of possible sources (own funds, funds from the issue of securities, and other borrowed funds, including loans) under the existing constraints.

$$\sum_{j=1}^{M}\sum_{t=1}^{T}\left[ACY_{jt}\cdot y_{jt}/\left(1+r\right)^{t}\right]\rightarrow \min \tag{5.44}$$

$$\sum_{j=1}^{M} y_{jt} \geq K_t - G_t \ \ (t=1,2,...,T), \tag{5.45}$$

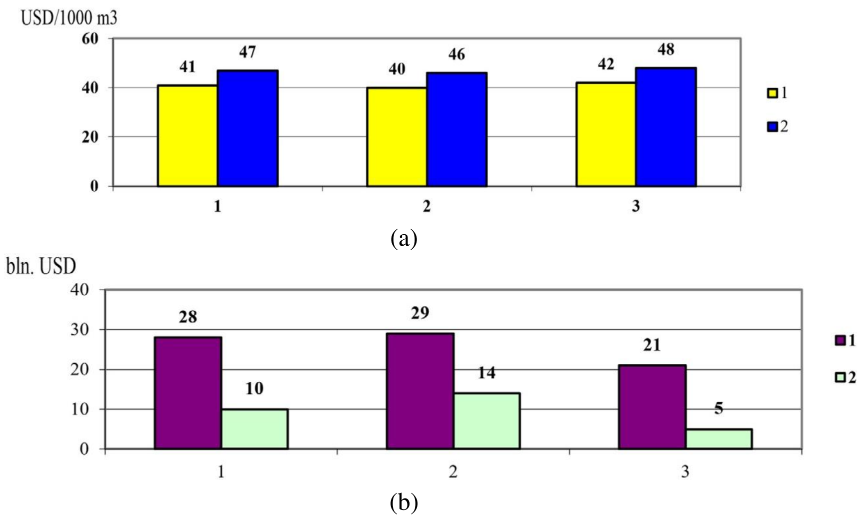
$$\sum_{j=1}^{M}[ACY_{jt}\cdot y_{jt}+y_{jt}] \leq B_t \ (t=1,2,...,T), \tag{5.46}$$

$$[\sum_{j=1}^{M1} y_{jt} / \sum_{j=M1+1}^{M} y_{jt}] \geq K_a \ (t=1,2,...,T), \tag{5.47}$$

where M is the number of possible funding sources; ACY_{jt} is the unit cost associated with the use of the jth source; Y_{jt} are funding sources; G_t is the amount of government subsidies in the tth time interval; K_a is the coefficient capturing the recommended ratio of own funds and other sources. The constraints stand for the following: (5.45) is the possibility of funding sources; (5.46) is enterprise budget coverage of investments and costs; (5.47) is structural constraints.

As a case study, we consider the choice of the optimal investment option for the development of the gas supply system of the Russian Federation. Let us consider three options:

Option one. Gazprom PJSC is being developed in line with the recommendations set out in the energy strategy of Russia. *Option two*. The first option is supplemented by accelerated development of new gas production companies and construction of gas transportation systems in Eastern Siberia and the Russian Far East. *Option three*. The second option is supplemented by accelerated development of new gas fields in the shelf of the Barents and Kara Seas. Studies have shown (Fig. 5.11) that for Gazprom PJSC the second option of GSS development will be optimal. The option has the lowest average costs for the minimum scenario of economic development and the highest discounted profit.



Average costs (a) and net discounted profit (b) by options of gas supply system development in Russia. Scenario: 1 – maximum, 2 – minimum.

FIGURE 5.11 Findings of the studies, by scenario: a) – average costs; b) – net discounted profit by options of the expansion of Russia's gas supply system under 1 – maximum and 2 – minimum scenarios.

Models of the comprehensive development of the GSS of the second level of the hierarchy [33,39]. *The model of managing the seasonal irregularity of gas consumption* is a system of linear equations and inequalities that consistently describe the processes of gas production, transport, storage, and consumption by seasons of the year and it is of the following form:

$$\sum_{i=1}^{n}\sum_{\tau=1}^{T}(c_{i\tau}^{P}x_{i\tau}^{P}+c_{i\tau}^{T}x_{i\tau}^{T}+c_{i\tau}^{Stor}x_{i\tau}^{Stor}+\sum_{l=1}^{L}c_{i\tau l}^{Subst}x_{i\tau l}^{Subst}+c_{i\tau}^{B}x_{i\tau}^{B}+u_{i\tau}z_{i\tau})\rightarrow \min; \tag{5.48}$$

$$\sum_{\tau=1}^{T}\left(a_{i\tau}^{P}x_{i\tau}^{P}+a_{i\tau}^{T}x_{i\tau}^{T}\pm a_{i\tau}^{Stor}x_{i\tau}^{Stor}+\sum_{l=1}^{L}a_{i\tau l}^{Subst}x_{i\tau l}^{Subst}+z_{i\tau}\right) = \sum_{\tau=1}^{T}\left(x_{i\tau}^{-T}+a_{i\tau}^{B}x_{i\tau}^{B}+b_{i\tau}\right), \tag{5.49}$$

$$\begin{gathered}0\leq a_{i\tau}^{P}x_{i\tau}^{P}\leq d_{i\tau}^{P},\\ 0\leq a_{i\tau}^{T}x_{i\tau}^{T}\leq d_{i\tau}^{T},\\ 0\leq a_{i\tau}^{Stor}x_{i\tau}^{Stor}\leq d_{i\tau}^{Stor},\\ 0\leq a_{i\tau}^{Subst}x_{i\tau}^{Subst}\leq d_{i\tau}^{Subst},\\ 0\leq \textstyle\sum_{i=1}^{n}\sum_{\tau=1}^{T}\sum_{l=1}^{L}a_{i\tau l}^{Subst}x_{i\tau l}^{Subst}\leq d^{m},\\ 0\leq \textstyle\sum_{i=1}^{n}\sum_{\tau=1}^{T}(\sum_{l=1}^{L}a_{i\tau l}^{Subst}x_{i\tau l}^{Subst}+a_{i\tau l}^{B}x_{i\tau l}^{B})\leq d^{C},\end{gathered} \tag{5.50}$$

$$0\leq\sum_{i=1}^{n}\sum_{\tau=1}^{T}(k_{i\tau}^{P}x_{i\tau}^{P}+k_{i\tau}^{T}x_{i\tau}^{T}+k_{i\tau}^{Stor}x_{i\tau}^{Stor}+\sum_{l=1}^{L}k_{i\tau l}^{Subst}x_{i\tau l}^{Subst}+k_{i\tau}^{B}x_{i\tau}^{B})\leq k; \tag{5.51}$$

$$0\leq\sum_{i=1}^{m}\sum_{\tau=1}^{T}\mu_{i\tau}x_{i\tau}^{T}\leq M, \tag{5.52}$$

where $x_{i\tau}^{P}, x_{i\tau}^{T}, x_{i\tau}^{-T}, x_{i\tau}^{Stor}, x_{i\tau}^{Subst}, x_{i\tau}^{B}$ — unknown variables for each node i of the equivalent flow diagram and for each season of the year τ ($\tau=\overline{1,T}$), reflecting, respectively, volumes of gas production at the fields, volumes of gas supply to the node and gas output from this node to other main gas pipelines, volumes of gas storage in UGS facilities, volumes of gas replacement with other fuel and volumes of gas use by buffer consumers; $z_{i\tau}$ is a dummy variable at the node i in the time period τ, showing a possible volume of mismatch of fuel resources and demand; L is the number of categories of consumers, allowing gas replacement with other fuel $l=\overline{1,L}$; $b_{i\tau}$ is mandatory demand for gas of the node i in the period τ; $a_{i\tau}^{P}$, $a_{i\tau}^{T}$, $a_{i\tau}^{Stor}$, $a_{i\tau l}^{Subst}$, $a_{i\tau}^{B}$ is coefficients that capture process performance metrics (losses due to unreliability, gas consumption for in-house needs, overconsumption of other fuels when replacing gas with them, etc.), respectively, for the above facilities for each node i in the time pe-

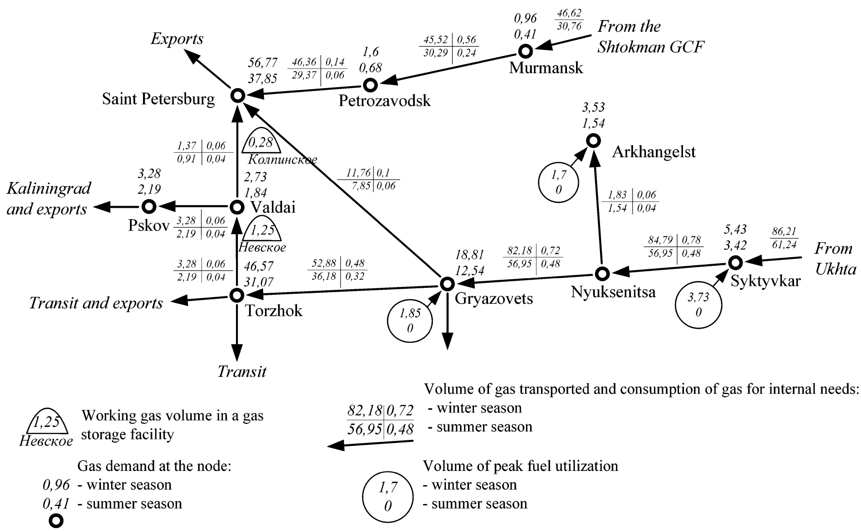


FIGURE 5.12 Control over seasonal irregularity of gas supply in the Northwestern Federal District in 2030, million tons of fuel equivalent.

riod τ; $d_{i\tau}^{P}$, $d_{i\tau}^{T}$, $d_{i\tau}^{Stor}$, $d_{i\tau}^{Subst}$ is capacity constraints of gas fields, main gas pipelines, underground gas storage facilities, possible maximum volumes of gas replacement by other fuel at different categories of consumers, respectively; $c_{i\tau}^{P}$, $c_{i\tau}^{T}$, $c_{i\tau}^{Stor}$, $c_{i\tau l}^{Subst}$, $c_{i\tau}^{B}$ is the discounted levelized cost of gas production, transport, and storage, consumption of other fuels by the consumers of the category l and consumption of gas by buffering units, respectively; $u_{i\tau}$ is discounted specific damages by nodes of the equivalent flow diagram due to possible energy resource shortages.

The criterion (5.48) is the minimum of the cost function in the production, transport, storage, and use of gas. And the following conditions must be met: the condition of equality of gas production, transport, storage, and consumption flows (5.49); constraints on gas flows (5.50); constraints on capital expenditures (5.51); constraints on metal investments (5.52).

The problem is solved by linear programming methods [40]. Using the gas supply system of the Northwestern Federal District as the case study we determined the production capacity of fields, gas transport enterprises, and underground gas storage facilities by seasons for the year 2030. Fig. 5.12 shows the justified volume of transported gas and gas consumption for auxiliaries in winter and summer, the volume of gas storage and utilization of underground gas storage facilities as well as the volume of peak fuel utilization.

Models of analysis and synthesis of reliability of complex gas supply systems Models of reliability analysis of GSS facilities [33,39,41] include main gas

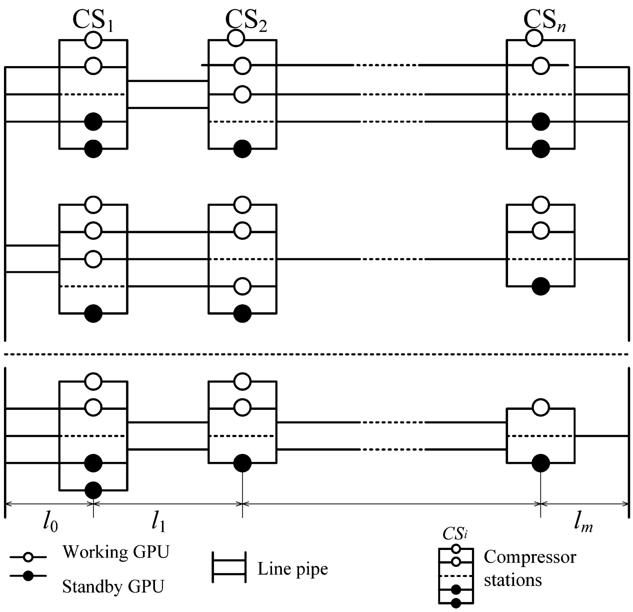


FIGURE 5.13 Equivalent flow diagram of the multi-line main gas pipeline.

pipelines (Fig. 5.13), gas fields (Fig. 5.14), and underground gas storage (UGS) facilities.

Analysis of the reliability of the above facilities is carried out as follows:

1) original links (line pipe, compressor stations, well clusters, field gas distributions stations) (Fig. 5.12, 5.13), consisting, in general, of heterogeneous components are replaced by a system consisting of homogeneous components by way of their reduction to equivalents;

2) probability distribution functions of the working condition are defined for these links, to this end we use the analytical method at the level of random (Markov) processes, i.e., the Death-Birth process that allows one to cover various types of deposits;

3) as per a predefined rule, taking into account a series and parallel connection, the composition of distribution functions of the working condition of a given facility is performed;

4) as a result the following parameters of a facility are determined: a series of the probability distribution of its operative state - $P(Q)$; cumulative probability function of the operational state - $F(Q)$; expected value, variance, and standard deviation of throughput capacity of the facility for the considered time interval - $M[Q]$, $D[Q]$, $[Q]$, and a number of other metrics. The reliability factor F_r is also determined for the main gas pipeline.

The reliability analysis model of a complex gas supply system [33] is an estimation model. The object of the study is a multi-node gas supply system

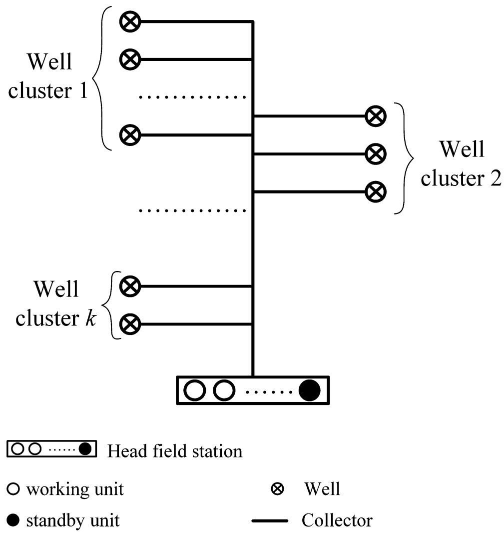


FIGURE 5.14 Equivalent flow diagram of the gas production system.

that is treated as a set of nodes, covering gas fields and other sources of gas, underground gas storage facilities, and gas consumption nodes (with categories of consumers indicated), connected to the system of gas main pipelines and including both existing facilities and available options of their expansion.

The goal of the problem of estimating the reliability of operation of a complex gas supply system is to determine if each consumer's demand for gas can be satisfied given available (or planned) capacity, redundancy, and reserves.

The conceptual statement of the problem is to determine the values of the main metrics of gas supply reliability for each node of the system, namely, the probability of meeting a given demand, the expected value of gas undersupply, and the ratio of the relative supply of consumers with gas. It is also required to determine possible measures to reduce or increase demand depending on the ratio of the obtained and the specified reliability of gas demand satisfaction for each consumption node in the calculation. This determination of the values is done on the basis of gas demand and gas supply to the system from fields (specified in a probabilistic form), gas withdrawal into the system, or injection into underground gas storage facilities with due consideration of gas reserves in UGS facilities, given existing throughput capacities of main gas pipelines, also specified in a probabilistic form, and with due consideration of gas losses for auxiliary needs at fields, at UGS facilities, and during gas transportation via main gas pipeline, as well as possible interchangeability of fuels.

The algorithm for the problem of evaluating the reliability of the gas supply system operation includes 3 modules:

I. Probabilistic module.

II. Module for calculation of the system operating conditions.

III. Reliability parameters calculation module.

The different nature of subproblems predetermines the use of different methods, namely: the method of statistical modeling for the composition of the design states of the system (Monte Carlo method); the method of calculating the cumulative distribution functions of random states of gas imbalances and the theorem of adding and multiplying the probabilities of various events; the method of load flow in networks for calculating operating conditions.

In the probability module, for simulating the states of the system facilities, a pseudo-random number generator (PRNG) is used to get the numbers uniformly distributed within the interval from 0 to 1.

The optimal operating conditions calculation problem (the second module) takes the following form:

$$\sum_{i\in R_1} C_i^m x_i^m + \sum_{i\in R_1} C_{oi}x_{oi} + \sum_{i\in R_3} C_i^- x_i^- + \sum_{(i,j)\in U} C_{ij}x_{ij} + \sum_{i\in R_2} y_{oi}x_i^{sh} \to \min \tag{5.53}$$

subject to the following constraints:

$$\left.\begin{array}{c} \sum_j \lambda_{ji}x_{ji} - \sum_j x_{ij} + \lambda_i^m x_i^m = 0 \\ 0 \le x_i \le X_i \end{array}\right\} i \in R_1;$$

$$\left.\begin{array}{c} \sum_j \lambda_{ji}x_{ij} - \sum_j x_{ij} + x_{0i} - x_i^u = 0, \\ x_i^u = X_i^I + X_i^{\mathrm{II}} + X_i^{\mathrm{III}} - x_i^{sh} \\ 0 \le x_i^{I(\mathrm{II},\mathrm{III})} \le X_i^{I(\mathrm{II},\,\mathrm{III})} \\ 0 \le x_{0i} \le B_i \\ 0 \le x_i^{sh} \le X_i^I + X_i^{\mathrm{II}} + X_i^{\mathrm{III}} \end{array}\right\} i \in R_2; \tag{5.54}$$

$$\left.\begin{array}{c} \sum_j \lambda_{ji}x_{ji} - \sum_j x_{ij} + \lambda_i^+ x_i^- = 0 \\ 0 \le x_i^+ \le min\left\{X_i^+, S_i\right\} \\ 0 \le x_i^- \le min\left\{X_i, V_i - S_i\right\} \end{array}\right\} i \in R_3;$$

$$\sum_j \lambda_{ji}x_{ji} - \sum_j x_{ij} = 0, i \in R_4; 0 \le x_{ij} \le X_{ij}, (i, j) \in U,$$

where x_i^{sh} is total gas shortage over all categories of the ith consumer node.

The minimum discounted costs of gas delivery to consumers and the expected value of damage due to under-supply of gas for individual nodes are considered as the criterion (5.53). The constraints (5.54) in the form of equations represent gas balances of the corresponding nodes, while the other constraints are set as two-sided inequalities.

The above reliability metrics are determined for each design consumer node, and integral performance values, i.e., its utilization factor, are determined for each facility (MGP, UGS, and the field).

The model of optimization of reliability of a complex gas supply system. To find the optimal reliability of the GSS, we propose *a two-stage methodological approach* that solves the following problems:

Stage 1. *Determination of equivalent reliability characteristics* (dependencies of mathematical expectations of actual capacity and discounted costs on the set capacity) for gas main pipelines, fields, and underground gas storage facilities, as well as for facilities storing reserves of gas and other fuels at the consumers' end that allow to use them as gas substitutes. For this purpose, we employ the models of reliability analysis of GSS facilities.

Stage 2. *Optimization of redundancy means* of the gas supply system. In this case, we assume that first, we should solve the problems of the upper level of the hierarchy: the network flow problem, i.e., to determine the rational volumes of gas production in the gas production centers, as well as the volumes and directions of cross-district gas flows. The solution obtained should be further detailed in the seasonal gas consumption optimization model and this solution should be the basic input for the two-stage approach to model optimal reliability.

The problem is to determine the optimal ways of ensuring system redundancy that would satisfy the balances of mathematical expectations of facilities performance and provide consumers with the required volumes of gas, taking into account the reserves of other fuels, with a given level of reliability, and under given constraints:

$$\overset{\Sigma}{\sum_{(i,j)\in U}} \left(c_{ij}x_{ij} + k_{ij}y_{ij}\right) + p_j z_j \to \min, \tag{5.55}$$

$$\sum_{i\in\Gamma_j^+} \left(\lambda_{ij}x_{ij} + \pi_{ij}y_{ij}\right) + \alpha_j z_j - \sum_{j\in\Gamma_j^-} x_{ji} = \begin{cases} -Q, \ j = s; \\ 0, \ j \neq s, t; \\ B, \ j = t. \end{cases} \tag{5.56}$$

$$0 \le x_{ij} \le d_{ij}; \qquad 0 \le y_{ij} \le d_{ij}^r - d_{ij}; 0 \le z_j \le Z_j. \tag{5.57}$$

The expression (5.55) represents the objective cost function to be minimized. The condition (5.56) shows the production balances of facilities with available redundancy (x) and with additional redundancy measures for these facilities (y) and backup fuel reserves (z). For each node j, a balance of incoming and outgoing capacity should be maintained (as per Kirchhoff's First Law). The expression (5.57) reflects two-sided constraints on the performance of facilities.

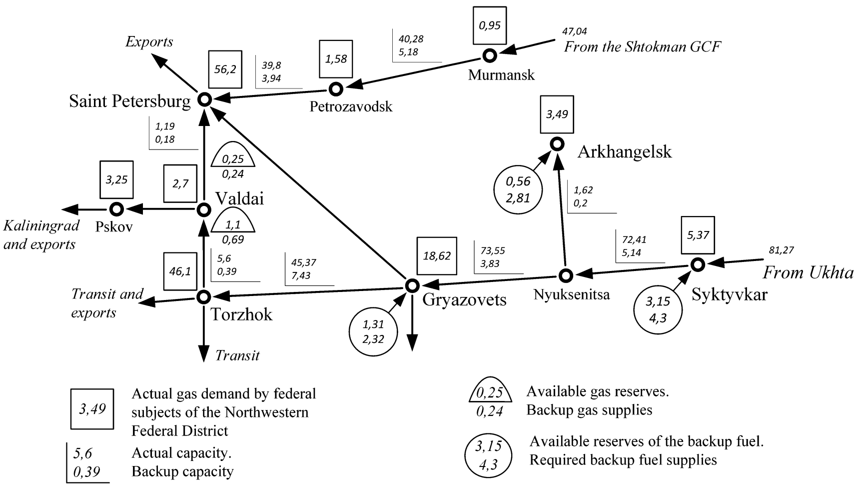


FIGURE 5.15 Optimal redundancy of the gas supply system of the Northwestern Federal District in the winter period of 2030 (provisionally).

Standard linear programming methods are used to solve this problem. Fig. 5.15 shows, by way of illustration, the results of system reliability optimization for the GSS of the Northwestern Federal District in the winter period for 2030 (the year is chosen provisionally), obtained on the basis of the developed toolkit taking into account detailing and seasonal irregularity. Meeting the required gas demand of the entities of this district with the reserves-to-production ratio of 0,99 leads to the need to have the redundant capacity of the elements in addition to their existing value, as well as backup fuel reserves at some of the consumers in the district, as shown in Fig. 5.15.

GSS integrated development models of the third hierarchical level. To solve parametric problems of this level, *we use models for determining the optimal parameters of GSS facilities [33], taking into account the reliability.* The computational process of finding the optimal parameters of the GSS and its components involves the following:

1. Consideration of multiple options of the ways of prospective development
2. Reliability analysis.
3. The optimal choice of a reasonable option on the basis of the calculation of technical and economic performance metrics and overall reliability metrics.

The problem of the determination of optimal values of parameters of the MGP currently being designed, while taking into account its reliability, in general terms is formulated as follows.

For a given average daily capacity of the MGP (Q), its technical (T) and economic (E) performance, levels of reliability (R), the schematic flow diagram of the MGP and redundant end methods of making reserves (r) it is necessary to determine the diameters of gas pipelines, the number of compressor stations (CS) and installed gas pumping units (GPU) so as to maximize the income I from gas sales, provided the specified standardized value of reliability R_{st} of gas supply.

$$I = f(T, E, R, r) \to \max \tag{5.58}$$

$$M_r = y(Q, R, r) \geq M_r^*. \tag{5.59}$$

The average daily calculated capacity (Q) is determined based on the annual calculated capacity of the MGP taking into account the coefficient of non-uniformity of gas consumption. For MGPs without underground gas storage (UGS) facilities at the consumers' end, it is typically assumed to be 0.85, while for branch lines of the main line it is 0.75.

Engineering metrics (E) include the length of the main line, a list of the number of runs of pipelines with their respective diameters, a list of sizes of nominal capacities of GPUs (the number of options under consideration for the line part (LP) and CS).

Reliability metrics (R) are represented by the rate of failures and recoveries of LPs and GPUs. As a reference reliability metric of gas pipeline $M_r{}^*$, we take the reliability factor K_r. Its current value (M_r) is the ratio of the mathematical expectation of MGP performance to its rated value:

$$K_r = \frac{M\,[Q]}{Q_r}. \tag{5.60}$$

The economic performance indicators refer to specific annual operating costs and capital expenditures of MGP LP; specific annual operating costs and specific annual capital expenditures proportional to the installed CS capacity; specific metal inputs.

As a result of solving this problem of optimization of MGH parameters with regard to their reliability, the following values are determined: the number of pipeline runs; their respective optimal diameters; the number of compressor stations; the number and length of line sections; the number of operating and reserve GPUs at each CS; optimal rated capacity of GPUs; metal inputs in the LP.

The number of all possible considered options of the MGP being designed is equal to the product of the number of MGP LP options and GPU schedules for the CS and the maximum number of backup units at the CS, which should not exceed the number of operating units.

The stated problem is considered a combinatorial optimization problem and combinatorial search methods are used to solve it.

TABLE 5.3 Optimization of gas transport system parameters of the Kovykta GCF - Irkutsk-Beijing, with reliability factored in.

Parameter	Kovykta GCF - Irkutsk	Irkutsk-Beijing
Diameter and number of lines	1220x2+1420	1.420
Pipeline length, km	470	2.170
Number of CSs	2 (3)*	16
Number of installed GPUs	9	6
Number of backup GPUs	3	3
GPU type	GPA-Ts-16	GPA-Ts-16
Resulting reliability	0.978	0.974
Capacity of a single CS	128.5	82.9
Specific capital expenditures per 1 km, million USD.	2.35	2.32
Net present value, mln. USD	36.035	25.263
Internal rate of return, %	58.9	25.2
Year of loan repayment	7	7
Metal inputs, thous. tons	886	1.634

Backed by the proposed methodological tools and computational software, to illustrate their capabilities, we have performed a study and obtained the results of parameters optimization given the reliability requirements for the gas transport system running from the Kovykta gas condensate field (GCF) to Irkutsk to Beijing, the key takeaways of this study are shown in Table 5.3.

5.4 Hierarchical modeling in the expansion planning of coal supply systems

Coal supply systems as objects of modeling. Coal is the energy resource most secure in terms of its availability in the future compared to oil and gas. The world's reserves of oil and gas are sufficient for less than 50 years, and those of coal - for about 130 years [42]. The coal industry for countries with significant coal reserves plays a major role in the economies of these countries. Countries with more than 10% of the world's coal reserves and those that have made it to the top ten with respect to this metric include: USA - 26.6% of world reserves, Russia - 17.6%, and China - 12.8%, and, those with a share of coal reserves below 10%, in descending order: Australia, India, Germany, Ukraine, Kazakhstan, South Africa, and Indonesia. The leaders in terms of production volumes are China - 47.3%, India - 9.3%, USA - 7.9%, Indonesia - 7.5%, Australia - 6.2%, Russia - 5.4%, South Africa - 3.1%. Some of the listed countries are also leaders in coal consumption. Coal is an important resource for providing fuel for the power industry and supplying coke for the metallurgical industry in such countries as China, India, the United States, Russia, etc. (Table 5.4). The large

TABLE 5.4 Characteristics of the coal industry of the world's leading coal-producing countries (2019).

Country	Reserves, bln. tons	Production, mln. tons	Consumption, Exajoules	Exports, Exajoules	Imports, Exajoules	Availability of reserves (years)
USA	249.5	639.8	12.4	2.1	0.8	390
Russia	162.2	441.1	3.6	5.9	*	369
China	141.6	3,846.0	81.7	0.3	5.7	37
Australia	149.1	506.7	0.1	9.7	*	294
India	105.9	756.4	18.6	-	4.9	140
South Africa	9.9	254.3	3.8	2.2	*	39
Indonesia	39.9	610.0	3.4	9.2	*	65
Colombia	4.6	82.4	0.3	2.1	*	55
World total	1,069.6	8,129.4	157.9	35.3	6.0	132

*Note: * statistically insignificant amount or zero. Source: [43].*

scale of the coal industry is particularly characteristic of the world's leading coal-producing countries (Table 5.4) [43]. Different countries perform differently in terms of production, exports, availability of coal reserves, and other metrics that characterize not only the scale of operation of the coal industry but also the distinctive features of the coal supply systems of each country. The United States, Russia, and Australia have the largest coal reserves among coal-exporting countries.

Different countries significantly differ in terms of conditions for the development of the coal industry, such as socio-economic, development of the transport system, tariff policy for transportation, competition with other types of energy resources (gas, hydropower, etc.), mining, geological, hydrological, and other conditions of coal mining. The difference in the qualitative characteristics of coal leads to a variety of areas of its use. This can be the energy, by-product coke-making, coal chemistry, etc. One of the essential features of the coal industry in such countries as Russia, Australia, Indonesia, and the USA is a large share of the export component in coal supplies. In 2020, more than 50% of the total coal supply was exported from Russia [43].

Hierarchical approach, aggregation, and disaggregation of same-type components that are used to describe and model the coal supply systems of different countries allow factoring in the large scale and structural complexity, cross-system links, territorial (levels of enterprises, regions, and aggregated regions), and other aspects of these systems.

When modeling the expansion and operation of the coal supply system (CSS) of any country, it is important to consider the main aspects of the conditions for the expansion of coal production and use. To this end, the main properties of the coal supply system as a component of the energy sector of the country are considered and systematized.

Basic properties of coal supply systems. Coal supply systems, as well as other large energy systems that make up the country's energy sector [44,45], have many properties that common to all of them and others that are specific to them, i.e., inherent in coal supply systems only. The main properties are divided into separate groups: facility properties (structural complexity, scale, heterogeneity of coal enterprises and their products), motion properties (inertia, boundedness), and information properties.

The notion of information properties of a facility [45] is introduced for the transition from a real facility to economic and mathematical models. Information properties are understood as properties of metrics of the input information used to describe and model the processes of expansion and operation of the facility, and also to capture the results of the solution. The properties of the input information are incompleteness, uncertainty, integrability, and aggregability.

Incomplete information refers to technical-and-economic and financial-and-economic metrics, transport capabilities, sources and volumes of funding, capabilities of linked industries that serve as suppliers of products required for the operation of the coal supply system, and the availability of human resources.

Uncertainty refers to the future conditions of coal supply systems, including the following: information about the current state of the coal industry; changes in the legislative framework; changes in the tariff policy of carriers; prices of vehicles, machinery, construction materials, etc.; availability of labor and other resources; global market prices; demand for Russian coal in the domestic and global markets.

Integrality (discreteness) is related to the fact that the enterprise (enterprise development option) either exists or does not exist. The same applies to the means of transport of coal. The weight of coal in a freight car in calculating the cost of its transport is always assumed based on the load capacity of the freight car, regardless of how much it is filled with freight, etc.

Aggregability is possible with respect to the purpose of coal use and territorial divisions (coal basin, administrative units of different levels of the country, the level of the country as a whole), method of mining, type of coal, and other characteristics. For Russia, the administrative units are federal subjects, federal districts, and, sometimes, economic regions are also considered. In other countries, such as the United States, Australia, and India, the administrative units are the states; in China, they are provinces. Coal mining and coal processing companies are often subsidiaries of larger companies/holdings that include coal-consuming companies, transport companies, etc. There are multinational companies that incorporate coal mining companies as their part. In some cases, in modeling, complex structures and the relationships between them can be aggregated with the most significant of them highlighted.

Modeling the expansion of coal supply systems. Modeling the expansion and operation of coal supply systems has a history that spans many years. Such modeling is presented in the works of experts from different countries, including Russia [46–66]. Models were developed to study the prospects of development of the industry as a whole, coal-mining regions, as well as the operation of enterprises. A considerable amount of work is devoted to modeling various aspects and conditions affecting the development of coal mining, including hazardous seismicity [46], hydrological conditions [47,48], coal consumption and coal prices [49], and others.

When studying the prospects of the expansion of coal supply systems, experts most often use optimization and simulation models [50–53], as well as logistic, static, and dynamic models [54]. Models are developed to study both individual processes related to the technology of coal mining and processing and the system aspects of the operation of enterprises, regions, and coal supply systems as a whole in interaction with other sectors of the economy.

The hierarchical approach is widely used in modeling the expansion of the coal supply systems of different countries [50,51,55]. It allows one to represent coal supply systems in models at different levels: the level of the energy sector of the country (in interaction with other sectors of the economy), and at the levels of individual areas, regions, and enterprises.

In the international experience in modeling the expansion of coal supply systems, it is the coal module of the U.S. National Energy Modeling System (NEMS) model [50] that is the most comprehensive and the one that takes into account the multiple links of the coal supply system to the sectors of the economy and its internal structure. Models of operation of the coal supply systems of Poland, South Africa, Australia, and other countries have also been developed [54,56,57].

Russian experience in modeling the expansion of coal supply systems spans over 70 years [52–66].

At the MESI studies and projections of the expansion of systems of coal supply of the country and regions as part of the energy sector have been conducted for over half a century [53,63]. The studies are backed by optimization and simulation models. A research workflow that takes into account the characteristics of the Russian coal industry, its international links have been developed there, along with the implementation of a system of models, software, and information support [53]. The proposed methodology appears to be versatile and can be applied to different levels and scales of studies.

Projecting the expansion of coal supply systems includes solving the following range of problems:

1. Analysis of the current state of the coal industry.
2. Building scenarios of economic development (national or regional).
3. Projection of electricity and heat demand.

4. Projection of fuel demand for energy facilities.
5. Projection of demand for coking coal for the needs of the metallurgical industry.
6. Projection of demanded volumes of coal production, volumes and directions of coal supplies.

Projections are made for several scenarios of economic development of the country given the current trends in production, supply, consumption of available coal resources, the capabilities of transport infrastructure, and other factors.

The problems of the study of the expansion of coal supply systems are interrelated. They can be characterized as weakly structured and having the multi-criteria nature. Ill-structured problems contain components with inherent uncertainties and heterogeneity that hinder formalization, and are close to being unstructured in terms of the human (expert) effort required. In such problems, the preferred solution is formed with human participation.

Overcoming the structural complexity of coal supply systems, including the presence of multiple links, and the ill-structured nature of problems became possible by applying an approach based on the hierarchy of their construction. Taking account of the levels of hierarchy in the system of models is implemented through the partitioning into territorial entities of different levels, from the level of the country as a whole to the level of enterprises. Four levels of the hierarchy are considered: the energy sector, the coal industry as a whole, aggregated regions and regions of the country, and enterprises (Fig. 5.16).

System of models. To solve problems corresponding to different levels of the hierarchy, a system of economic and mathematical models [63] (Fig. 5.17) was developed and adopted, these include:

1. The level of the energy sector of the country - the energy sector development model.
2. The level of the coal supply system of the country - 'COAL TRANS' and 'COKE' models. The "COAL TRANS" model deals with steam coal, and the "COKE" model covers coking coal.
3. The level of regions - simulation models of aggregated regions and regions proper.
4. The level of companies: a model of financial and economic valuation of investment projects of coal mining companies.
5. Linear programming (LP) models and methods are used at the levels of the energy sector and coal supply system. The objective function usually contains financial and economic metrics. At the level of the energy sector of the country, one makes a projection of fuel demand for energy facilities and the projection of demand for coking coal. At the level of the coal supply system, the volumes of coal production, volumes and

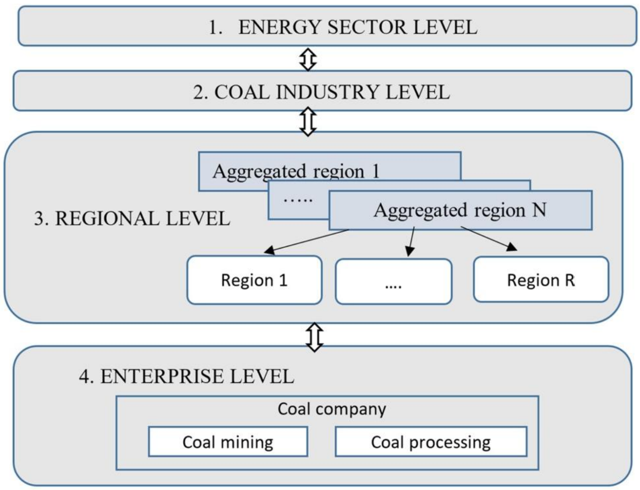


FIGURE 5.16 Levels of modeling the expansion of the country's coal-supply system.

directions of coal supply are determined for a given demand for coal as obtained from the energy sector model given the constraints on coal resources, CapEx, and other metrics of the development of the coal supply system.

As a result of the mutual linking of problem solutions, an optimal solution to the original problem as a whole can be found. Depending on the state of the research problem, the models can be used together or in a stand-alone fashion. Several problems can be solved with the use of a single model.

The level of the country's energy sector is a module of the coal system in the energy sector model.

The model of energy sector development [63] is designed to study the dependency of the main parameters of the country's energy sector development for the future 20–25 years on such conditions as energy consumption levels, supply of territories with primary energy resources, etc. The structure of the energy sector model is described in Chapter 2 of this book. In the energy sector model, energy supply systems are represented by separate interconnected modules (oil, gas, coal, electric power, and heating components). The energy sector model is used to determine the demand for energy resources, including coal for power generation and district heating.

The module of the coal-supply system in the energy sector model has the following form.

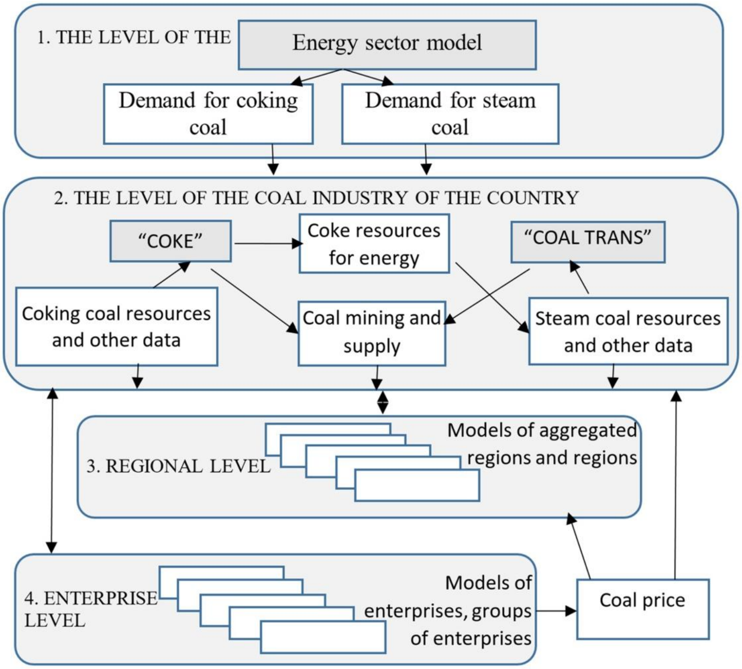


FIGURE 5.17 Diagram of the relationship between models in the system of models.

Find:

$$Min\left\{\sum_{f}\left[\sum_{i,y}C^{y}_{fi}X^{y}_{fi}+\sum_{ky,d}(C^{ky}_{fd}X^{ky}_{fd}+\sum_{n}C^{ky}_{fd}X^{ky}_{fd})+\sum_{ko,n}C^{ko}_{fn}X^{ko}_{fn}\right]+\right.$$
$$\left.+\sum_{k}\left[\sum_{y}(\sum_{k'}C^{y}_{kk'}X^{y}_{kk'}+\sum_{dj}C^{y}_{kdj}X^{y}_{kdj})+\sum_{ny,k'}C^{ny}X^{ny}_{kk'}\right]\right\} \tag{5.61}$$

subject to the following constraints:

$$\sum_{i}a^{ky}_{fi}X^{y}_{fi}-\sum_{d}\left(X^{ky}_{fdn}\right)+\sum_{n}X^{ky}_{fdn}=A^{ky}_{f},\quad f=1,\ldots,F;ky=1,\ldots,KY\ ; \tag{5.62}$$

$$\sum_{f\in k,i}a^{y}_{fi}X^{y}_{fi}+\sum_{k'}(X^{y}_{kk'}-b^{y}_{kk'}X^{y}_{kk'})-\sum_{dj}X^{y}_{kdj}$$
$$=A^{y}_{k}+X^{y\ni}_{k}+X^{y}_{k}\ ;y=1,\ldots,Y;k=1,\ldots,K \tag{5.63}$$

$$\sum_{d} a_{fd}^{ky,ko} X_{fd}^{ky} - \sum_{n} X_{fn}^{ko} = 0; n = 1, \ldots, N; ko = 1, \ldots, KO; \tag{5.64}$$

$$\sum_{fd} a_{fdn}^{ky,ko} X_{fdn}^{ky} - \sum_{s} X_{fn}^{ko} = A_{n}^{ko}; f = 1, \ldots, F; ko = 1, \ldots, KO; \tag{5.65}$$

$$\begin{gathered}\sum\nolimits_d \Big[\sum\nolimits_{ky} (\sum\nolimits_{f\in k} a_{fd}^{ky,ny} X_{fd}^{ky} + \sum\nolimits_{n\in k,f} a_{fdn}^{ky,ny} X_{fdn}^{ky}) + \sum\nolimits_j a_{kdj}^{y,ny} X_{kdj}^{y}\Big] + \\ + \sum\nolimits_k (X_{k'k}^{ny} - b_{kk'}^{ny} X_{kk'}^{ny}) = A_k^{y} + X_k^{ny,\ni} + X_k^{ny}; \\ k = 1, \ldots, K; ny = 1, \ldots, NY;\end{gathered} \tag{5.66}$$

$$0 \le X_{fi}^{y} \le B_{fi}^{y}; 0 \le X_{fd}^{ky} \le B_{fd}^{ky}; 0 \le X_{fdn}^{ky} \le B_{fdn}^{ky}. \tag{5.67}$$

Here, the condition (5.61) reflects the minimum costs at the consumer, taking into account the prices of coal mining, processing, and transportation.

Eq. (5.62) describes the balance of coking coal. Mining of coal of each grade ky by all groups of coal mining enterprises of basins and deposits should ensure its consumption for processing by beneficiation plants d both within the basin f and at by-product coke-making plants and metallurgical plants n, as well as cover the mandatory demand A_f^{ky} in coking coal of each basin or field, where A_f^{ky} is the share of coal grade ky in the annual coal production X_{fi}^{y} by the ith group of coal mining enterprises of the basin or field. The input part of Eqs. (5.63), the balance of steam coal of various quality y, is made up of the following:

a) production of this steam coal by all basins and fields located in the area under consideration $f \in k$, is calculated given the coefficient a_f^{y}, which means the output of steam coal by the group of mines and open-pit mines i;

b) the possible supply of this coal from other areas X_{kk}^{y}.

These resources must provide: different ways j of coal processing (beneficiation, sorting, semi-coking, etc.); its delivery to other districts $X_{kk'}^{y}$, taking into account losses during transport $b_{kk'}^{y}$, coal supply to power plants $X_k^{u\in}$ and other consumers X_k^{y} of this district, as well as covering the mandatory demand of the district in coal A_k^{y} (including exports).

The second group of conditions (Eqs. (5.64), (5.65)) describes coal processing. For coking coal (Eq. (5.64)), the total production of coking coal concentrate ko by coal beneficiation plants in the basin f should be equal to the sum of its supplies to coking plants and metallurgical plants (here $a_{fd}^{ky,ko}$ is the specific yield of concentrate from run-of-mine coking coal of grade ky). Eq. (5.65) sets the conditions for obtaining the concentrate of ko grade for the plant n at beneficiation plants of the basin f and in-house beneficiation plants (here, $a_{fd}^{ky,ko}$ is specific yield of concentrate from coking coal of ky grade; A_n^{ko} is the expected demand of the plant in concentrate, which is determined in advance in accordance with the selected composition of the charge).

Eq. (5.66) captures the balance of production, distribution, and consumption of each type of processing products ny (sized coal, briquettes, semi-coke, low-grade processing products) in a given area k. The input part of the balance is the production of these products by enterprises of the district ($a_{kdj}^{y,ny}$ is the yield from a ton of run-of-mine coal), including the output of low-grade coking coal beneficiation products by beneficiation plants and supply from other areas of the country $X_{kk'}^{ny}$. In total, they should ensure possible transport to other areas $X_{kk'}^{ny}$ (taking into account losses during transport $b_{kk'}^{ny}$), the consumption of processing products by power plants $X_k^{ny,\in}$, and other consumers X_k^{py} of this area and its mandatory demand A_k^{ny}.

Along with the above equations, the model includes the constraints (5.67) on the capability of coal production by the ith group of coal mining enterprises in the basin or field f; on the production capacity of the operating fuel processing enterprises d.

The level of the country's coal supply system. The level of the country's coal supply system is represented by two production and transport models of expansion of production and consumption of steam coal ("COAL TRANS") and coking coal ("COKE"). The need to develop separate models for different uses of coal (energy and by-product coke-making) is due, first and foremost, to the significant difference in the way the demand for coking and steam coal forms and its measurement units.

The COAL TRANS model is designed to project the structure and volume of cross-regional supplies of steam coal given changing prices, transport tariffs, the demand for coal, and other conditions of the industry development. The model takes into account the territorial factor and identifies coal consumers corresponding to the regions of the country and suppliers of lignite and bituminous coal. To analyze the solution of the LP problem, the results of calculations obtained for the regions are aggregated into indicators for larger territorial entities: aggregated regions and the country as a whole. The model is formed as an LP problem. We minimize consumer costs for the purchase and transport of coal at a given demand for steam coal in the regions and the assumed constraints on the technically possible volumes of coal production while taking into account the technologically established mandatory supply of certain types of coal in certain regions. The economic and mathematical statement of the problem is as follows:

Find:

$$Min\left[\sum_{fivt} c_{fiv}^{st} B_{fiv}^{t} a_{fiv}^{st} \lambda_{fiv} + \sum_{frjs}\left(c_{frj}^{st} + u_{fij}^{st}\right) X_{frj}^{st}\right]; \tag{5.68}$$

subject to the following constraints:

$$\sum_{fiv} B_{fiv}^{t} a_{fiv}^{st} \lambda_{fiv} - \sum_{rj} X_{frj}^{st} = 0\,; \tag{5.69}$$

$$\sum_{rj} \eta_{frj}^{st}\, X_{frj}^{st} \geq B_{rj}^{st}; \tag{5.70}$$

$$\sum_{v} \lambda_{fiv} = 1;\;\; f = 1, \ldots, F; i = 1, \ldots, I_f; \tag{5.71}$$

$$\lambda_{fiv} = 0 \;\text{ or }\; 1; \tag{5.72}$$

$$X_{frj}^{st} \geq 0; f = 1, \ldots, F; s = 1, \ldots, S; j = 1, \ldots, J; r = 1, \ldots, R; t = 1, \ldots, T; \tag{5.73}$$

where: f – index of the basic or field $f = 1, \ldots, F$; i – index of the coal-mining enterprise $i = 1, \ldots, I_f$; v – index of the option of enterprise development $v = 1, \ldots, V$; s – index of steam coal that is of the same type in terms of their quality s$= 1, \ldots, S$; j – index of consumers $j = 1, \ldots, J$; r – index of consumption area $r = 1, \ldots, R$; t – index of projection period $t = 1, \ldots, T$; B_{fiv}^{t} – technically possible volumes of run-of-ming coal production at the enterprise i according to the vth development option in the tth period; d_{fiv}^{ts} – coefficient of the yield of steam coal (having the same type in terms of their quality) s at the enterprise i, basin f according to the vth option in the period t; λ_{fiv} – the condition for the choice of the option of enterprise development; c_{fij}^{ts} – the price at the place of coal mining of the ith enterprise, basin f in the period t of the sth type of coal; u_{fiv}^{ts} – the price of coal transport from the coal basin f to the area r in the period t if the sth type of coal; c_{frj}^{ts} – the costs of using the sth type of coal from the coal basin f in the area r by the jth consumer in the period t; x_{frj}^{ts} – the volume of transported sth type of coal from the coal basin f to the area r in the period t; λ_{frj}^{ts} – coefficient of interchangeability of different steam coal s in different consumer groups j; B_{rj}^{st} – demand for sth type of coal in period t in the rth region at the jth consumer.

The model (5.68)–(5.72) describes the entire process chain of operation of the industry for mining, processing, and distribution of steam coal. The objective function of the model (5.68) minimizes consumer costs. Eqs. (5.69), (5.70) characterize balances of distribution and consumption of steam coal. Eqs. (5.71), (5.72) represent the conditions of the integrality of development options by groups or individual coal enterprises. And the last group of conditions (5.73) reflects the conditions of non-negativity of model variables.

As a result of solving the LP problem, the dual estimates determine the marginal prices of coal.

The COKE model is designed to project the structure and volumes of coking coal production, beneficiation, transport, and use in the context of ongoing changes in prices, transport tariffs, coal demand, and possible constraints on supply volumes.

When projecting the development of coking coal production, it is necessary to take into account the following features. Mining and beneficiation of coal of coking grades produce low-grade processed products suitable for use as a power fuel. Mines and open-pit mines can produce several grades of coking and steam coal. The structure of the charges of coke plants is represented by sets of coal grades in a certain proportion. For a particular type of charge, coal can be supplied from different coal mines, including imported coal. In turn, a significant amount of coking coal mined in Russia is exported. The economic and mathematical statement of the problem is as follows:

Find:

$$\min\left\{\sum_{fiv} c_{fiv}\lambda_{fiv} - \sum_{t}\left[\sum_{fm}\left(\sum_{j=1} c_{fj}^{mt}x_{fj}^{mt} + \sum_{j=J_1+1} c_{fj}^{mt}x_{fj}^{mt}\right) + \sum_{nj} c_{nj}^{t}B_j^t Z_{nj}^t - \sum_{tls}\psi_f^{ts}X_f^{ts}\right]\right\}. \tag{5.74}$$

Subject to the following constraints:

$$\sum_{iv}\delta_{fiv}^{mt}B_{fiv}^{mt}\lambda_{fiv} - \sum_{j=1}^{J_1} x_{fj}^{mt} - \sum_{j=J_1+1}^{J} x_{fj}^{mt} = 0; \quad f = 1,\ldots,F;\ m = 1,\ldots,M;\ t = 1,\ldots,T; \tag{5.75}$$

$$\sum_{f} x_{fj}^{mt} + \sum_{n} a_{nj}^{mt}B_j^t Z_{nj}^t = 0; m = 1,\ldots,M;\ j = 1,\ldots,J_1; t = 1,\ldots,T; \tag{5.76}$$

$$\sum_{f} x_{fj}^{mt} + \sum_{n} a_{nj}^{mt}B_j^t Z_{nj}^t = 0; m = 1,\ldots,M;\ j = J_1+1,\ldots,J; t = 1,\ldots,T; \tag{5.77}$$

$$\sum_{iv} a_{fiv}^{st}B_{fiv}^{ts}\lambda_{fiv} + \sum_{j=1}^{J_1} a_{fj}^{mts}x_{fj}^{mt} - \sum_{j=J_1+1}^{J} a_{fj}^{mts}x_{fj}^{mt} - x_f^{ts} = 0; \quad f = 1,\ldots,F;\ s = 1,\ldots,S; t = 1,\ldots,T; \tag{5.78}$$

$$\sum_{fm} x_{fj}^{mt} \le B_j^t; \quad j = 1, \ldots, J_1; t = 1, \ldots, T; \tag{5.79}$$

$$\sum_{v} \lambda_{fiv} = 1; \; f = 1, \ldots F; \; i = 1, \ldots, I; \; v = 1, \ldots, I; \tag{5.80}$$

$$\lambda_{fiv} = 0 \text{ or } 1; \tag{5.81}$$

$$\sum_{n} Z_{nj}^t = 1; \quad j = 1, \ldots, J; \quad t = 1, \ldots, T; \tag{5.82}$$

$$Z_{nj}^t = 0 \text{ or } 1 \tag{5.83}$$

$$\begin{gathered} x_{fj}^{mt} \ge 0; \; x_f^{ts} \ge 0; \; f = 1, \ldots, F; s = 1, \ldots, S; j = 1, \ldots, J; \\ r = 1, \ldots, R; \; t = 1, \ldots, T. \end{gathered} \tag{5.84}$$

The model (5.74)–(5.84) uses the following notations: m is the coking grade index, mM; j – index of the by-product coke-making plant, $j = 1, \ldots, J$ – plants that have beneficiation shops; $j = J_1 + 1, \ldots, J$ – coking plants that do not have beneficiation shops; n is the index of the coal charge option for coke production, $n \in N$; δ_{fiv}^{mt} is the coefficient of conversion of the concentrate of the m-th grade of the listed moisture, obtained from the coal of the ith mine under the vth option into the dry concentrate (with standard content of ash, sulfur, and volatile matter); a_{nj}^{mt} is the share of the mth coal grade in the nth option of the charge at the jth coking plant; B_{fjv}^{ts} is the volume of by-product production of steam coal at the ith mine as per the vth option in period t; a_{fj}^{mts} – the proportion of the yield of low-grade processed products in the beneficiation of coking coal grade m relative to the yield of concentrate; a_{fj}^{mts} – the average annual cost of beneficiation in the fth basin or field and transport of concentrate to the jth by-product coke-making plant in period t, per ton of concentrate of the listed moisture; c_{fj}^{mt} – the average annual cost of beneficiation at the shop of the jth by-product coke-making plant and transport of run-of-mine coal to the jth by-product coke-making shop per ton of concentrate of the listed moisture ($j = J_1 + 1, \ldots, J$); c_{nj}^t – the costs associated with the use of the nth coal charge variant at the jth coking plant per ton of dry charge; ψ_f^{ts} – the price of steam coal of the type s at the production (processing) site in period t; x_{fj}^{mt} $j = J_1 + 1, \ldots, J$ – the amount of coal of grade m mined in the basin f, beneficiated in the basin itself ($j = J, \ldots, J_1$) or at the by-product coke-making and metallurgical plants ($j = J_1 + 1, \ldots, J$), supplied to the jth metallurgical or by-product coke-making plant measured as dry concentrate in the period t; Z_{nj}^t is an integer variable indicating whether the nth version of the charge is applied at the jth plant in period t; x_f^{ts} – the volume of steam coal resources (ancillary mining products, low-grade processed coking coal products) in the fth basin or field in the period t.

The model (5.74)–(5.84) reflects the technological chain of coking coal mining, their beneficiation, and use at coking plants.

The objective function (5.74) characterizes the total costs for the entire period under consideration for mining, beneficiation, and transport of coking coal. The group of Eqs. (5.75) reflects the balances of production and distribution of coking coal. Eqs. (5.76)–(5.77) stand for the balances of beneficiated coal at beneficiation plants of basins or fields, or at beneficiation plants under by-product coke-making plants and metallurgical plants, and Eqs. (5.78) stand for the balance of steam coal. Constraints on the processing volumes of coking coal in basins and fields and at beneficiation plants of basins or fields, or at beneficiation plants under by-product coke-making plants and metallurgical plants are represented by equations of the form (5.79). Eqs. (5.80)–(5.83) describe the conditions of integrability of choices of coal mining enterprises and charges at by-product coke-making plants, and (5.84) describes the conditions of non-negativity of variables.

Levels of regions and enterprises. Optimization models provide projections that sometimes require clarification with the participation of an expert since the study of the expansion of the coal supply system is ill-structured and has elements of uncertainty to it. The participation of an expert allows taking into account the special aspects of the operation and development of the processes of coal mining and consumption, which do not lend themselves to formalization. Simulation models are suitable for such purposes. At the beginning of the study, as a rule, there is uncertainty in the composition of the available input data, the volume and algorithm of preliminary calculations of metrics. The input information available at the beginning of the study, and the uniqueness of the facilities of coal supply systems do not allow creating tools for simulation models with fixed input and output. The specific nature of scholarly research is such that for almost each of such studies one created their own simulation models on the basis of models developed earlier.

Four types of simulation models have been developed: “BALANCES”, “REGIONAL BALANCES”, “REGION”, and “INVEST COAL”. The models differ in the details of the representation of facilities and some other aspects, without significant differences in structure (Table 5.5, Fig. 5.18). Models 1-3 correspond to the level of regions, the model 4 corresponds to the level of enterprises.

The presented simulation models have three dedicated functional modules: “Production”, “Consumption”, and “Coal balances” (Fig. 5.18).

The models 1-3 (Table 5.5) are of the same type and are created for specific studies, they differ in the composition of the available information and the purposes of the study. Depending on the level of detail, coal mining and coal processing companies and regions act as the market players. The links between market entities are represented by supply volumes and transport costs. Coal shipment and consumption are projected taking into

TABLE 5.5 Characteristics of simulation models.

No.	Name	Level of detail	Entities of the coal market	Result
1	"BALANCE"	Coal, aggregated region	Producers: coal*; Consumers: aggregated regions, exports	Projection of coal production and supply by country and aggregated regions
2	"BALANCES OR REGIONS"	Coal, region, coal mining companies, supply, exports	Producers: coal, coal mining companies. Consumers: region, exports	Projection of coal production, coal supply logistic structures and volumes, coal balances by regions and aggregated regions
3	"REGION"	Enterprises, beneficiation plants, commercial products, administrative divisions within the region	Producers: coal mining and coal processing companies. Consumers: regions, territorial entities within the region, exports	Projections for regions: coal mining and processing and coal balance, coal supply to other regions of the country
4	*"INVEST COAL"* 1) Direct problem 2) Inverse problem	Enterprise or group of enterprises	Technical and economic performance metrics of the project	1) Performance metrics: payback period, internal rate of return, profitability index, net present value 2) The price of coal or other metrics

** Coal refers to a group of enterprises producing coal from a particular field or group of fields. For example, "Kansko-Achinsky" is the coal from the Kansko-Achinsky basin.*

account the current trends in coal supply and consumption in the regions of Russia and its exports to other countries.

The models use metrics with varying degrees of detail for different models, the main ones being the following:

- projection of coal demand;
- projection of coal resources constraints;
- projection of constraints on steam coal and coking coal mining;
- the authors' estimates of the opportunities for the development of coal mining enterprises in the regions;
- qualitative characteristics of coal;

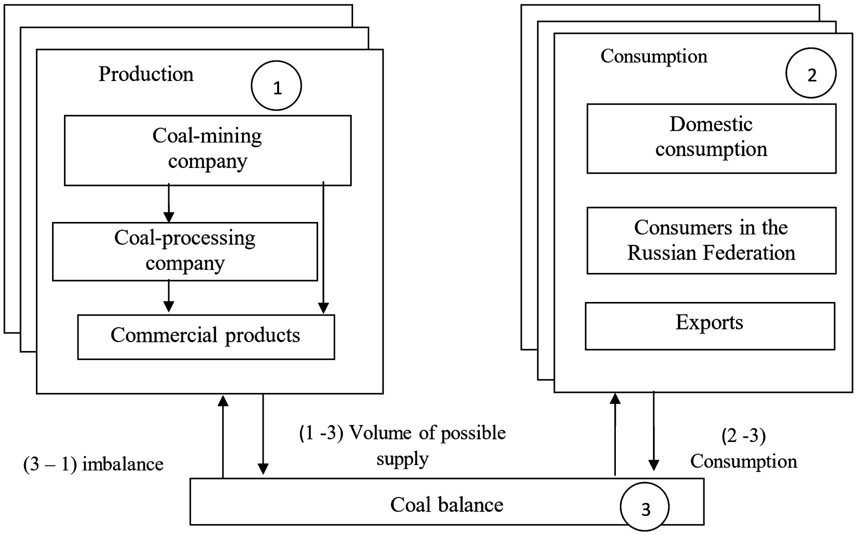


FIGURE 5.18 Structure of "BALANCES", "REGIONAL BALANCES", and "REGION" models.

- technical and economic performance of enterprises;
- the existing transport scheme of supply.

The "INVEST COAL" model is designed to assess the economic performance of the operation and development of an enterprise or group of enterprises [65]. The general methodological approaches employed in international and domestic practice are tailored in the model to the facilities of coal supply systems. The time period, as a rule, is 10-15 years.

The following metrics serve as criteria for each year under consideration: current account status, discounted current account, net present value, profitability index, product profitability, internal rate of return, payback period. The values of these metrics are calculated on the basis of the cash flow table. The input data in the model are set as indicators corresponding to each year under consideration: the price of coal, coal production volume, production costs of coal mining, taxes, capital expenditures, and other metrics that allow performing a valuation of the investment project. Production costs for coal mining include electricity, heat, materials, labor, industrial services, depreciation, taxes, payment of interest on loans, and other expenses. To increase the reliability of the estimates obtained, a sensitivity analysis is performed, which is the calculation of the dependency of overall financial and economic performance metrics on certain changes in the initial parameters of the project. Aided by this model, one can also solve the inverse problem, which determines the price of coal and other metrics for a given performance metric of the enterprise.

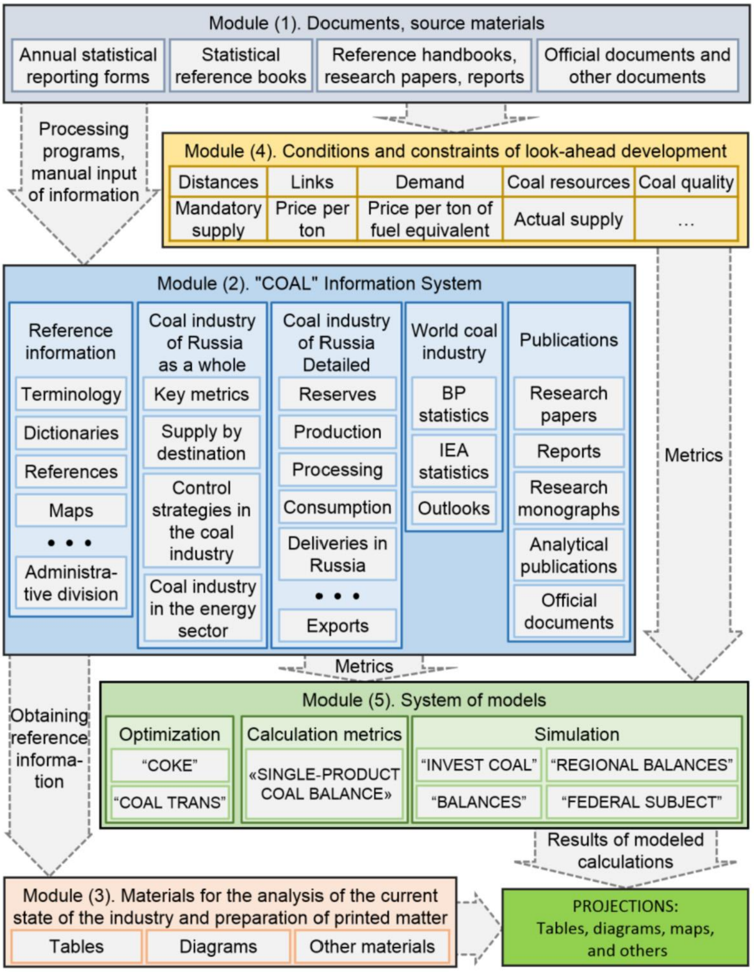


FIGURE 5.19 Structure of the "COAL" information and model software package.

5.5 Information and model software for the expansion planning of coal supply systems based on the hierarchical approach

To carry out studies of the prospects of expansion of coal supply systems, we have developed an information and model software package (IMSP), which includes an information system, a system of models, projections of constraints and conditions of expansion in the future, and programs to form models and process the results of calculations (Fig. 5.19).

The composition and structure of the IMSP takes into account the hierarchy of models to study the prospects of expansion of coal supply systems that corresponds to the second, third, and fourth levels of the hierarchy.

The computational process of expansion planning of coal supply systems includes the following main stages:

1. Analysis of the current state of the coal supply system and prospects for its expansion.
2. Preliminary calculations to analyze the current state of the coal supply system and the calculation of metrics needed to build models.
3. Building computer versions of models.
4. Modeled calculation.
5. Analysis of calculation results.
6. Returning to one of the previous steps or forming a final decision.

Sources of information for Stages 1 and 2 are forms of state and industry-specific statistics, statistical compilations, expert estimates, preliminary calculation of metrics, and projections. Stages 1, 2, and 6 are quite time consuming and poorly formalized. Calculations using mathematical models cannot fully replace the detailed elaboration of options by experts. Stages 3 and 4 require a qualified programmer to implement them and to maintain and modify the programs according to the dynamically changing needs of the researcher.

Fig. 5.20 shows the interface of the information and model software package "COAL", including the main sections and subsections. For the sake of coherence of arranging the data processing procedure, individual source files are converted to the MS Excel spreadsheet format and structured so as to enable quick access, selection, sorting, copying, and calculation operations. The IS contains both rigidly structured and loosely structured files, where the structure can be changed at the discretion of the user. The system can be populated by a non-programmer user who has skills in working with MS Excel spreadsheets, which ensures the independence of the analyst and researcher. In the IS, one can put unstructured information along with structured data, such as comments on the entered data and, if necessary, calculate any metrics based on already available functions of MS Excel.

The arrangement of the interface of access to the individual sections is homogeneous both in the structure of the organization and in the names of the subsections: the sections "Production" and "Reserves" have homogeneous interfaces tailored to the administrative division of the country. The "Coal Quality" section is organized similarly but focuses on coal grades. The calling of primary sources, publications, maps, and other files is also organized in the same way. The rational combination of rigid and loosely structured forms of information and data storage makes the IS IMSO "COAL" quite convenient for research.

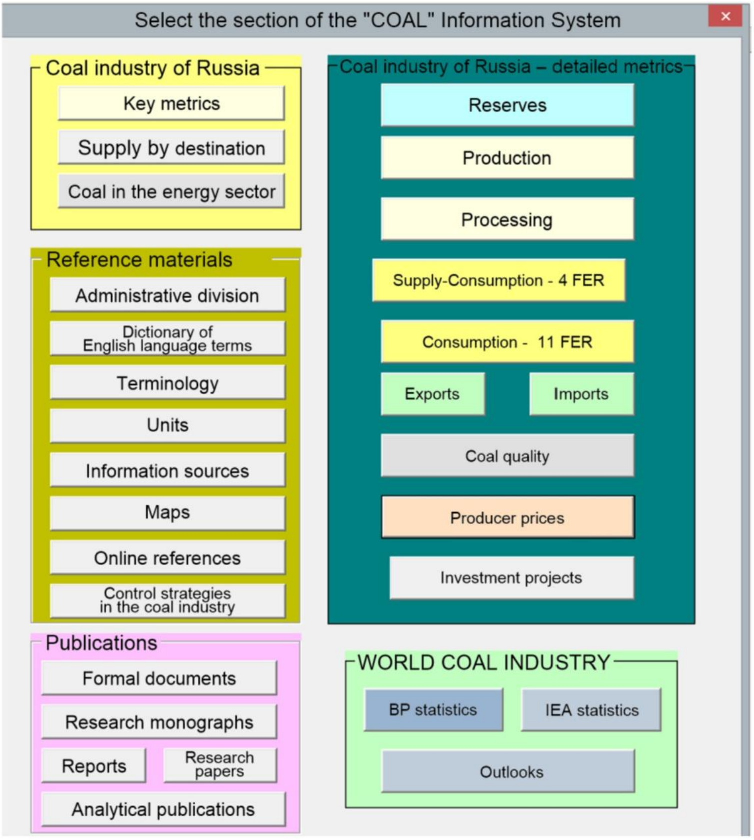


FIGURE 5.20 User interface of IS IMSP "COAL".

The information entered into the system can both originate from sufficiently reliable sources and include certain hypotheses, for example, those on investment projects. Maintaining and populating the IS with up-to-date annual statistics is done with the aid of the special statistical processing software, where possible, or manually, where the source of information is limited to printed matter.

The system of models and all programs are also implemented by means of MS Excel.

The results of calculations using the IMSP are formed in the form of tables and charts presented in the form of common metrics in physical and monetary terms: production (industry-specific, general energy), economic and financial.

Detailed and aggregated metrics of the development of the coal supply system are formed, with the coal at the levels of the energy sector and the coal supply system presented in accordance with the nomenclature adopted in the tables of statistical reporting.

The results of the modeled calculations are presented in the following tables by administrative division of the country and regions:

- potential opportunities for the expansion of coal mining and possible volumes of export-quality coal production;
- volumes and directions of coal supply, including exports;
- volumes of demanded coal production, including that by individual enterprises;
- coal resources for the energy industry;
- capacity additions in the coal supply system;
- coal processing volumes;
- yield of marketable coal products;
- balances of coal in general and steam coal in particular;
- the demand for resources inclusive of the following: capital expenditures of the expansion of the coal supply system; the number of people employed in coal mining and processing; heat for coal mining and processing; electricity for coal mining and processing;
- directions of development of the coal supply system (new construction, capacity expansion);
- structure of mining (surface and underground techniques, lignite and bituminous coal, steam and coking coal) and processing.

The outlined hierarchical approach to modeling of coal supply systems and the presented IMSP "COAL" over years were used in the development of energy strategies and development programs of the regions of Russia. There are studies on the subject of the changing conditions of the prospects of expansion of the coal supply system of Russia and its regions, valuation of investment projects of new coal mining enterprises and those of reconstruction of existing ones [66–69].

5.6 Hierarchical modeling of integrated energy systems with renewable sources

Conceptual considerations for the building of intelligent integrated energy systems. The modern energy industry is a complex infrastructure complex that includes fuel-, electric power-, heat-, and cold-supply systems. Despite the different types of services they provide, their common goal is to create comfortable working and living conditions for the population, as well as to effectively contribute to the development of the country's economy. To perform their functions, each of them has its own production, transportation, and distribution structure that connects them to consumers.

Production and transport energy systems (super-systems) have a certain integration in terms of use of the energy carrier of one system in another (for example, gas as fuel at power plants and boiler houses, electric power at gas pumping units, etc.), interchangeability of energy carriers, especially in emergency conditions (for example, fuel oil instead of gas at power plants and boiler houses, etc.), integrated use of the primary energy carrier to produce several final energy carriers (for example, gas as fuel at CHPPs to generate electricity and heat). The specified integration predetermines the leading role of the considered energy systems in the energy sector, with the optimization of the energy sector determining the rational scale of interaction and mutual influence of production and transport energy systems, and then their expansion and operation as well the control over them are studied independently. Production and transport systems of the energy sector, due to their large scale, enjoy increased attention in the sense of ensuring the efficiency, reliability, and quality of their operation and the expediency of expansion. To ensure the efficiency and reliability of these systems and the quality of energy supply, one employs advanced technologies and means of control and automation to manage their operation [70].

Energy distribution systems (mini-systems) are mainly represented by the energy infrastructure of cities, industrial centers, and rural areas. These centralized systems are formed either on the basis of CHPPs with combined generation of electricity and heat, or on the basis of boiler houses and power plants with separate generation of these types of energy. The energy infrastructure of cities, industrial centers, and rural areas also includes gas distribution networks that bring gas to specific consumers. The energy distribution systems of cities, to a lesser extent those of industrial centers and rural areas, are often large in scale, have the considerable capacity, and connect dozens or even hundreds of thousands of consumers. At the same time, they have simplified flow diagrams of the distribution of energy carriers, are insufficiently equipped with control and automation means, which does not allow controlling them in real-time and leads to increased financial and tangible costs, as well as significant energy losses [70].

Oftentimes, these systems overlap and compete in the current market for energy services. In particular, this applies to the systems of electricity-, heat-, gas-supply, etc. The problems of managing the expansion and operation of energy supply systems of cities, industrial centers, and rural areas are currently solved separately by type of system, often without linking the resulting solutions [71]. The comprehensive consideration of the problems of regional energy supply that is being developed [72] is limited to the optimization of design solutions within the regional energy sector without their additional optimization at the level of energy supply systems of cities, industrial centers, and rural areas and without studying the modes of operation of these systems and their management.

Having certain functional independence, these systems can interact with each other in normal and emergency modes of operation, as well as at the level of interchangeability of primary energy resources and use of energy carriers. Conventional and modern energy technologies at the functional level integrate combined heat and power plants (cogeneration units) linking electricity, heat, cold, and gas supply systems, as well as alternative devices for the use of different types of energy at active consumers managing their own energy consumption. All this testifies to their natural integration, which is further enhanced as the intelligent information and communication system is formed and developed. Together, they represent a new design in the form of an Intelligent Integrated Energy System (IIES). This design combines certain independence of its constituent systems with their coordinated participation in solving the main problem related to ensuring social and economic activity. Its unity is ensured by the information system, which is the infrastructural basis of the IIES [73,74]. In this regard, the organization of a coordinated process of development and operation of these systems and consideration of different types of energy systems as a single integrated energy supply system can significantly improve their safety, reliability, efficiency, and environmental friendliness. The inevitable development of distributed generation based on unconventional and renewable energy sources both at the level of energy supply systems and directly at the consumers, and their integration into centralized systems requires the implementation of new principles of building these systems and creating intelligent systems of their control with elaborate information and communication support. Combining disparate systems of different types into a single technological complex will ensure the implementation of new functional capabilities, the use of improved technologies in operation, and the creation of integrated hybrid centralized and distributed systems with coordinated control of their modes of operation and the active participation of consumers in the energy supply process.

In the last decade, research at the microsystems level has been actively pursued [75,76, etc.]. This level has hardly been considered in Russia yet. Therefore, it is necessary, first of all, to conduct a thorough in-depth analysis of international experience in this area, as well as the Russian specifics, on the basis of which it would be possible to outline the actual directions of comprehensive research.

The integrating properties of energy systems manifest themselves at different levels. At the upper national level it is typical for the electricity and gas supply systems, at the cross-regional level they are joined by the heating systems, in particular as part of the CHPP, at the level of cities and industrial agglomerations all of the above systems may be represented. This differentiation allows us to consider the hierarchical integration of energy systems. It is most pronounced on the lower city level. Such technological, organizational, and other integration is further enhanced by the increasing role of retail markets of energy carriers in the future.

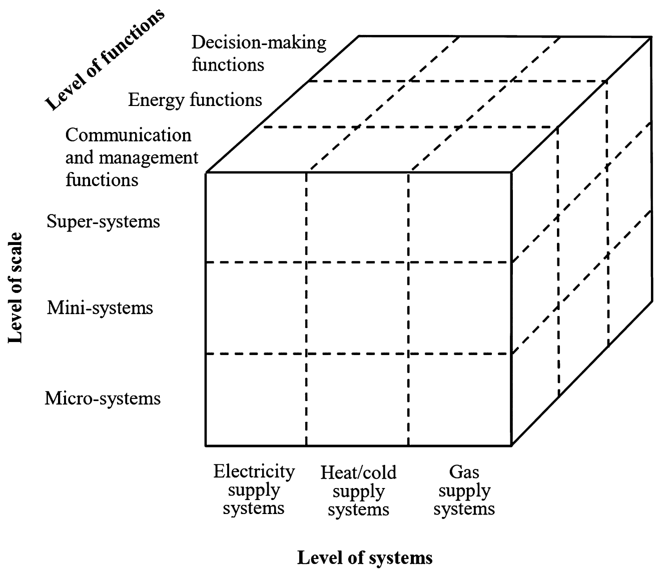


FIGURE 5.21 Multilevel structure of intelligent integrated energy systems in three dimensions.

IIESs have a multidimensional structure of functional features and properties of development, combining multicomponent, intelligence, efficiency, reliability, controllability, flexible use of energy conversion, transport, storage, and active consumer technologies.

The technological structure of the IIES should ensure:

- effective integration of renewable energy sources (RES) into the system;
- use of alternative energy sources, sources running on hydrocarbon fuels, as well as easily transportable fuels;
- system maneuverability;
- supporting the effective integration of energy and fuel infrastructures.

Different in scale and capacity electric, heating/cooling, and fuel supply systems are combined in the IIES, taking this into account, their integration into a unified structure is performed at different levels of capacity within the framework of the energy system of a certain type [77]. The IIES can be metaphorically represented as some three-level structure in three dimensions like a Rubik's cube, according to Fig. 5.21 [71,77]. Let us define these groups of levels as follows: level of systems (electricity, heat/cold, and gas supply systems), level of scale (super-, mini-, micro-systems), level of functions (energy functions, communication and management functions, decision-making functions). Let us consider in more detail the multilevel structure presented.

The systems level is the key infrastructure systems of the energy industry.

The scale level is represented as the following interconnected systems:

- super-systems include large power plants (condensing and combined heat and power plants, hydroelectric power plants and nuclear power plants), wind farms, large boiler houses, gas fields, underground gas storage facilities, large system-wide energy storage facilities, and electric, gas, and heat transportation networks;
- mini-systems include mini-energy sources connected to electric, heat, and gas distribution networks (mini-CHPPs, peak boiler houses, mini-CHPPs, large wind turbines, photovoltaic complexes, mini-energy storage units, etc.), as well as the mentioned distribution networks themselves;
- micro-systems include single wind turbines of small capacity, micro-turbines, solar collectors and photovoltaic panels, micro-storage facilities of electricity and heat, etc.), as well as domestic electrical, heating, and gas networks.

The function level includes the following constituent functions:

- energy functions: production, transport, distribution, and consumption of energy resources (electricity, heat/cold, gas) at all system levels and scales;
- communication and management functions: measurement (acquisition) of information, its processing, transfer, and presentation, as well as control systems for the modes operation and expansion of the IIES;
- decision making functions include models and methods for expansion planning decisions for the IIES as well as determining the settings of their control systems.

Let us note quite strong interrelations between the levels of functions: the level of communication and management uses information from the level of energy functions (current parameters of the structure and operation mode of systems, projected information for near and distant future, etc.), as well as the results of using models and methods of the decision-making level; the level of decision-making uses information from the levels of energy functions and levels of communication and management and on this basis develops solutions for the level of communication and management.

The fundamental principles of the construction of the IIES implement the following functionalities:

- ensuring the consumer's active participation in the energy supply process;
- the coordinated use of different ways of generating and storing different forms of energy;

- the ability to create new products, services, and markets;
- ensuring the quality of energy supply;
- integrated application of information and communication technologies;
- optimal use of resources and ensuring efficient operation of the system;
- system self-recovery;
- system stability to external influences.

The multidimensional structure of the IIES, a high level of association and self-organization, intelligence, integrated use of energy conversion, transport, storage, and active consumer technologies significantly expand the functionality of the emerging meta-system and provide it with the emergence of new properties. Among the most significant properties of the IIES one should highlight those that are aimed at quality and timely satisfaction of consumer demands:

- Flexibility is the ability of the system to adapt to the current level of production and consumption of energy, changes in outdoor temperature, taking into account general changes in the infrastructure system of the city, to respond adequately to internal and external influences.
- Intelligence is the ability of the system to respond to consumer demands (reduce or increase energy production).
- Integration: the system is integrated into the urban environment, both in terms of urban planning of the area and location of energy supply facilities, and in terms of the interaction of all life support systems of the city (power supply system, heating, water supply, sewerage, fuel supply, etc.).
- Network-centricity: the implementation of management based on a branched network of communication where each element of the system gets the opportunity to interact with any other element. The telecommunications network becomes the backbone of management.
- Efficiency: the equipment used meets all modern requirements for energy efficiency. Maximum efficiency of the system is provided by the optimal combination of technologies, including the maximum utilization of local energy resources.
- Competitiveness: technologies are cost-efficient and energy resources are available to the public. Consumers have the ability to manage their energy consumption to reduce the amount they pay for it.
- Reliability: the system meets the growing demand for energy, including the use of renewable resources and local fuels.

Directions of IIES research and functional problems. The process of the transition to the IIES is a rather complex multifaceted problem that includes technological, organizational, and other transformations of systems, as well as their methodological revamping. At the same time, while much has been prepared in terms of engineering, the methodological de-

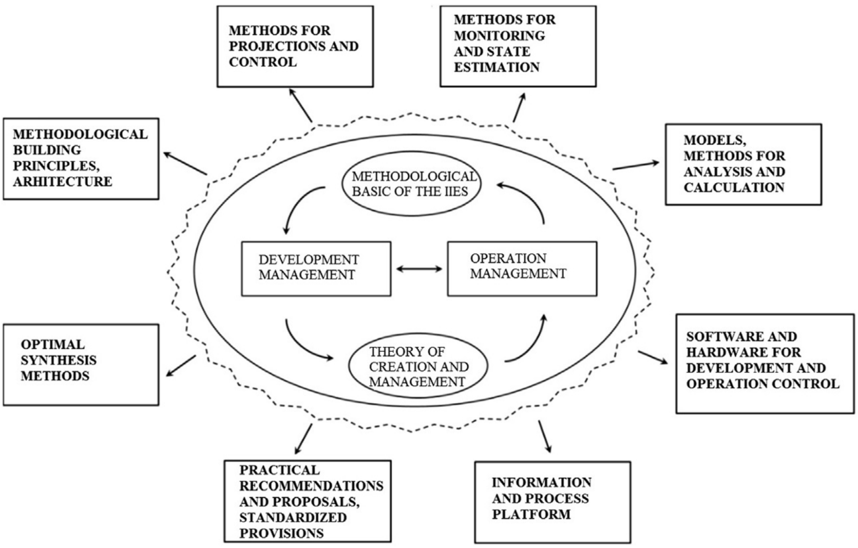


FIGURE 5.22 Methodological basis for the creation and management of intelligent integrated energy systems.

velopments are currently only at the level of problem statements. Their main directions are shown in Fig. 5.22.

The presented conceptual considerations with respect to the IIES allow one to approach the problem from different standpoints and to formulate the research tasks in a more systematic way.

In its general form, the set of problems requiring scientific and practical studies can be represented as having the following composition:

- Development of technological principles for the construction of IIES in combination with intelligent tools and their control systems.
- Forming the engineering solutions for process flow diagrams of energy sources and transport systems of energy supply systems.
- Development of methodological and technological foundations for the creation of intelligent control systems for energy supply of cities and industrial centers.
- Development of methods for monitoring the state of equipment and its modes of operation in energy supply systems.
- Development of models and methods for the analysis and calculation of electricity, heat, cold, and gas supply systems.
- Development of new generation methods and software packages for the calculation and optimization of IIESs and their elements.
- Development of universal information and computing technologies for computer modeling, calculation, and optimization of the IIES.

- Drafting practical recommendations and proposals for the creation of integrated intelligent systems of electricity, heat, and cold supply to consumers.

This is just a short, aggregated list of problems that arise in the process of integration and intellectualization of energy supply systems. They can be further differentiated according to the different levels of the systems in question.

Level of systems. Many new challenges arise at the level of systems. For certain types of systems, there are methodological and computational tools in terms of calculation and optimization of solutions for the expansion and operation of the IIES, which allows one to obtain separate solutions and then integrate them within a single IIES. However, firstly, they are focused on super-systems and, to some extent, on mini-systems, secondly, they require the involvement of artificial intelligence apparatus, which provides training, forming, and implementation of control actions, thirdly, they should take into account the multi-directional movement of the energy carrier due to the involvement of distributed energy generation in the energy supply. The level of micro-systems appears to be a new object for research in practical terms.

The use of intelligent technologies and tools can fundamentally alter the properties of energy systems and initiate new problems that need to be solved.

Level of scale. The problems associated with the physical interconnections between energy systems of different levels have been sufficiently well studied. They are characterized by ordinary conditions and situations and correspond to the traditional paradigm of building energy systems. The use of intelligent technologies and devices at all levels of energy systems and a fundamental change in their properties will call for the development of new methodological support, additional research on the adjustment of interface requirements, and the creation of appropriate software tools and hardware for computing, control, and measurement systems.

Modeling of multilevel energy systems of different scales in the context of advanced computer tools can be carried out in their original form, but more effective is the use of aggregated models of adjacent levels when considering the model of the investigated level. This implements a hierarchical approach and corresponds to the physical understanding of multilevel systems (for more detail see also the section "Special aspects of modeling of IIESs").

Level of functions. In the study of the technological functions of the IIES, the problems of communication and management are of fundamental importance. They implement intelligent information and computer technologies, fast and accurate means of measuring, processing, transferring, and presenting information, intelligent technologies and control methods. Information support of the corresponding problems is achieved by reasonable placement of measuring devices with the necessary redundancy. It is important to be able to place them correctly in order to be able to estimate the state of the system and monitor its modes of operation.

Control efficiency is achieved not only by intelligent information technologies and computer models. Equally important are the modern high-performance physical devices where intelligent information technologies and models are implemented. In general, these two aspects of control systems are inseparable and must be considered together. Development of methodology and methods for such integrated control of operation modes of jointly operating energy systems is the most important task of research as part of the problem in question.

In terms of decision-making, problems arise as to how to adapt existing and develop new models and methods for the IIES as they acquire new properties while taking into account all the features related to the uncertainty of information, multi-criteria nature, and mismatch of interests of the entities of relations. Building a new methodology for making decisions on justifying the development and management of the operation of the IIES, establishing an appropriate system of models and methods - these are the priorities of further research.

When solving the problems listed above, there are problems of modeling of IIESSs as new objects of research with the corresponding new properties and features. They manifest themselves primarily with respect to the following issues:

- Alignment of the overall goal with multiple targets by systems.
- The distributed cross-system nature and multiplicity of decision centers.
- Development and implementation of an optimal strategy in general and by individual systems.
- Resolution of cross-system conflicts.
- Aligning the interests of suppliers and consumers.
- Coordination of multiple decision centers.
- The coupling of hierarchical levels in each system and horizontal links between individual systems.

Along with these considerations, the research should take into account all the features associated with the uncertainty of information, multiple criteria, and the mismatch of interests of the entities of relations. Building a new methodology for making decisions on justifying the development and management of the operation of the IIES, establishing an appropriate system of models and methods are important tasks of further research.

Statement of the problem of optimizing the energy supply to consumers of the IIES. The problem is to find the optimal organization of energy supply to consumers at all hierarchical levels of the systems. As outlined above, there are three levels of hierarchy in the IIES:

1. the level of super-systems of energy supply;
2. the level of mini-systems of energy supply;
3. the level of micro-systems of energy supply located at the consumer's end;

It is required to minimize the cost of energy supply in the IIES built on a hierarchical principle:

$$\left[Z^1 + \sum_{i=1}^{N_2} \left(Z_i^2 + \sum_{j=1}^{N_3} Z_{j,i}^3\right)\right] \to \min, \tag{5.85}$$

where Z^1 - energy supply costs of the first-level system; Z_i^2 - energy supply costs of the ith second-level system; $Z_{j,i}^3$ - energy supply costs of the jth third-level system connected to the ith second-level system; N_2 - the number of systems at the second level; N_3 - the number of systems at the third level.

The costs of energy supply at any level of the IES hierarchy are determined as follows:

$$\begin{aligned} Z = \sum_{t=1}^{p} \Bigg[\sum_{m=1}^{N_G} \left(Z_G^t\left(e_m^t, S_m(t)\right) + Z_E^t\left(e_m^t\right)\right) + \\ + \sum_{k=1}^{N_S} \left(Z_S^t\left(l_k, e_k^t\right) + Z_N(l_k)\right) + \sum_{n=1}^{N_R} \left(Z_T^t\left(e_r^t, S_r(t)\right)\right) \Bigg], \end{aligned} \tag{5.86}$$

where $Z_G^t\left(e_m^t, S_m(t)\right)$ – costs of generating energy at the moment of time t; $Z_E^t\left(e_m^t\right)$ – costs of the generating unit at the moment of time t; $Z_S^t\left(l_k, e_k^t\right)$ – costs of transporting energy at the moment of time t; $Z_N(l_k)$ – costs of the network section at the moment of time t; $Z_T^t\left(e_r^t, S_r(t)\right)$ – costs of converting energy from one type to another at the moment of time t; e_m^t- volume of energy generation at the moment of time t; e_k^t – volume of energy flowing through the network section at the moment of time t; e_r^t – volume of energy received after conversion at the moment of time t; $S_m(t)$ – cost of generating energy; $S_r(t)$ – cost of energy conversion; l_k – length of the network section; N_G – the number of power generators; N_S – number of network sections; N_R – number of energy converters; p – time period considered.

Subject to the following conditions:

- energy balance in the IIES

$$B_t(E_t, \Delta E_t, G_t) = 0, \tag{5.87}$$

where B_t – a system of balance equations; E_t – energy flows in the system at the time t; ΔE_t – energy losses in the system at the time t; G_t

– nodal values of the volumes of energy supplied to the system, and energy withdrawn from the system, at the time t;

- material balance for gas, heat, cold, and water supply systems as part of the IIES

$$M_t(C_t,\ Q_t) = 0, \tag{5.88}$$

where M_t – a system of balance equations; C_t – flow rates of the transported medium in the systems of gas, heat, cold, water supply at the moment of time t; Q_t – nodal values of inflows and outflows of the transported medium at the moment of time t.

- the law of variation of the variables describing the operation of the system (constituent relation)

$$f\,(E_t,\ \Delta F_t) = 0, \tag{5.89}$$

where ΔF_t are the values of changes in the variables describing the operation of the system at the time t.

Subject to the following constraints:

- constraint on energy generation by the generator

$$e_m^{\min} \le e_m^t \le e_m^{max}, \tag{5.90}$$

- constraint on the capacity of the network section

$$e_k^{\min} \le e_k^t \le e_k^{max}, \tag{5.91}$$

- constraint on the conversion of energy from one type to another

$$e_r^{\min} \le e_r^t \le e_r^{max}, \tag{5.92}$$

- constraint on the joint generation of electricity and heat at CHPPs

$$\nu^{\min} \le \frac{e_{m,e}^t}{e_{m,h}^t} \le \nu^{\max}, \tag{5.93}$$

where $e_{m,e}^t$ is the volume of electricity generation at the CHPP at the time t; $e_{m,h}^t$ is the volume of heat generation at the CHPP at the time t.

The solution to this problem requires the development of new methods and the development of existing ones. For this purpose, one uses available approaches for calculating the load flow as well as mixed-integer linear and nonlinear programming procedures. Their implementations are illustrated below.

Special aspects of modeling the IIES. There are two fundamentally different approaches to modeling multilevel energy systems represented by a set of different scale layers. The first one consists in joint modeling of energy systems of different scale layers (super, mini-, micro-systems) in the original form. This approach seems productive, but can be difficult to implement due to the intractability of the model formed in this way, the difficulties faced when using it because of the different scales of parameters, etc.

Another approach may prove more acceptable, that is the one using the aggregation of models of adjacent levels while considering the model of the level in question. This means that when considering the super-system, the electricity supply systems at the level of mini- and micro-systems are taken into account in an aggregated form and when considering the mini-system, the super-system, on the one hand, and the micro-system, let it be the level of a residential building for the sake of argument, on the other hand, are modeled in an aggregated form. This implements a hierarchical approach to modeling the original super-, mini-, micro-systems, which is most consistent with the representation of multilevel systems.

The application of hierarchical modeling approaches in the study of IIES allows one to perform a study of systems of different types and scales that a part of the IIES. They consist of different types of energy supply systems, which are subsystems in such systems. Each of the subsystems contains its specific set of components. These components can be grouped according to the following energy functions performed: generation, transport, storage, distribution, and consumption. In turn, each component has its own set of equipment in accordance with the energy functions performed and its belonging to the type of energy supply system. Modeling is performed for all subsystems, their set of components, and the mix of equipment, which corresponds to the modeling of individual energy systems. At the same time, there are certain idiosyncratic features of modeling in the joint consideration of different types of systems within the framework of the IIES. These features are related to engineering and technological solutions for integration, so it is necessary to perform modeling of individual subsystems and take into account the engineering and technological solutions for integration so as to ensure coordination of subsystems and achieve system-wide targets.

The use of hierarchical modeling also provides the possibility of a joint study of systems of different scales by aggregating information on individual systems of smaller scale and its presentation for the coordination of larger-scale systems, or conversely, its disaggregation for the coordination of large systems with smaller-scale systems.

Modeling of the IIES begins with the construction of its model, which is a set of data structures that describe the configuration of the system, the array of its equipment and its characteristics, the state of components and their properties. Energy supply systems of different types, which are part of the IIES, share structural and topological properties and physical laws of energy transport, which allows us to formulate the following general statements characteristic of the methodology of hierarchical modeling of the IIES:

- All energy supply systems can be represented by a graph, the vertices of which correspond to nodes (sources, connection nodes, consumers), and the edges are branches (pipelines, power transmission lines, etc.).
- Mathematical modeling of pipeline energy systems shares their conceptual and mathematical statements, and the methods, algorithms, and specialized software used to solve them can be universal.
- A computer model of the energy supply system of a certain type can be represented as the total of a graph describing the configuration of this system and a set of graphical and mathematical models describing the properties of its components.
- Hierarchical construction of the IIES model is provided by the formation of flow diagrams of individual components and subsystems nested at several levels of the hierarchy.

At the same time, different types of energy supply systems have their own individual characteristics, which must be taken into account when modeling them as part of the IIES. For example, unlike other large energy systems and large pipeline systems, the mode of operation of the heating system is characterized by two different parameters that are different in their physical meaning: the dynamic characteristics along the pressure transmission paths (flow rate change) and temperature values differ sharply from each other. Water flow rates in the network change in an almost inertia-free fashion. The process of passing a temperature wave through the heating network, which is determined by the speed of the heat transfer fluid, can last for hours.

Example of a digital model for short-term planning of IIES operating conditions. Let us consider an example of applying hierarchical modeling when solving the problem of short-term planning of the IIES that includes electricity and heating subsystems. Planning and management of each subsystem is performed both centrally and autonomously while taking into account tariffs for electricity and heat with day-ahead planning and adjustment of planned modes during operational control. The interaction between them is currently reduced to the exchange and processing of information in a digital format, carried out by automated systems of commercial metering of energy consumed, which is the basis for forming the models of virtual power plants that provide the joint operation of decentralized and centralized subsystems of energy supply to consumers.

When planning the daily profiles of electricity and heat consumption of the IIES, one considers storage facilities for electricity (batteries) and heat (electric water heaters), the electric loads of individual consumers (dryers, washing machines, etc.) that can be shifted in time, as well as power generation by additional sources of electricity and heat (photovoltaic panels, wind turbines, heat pumps), taking into account the daily profile of tariffs for electricity and heat from centralized systems.

The IIES model includes the following two levels of hierarchy:

1. the level of centralized electricity and heating systems;
2. the level of electricity and heat consumers.

Each hierarchical level is represented by its own energy supply flow diagram. The procedure for forming the optimal daily profiles of electricity and heat consumption is performed for each of the levels of the IIES model and contains the following steps:

- calculation of the initial load flow in the electric and heat networks for the given standardized or projected daily load profiles of individual consumers of electricity and heat, taking into account technological limitations;
- optimization of daily profiles of electricity and heat consumption for each individual consumer;
- evaluation of the admissibility of the obtained solution at the level of centralized systems.

To illustrate how the algorithm work, let us consider a numerical example of optimization of the daily profiles of electricity and heat consumption of a single utility consumer with respect to the criterion of minimum cost of energy purchased for a given daily profile of electricity and heat tariffs. The test flow diagram of the IIES is shown in Fig. 5.23. The 6 kV electrical network and the heat network contain six nodes, one of which is a power source, and four nodes have electricity and heat consumers connected to them. Consumers have renewable energy sources (photovoltaic panels), electric and thermal energy storage facilities, as well as shifting electric loads, the control time of which is determined by economic considerations. Each consumer is connected to the centralized electricity supply system. The consumer knows the daily price profile for electricity and heat. As an initial approximation, a characteristic profile of electricity and heat consumption is set for each consumer.

The optimal daily profiles of electricity and heat consumption for each consumer were calculated for the aggregated flow diagram of the IIES presented in Fig. 5.23. Fig. 5.24 and 5.25 show the results of the calculation of optimal daily heat and electricity load profiles for one node. Fig. 5.24 shows the daily profiles of initial and optimal daily electricity load profiles, electricity rates and the profiles of daily photovoltaic generation, optimal switching of the shiftable load, operation of energy storage device and electricity consumption by heat storage system. Fig. 5.25 shows daily profiles of initial and optimal load profiles, optimal profiles of heat storage operation and the profile of heat rates. Daily tariff profiles are of a sinusoidal nature, which is adopted to test the correctness and performance

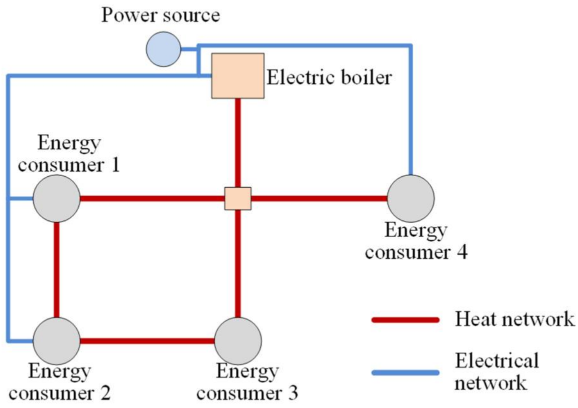


FIGURE 5.23 Aggregated flow diagram of the investigated intelligent integrated energy system.

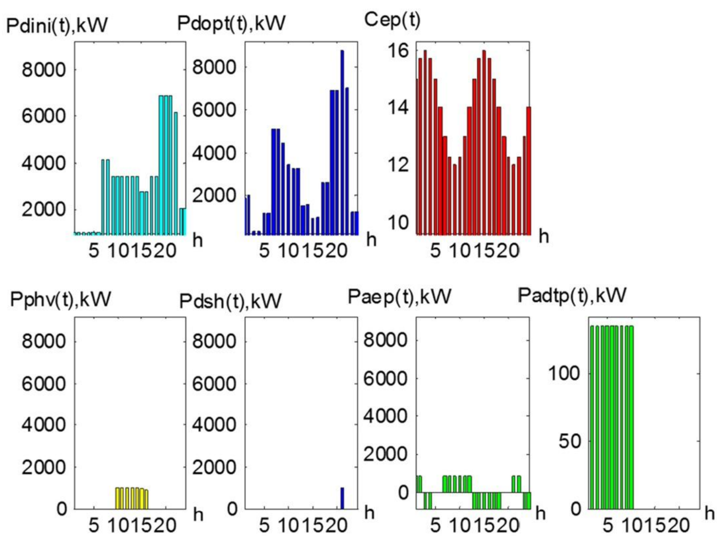


FIGURE 5.24 Daily active power load profiles. Pdini(t) – initial daily electricity load profile; Pdopt(t) – optimal daily electricity load profile; Cep(t) – daily electricity rate profile; Pphv(t) – daily PV-based power generation profile; Pdsh(t) – daily shiftable load profile; Paep(t) – daily electricity storage profile; Padtp(t) – Daily profile of electricity consumption by thermal energy storage; h – hour.

of the algorithm for obtaining the optimal daily profiles of electricity and heat consumption.

The optimal daily profiles are obtained by summing up the original profiles of electricity and heat loads, photovoltaic generation, and the optimal profiles of electricity and heat storage facilities, as well as the shifting load.

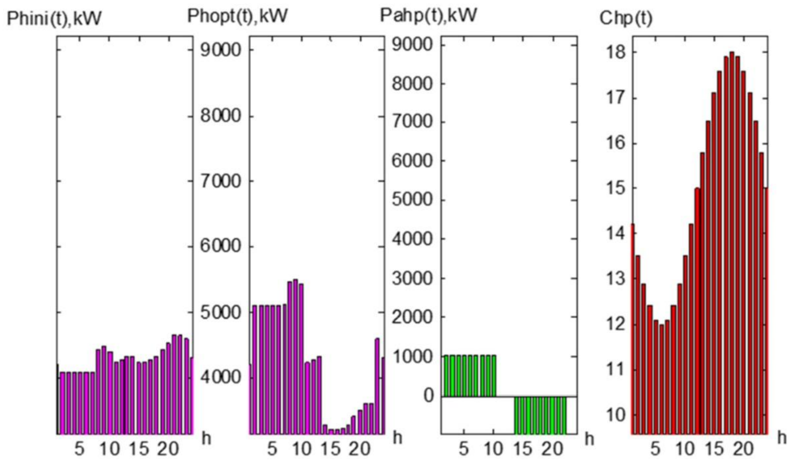


FIGURE 5.25 Daily heat load profiles. Phini(t) – initial daily heat profile; Phopt(t) – optimal daily heat profile; Pahp(t) – daily heat storage profile; Chp(t) – daily heat rate profile; h – hour.

The daily electricity and heat load profiles obtained on the basis of the calculations differ significantly from the initial ones, ensuring a reduction in the cost of energy purchased by consumers.

Thus, the rising trend of active consumer behavior, the growing use of distributed power generation, the deep penetration of Internet technologies, the intellectualization of control processes pose new challenges, which cannot be solved on the basis of conventional structural and technological designs and control models. The need to move to new structures in the form of integrated intelligent energy supply systems is becoming increasingly evident.

New properties of the IIES related to the multi-dimensional structure, multi-purpose aspects, activity of consumers, mismatch of their interests, network principles of construction of such a meta-system necessitate the development of appropriate methodology of justification of their creation and management that would combine appropriate models and methods.

Significant spatial distribution, the multiple facets of research, and multi-functionality provide the IIES with the properties of multilevel systems. The most appropriate approach to studying them is the methodological approach based on hierarchical modeling.

Acknowledgments

The research was carried out under State Assignment Project (no. FWEU-2021-0002) of the Fundamental Research Program of Russian Federation 2021-2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] E. Mednikova, V. Stennikov, I. Postnikov, A. Penkovskii, Development features of heat power industry legislation in Russia, Environmental and Climate Technologies 23 (2) (2019) 22–35.

[2] V. Stennikov, S. Senderov, B. Saneev, N. Novitsky, Energy systems as objects of hierarchical modeling, Energy Systems Research 2 (4) (2019) 6–16.

[3] A. Merenkov, V. Khasilev, Theory of Hydraulic Circuits, Nauka, Moscow, 1985 (in Russian).

[4] A. Alekseev, N. Novitsky, V. Tokarev, Z. Shalaginova, Multi-level modeling and optimization of large-scale pipeline systems operation, in: Proceedings of the 2nd International Conference 'Shaping Research in Integrated Gas-, Heat- and Electric-Energy Infrastructures', 2016, pp. 5–6.

[5] V. Stennikov, E. Sennova, T. Oshchepkova, Methods for complex optimization of the development of heating systems, Izvestija RAN. Jenergetika 3 (2006) 44–54 (in Russian).

[6] V. Stennikov, E. Barakhtenko, D. Sokolov, T. Oshchepkova, Problems of modeling and optimization of heat supply systems: new methods and software for optimization of heat supply system parameters, in: P. Vasant, N. Voropai (Eds.), Sustaining Power Resources Through Energy Optimization and Engineering, Hershey PA, 2016, pp. 76–101.

[7] O. Nekrasova, V. Khasilev, Optimal tree of the pipeline system, Ekonomiko-Matematicheskie Metody 4 (3) (1970) 427–432 (in Russian).

[8] V. Stennikov, T. Oshchepkova, N. Stennikov, Problems of modeling and optimization of heat supply systems: methods to comprehensively solve the problem of heat supply system expansion and reconstruction, in: P. Vasant, N. Voropai (Eds.), Sustaining Power Resources Through Energy Optimization and Engineering, Hershey PA, 2016, pp. 26–53.

[9] V. Stennikov, E. Barakhtenko, D. Sokolov, A methodological approach to the determination of optimal parameters of district heating systems with several heat sources, Energy 185 (2019) 350–360.

[10] S. Sumarokov, A method for solving a multi-extremum network problem, Ekonomiko-Matematicheskie Metody 12 (5) (1976) 1016–1018 (in Russian).

[11] D. Sokolov, V. Stennikov, T. Oshchepkova, E. Barakhtenko, The new generation of the software system used for the schematic-parametric optimization of multiple-circuit heat supply systems, Thermal Engineering 59 (4) (2012) 337–343.

[12] A. Alexeev, N. Novitsky, The information and computing complex 'ANGARA-VS' for end to end modeling of water supply systems when developing development schemes, scheduling modes, and dispatching management, MATEC Web of Conferences 212 (2018) 06001.

[13] E. Sennova, V. Sidler, Mathematical Modeling and Optimization of Expansion of Heating Systems, Nauka, Novosibirsk, 1987 (in Russian).

[14] V. Stennikov, I. Postnikov, Search the optimal ratio of system's component reliability parameters and the heat capacity of prosumers in the district heating system, in: E3S Web Conferences 'Mathematical Models and Methods of the Analysis and Optimal Synthesis of the Developing Pipeline and Hydraulic Systems', vol. 219, 2020, 02004.

[15] N. Novitsky, A. Alekseev, O. Grebneva, A. Lutsenko, V. Tokarev, Z. Shalaginova, Multi-level modeling and optimization of large-scale pipeline systems operation, Energy 184 (2019) 151–164.

[16] A. Alexeev, N. Novitsky, The information and computing complex 'ANGARA-VS' for end-to-end modeling of water supply systems when developing development schemes, scheduling modes, and dispatching management, MATEC Web of Conferences 212 (2018) 06001, https://doi.org/10.1051/matecconf/201821206001.

[17] A. Alekseev, N. Novitsky, V. Tokarev, Z. Shalaginova, Multi-level modeling and optimization of large-scale pipeline systems operation, in: 2nd International Conference 'Shaping Research in Integrated Gas-, Heat- and Electric-Energy Infrastructures', 2016, pp. 5–6.
[18] V. Stennikov, E. Barakhtenko, D. Sokolov, Use of multilevel modeling for determining optimal parameters of heat supply systems, Thermal Engineering 64 (7) (2017) 518–525.
[19] F.J. Nogales, F.J. Prieto, A.J. Conejo, A decomposition methodology applied to the multi-area optimal power flow problem, Annals of Operations Research 120 (2003) 99–116.
[20] M. Arnold, G. Andersson, Decomposed electricity and natural gas optimal power flow, in: 16th Power Systems Computation Conference (PSCC 2008 Glasgow), July 14–18, Curran, Red Hook, NY, 2008, pp. 654–660.
[21] M. Zhu, C. Wu, N. Rao, S. Iyengar, Adaptive visualization pipeline decomposition and mapping onto computer networks, in: Third International Conference on Image and Graphics (ICIG'04), Hong Kong, China, 18–20 December 2004, IEEE Xplore, 2005, pp. 402–405.
[22] M. Mans, T. Blacha, P. Remmen, D. Mueller, Automated model generation and simplification for district heating and cooling networks, in: A. Haumer (Ed.), Proceedings of 13th International Modelica Conference, March 4–6, 2019, Ostbayerische Technische Hochschule Regensburg, Germany, 2019, pp. 179–186.
[23] H.V. Larsen, H. Pálsson, B. Bøhm, H.F. Ravn, Aggregated dynamic simulation model of district heating networks, Energy Conversion and Management 43 (8) (2002) 995–1019.
[24] H. Larsen, B. Bøhm, M. Wigbels, A comparison of aggregated models for simulation and operational optimisation of district heating networks, Energy Conversion and Management 45 (2004) 1119–1139.
[25] L. Wang, Z.X. Jing, J.H. Zheng, Q.H. Wu, F. Wei, Decentralized optimization of coordinated electrical and thermal generations in hierarchical integrated energy systems considering competitive individuals, Energy 158 (2018) 607–622.
[26] M. Hu, Y.W. Wang, J.W. Xiao, X. Lin, Multi-energy management with hierarchical distributed multi-scale strategy for pelagic islanded microgrid clusters, Energy 185 (2019) 910–921.
[27] M. Xia, Y. Song, Q. Chen, Hierarchical control of thermostatically controlled loads oriented smart buildings, Applied Energy 254 (2019) 113493.
[28] V. Stennikov, E. Barakhtenko, D. Sokolov, A methodological approach to the determination of optimal parameters of district heating systems with several heat sources, Energy 185 (2019) 350–360.
[29] E. Todini, S. Pilati, A gradient algorithm for the analysis of pipe networks, in: B. Coulbeck, C.H. Orr (Eds.), Computer Applications in Water Supply, John Wiley & Sons, London, 1988, pp. 1–20.
[30] N. Novitsky, Calculation of the flow distribution in hydraulic circuits based on their linearization by nodal models of secants and chords, Thermal Engineering 60 (2013) 1051–1060.
[31] D. Sokolov, E. Barakhtenko, Development of a software platform for the design of district heating systems, in: Proceedings of International Conference 'Energy-21: Sustainable Development & Smart Management', in: E3S Web Conf., vol. 209, 2020, 02027.
[32] D.V. Sokolov, V.A. Stennikov, T.B. Oshepkova, E.A. Barakhtenko, The new generation of the software system used for the schematic–parametric optimization of multiple circuit heat supply systems, Thermal Engineering 59 (4) (2012) 337–343.
[33] N. Ilkevich, T. Dzyubina, Zh. Kalinina, Multilevel Modeling of Gas Supply Systems Development, Nauka, Novosibirsk, 2014 (in Russian).
[34] Statistical review of world energy 2020, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf, 2020. (Accessed 1 December 2022).
[35] A. Makarov, T. Mitrova, V. Kulagin, Global and Russian Energy Outlook 2019, ERI RAS – Moscow School of Management SKOLKOVO, Moscow, 2019 (in Russian).

[36] European Network of Transmission System Operators for Gas (ENTSOG), https://www.entsog.eu. (Accessed 1 December 2022).
[37] Official website of Gazprom JSC, https://www.gazprom.ru. (Accessed 1 December 2022).
[38] M. Sukharev, A. Karasevich, Process Design and Ensuring the Reliability of Gas and Oil Pipelines, State unitary enterprise 'Neft' i gaz', Publishing house Gubkin Russian State University of Oil and Gas, Moscow, 2000 (in Russian).
[39] N. Ilkevich, T. Dzyubina, Zh. Kalinina, Multi-level modeling of optimal development and pricing in the gas industry, Energy Systems Research 2 (4) (2019) 67–83.
[40] L.R. Ford, D.R. Fulkerson, Flows in Networks, Princeton University Press, New Jersey, 1962.
[41] A.F. Dyakov, V.A. Stennikov, S.M. Senderov, N.I. Voropai, et al., Reliability of Energy Systems: Problems, Models, and Methods for Solving Them, Nauka, Novosibirsk, 2014 (in Russian).
[42] Centre for Energy Economics Research and Policy, Statistical review of world energy 2020, 69th edition, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf, 2020. (Accessed 22 December 2021).
[43] I.G. Tarazanov, D.A. Gubanov, Russia's coal industry performance for January – December 2019, Ugol 3 (2020) 54–69, https://doi.org/10.18796/0041-5790-2020-3-54-69 (in Russian).
[44] L.A. Melentiev, Energy Systems Studies, Nauka, Moscow, 1983 (in Russian).
[45] A.D. Sokolov, L.N. Takaishvili, A study of factors influencing the development prospects of the coal industry in the eastern regions of Russia, Energy Systems Research 2 (3) (2019) 40–50, https://doi.org/10.25729/esr.2019.03.0005.
[46] R. Bogucki, J. Lasek, J.K. Milczek, M. Tadeusiak, Early warning system for seismic events in coal mines using machine learning, in: Proceedings of the 2016 Federated Conference on Computer Science and Information Systems, FedCSIS, Gdansk, Poland, 11–14 September, 2016, pp. 213–220.
[47] N. Zégre, A. Miller, A. Maxwell, S. Lamont, Multiscale analysis of hydrology in a mountaintop mine-impacted watershed, Journal of the American Water Resources Association 50 (5) (2014) 1257–1272.
[48] J.V. Bonta, C.R. Amerman, W.A. Dick, G.F. Hall, T.J. Harlukowicz, A.C. Razem, et al., Impact of surface coal mining on the three Ohio watersheds–physical conditions and ground-water hydrology, Journal of the American Water Resources Association 28 (1992) 577–596.
[49] S. Jiang, C. Yang, J. Guo, Z. Ding, ARIMA forecasting of China's coal consumption, price and investment by 2030, Energy Sources, Part B: Economics, Planning, and Policy 13 (3) (2018), https://doi.org/10.1080/15567249.2017.1423413.
[50] U.S. Energy Information Administration, Coal market module of the national energy modeling system: model documentation 2018, https://www.eia.gov/outlooks/aeo/nems/documentation/coal/pdf/m060(2018).pdf, 2018. (Accessed 18 December 2021).
[51] W. Suwala, Modelling adaptation of the coal industry to sustainability conditions, Energy 33 (7) (2008) 1015–1026, https://doi.org/10.1016/j.energy.2008.02.009.
[52] L. Plakitkina, World crisis (2020): plans and reality for implementation of the 'Program of Development of the Coal Industry for the Period up to 2035', in: E3S Web Conferences, International Conference 'Energy-21: Sustainable Development & Smart Management', Irkutsk, Russia, September 7–11, 2020, vol. 209, 2020, 05025, https://doi.org/10.1051/e3sconf/202020905025.
[53] A.D. Sokolov, L.N. Takaishvili, Modeling the development prospects of the coal industry of Russia and its regions, Energy Systems Research 2 (4) (2019) 59–66, https://doi.org/10.25729/esr.2019.02.0008.

[54] S. Mohr, M. Höök, C. Mudd, G. Evans, Projection of Australian coal production – comparisons of four models, in: Proceedings of the International Pittsburgh Coal Conference, Pittsburgh, USA, 2011, pp. 1–23.
[55] Enerdata, Energy forecasting and modelling, https://www.enerdata.net/brochure/energy-forecast-models-consulting-brochure-enerdata.pdf. (Accessed 22 December 2021).
[56] M.D. Budeba, J.W. Joubert, R.C.W. Webber-Youngman, A proposed approach for modelling competitiveness of new surface coal mines, Journal of the Southern African Institute of Mining and Metallurgy 115 (11) (2015) 1057–1064, https://doi.org/10.17159/2411-9717/2015/v115n11a10.
[57] E.R. Merriam, J.T. Petty, M.P. Strager, A.E. Maxwell, P.F. Ziemkiewicz, Scenario analysis predicts context-dependent stream response to landuse change in a heavily mined central Appalachian watershed, Forest Science 32 (4) (2013) 1246–1259.
[58] S.A.U. Rehman, Y. Cai, R. Fazal, G. Das Walasai, N.H. Mirjat, An integrated modeling approach for forecasting long-term energy demand in Pakistan, Energies 10 (11) (2017) 1868, https://doi.org/10.3390/en10111868.
[59] M.P. Strager, J.M. Strager, J.S. Evans, J.K. Dunscomb, B.J. Kreps, A.E. Maxwell, Combining a spatial model and demand forecasts to map future surface coal mining in Appalachia, PLoS ONE 10 (6) (2015) e0128813, https://doi.org/10.1371/journal.pone.0128813.
[60] Y. Li, Z. Li, Forecasting of coal demand in China based on support vector machine optimized by the improved gravitational search algorithm, Energies 12 (12) (2019) 2249, https://doi.org/10.3390/en12122249.
[61] M.R. Betz, M.D. Partridge, M. Farren, L. Lobao, Coal mining, economic development, and the natural resources curse, Energy Economics 50 (2015) 105–116, https://doi.org/10.1016/j.eneco.2015.04.005.
[62] W. Suwala, Modelling adaptation of the coal industry to sustainability conditions, Energy 33 (7) (2008) 1015–1026.
[63] A.A. Makarov, L.A. Melentiev, Methods of Research and Optimization of the Energy Economy, Nauka, Moscow, 1973 (in Russian).
[64] N. Pavlov, N. Petrov, Coal industry of the Republic of Sakha (Yakutia): tools and forecast, in: E3S Web of Conferences, International Conference 'Regional Energy Policy of Asian Russia', Irkutsk, Russia, June 4–7, 2018, vol. 77, 2019, 03002, https://doi.org/10.1051/e3sconf/20197703002.
[65] L. Takaishvili, Simulation models to study the development of the coal industry as an energy sector component, in: E3S Web of Conferences, International Conference 'Regional Energy Policy of Asian Russia', Irkutsk, Russia, June 4–7, 2018, vol. 77, 2019, 02004, https://doi.org/10.1051/e3sconf/20197702004.
[66] N. Pavlov, L. Takaishvili, V. Zakharov, Prospects for the use of coal of the Republic of Sakha (Yakutia) for energy needs, in: E3S Web Conferences, International Conference 'Energy-21: Sustainable Development & Smart Management', Irkutsk, Russia, September 7–11, 2020, vol. 209, 2020, 05016, https://doi.org/10.1051/e3sconf/202020905016, 2020.
[67] N. Pavlov, L. Takaishvili, Prospects for the development of coal exports of Republic of Sakha (Yakutia), in: Proceedings of the International Multi-Conference on Industrial Engineering and Modern Technologies (FarEastCon), Vladivostok, Russia, 01–04 October, 2019, 2019, pp. 1–4, https://doi.org/10.1109/FarEastCon.2019.8934046.
[68] F.D. Sokolov, L.N. Takaishvili, Coal resources of the eastern regions of Russia for power plants of the Asian super ring, in: E3S Web of Conferences, 10th International Conference on Asian Energy Cooperation, AEC 2017, Irkutsk, Russia, August 29–31, 2017, vol. 27, 2017, 02004, https://doi.org/10.1051/e3sconf/20182702004, 2018.
[69] A.D. Sokolov, L.N. Takaishvili, Coal industry of East Siberia - prospects for development, in: E3S Web of Conferences, International Conference 'Regional Energy Policy of Asian Russia', Irkutsk, Russia, June 4–7, 2018, vol. 77, 2019, 03001, https://doi.org/10.1051/e3sconf/20197703001.

[70] N.I. Voropai, et al. (Eds.), Energy of the 21st Century: Preconditions for Development, Technologies, and Projections, Nauka, Novosibirsk, 2004 (in Russian).

[71] N.I. Voropai, V.A. Stennikov, S.M. Senderov, E.A. Barakhtenko, O.N. Voitov, A. Ustinov, Modeling of integrated energy supply systems: main principles, model, and applications, Journal of Energy Engineering 143 (5) (2017), https://doi.org/10.1061/(ASCE)EY.1943-7897.0000443.

[72] A.V. Fedyaev, B.V. Sennova, O.N. Fedyaeva, A.M. Karasevich, Effectiveness of development of small CHPPs based on gas turbine and diesel units in gasification of regions, Teploenergetika 1 (2000) 24–26 (in Russian).

[73] N.I. Voropai, V.A. Stennikov, E.A. Barakhtenko, Methodological principles of constructing the integrated energy supply systems and their technological architecture, in: Journal of Physics: Conference Series, 14th International Scientific and Technical Conference 'Problems of Energy Systems and Thermal Power Complexes', 30 October – 1 November, 2018, Saratov, Russia, vol. 1111 (1), 2018, 012001, https://doi.org/10.1088/1742-6596/1111/1/012001.

[74] V.A. Stennikov, N.I. Voropai, E.A. Barakhtenko, A.D. Sokolov, O.N. Voitov, B. Zhou, Application of digital technologies for expansion planning of integrated energy systems, in: E3S Web Conferences, International Conference 'Energy-21: Sustainable Development & Smart Management', Irkutsk, Russia, September 7–11, 2020, vol. 209, 2020, 02003, https://doi.org/10.1051/e3sconf/202020902003.

[75] N. Hatziargyriou, H.I. Asano, R. Marnay, Microgrids, IEEE Power & Energy Magazine 5 (4) (2007) 78–94.

[76] R. Marnay, Worldwide microgrid development: the evolving power supply paradigm, in: Proceedings of the Applied Power Electronics Conference, Orlando, FL, USA, February 21–24, 2012, 8 p.

[77] N.I. Voropai, V.A. Stennikov, E.A. Barakhtenko, Integrated energy systems: challenges, trends, philosophy, Studies on Russian Economic Development 28 (5) (2017) 492–499, https://doi.org/10.1134/S107570071705015X.

This page intentionally left blank

CHAPTER

6

Hierarchical modeling of analysis and control of operating conditions of pipeline energy systems

V.A. Stennikov, N.N. Novitsky, A.V. Alexeev, O.A. Grebneva, A.V. Lutsenko, A.V. Penkovsky, I.V. Postnikov, V.V. Tokarev, Z.I. Shalaginova, E.E. Mednikova, and O.V. Khamisov

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Chapter outline

The first section of the chapter is an introduction, which reveals the relevance, main provisions, methodological framework and principles of computer implementation of the hierarchical approach in modeling energy pipeline systems. The second section focuses on the technology for hierarchical modeling of steady-state hydraulic and temperature conditions of large heat supply systems, which drastically reduces the calculation time. The third section presents new statements and methods for solving the optimization problems for hydraulic conditions as mixed discrete-continuous optimization problems with several criteria. The next section addresses the methods designed to model and analyze the ways of organizing a competitive heat market in large heat supply systems with several sources. The last sections describe a new approach to the analysis of the reliability of heat supply systems, based on the theory of Markov processes, given the hierarchical representation of the object of study. This chapter

Hierarchical Modeling of Energy Systems
https://doi.org/10.1016/B978-0-44-313917-8.00015-8

also presents the statements of reliability analysis problems, methods for solving them, and examples of practical application.

Abbreviations

AF – availability factor
BC – boundary condition
CHPP – combined heat and power plants
DHN – distribution heat networks
DHS – district heating system
FSS – fuel supply system
HC – heating complex
HN – heat networks
HS – heat sources
ICE – information-and-computing environment
IE – industrial enterprise
MHN – main heat networks
PFFO – probability of failure-free operation
PLS – pipeline system
PS – pumping stations
RI – reliability index
UHO – unified heating organization

6.1 Methodological foundations of hierarchical modeling and optimization of operating conditions of large pipeline systems

The key trends in the innovative transformation of pipeline systems. Pipeline systems (PLSs) supplying heat, water, oil, gas, etc. are becoming increasingly important in the energy industry, industrial sector, public utilities sector, and other areas of operation and economic development and life of the population in most developed countries. They are engineering structures unique in scale and complexity, characterized by large size, structural heterogeneity, equivalent flow diagrams with multiple loops, spatial separation, hierarchy, variable structure, parameters, and conditions of operation, the presence of many other properties. All of the above implies the need to consider them as large and complex physical and engineering systems.

Recently, the processes of technological transformation, renovation, and modernization of PLSs have become more active through the introduction of new equipment, control, monitoring, and measurement tools, computational tools, methods of mathematical modeling, computer systems for the collection and processing of measurements and decision-making related to control. The main goal of these transformations is increasingly associated with the intellectualization of the PLSs. It seems that the formation of intelligent PLSs, as well as their integration with related systems (e.g., electric power systems), is a natural process, an objective consequence of the accumulation of a critical mass of achievements of science, technology, and socio-economic development of society, which should be considered as a strategic direction of their innovative transformation.

The main purpose of creating intelligent PLSs is to obtain a fundamentally new platform that ensures the harmonization of requirements and capabilities of all parties involved in the processes of receiving, transporting, and consuming the working medium (water, gas, heat, etc.). Moreover, the consumer is given the role of an active participant influencing the volume of consumption, quality, and prices on an equal footing.

In summary, the main features of PLS intelligence are associated with the presence of the following [1]:

1. a unified information space as the main system-forming factor responsible for the observability of the processes of production, distribution, and consumption for all participants in these processes;
2. a high level of controllability of the system as the main way to harmonize the requirements of consumers and producers;
3. a system of dynamic pricing that provides incentives for consumers to change their habitual consumption profiles.

The implementation of these tasks involves addressing a large set of regulatory, engineering, technological, economic, informational, and other issues. Among other things, it is necessary to reconsider the current practice of design, operation, and supervisory control of the PLSs.

It seems that the intellectualization of the PLSs can be associated with a full-scale transition to the concept of compromise-driven adaptive control in the space of states with feedback. The concept of compromise-driven control means the need to dynamically match supply and demand between suppliers and consumers, as well as with linked systems, through the effective use of technically available capacity and a flexible pricing (tariff) policy. The space of states is understood as the space of parameters of operating conditions, the relationship between which satisfies the physical laws of load flow, which implies the involvement of appropriate models. Adaptive control with feedback means the ability to adapt the models involved (by means of their identification) to changes in the internal state of the PLS and external impacts based on observation and measurement of the parameters of operating conditions and manifestations of the external environment.

The intellectualization of PLSs of specific types will create the necessary prerequisites for overcoming their departmental fragmentation. The expediency of integration of systems of heating and supply of water, gas, and electricity to settlements and territories is due to the interconnection of their operating conditions, increasing degrees of freedom of consumers in choosing the type of resource, the volume, and time of its consumption, the needs of producers to expand markets, and many other factors.

The transition to the new concept of intelligent control is associated with a sharp increase in the complexity of emerging problems of modeling, identification, optimization, and control, especially for large PLSs, and even more so for integrated ones. In mathematical terms, these difficulties are due to the high dimensionality of PLSs (counting many hundreds of thousands of components), the nonlinearity of the main physical-and-engineering and engineering-and-economic relations, discreteness of some variables, multi-criteria nature of arising optimization problems, information uncertainty, and many other factors.

The hierarchical approach to mathematical and computer modeling of PLSs developed at the MESI can be used as a basis for overcoming the above difficulties. This section and the two that follow it set forth the following:

1. the main points of this approach;
2. the main characteristics of the information and computational technologies developed by the team of the authors for its application;
3. experience in solving problems of hierarchical modeling of hydraulic and temperature operating conditions as applied to large district heating systems;
4. results of the development of a new methodology and methods of hierarchical optimization of load flow.

The main attention is paid to the problems of analysis and planning of PLSs operating conditions on the basis of steady-state models. Such models have wide application at different temporal levels of analysis and decision-making:

- in design: to analyze the throughput capacity of the PLSs for prospective loads, to check the possibility of PLSs operation in non-design operating conditions, to analyze and justify the reliability of design options;
- in operation: to analyze the admissibility of existing operating conditions, identify the causes of existing violations, develop options to optimize the process flow diagrams of PLSs operation, determine the rational locations and effectiveness of the introduction of new equipment, the possibility of connecting new consumers, the consequences of accidents, etc.;
- in supervisory control: to analyze and justify control decisions under normal, restorative, and post-emergency operating conditions of the PLSs.

The main tenets of the hierarchical approach to the mathematical and computer modeling of PLSs. The complexity of PLSs and the processes occurring in them, as well as the multiple facets of their possible study, cause the traditional fragmentation of information, methodological, modeling, and algorithmic support and, accordingly, the processes of decision-making on the management of expansion and operation of PLSs. The approach developed at the MESI, that of multi-level modeling of PLSs, has the potential to overcome the problems of such fragmentation that manifest themselves as inconsistency of input information and methodological apparatus, high labor-intensity of quantitative planning and coordination of decisions made at different temporal, organizational and territorial levels.

Multi-level modeling can be viewed as a comprehensive approach that is a superposition of three basic approaches:

1. hierarchical modeling of PLSs as a means of overcoming the problems of high dimensionality of models by their decomposition and aggregation (reducing to equivalents) according to the territorial levels;
2. multi-dimensional modeling, which involves solving different problems that require different degrees of detail of the models obtained by aggregation and disaggregation;
3. end-to-end modeling, which presupposes the unity of information and methodological basis in solving the conceptual problems of controlling the expansion and operation of PLSs at different time levels.

Thus, the technology of hierarchical modeling of PLSs provides opportunities for the following:

1. reducing the dimensionality of computational problems;
2. the visibility of the results of calculations;
3. matching the results of solving problems that require varying degrees of model detail;
4. overcoming the fragmentation of information and mathematical models in solving the problems of PLS control at different departmental, territorial, organizational and temporal levels;
5. the potential applicability of parallel computing technologies, which, in turn, allows calculations of high-dimensional PLSs in less time.

It should be noted that various methods of simplification and reduction of dimensionality of equivalent flow diagrams are used quite often in modeling of PLSs Most of the publications on this topic are of abstract theoretical nature and disregard specific objects of application [2,3, etc.]. The rest of the studies is devoted to specific problems where simplification methods are considered in passing and that are oriented toward special properties of: 1) systems [4–6, etc.]; 2) tasks (design and reconstruction [4,7, etc.], operational control [5,8, etc.]); 3) models employed (stationary [4,5,7,8], dynamic [6,9–12], etc.). The authors are not aware of any works having as their main subject the hierarchical modeling of PLSs as a comprehensive approach.

Theoretical background. The theory of hydraulic circuits, an original scientific contribution originated and developed at the MESI is used as a scientific and methodological base for hierarchical mathematical modeling of PLSs [12–17].

The subject of the theory is the methods of mathematical modeling, calculation, and optimization, which are of general importance for PLSs of various types and purposes (supply of heat, water, gas, oil, etc.). The object of the theory is the hydraulic circuit as an array of devices and pipelines connecting them, closed or open channels that transport compressible and incompressible fluids. The expediency of having a unified theory for PLSs of various types is due to the commonality of the following: 1) their structural and topological properties; 2) physical laws of liquid (gas) flow in individual components; 3) conservation laws of networks; 4) conceptual and mathematical statements of calculation problems.

The set of such problems can be grouped into three main classes, which are of general importance for PLSs of various types and purposes: analysis, synthesis, and control. These problems arise at almost all stages of the life cycle of these facilities (design, operation, and supervisory control).

This level of consideration of the problems of modeling, calculation, and optimization of PLSs is potentially capable of the following: 1) avoiding unproductive duplication of development of the problems that are similar in their statements: 2) concentrating efforts on nodal problems and issues; and 3) obtaining a broad output for applications.

Information and computing technology. The basis of the computer implementation of the hierarchical approach for modeling of PLSs is the information-and-computing environment (ICE) "ANGARA" developed at the MESI [18].

This R&D product is designed to automate the processes of configuration, maintenance, and application of the information-and-computing environment to different types of PLSs, classes of problems to be solved (analysis, synthesis, control) and areas of possible application (design, operation, supervisory control, research, and training). Acting as a single user interface (see Fig. 6.1), the ICE provides the following functions:

1. informational: creating, editing, and displaying of information models of PLSs, including electronic maps and location plans, graphic images of network flow diagrams and network facilities, digital and text information on the parameters of PLS components;
2. computational: the ability to connect and execute computational tasks in the dialog mode, supporting their interconnection with their types of flow diagrams (network problems) or types of components (local problems), as well as in the problem hierarchy;
3. analytical: the ability to graphically interpret and visualize the original and equivalent structural and parametric information by highlighting (by color and size of components) directly in the flow diagrams, as well as in the form of charts and graphs.

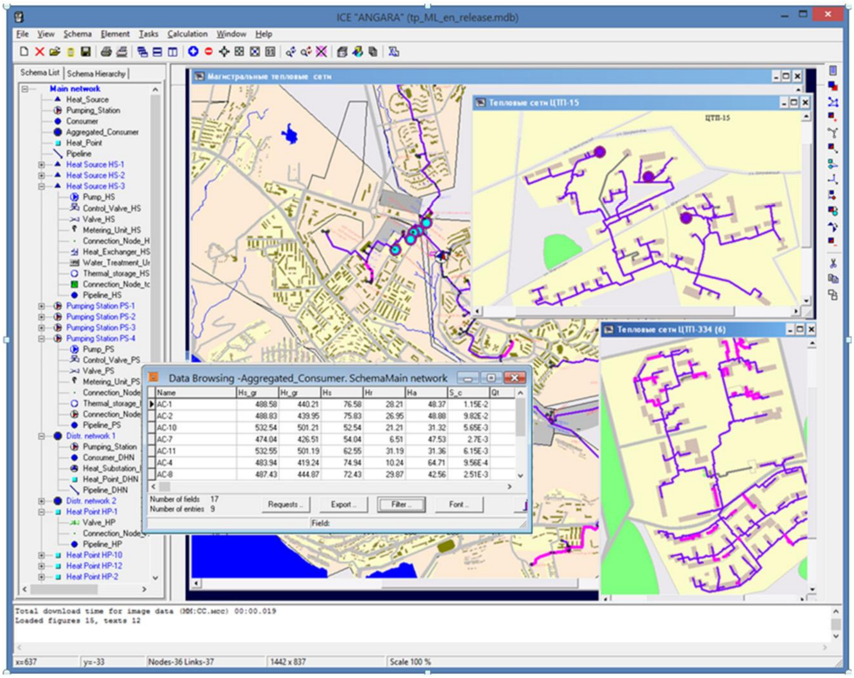


FIGURE 6.1 User interface of the ICE “Angara”.

Among other things, these functions are supported simultaneously for different types of PLSs united by a single location plan.

Support for hierarchical models of PLSs is implemented using relational database technologies, which allow storing not only information about flow diagrams and PLS parameters but also about the relationship between equivalent flow diagrams, solved problems, and data.

Hierarchical representation of PLS information models is provided on the basis of the following basic principles:

1. the modeled PLS can consist of any number of equivalent flow diagrams of different types (flow diagrams of pipeline networks, pumping stations, sources, etc.);
2. a flow diagram of a certain type is assembled from its own array of component types;
3. each component of a particular type of equivalent flow diagram can be represented by its own lower-level equivalent flow diagram;
4. the following relational links are established: each element with its data; elements of the flow diagram with each other; different flow diagrams with each other; each flow diagram with its plan (map); each flow diagram with its set of calculation problems. Fig. 6.2 illustrates a typical

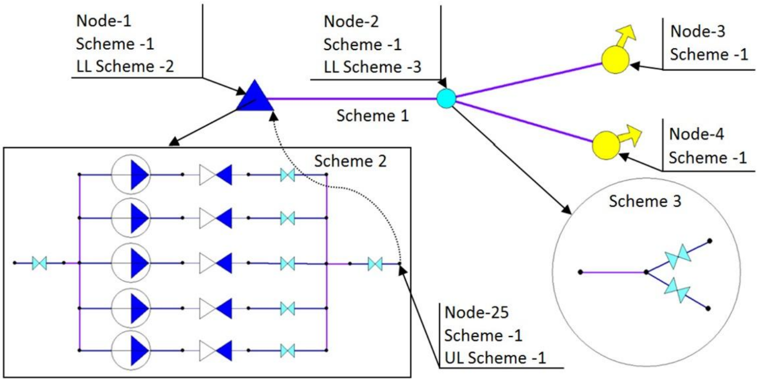


FIGURE 6.2 Illustration of relations in the hierarchy of equivalent flow diagrams LL – lower level, UL – upper level.

way of encoding relational links between flow diagrams of different levels.

The ICE "ANGARA" implements three ways to support relational links of hierarchical information models of PLSs:

1. hierarchical: each component can be represented by its own equivalent flow diagram of the lower level;
2. parallel: a new flow diagram is formed from the individual lower-level flow diagrams, which contains relational links to the original flow diagrams of different levels;
3. nested: components of the flow diagram of the lower level have relational links to the boundary components of its generalizing component at the upper level.

Each method influences the graphical representation of the PLS model. In the first case, flow diagrams of different levels are displayed independently. In the second case, it is possible to display the same flow diagram with varying degrees of detail. In the third case, the required degree of detail can be obtained promptly by changing the scale of the display.

Support for a flexible and extensible computing environment for single- and multi-level calculations is provided by:

1. independence of the implementation of calculation modules from the ICE, while preserving the dependence on the principles of data organization only;
2. interaction of the ICE and calculating modules with respect to control while the exchange of data and results of calculations is carried out through a common database;
3. linking each problem to its own type of equivalent flow diagram;

4. linking any problem to a parent problem that allows it to be executed.

The array of information about the composition of problems and their relational links affects the order in which the problems are displayed in the menu (including the possibility of the hierarchical grouping of problems related with respect to their meaning) and the availability of problem execution in the current computational situation. In addition to the "network" problems designed to calculate the current equivalent flow diagram, it is possible to connect and apply "local" problems to individual components of the flow diagram.

Thus, the ICE is an open system with respect to both the data and functions. Compatibility with GIS systems, office applications, various database formats, and the ability to work both at the local workplace and in a computer network is provided.

Integration of applied software packages in the ICE produces the final information and computational systems for the relevant subject area. By now, the MESI has elaborated several such systems based on this technology to the level of practical application in design, operational, research, and educational organizations: they are "Angara-HS" for operating conditions planning and supervisory control of heat networks [19,20]; "ANGARA-VS" for calculation and analysis of water supply systems operating conditions [21,22]; "DISRPMS" for calculation and optimization of operating conditions of reservoir pressure maintenance systems of oil fields [23]. Work is underway to integrate other legacy and newly created software into the ICE.

6.2 Hierarchical modeling of operating conditions of heating systems

Heating systems as an object of modeling. District heating systems (DHS) of municipalities and urban agglomerations of Russia and several Western European countries are complex, structurally heterogeneous high-dimensional engineering facilities. The presence of heat sources of different types (co-generation plants, district and peak boilers), pumping stations (PS), control units, numerous consumers (with different combinations of loads), extensive and looped heat networks operating under constantly changing conditions of heating system operation all contribute to the complexity of tasks of arrangement of operating conditions and control over them.

Many heating systems are organized process-wise according to the hierarchical principle to provide multi-stage output of heat: at heat sources, at intermediate facilities (central heat points or individual heat points); directly at heat-consuming installations (in heating, ventilation, and hot water supply systems). In such heating systems, different levels (e.g., main

[MHN] and distribution [DHN] heat networks) may not be connected by a single hydraulic state but only by a temperature state. In other cases, heating systems have no intermediate control stages, but can be provisionally divided into hierarchically related levels by the conditions of subordination of operating conditions of some fragments of the heat network to others.

In addition to the natural structural-and-topological preconditions, the feasibility of the hierarchical approach is evident at different temporal levels of heating system management. For example, design and development problems are usually solved for aggregated MHS flow diagrams. When planning operating conditions for the upcoming heating season, it is necessary to introduce into consideration all networks down to the end consumption nodes. Supervisory control requires a high level of detail of the heating system (down to the shut-off and control valves) when there is a conflict between the degree of detail and clarity of network flow diagrams and the results of their modeling.

When modeling heating system operating conditions, the hierarchical approach, in addition to the previously listed general advantages, also provides the following ones:

1. a number of issues can be contained at the level of a single fragment, and these issues do not require contingency calculations of the entire heating system;
2. it is possible to carry out independent calculations of heating system fragments having different departmental affiliations, provided that operating conditions parameters are set at the interfaces of the section. Conversely, such calculations can form the basis for matching operating conditions parameters at these interfaces;
3. separate calculation of heating system fragments significantly increases the convergence of computational algorithms, which depends on the degree of parametric heterogeneity of networks. This heterogeneity increases dramatically, for example, in the joint modeling of main and distribution networks.

The task and objectives of modeling operating conditions of heating systems. The problem of calculating the operating conditions of the heating system is to determine the distribution of heat transfer fluid flows (in most cases, it is water), pressures, and temperatures over all elements of the equivalent flow diagram given the following: the topology of the flow diagram; hydraulic and thermophysical characteristics of its components and boundary conditions (BC), which include operating conditions parameters that depend on the manifestations of the external environment.

The system of equations, which should satisfy the steady-state thermal-hydraulic state of water heating systems, as a particular case of nonisothermal mode [13], in its vector-matrix form of notation has the form

$$Ax = Q, \tag{6.1}$$

$$A^T P = y, \tag{6.2}$$

$$y = f(x), \tag{6.3}$$

$$A_{init} X t_{init} + A_{fin} X t_{fin} = \theta, \tag{6.4}$$

$$t_{init} = A_{init}^T T, \tag{6.5}$$

$$t_{fin} = g(x, t_{init}, t_0). \tag{6.6}$$

Here (6.1) – equations of material balance at nodes of the equivalent flow diagram (the first Kirchhoff law); (6.2) – equations of the second Kirchhoff law in the nodal form; (6.3) – equations capturing laws of pressure drop during the flow of the medium along the branches of the equivalent flow diagram; (6.4) – equations, following from requirement of heat balance at nodes given identical heat capacities of all flows; (6.5) – the condition of complete mixing of flows at nodes; (6.6) – equations capturing laws of temperature drop during the flow of the medium along branches of the equivalent flow diagram. Also, the following notations are used: A – full incident $(m \times n)$-matrix with elements $a_{ji} = 1(-1)$, when the node j is initial (final) for the branch i and $a_{ji} = 0$, if the branch i is not incident to the node j; m, n – the number of nodes and branches of the equivalent flow diagram; A_{init}, A_{fin} – $(m \times n)$ – incident matrices of outgoing and incoming branches of the flow diagram nodes, respectively, so that $A_{init} + A_{fin} = A$; Q – m-dimensional vector of nodal flow rate with elements $Q_j > 0$ for inflows, $Q_j < 0$ – for withdrawals, and $Q_j = 0$ – for simple connection nodes; P – m-dimensional vectors of nodal pressure; x, y – n-dimensional vectors of flow rates and pressure drops at branches; $f(x)$, $g(x, t_{init}, t_0)$ – n-dimensional vector-functions with elements $f_i(x_i)$ and $g(x, t_{init}, t_0)$, $i = \overline{1, n}$, respectively, capturing the laws of pressure and temperature drops at the branches; t_{init}, t_{fin} – n-dimensional vectors of temperatures at the beginning and at the end of branches; X – diagonal matrix with elements x_i, $i = \overline{1, n}$, on the main diagonal; T – m-dimensional vector of mixed flows temperatures at nodes; t_0 – ambient temperature; θ – nodal heat flow rate vector (with heat capacity equal to 1), and $\theta_j = Q_j T_{HS,j}$ if the node j has external medium inflow ($Q_j > 0$) with the temperature $T_{HS,j}$ and $\theta_j = Q_j T_j$ in case of withdrawal ($Q_j \le 0$).

It is known that the system of hydraulic state equations (6.1)–(6.3) is solvable with respect to the unknown flow rates and pressures, if the flow rate Q_j or the pressure P_j, and the pressure must be specified at one node at least. The system of temperature state equations (6.4)–(6.6) is solvable with respect to the unknown temperatures, if the temperatures of all inflows $T_{HS,j}$ and ambient air t_0 are specified (as boundary conditions), and the distribution of flows is known (values of the vectors x, Q).

The thermal-hydraulic state model (6.1)–(6.6) is universal with respect to arbitrary fragments or levels of the heating system. The unique features of these levels are related only to the type of ratios involved for the laws of pressure drop (6.3) and temperature (6.6) of individual components.

Principles of decomposition of models and problems of calculation of heating system operating conditions. The problem of calculating the thermal-hydraulic state of the heating system is reduced to solving the nonlinear system of Eqs. (6.1)–(6.6) of high dimensionality, counting many hundreds of thousands of variables for large heating systems To reduce this dimensionality, it is possible to use different ways of decomposition of both the equivalent flow diagrams and the problem itself as solved for each fragment of the flow diagram.

In general terms, the principles of decomposition of equivalent flow diagrams are as follows (Fig. 6.3) [24,25]. The upper level (MHN) includes a looped part (in the single-line representation) of the equivalent flow diagram from heat sources to central heat points or DHN connection nodes. The lower level (DHN) includes tree-shaped (in the single-line representation) heat networks to end consumers. Such decomposition allows one to calculate in advance the loads (or equivalent characteristics) at the nodes of the DHN connection, and such nodes are considered as aggregate consumers for the MHN. After the calculation of the MTS operating conditions, it is possible to set the boundary condition at the nodes of the interface between MHN and DHN nodes to calculate the operating conditions of the lower-level networks, when such nodes are considered as aggregate sources for the DHN.

Simultaneously with the rules for decomposition of equivalent flow diagrams and coordination of solutions at the nodes of the section of hierarchical levels, a set of methods of reducing to equivalents is employed. Thanks to this it is possible to further reduce the dimensionality of the problem, and after solving it, it is possible to detail the results to the primary components represented in the calculations of the operating conditions by their equivalent. Such techniques are used for heat sources, pumping units, DHN, heat points, and other process facilities represented in the model (6.1)–(6.6) by equivalent branches of the equivalent flow diagram in a two-line representation.

Analysis of the model (6.1)–(6.6) shows that the temperature state equations (6.4)–(6.6) depend on the load flow (on the hydraulic state). However, the hydraulic state equations (6.1)–(6.3) are practically independent of temperatures. Hence, it is possible to decompose the general problem and reduce it to sequential solving of the equations of hydraulic and temperature states.

Fig. 6.4 shows an illustration of the computer hierarchical representation of equivalent flow diagrams of the heating system, and Fig. 6.5 shows a diagram of coordination of calculations of hydraulic and temperature states of flow diagrams of different levels.

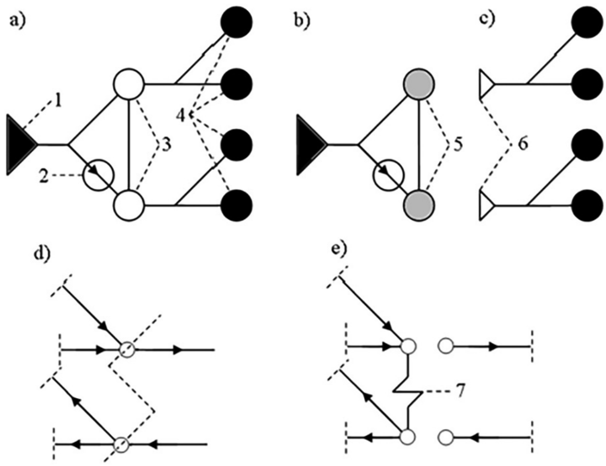


FIGURE 6.3 Illustration of the DHS flow diagram decomposition principles a) the flow diagram of the DHS in its single-line representation; b) THN; c) DHN; d) boundary nodes of hierarchical levels in the two-line flow diagram; e) the result of decomposition for a fragment of the flow diagram in its two-line representation. 1 – HS; 2 – PS; 3 – decomposition (boundary) nodes; 4 – consumers; 5 – aggregate consumers; 6 – aggregate HS; 7 – branch with the equivalent characteristic that replaces the DHN.

Notation used: P, t – vectors of pressures and temperatures at the nodes of the interface of hierarchical levels; superscripts "T", "D" refer to parameters of MHN and DHN levels; subscripts "1, 2" refer to supply and return pipelines; – indices "ihp", "chp" are for parameters at the outlet of heat consumption plants and central heating points x, s, δx – vectors of flows, flow frictions and adjustments to the flow rates for compensation of heat losses in the networks.

As can be seen from Fig. 6.5, the process of calculation of thermal-hydraulic state of the heating system as a whole is provided by separate calculations of hydraulic and temperature state of the MHN and DHN in combination with the operations of aligning boundary conditions at the nodes of level interfaces.

Calculations of operating conditions can be performed for two purposes:

1. determination of flow frictions of heat-consuming installations of end-users, at which they will be provided with a given amount of heat: the adjustment calculation;
2. determination of the amount of heat that consumers will receive when such flow frictions are set: verification analysis.

In both cases, real or dummy heat points act as nodes for setting the boundary condition.

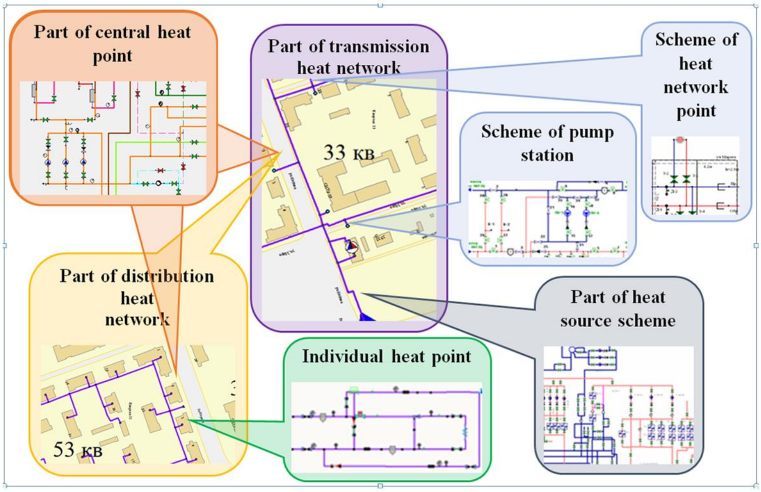


FIGURE 6.4 The computer representation of the hierarchy of equivalent flow diagrams of the heating system.

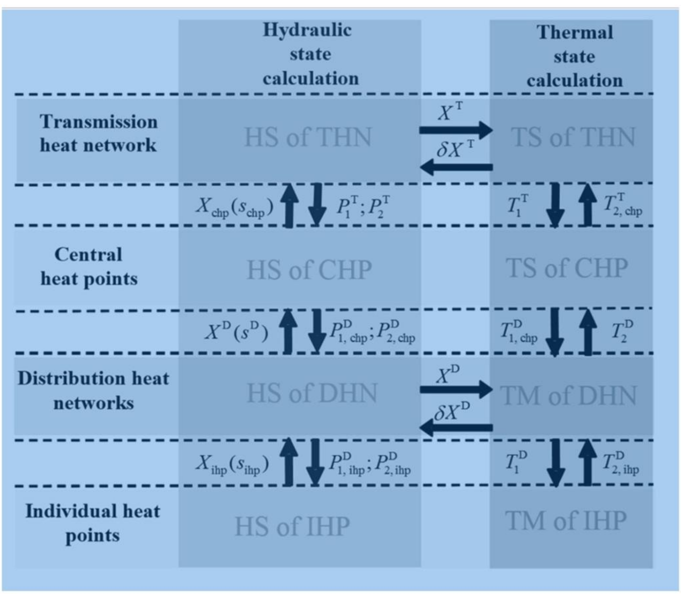


FIGURE 6.5 Coordination of solutions for decomposition (boundary) nodes of hierarchical levels.

The essence of the calculation process [19,25] boils down to the following stages:

1. calculation of the total loads (bottom-up) to set the boundary condition with respect to flow rates to calculate the hydraulic state of the MHN, or the calculation of the equivalent hydraulic characteristics of the branches, capable of replacing the dependency of the flow rate for each DHN on its aggregate flow friction;
2. calculation of the hydraulic state of the MHN;
3. calculation of the hydraulic state of the DHN when the pressures obtained from the calculation of the MHN in the places where the levels interface are set as a boundary condition;
4. calculation of the temperature state at given flow rates and temperature distributions in the places where the heat transfer fluid enters.

In the adjustment calculations to compensate for heat losses in the networks, adjustments δx to the consumer loads are calculated in units of flow rate x and the entire calculation process is repeated until these adjustments get negligibly small. Calculation methods for hydraulic and temperature modes of heat networks as well as heat points are given in [12–14,25–30].

Computer implementation of multi-level modeling methods for heating system operating conditions. Models, methods, and algorithms of multilevel modeling of heating system operating conditions are implemented in the form of information and computing system (ICC) "ANGARA-HS" [20] based the platform of ICE "ANGARA" [18].

ICC "ANGARA-HS" has the following basic computing capabilities:

- single- and multilevel calculation of hydraulic, temperature, and thermo-hydraulic states of the heating system of an arbitrary configuration (branched, with multiple loops) and structure (with an arbitrary number and location of PSs, heat sources, automatic pressure or flow control devices, heterogeneous consumers, and other components);
- for calculating operating conditions for heating systems of almost any dimensionality with their multi-level representation and for equivalent flow diagrams counting tens of thousands of nodes in a single level;
- high performance as expressed in solving (while running on standard average performance computers) of the most time-consuming problem of hydraulic analysis in a few seconds for a multiple loop flow diagram counting thousands of nodes;
- increased reliability due to automated control of the correctness of setting the input data and theoretically fail-proof convergence of the computational process, which provides a solution with a predetermined accuracy;
- automatic detection of disturbances in design operating conditions with their subsequent allocation on the flow diagrams;
- calculation of the parameters of throttling devices at the consumption nodes and in the heat network, ensuring the transfer of operating conditions into the admissible range, including the required degree of satisfying consumer demand;

- interactive construction and display of piezometric and temperature graphs, reflecting the distribution of pressures along any route in the heating system flow diagram and the dependency of the required temperatures at heat sources on the ambient air temperature.

Information and computing system "ANGARA-HS" inherits the elaborate user interface of the ICE "ANGARA" (Fig. 6.1) and all the relevant functions that automate the processes of entering and debugging information, making calculations, and analyzing results. The information and computing system has been tested extensively in practice as applied to real heating systems of dozens of cities in Russia and in other countries [19,31,32, etc.] in the process of cooperation with a number of design, operational, research, and educational organizations.

Examples of practical applications. Table 6.1 shows quantitative characteristics of the equivalent flow diagrams of heating systems of some Russian cities, for which calculations were performed at the MESI with the aid of the ICC "ANGARA-HS". The dimensionality of the MHN equivalent flow diagrams is 6 - 10 times less than the dimensionality of the DHN of the same city. MHN flow diagrams can have several unconnected or weakly connected networks (highlighted in different colors in Fig. 6.6a), and DHNs are broken up into hundreds of unconnected fragments, which can be calculated in parallel. Fig. 6.6b shows the MHN of Angarsk City and the DHN of a single micro-district. The DHN flow diagram of this micro-district consists of 17 unconnected fragments. There is a total of 397 DHN equivalent flow diagrams here.

Statistical processing of the results of heating system calculations as a whole and when using the multi-level approach for a number of cities produced the following dependencies of calculation time on the number of nodes in the equivalent flow diagram (Fig. 6.7). The graphs show that given the same dimensionality of the flow diagram and using the same calculation module, when executed on a personal computer, the calculation time for the heating system as a whole is on average almost 2 times longer than the calculation time for the MHN, and 4 times longer than the calculation time for the DHN.

Let us consider this effect in more detail as exemplified by the Angarsk City heating system (Table 6.2).

The table shows that the total computation time of the load flow for a flow diagram with a dimension of more than 22 thousand nodes is 2.68 seconds for the network with a breakdown into levels, and 7.09 seconds without such a breakdown. The application of the multi-level method provided a 2.64-fold acceleration of calculations, even without taking into account the possibilities of setting up parallel calculations of different DHNs. Given the possibility of parallel computing, the counting speed for this flow diagram can be accelerated by an order of magnitude.

TABLE 6.1 Quantitative characteristics of computational DHS flow diagrams of some of the municipalities of Russia.

Municipality	Number of nodes (m), branches (n), DHS fragments (N) of the equivalent flow diagram of the heat network						
	THN		DHN			HS	
	m	n	N	m	n	m	n
	0	3.904	397	21.36	26.564	22.588	29.101
Angarsk	1.046	1.313	115	7.634	9.452	8.220	10.305
Bratsk	1.194	1.398	101	12.50	15.137	13.104	16.037
Petropavlovsk-Kamchatsky	2.554	3.373	247	19.37	24.325	21.722	26.710

a)

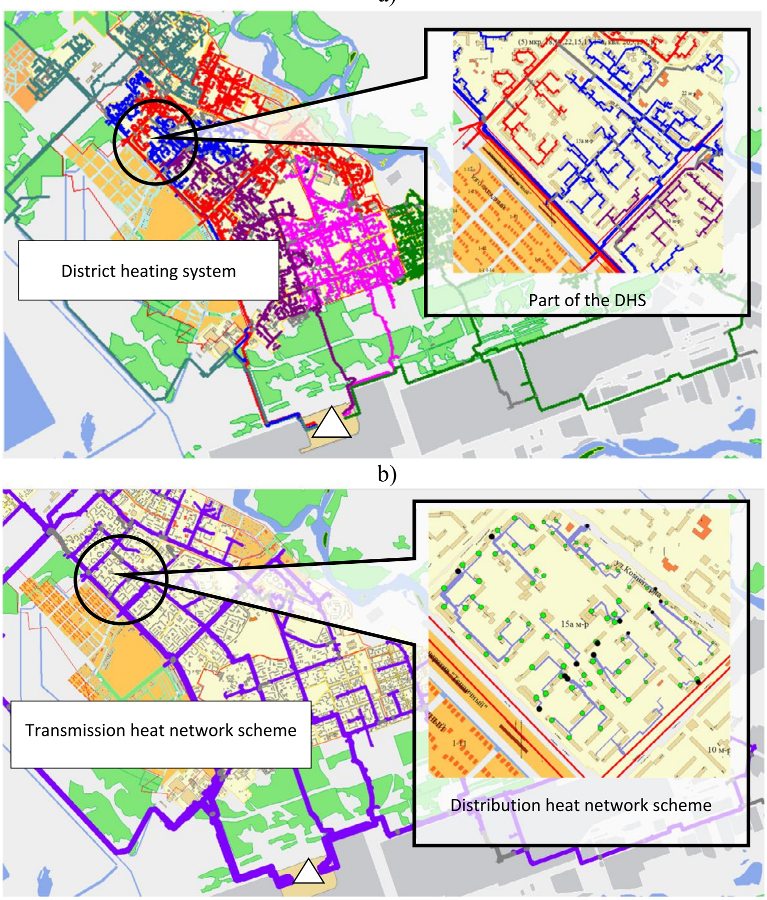


FIGURE 6.6 District heating system of Angarsk City: a) One-level flow diagram; b) The flow diagram after decomposition into transmission and distribution heat network levels.

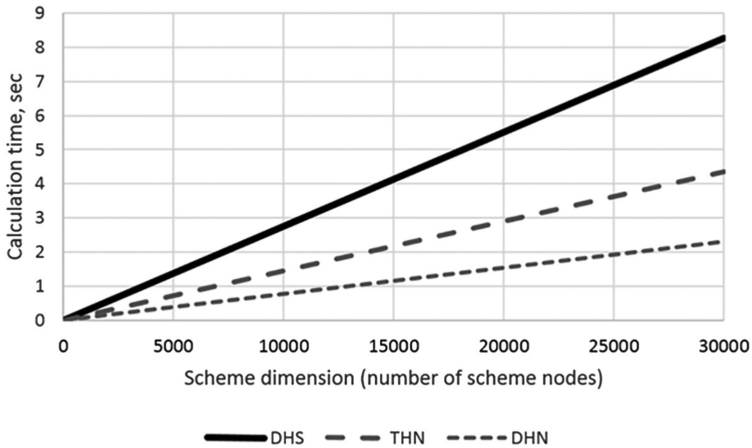


FIGURE 6.7 Plots of the relationship between the hydraulic calculation time and the number of nodes in the equivalent flow diagram of the DHS as a whole, THN, and DHN.

TABLE 6.2 Comparison of the efficiency of single- and multi-level load flow calculation as exemplified by DHN of Angarsk City (Computer 15/3500).

Calculation	Number of iterations	Calculation time, s	Relative time expenditure, %
THN	43	0.57	21
DHN	15	2.11	79
DHS Total		2.68	100
DHS (calculation for a single level)	47	7.09	264
DHN of a single district	7	0.13	5

6.3 Hierarchical optimization of operating conditions of heating systems

Conceptual statement of the optimization problem. Currently, there is a significant body of work related to heating system optimization. Most of them are devoted to the problems of synthesis of heating system structure and parameters that arise during design [2,13,14,33, etc.], or to problems of control of operating conditions [8,34, etc.]. This section deals with the problem of planning optimal hydraulic states of heating systems of cities and settlements, which occurs at the stage of preparation for the heating season and is related to the choice of parameters of the controlled equipment, as well as the composition and parameters of additional control devices. The relevance of the independent consideration of this problem is determined by the significant potential of energy savings, which can be realized by creating conditions in advance to maintain optimal operating conditions of the heating system. Similar statements are available, for example, in [7,9], where, however, no special methods are proposed, and the optimization problem is solved by time-consuming genetic algorithms.

Content-wise, this problem consists in the search for controls that ensure the implementation of operating conditions that satisfy the requirements of admissibility (in terms of equipment operating conditions and satisfaction of consumer demand) and optimality in terms of a given criterion or a system of such criteria [15].

It is further assumed that the temperature profiles at the heat sources are specified, the heat losses in the networks are eliminated, and their residual value can be neglected. In this case, the requirements of providing consumers with thermal energy are reduced to the need to maintain the required heat transfer fluid flow rate, and the problem is reduced to the optimization of the hydraulic state.

By its nature, the problem under consideration is a multi-criteria problem. Energy-saving requirements can be reduced to a single economic criterion, other (process-related) criteria are associated with the desire to minimize the labor intensity of preparatory work for the implementation of operating conditions, reducing possible leaks of the heat transfer fluid and risks of emergencies. These criteria can be reduced to the requirements of minimizing additional flow control points and the overall pressure level in the network.

General flowchart of hierarchical optimization of heating system hydraulic states. The accumulated experience of hierarchical modeling of operating conditions can be the basis for a new methodology of hierarchical optimization of hydraulic steady states of heating systems. In this case, it is possible to resolve not only the issue of dimensionality of the problem but also to simplify the issue of its multiple criteria.

To solve the first issue, let us apply the principles of decomposition of the heating system equivalent flow diagram into MHN and DHN as discussed above. As before, when optimizing the hydraulic states of the MHN, the flow rates corresponding to the total load of this DHN are taken as the boundary condition at the connection nodes of the DHN. The pressures at these nodes, obtained as a result of the MHN optimization, already act as the boundary connection in the optimization of DHN operating conditions. The difference is that in order to provide the required degrees of freedom in the optimization of the MHN, it is necessary to set such limits of possible pressure changes at these nodes, which guarantee obtaining the admissible operating conditions within the DHN. Hence the stand-alone subproblem of determining such limits arises.

To solve the problem of having multiple criteria we will take as a basis the principle of the lexicographic ordering of criteria [35], according to which, after the optimization with respect to the current criterion (in an ordered sequence thereof), its value is fixed and optimization with respect to the next one is performed in descending order of importance. We will call this approach “sequential optimization”.

A unique feature of the proposed decomposition principles is that all facilities (sources, PSs, etc.) that consume external energy resources (electricity for pumping and fuel for heating the heat transfer fluid) are concentrated in the MHN, and all additional control devices are usually concentrated in the immediate vicinity of consumers, that is, in the DHN. Moreover, the requirement to minimize the total pressure level in the network is automatically met when minimizing the economic criterion, since increasing the pressure requires additional energy costs for pumping the heat transfer fluid. Thus, among the listed optimality criteria for the MHN, we can take a single one, that is, the economic criterion, also taken as the main criterion for the heating system as a whole. For the DHN we have a two-criteria problem of the minimum of the number of additional control points (as the main criterion for the DHN) and the minimum of the total pressure level in the DHN (as an additional criterion for the DHN).

In connection with the above, we propose the following methodology of hierarchical optimization of the hydraulic state of the heating system, based on a preliminary decomposition of the equivalent flow diagram of the heating system into the MHN and DHN and including three main stages.

1. Determination of the total load and allowable limits of pressure changes for each generalized MHN consumer based on the conditions of the existence of admissible operating conditions in the DHN substituted by this consumer.
2. Optimization of MHN operating conditions, taking into account the required loads and pressure limits for generalized consumers obtained at the previous stage.
3. Optimization of operating conditions of each DHN given the values of pressures at the nodes of connection to the MHN (as the boundary condition) as obtained at Stage 2.

This technique guarantees an economically optimal and coordinated hydraulic state for the heating system as a whole if there is an area of admissible operating conditions for all DHSs (which is checked at Stage 1) and at least one admissible operating condition of the MHN (which is checked at Stage 2). In this case, the solution is obtained in one pass and no iterative coordination of the obtained MHN and DHN operating conditions is required.

Mathematical statement of hierarchical optimization problems. Let us state a formalization of the optimization problems that arise at the stages of the outlined methodology and include equality constraints, inequalities, and objective functions.

The equations of the hydraulic state model (6.1)–(6.3), where the relation (6.3) is represented in the form of $y = f(x, u)$, and u is a vector of controls, act as the main equality constraints. Targeted impact on operating conditions is associated with a change in the characteristics of the elements, for example, by increasing the flow friction of the i-th branch to the value of $z_i s_i$, $z_i \geq 1$. Special methods of control at a branch with the PS can include changing the relative speed of centrifugal pumps (or diameters of their impellers) (γ_i), as well as the number of switched on pumps $\kappa_i \in \{0, 1, 2, ..., K_i\}$, where K_i is the number of pumps at the i-th branch with the PS. If the pumps are connected in parallel, the flow rate of one pump is x_i/κ_i. Then [36] $f_i(x_i, u_i) = z_i \frac{\tilde{s}_i}{\kappa_i^2} x_i |x_i| - \gamma_i^2 H_i$, where $\tilde{s}_i$, H_i is the flow friction and effective head of one pump. This relation can be seen as a generalization of the model of the controlled pipeline section, when $\kappa_i = 1$, $\underline{\gamma}_i = \bar{\gamma}_i = 1$, $H_i = 0$, and $\tilde{s}_i = s_i$ is the pipeline friction. Thus, in the general case, $u_i = (z_i, \gamma_i, \kappa_i)^T$ and z_i, γ_i are continuous controls (real values), and κ_i – discrete controls (integer values). All equality constraints can also be represented in the general form as $U(X) = 0$, where $X = (P, x, y, Q, u)$ is the vector of unknowns, including operating conditions parameters and control parameters.

The basic inequalities arising from the process requirements to the admissibility of operating conditions and control limits can be reduced to the form $\underline{X} \leq X \leq \bar{X}$, where $\underline{X}$, $\bar{X}$ are the vectors of lower and upper bounds of the admissible change in the unknowns. Their components can take infinite values to model one-sided inequalities (or their absence), as well as the same values of $\underline{X}_i = X_i = \bar{X}_i$ to fix individual operating conditions parameters (e.g., the boundary condition) or prohibit controls.

The variable component of operating costs to maintain operating conditions – $F_C = F_C^{EP} + F_C^F$, where F_C^{EP} – electricity costs for pumping the heat transfer fluid to the PS, F_C^F – fuel costs for water heating at the sources. Let us denote I_{HS}, I_{PS} the sets of sources and NS, and $I_{HS} \subset I_{PS}$. Then $F_C = \sum_{i \in I_{PS}} F_{C,i}^{EP} + \sum_{i \in I_{HS}} F_{C,i}^F = \sum_{i \in I_{PS}} A_i^{EP} N_i + \sum_{i \in I_{HS}} A_i^F B_i$, where A_i^{EP}, N_i – price and consumption of electricity, A_i^F, B_i – price and consumption of fuel. For a given (planned) temperature profile of operation of heat sources, the fuel costs can be represented as a known function of the heat transfer fluid flow rate $B_i(x_i)$. The characteristic of the power consumed by one pump can be approximated with sufficient accuracy by the polynomial $N(x) = \beta_0 + \beta_1 x + \beta_2 x^2$. Taking into account the possible ways of control, for the PS as a whole we have [36] $N_i(x_i, \gamma_i, \kappa_i) = \beta_{0,i} \kappa_i \gamma_i^3 + \beta_{1,i} \gamma_i^2 x_i + \beta_{2,i} \frac{\gamma_i}{\kappa_i} x_i^2$, $i \in I_{PS}$. Hence, the economic criterion of optimality has the form $F_C(x, \gamma, \kappa) = \sum_{i \in I_{HS}} A_i^F B_i(x_i) + \sum_{i \in I_{PS}} A_i^{EP} N_i(x_i, \gamma_i, \kappa_i)$.

Let us introduce the vector of boolean variables δ whose components $\delta_i \in \{0, 1\}$ are responsible for the presence of control (z_i) at the i-th branch of the equivalent flow diagram, and let us also introduce the inequality $1 \leq z_i \leq 1 + \delta_i (\bar{z}_i - 1)$. Then for the network as a whole, the inequality constraints will take the form of $\underline{X} \leq X \leq \bar{X}(\delta)$, and the criterion for the number of additional places of flow control – $F_Z = \sum_{i \in I_{PL}} \delta_i$. As a metric of the total pressure level in the network, we use the average (over all nodes) pressure $F_P = \sum_{j=1}^{m} P_j/m$.

With due regard to the symbols introduced, let us give mathematical statements of the optimization problems arising at the stages of the methodology.

1. Finding the allowable limits of pressure changes at the MHN and DHN interface node comes down to solving for each DHN of the following:
   a. three optimization problems of the minimization of P_{in}, P_{out}, y_d subject to the constraints $Ax = Q$, $A^T P = y$, $y = f(x, z)$, $\underline{X} \le X \le \bar{X}$, where P_{in} is the pressure in the supply pipeline, P_{out} is the pressure in the return pipeline, $y_d = P_{in} - P_{out}$ is the pressure drop at the DHN inlet, $X = (P, x, y, Q, z)$;
   b. three optimization problems of the maximization of P_{in}, P_{out}, y_d subject to the same constraints.
2. Optimization of the MHN operating conditions:
   $\min F_C(x, \gamma, \kappa)$ given the conditions $Ax = Q$, $A^T P = y$, $y = f(x, z, \gamma, \kappa)$, $\underline{X} \le X \le \bar{X}$, $\kappa_i \in \{0, 1, 2, ..., K_i\}$, $i \in I_{PS}$, where $X = (P, x, y, Q, z, \gamma)$.
3. Consistent optimization of the DHN operating conditions:
   a. $\min F_Z(\delta)$, $Ax = Q$, $A^T P = y$, $y = f(x, z)$, $\underline{X} \le X \le \bar{X}(\delta)$;
   b. $\min F_P(P)$, $Ax = Q$, $A^T P = y$, $y = f(x, z)$, $\underline{X} \le X \le \bar{X}(\delta)$, $F_Z(\delta) \le F_Z^*$, where F_Z^* – is the smallest number of controls needed to achieve admissible operating conditions as obtained by solving Problem 3a.

Methods for solving hierarchical optimization problems. It can be seen from the above statements that mathematically the above problems are reduced to the following classes:

1. nonlinear mathematical programming problems (Problem 1);
2. mixed (discrete-continuous) problems of mathematical programming with integer variables (Problem 2);
3. one- and two-criteria mixed conditional optimization problems with Boolean variables (Problem 3).

To solve the most general mixed problem of discrete-continuous optimization we propose the following approach. The enumeration of options by discrete variables is arranged in one way or another. For each option of discrete variables, we perform optimization over continuous variables based on the search for admissible operating conditions.

The search for admissible operating conditions consists in finding the vector of continuous variables X satisfying the constraints $U(X) = 0$, $\underline{X} \le X \le \bar{X}$. The need for special consideration of this problem is due to the fact that the existence of admissible operating conditions is a necessary condition for its optimization, an admissible point is required as an initial approximation, and the procedure for entering the admissible range is an integral part of the optimization process.

To solve this problem, it is proposed to use the interior-points method initially proposed and being developed at the MESI SB RAS [37]. The method has good convergence, easy implementation, requires minimal modifications in the transition to the optimization statements, is universal in terms of taking into account both linear and nonlinear constraints, and provides the ability to identify the fact of their incompatibility.

The essence of the method consists in arranging the process $X_{k+1} = X_k + \lambda_k \Delta X_k$, $k = 1, 2, ...$ (where λ_k, ΔX_k is the length and direction of the step), at each k-th iteration of which the square of the shortest weighted distance $L_k^2 = \Delta {X_k}^T \Omega_k^{-1} \Delta X_k$ from the current point X_k satisfying the strict inequalities $\underline{X} < X < \bar{X}$ to the point satisfying the linearized equality constraints $J_k \Delta X_k + U(X_k) = 0$, where $J_k = \partial U / \partial X$ is the Jacobian matrix at the point X_k.

The existence of efficient algorithms for calculating admissible operating conditions allows us to arrange the solving of the continuous minimization problem [36] by sequentially reducing the initial uncertainty interval $\left[\underline{F}_0,\ \bar{F}_0\right]$, knowingly containing the optimal value of some objective function $F(X)$, for example, by dividing it in half. At each r-th step of this procedure we involve the additional conditions $F_r + \varphi - F(X) = 0$, $\varphi \geq 0$, where F_r is the value $F(X)$ for the last admissible solution, and φ is an additional variable.

To solve the problem of MHN operating conditions optimization with integer variables, four methods were investigated [36]: the full enumeration method; the directed full enumeration method; the branch-and-cut method; the continuous branch-and-bound method. According to the results of computational experiments, the latter turned out to be the most promising. The essence of the method is that integer variables are considered continuous, and the region of their values, shifted to the nearest integer boundaries, is subjected to fractionation until they take discrete values. This principle is illustrated by Fig. 6.8 using the example of two PSs containing 4 and 6 pumps, respectively.

To optimize the DHN mode with respect to the criterion $\min F_Z(\delta)$ (Problem 3a), three methods were investigated [38]: the exhaustive enumeration method; the branch-and-cut method; the discrete branch-and-bound method. A combination of the last two methods (branches, cuts, and bounds) proved to be the most effective. It consists in cutting off both knowingly unacceptable and unpromising options of the value of δ in accordance with the depth-first search tree (Fig. 6.9). Inadmissibility of child variants is determined by the absence of admissible operating conditions in the parent variant, and inadmissibility - on the basis of comparison of

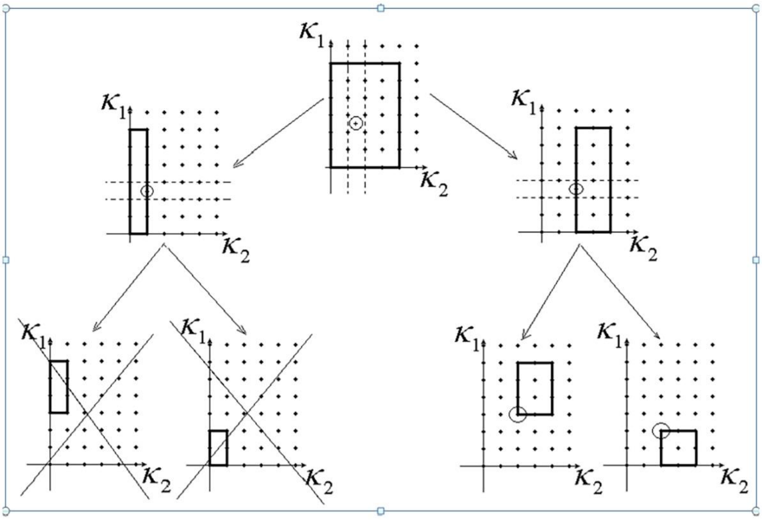


FIGURE 6.8 An example of the fractioning of the solution range based on the condition of belonging to the nearest integer boundary. Points – the integer solution, circles – continuous solutions, dotted line – nearest integer boundaries, bold line – the region of a continuous solution search, crossed out – no continuous solution.

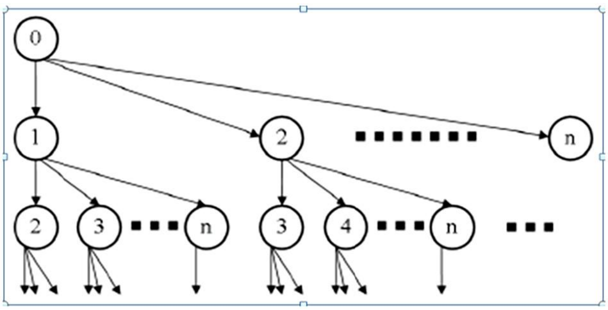


FIGURE 6.9 A fragment of the tree that illustrates the depth-first search. Numbers of branches with prohibited controls are in circles.

the current objective function record with its expected values in the child variants.

To solve the problem of two-criteria optimization of DHN operating conditions, three approaches were compared [38,39].

The first contains the following operations: 1) solving Problem 3a by the combined method (branches, cuts, and bounds) delivering the optimal value of F_Z^*; 2) arranging an exhaustive search of all possible combinations of control points with a total number of F_Z^*; 3) optimization with respect to the criterion F_P of each permissible k-th option δ^k of placing control points, such that $\sum_{i=1}^{n} \delta_i^k = F_Z^*$, (Problem 3b is solved at fixed $\delta = \delta^k$), by the continuous optimization methods considered above; 4) from the obtained variants, the optimal one is selected with respect to the criterion F_P.

The essence of the second approach, called the method of majorizing sequence, consists in such an arrangement of the enumeration of control points (within the framework of the discrete branch and bound method) that among all options with the same value of the criterion F_Z, the options that have a smaller value of F_P are considered earlier. In this case, the first option, delivering the solution with respect to the criterion F_Z, will be optimal in terms of the two-criteria problem. The possibility of arranging such a sequence of enumeration is achieved due to the fact that the directions of flows in the DHN are known in advance. The further upstream the control is from the connection point of the MHN return pipeline (and the closer to the connection point of the MHN supply pipeline), the stronger its effect on the pressure drop in the network.

The third approach (method of dynamic programming with circuit equivalence – DPCE) is based on a combination of dynamic programming methods and equivalence of series-parallel branches of the equivalent flow diagram [39,40]. It relies on special properties of the DHN (tree-shaped topology in a single-line display and a specified load flow) and consists in generating possible paths of pressure changes (as a phase variable) along the branches of the equivalent flow diagram and rejecting unacceptable or non-optimal paths when making equivalents of series or parallel connections of branches. As a result of such operations (constituting a forward pass of the dynamic programming method) only one branch remains with the pressure drop corresponding to the optimal solution (Fig. 6.10. The backward pass is related to restoring the components of this solution (restoring the pressure distribution in the original flow diagram). This method has a number of advantages:

1. linear (in terms of the dimensionality of the problem) growth of computational costs, which allows one to solve optimization problems for DHNs of high dimensionality;
2. unlike semi-heuristic methods, it is guaranteed to find the optimal solution;
3. provides the ability to optimize over several objective functions simultaneously, without requiring the setting up of an iterative process.

In Fig. 6.10 the series connections of the branches are shown in bold, the dotted line is the parallel connections.

Results of computational experiments. Let us show examples of the application of the described methods of discrete-continuous optimization of the operating conditions of the MHN and DHN, which can be linked by a single hydraulic state.

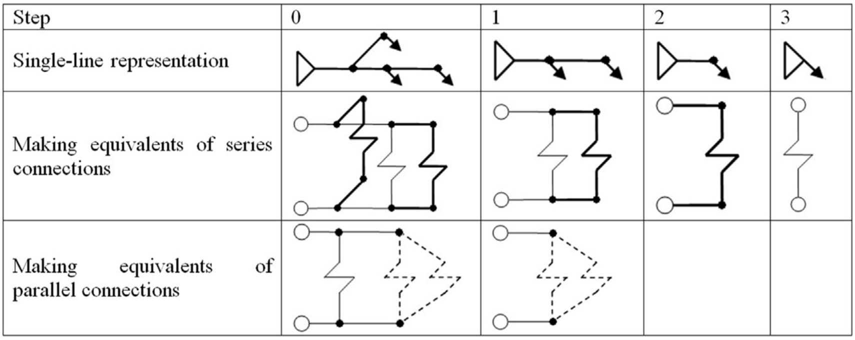


FIGURE 6.10 Illustration of reducing the equivalent flow diagram of the DHN to a single branch by means of equivalence of series and parallel connections of branches.

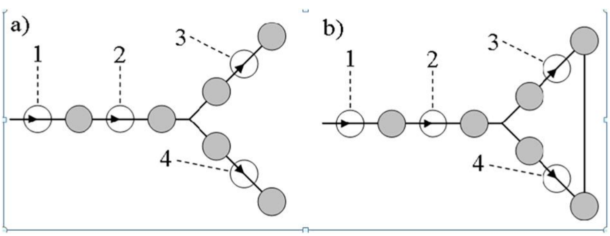


FIGURE 6.11 Flow diagrams of THNs of tree-shaped (a) and looped (b) structure (1-4 – number of a pumping station).

Fig. 6.11 shows an example of two MHN flow diagrams. One of is (a) is of a tree-shaped structure (in a single-line representation), the other (b) has a loop that allows load redistribution between PS-3 and PS-4. In addition, frequency control of electric motors is allowed for all PSs of the flow diagram (b), while for (a) it is prohibited. If the prices of electricity are the same for all PSs, and given the fact that with one source (whose capacity is equal to the total load of consumers) the optimal solution does not depend on the cost of fuel F_C^F – the objective function takes the form of $\sum_{i \in I_{PS}} N_i(x_i, \gamma_i, \kappa_i)$. Optimization of operating conditions of each MHN was carried out for two levels of heat consumption: increased ("winter conditions") and reduced ("summer conditions").

All the above-considered methods of integer MHN optimization yield the same optimal solution κ^* for each combination of computational conditions (Table 6.3). This table shows:

1. the flow redistribution possibilities and frequency control for the flow diagram (b) given the same load as for the flow diagram (a) allow to almost half the electric power consumption;

TABLE 6.3 Optimal number of pumps switched on at the PS.

Terms of computational experiments	PS-1	PS-2	PS-3	PS-4	F_C^*, kW
Flow diagram a) Winter conditions	3	4	2	0	1.445
Flow diagram a) Summer conditions	1	2	0	1	426
Flow diagram b) Winter conditions	3	4	0	1	605
Flow diagram b) Summer conditions	1	0	0	2	228

TABLE 6.4 Comparison of the methods in terms the number of considered variants.

Terms of computational experiments	Exhaustive search method	Directed search method	Branch-and-cut method	Discrete branch-and-bound method
Flow diagram a) Winter conditions	288	286	30	27
Flow diagram a) Summer conditions	288	70	112	34
Flow diagram b) Winter conditions	288	207	144	35
Flow diagram b) Summer conditions	288	45	144	29

2. the "winter" conditions require about twice as many pumps as the "summer" conditions;
3. pumps at some PSs can be completely switched off.

Table 6.4 shows the results of the comparison of methods in terms of the number of options considered, for each of which the continuous optimization problem is solved with approximately the same computational costs.

As one can see from this table:

1. the exhaustive search method leads to the need to look at more options than others;
2. the efficiency of the directed search method strongly depends on the number of pumps in the solution;
3. the branch-and-cut method finds a solution with a large number of pumps in the solution faster than the previous one, however, where it is possible to redistribute the PS load, when the number of admissible options increases, its efficiency falls down;
4. the continuous branch-and-bound method showed greater independence from design conditions, and, on average, better results compared with other methods.

Fig. 6.12 shows an example of the flow diagram of the DHN with the open withdrawal of the heat transfer fluid for hot water supply. Consumers are located at different heights, which leads to the need to install

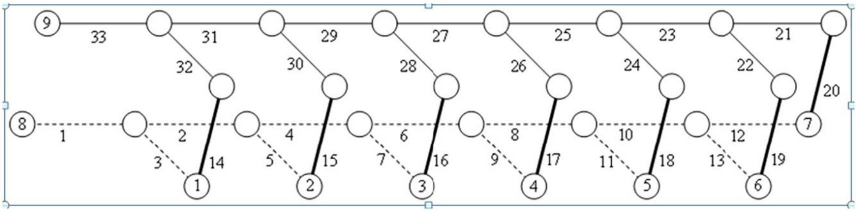


FIGURE 6.12 Equivalent flow diagram of the DHN. The solid line is the supply pipeline, dotted line – return pipeline, bold line – consumer pipeline.

TABLE 6.5 Comparison of computational costs of two-criteria methods of optimization of the DHN operating conditions.

Method	Number of admissible conditions calculations	Number of optimization calculations with respect to the criteria of F_P	Time (s)
A combination of branch-and-bound methods to find the optimal F_z^* and the method of exhaustive enumeration of options that satisfy F_z^*	34	325	32.500
Majorizing sequence method	34	1	300
Method of dynamic programming with circuit equivalence	–	–	5

additional pressure control devices in the network to bring it into the admissible range. Throttling is not prohibited at consumers.

Table 6.5 shows the computational costs of solving the two-criteria problem of optimizing the operating conditions of this DHN by the three previously considered methods. All methods found the same operating conditions, which required two additional control points.

Note that the computational cost of the first two (combinatorial) methods is proportional to the number of the most time-consuming calculations of the admissible operating conditions by the internal point method. In turn, the computational costs of this method are proportional (approximately) to the square of the dimensionality of the problem, since it involves solving systems of equations. At the same time, the computational cost of the method of dynamic programming with circuit equivalence almost linearly depends on the dimensionality of the network [39], which makes this method more preferable for such problems.

It seems that the accumulated experience in the field of multi-level modeling of PLSs can be useful in solving problems of calculation, analysis, and optimization of intelligent and integrated energy systems (heat, gas, water, electricity, etc.) of high dimensionality.

6.4 Two-level model of the heat market

District heating plays an important role in heat markets in many countries around the world. Currently, there are about 80,000 district heating systems in the world [41], of which 50,000 are in the Russian Federation [42], 6,000 large district heating systems operate in Europe [43], and another 24,000 district heating systems are located in China, the United States, Canada and the former Soviet Union (Ukraine, Kazakhstan, Belarus, etc.).

At present, there are two organizational models for the management of district heating markets adopted internationally: the competitive model and the model of natural monopoly.

Competition in the district heating market, as well as in other areas, is an important element of the market economy, as it promotes the growth of efficiency of heat production, improving its quality and, as a consequence, reducing its price, which can have a favorable effect on its development. The technological basis of the competitive model is the presence of several independent heat sources (HS), heat networks (HN) connecting them to consumers, which in terms of the organizational structure should be separated from heat generation and integrated into a single heat network company, which is an independent area of business activity. This organizational model is commonly referred to as "Single Buyer" [44,45]. The competitive model in the district heating market successfully operates in some European countries, such as Germany [43], Sweden [46], Finland [47].

The most common type of organization of supplying heat to consumers is the model of the heat market in the form of a natural monopoly with the regulation of the tariff for consumers. Such model of the heat market takes place in many countries of the European Union such as the Netherlands [48], Poland [49], Lithuania [50], Latvia [51,52], Norway [53], Estonia [54], and others, as well as in Russia, China, and others. In each specific country, control over the regulation of heat energy tariffs is usually carried out by a government agency responsible for state regulation of prices (tariffs), or local authority in the case when it is vested with the relevant powers (Table 6.6).

The organizational model for managing the heating of consumers in the form of a natural monopoly with tariff regulation for consumers can be represented as a hierarchical vertically integrated system consisting of two levels (Fig. 6.13).

The upper level of the heat market is represented by the regulator, whose responsibilities include regulating the heat tariff for consumers,

TABLE 6.6 Government agencies responsible for regulating heat tariffs in different countries.

Country	Netherlands	Poland	Lithuania	Latvia
Regulatory authority	Authority for Consumers and Markets [55]	Energy Regulatory Office [56]	National Control Commission for Prices and Energy [57]	Sabiedrisko pakalpojumu regulēšanas komisijas [58]
Country	**Norway**	**Estonia**	**Russia**	**China**
Regulatory authority	Norwegian Water Resources and Energy Directorate [59]	Estonian competition authority [60]	Federal/regional tariff services, local government authorities [61]	Municipal authorities [62]

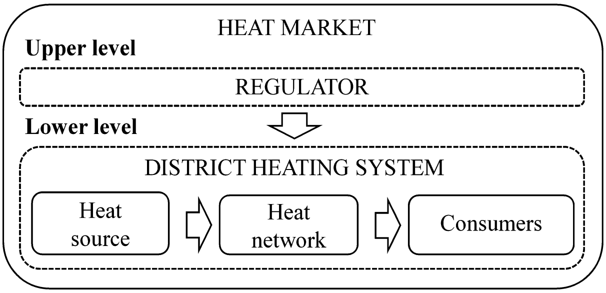


FIGURE 6.13 Two-level model for managing the heating of consumers.

while the lower level is the district heating company, which technologically and organizationally combines the functions of heat production and transport within the Unified heating organization (UHO). The main idea of the two-level construction of the management arrangement of the district heating monopolistic market consists in partitioning into subsystems corresponding to the specific entities of the market for their further modeling, taking into account the attainment of the set targets.

The relationship between the participants of the heating process is as follows. Based on the projections of demand for heat from consumers, the UHO produces heat and sells it to consumers provided that the HSs taken together would produce such a total volume of heat, which would cover a given demand on the part of consumers based on the condition of obtaining maximum profit, given the available capacity of HSs and the physical and engineering limitations of the HN. In turn, the regulator, protecting the rights of consumers, sets such a level of heat tariff, which, on the one hand, would encourage HSs to meet a given demand of consumers, and on the other hand, would allow them to maximize profits from the sales to HN while respecting the optimal operating conditions of the HN.

Modeling of such a system is carried out by means of bilevel programming [63]. The transition to a one-level optimization problem is done by replacing the second (lower) level extremum problem with their optimality conditions.

When modeling the DHS, it is assumed that it has a nodal structure and lends itself to modeling by a hydraulic circuit consisting of m nodes and n branches [13]. The structure of a hydraulic circuit is described by a complete coupling matrix $\overline{A}$, in which the number of rows coincides with the number of nodes and the number of columns coincides with the number of branches. The elements a_{ij} of the matrix $\overline{A}$ are defined as follows:

$$a_{ij} = \begin{cases} 0, & \text{if branch } i \text{ has no connection with node } j; \\ 1, & \text{if flow in branch } i \text{ goes from note } j; \\ -1, & \text{if flow in branch } i \text{ enters node } j. \end{cases}$$

A hydraulic circuit is an array of ordered sets: those of nodes $J = \{j : j = 1, ..., m\}$ – consisting of subsets J_{HS} – heat sources, J_C – consumers, and J_0 – simple branching nodes of the flow diagram:

$$J = J_{HS} \cup J_C \cup J_0,$$

branches – $I = \{i : i = 1, ..., n\}$, representing the given pairwise connections between the nodes.

Modeling of such a system is performed with a certain time interval, starting from the initial moment of time (corresponding to the calculated heat load) and ending at the final (calculated) moment of time T (for example, the calendar number of hours in the year – 8.760).

Mathematical modeling of the heat source. When modeling the behavior of heat sources in the market environment, it is assumed that at any given time $\tau = \tau_0, ..., T$ they would receive the maximum profit, taking into account the costs of heat production and the constraints, produce together a volume of heat energy that would, on the one hand, cover a given consumer demand, and on the other hand allow for their productivity.

The available experience in processing data on heat sources has shown that the best fit of the total cost function to their real-life data can be obtained when it is set in the form of a second-order polynomial [64]:

$$Z^{HS}_{j\tau}(Q^{HS}_{j\tau}) = \alpha_j \cdot (Q^{HS}_{j\tau})^2 + \beta_j \cdot Q^{HS}_{j\tau} + \gamma_j, \ \ \alpha_j > 0, \ \ \beta_j > 0, \ \ \gamma_j > 0, \ \ j \in J_{HS}, \tag{6.7}$$

where α_j (rub./(Gcal/h)^2), β_j, (rub./(Gcal/h)) γ_j (rub.) are approximation coefficients of the HS cost characteristic.

Due to the positivity of the coefficients α_j, β_j, and γ_j, the cost function is a strongly convex, monotonically increasing function that takes positive values given $Q^{HS}_{j\tau} \geq 0$.

Let us denote by $w^{HE}_{j\tau}$, $j \in J_{HS}$ the price of the production of a unit of heat, and by $w^{POW}_{j\tau}$, $j \in J_{HS}$ – the price (rate) of capacity. Then the profit of the j-th source from the heat produced by it, taking into account its constraints on heat output, will be determined from the solution to the following optimization problem:

$$F_{j\tau}^{HS}(Q_{j\tau}^{HS}) = w_j^{POW} \cdot Q_{jmax}^{HS} + w_{j\tau}^{HE} \cdot Q_{j\tau}^{HS} - Z_{j\tau}^{HS}(Q_{j\tau}^{HS}) \rightarrow \max, \quad j \in J_{HS}, \tag{6.8}$$

$$Q_{jmin}^{HS} \le Q_{j\tau}^{HS} \le Q_{jmax}^{HS}, \quad j \in J_{HS}, \tag{6.9}$$

where Q_{jmin}^{HS} and Q_{jmax}^{HS} are heat source j power constraints, Gcal/h.

Let us rewrite the problem (6.8)–(6.9) given (6.7):

$$\left(w_j^{POW} \cdot Q_{jmax}^{HS} - \gamma_j\right) + \left(Q_{j\tau}^{HS} \cdot (w_{j\tau}^{HE} - \beta_j) - \alpha_j \cdot (Q_{j\tau}^{HS})^2\right) \rightarrow \max, \quad j \in J_{HS}, \tag{6.10}$$

$$Q_{jmin}^{HS} \le Q_{j\tau}^{HS} \le Q_{jmax}^{HS}, \quad j \in J_{HS}. \tag{6.11}$$

From the problem (6.10)–(6.11) it can be seen that the dependency of the optimal amount $Q_{j\tau}^{HS(*)}$ of heat production on the heat price $w_{j\tau}^{HE}$ is determined by the following relations:

$$Q_{j\tau}^{HS(*)} = \begin{cases} Q_{jmin}^{HS}, & w_{j\tau}^{HE} < \alpha_j \cdot Q_{jmin}^{HS} + \beta_j, \\ \frac{w_{j\tau}^{HE} - \beta_j}{2 \cdot \alpha_j}, & 2 \cdot \alpha_j \cdot Q_{jmin}^{HS} + \beta_j \le w_{j\tau}^{HE} \le 2 \cdot \alpha_j \cdot Q_{jmax}^{HS} + \beta_j, \\ Q_{jmax}^{HS}, & w_{j\tau}^{HE} > 2 \cdot \alpha_j \cdot Q_{jmax}^{HS} + \beta_j. \end{cases} \tag{6.12}$$

From the above system of Eqs. (6.12) it follows that if heat prices vary within the values corresponding to the expression

$$2 \cdot \alpha_j \cdot Q_{jmin}^{HS} + \beta_j \le w_{j\tau}^{HE} \le 2 \cdot \alpha_j \cdot Q_{jmax}^{HS} + \beta_j,$$

then the amount of heat produced, which provides the maximum profit, linearly depends on the price:

$$Q_{j\tau}^{HS} = \frac{w_{j\tau}^{HE} - \beta_j}{2 \cdot \alpha_j}, \quad j \in J_{HS}. \tag{6.13}$$

Eq. (6.13) points to the fact that in the market environment the maximum profit that each source can make depends only on fuel costs. Compensation of semi-constant costs is carried out at the expense of the rate (price) for capacity per w_j^{POW} in the final price of heat production by the source j, rubles per Gcal:

$$w_{j\tau} = w_j^{POW} + w_{j\tau}^{HE}, \quad j \in J_{HS}. \tag{6.14}$$

Modeling of heat consumers. The set of heat consumers J_C can be represented in an aggregated way as a union of three subsets: $J_C = J_C^{UTIL} \cup$

$J_C^{C.HN} \cup J_C^{C.HS}$ where J_C^{UTIL} – consumers of the utilities sector, $J_C^{C.HN}$ – industrial consumers connected to heat networks, and $J_C^{C.HS}$ – industrial consumers, located at the headers of heat sources.

Let $Q_{j\tau}^C$ be the total demand of consumers at the node $j \in J_C$; given this, in what follows for brevity we will denote the demand of consumers of the utilities sector for heat energy $Q_{j\tau}^C$, $j \in J_C^{UTIL}$ as $Q_{j\tau}^{UTIL}$, the demand of industrial consumers connected to the heat networks $Q_{j\tau}^C$, $j \in J_C^{C.HN}$ by $Q_{j\tau}^{C.NT}$, and the demand of industrial consumers located at the headers of sources $Q_{j\tau}^C$, $j \in J_C^{C.HS}$ by $Q_{j\tau}^{C.HS}$, then:

$$Q_{j\tau}^C = Q_{j\tau}^{UTIL} + Q_{j\tau}^{C.NT} + Q_{j\tau}^{C.HS}, \quad j \in J_C^{C.NT} \cap J_C^{UTIL} \cap J_C^{C.HS},$$
$$Q_{j\tau}^C = Q_{j\tau}^{UTIL}, \quad j \in J_C^{UTIL} \backslash (J_C^{C.NT} \cup J_C^{C.HS}),$$
$$Q_{j\tau}^C = Q_{j\tau}^{C.NT}, \quad j \in J_C^{C.HN} \backslash (J_C^{UTIL} \cup J_C^{C.HS}),$$
$$Q_{j\tau}^C = Q_{j\tau}^{C.HS}, \quad j \in J_C^{C.HS} \backslash (J_C^{UTIL} \cup J_C^{C.HN}).$$

The demand of consumers of the utilities sector for heat $Q_{j\tau}^{UNTIL}$ is determined by the Rossander equation [65], according to which the heat load of each j-th consumer of the utilities sector at the time τ can be represented as follows, Gcal/h:

$$Q_{j\tau}^{UNTIL} = \left[1 - (1-r) \cdot \left(\frac{\tau}{\tau_{hp}}\right)^{\frac{g-r}{1-g}}\right] \cdot Q_j^{heating} + Q_j^{hws}, \quad j \in J_C^{UNTIL}, \tag{6.15}$$

where $Q_j^{heating}$ – design load of heating, Gcal/h; Q_j^{hws} – design load of hot water supply, Gcal/hour; τ_{hp} – duration of the heating period, hours; r and g – coefficients of irregularity of the heat load profile.

Demand for heat energy by industrial sector consumers is modeled by the demand characteristic, which, as a rule, is built on the basis of actual calculations for separately considered industrial consumers by approximating retrospective data, while taking into account projected estimates of heat energy consumption volumes and its prices. In more general terms, it can be represented as a linear dependence. Thus, for industrial consumers connected to heat networks, the demand function is of the form [66]:

$$Q_{j\tau}^{C.HN} = \xi_j - \vartheta_j \cdot w_{j\tau}^{C.HN}, \ j \in J_C^{C.HN}, \tag{6.16}$$

where $\xi_j > 0$, $\vartheta_j > 0$ – constants obtained in the process of approximation of actual data on the volume of heat energy purchase by an industrial enterprise based on its price; $w_{j\tau}^{C.HN}$ – purchase price, including the price of heat energy production and its transport, rubles per Gcal.

For industrial consumers located at the source header, the demand function has the form [66]:

$$Q_{j\tau}^{C.HS} = \mu_j - \pi_j \cdot w_{j\tau}^{C.HS}, \; j \in J_C^{C.HS}, \tag{6.17}$$

where $\mu_j > 0, \pi_j > 0$ – constants obtained in the process of approximation of the actual data of the volume of heat energy purchase by an industrial enterprise based on its price; $w_{j\tau}^{C.HS}$ – purchase price, which is determined only by the price of heat energy production, rub./Gcal.

Heat demand volatility is one of the main market problems for heat. In this regard, it is proposed to consider the interaction of producers and consumers during each hour of a given time period. Such discrete-time modeling is of significant practical interest because it allows one to take into account both daily and seasonal factors of heat demand, which can significantly affect the solution to the problem of heat demand and production for each HS, and therefore on the amount of profit they receive.

Mathematical modeling of heat networks. The mathematical model of the load flow in the nodal form for the conditions of the district heating system with a set of different-type consumers and heat sources in the algebraic form is written as follows [13]:

$$\begin{gathered} A_j x_\tau = Q_{j\tau}^{HS} - Q_{j\tau}^{C.HN} - Q_{j\tau}^{C.HS} - Q_{j\tau}^{UNTIL}, \\ j \in J_{HS} \cup J_C^{UTIL} \cup J_C^{C.HN} \cup J_C^{C.HS}, \end{gathered} \tag{6.18}$$

$$A_j x_\tau = Q_{j\tau}^{HS}, \quad j \in J_{HS} \backslash J_C^{UTIL} \cup J_C^{C.HN} \cup J_C^{C.HS}, \tag{6.19}$$

$$A_j x_\tau = -Q_{j\tau}^{C.HN}, \quad j \in J_C^{C.HN} \backslash J_{HS} \cup J_C^{C.HS} \cup J_C^{UNTIL}, \tag{6.20}$$

$$A_j x_\tau = -Q_{j\tau}^{C.HS}, \quad j \in J_C^{C.HS} \backslash J_{HS} \cup J_C^{C.HN} \cup J_C^{UNTIL}, \tag{6.21}$$

$$A_j x_\tau = -Q_{j\tau}^{UNTIL}, \quad j \in J_C^{UNTIL} \backslash J_{HS} \cup J_C^{C.HN} \cup J_C^{C.HS}, \tag{6.22}$$

$$A_j x_\tau = 0, \quad j \in J_0, \tag{6.23}$$

$$\overline{A}_i^T P_\tau = h_{i\tau} - H_{i\tau}, \quad i \in I, \tag{6.24}$$

$$h_{i\tau} = s_i \, |x_{i\tau}| \, x_{i\tau}, \;\; i \in I, \tag{6.25}$$

where A is the incident matrix of $m-1$ linearly independent nodes and n branches; $x_\tau = (x_{1\tau}, \ldots, x_{n\tau})$, $x_{i\tau}$ – flow rate of the heat transfer medium at the ith heat network section at the time τ, t/h; $\overline{A}^T$ – transposed matrix of connections; $P_\tau = (P_{1\tau}, \ldots, P_{m\tau})$, $P_{j\tau}$ – pressure at the jth node at the time τ, meters of water gauge; $H_{i\tau}$ pressure loss at the i-th section of the heat network at the time τ, meters of water gauge; $H_{i\tau}$ – effective pressure at the ith section of the heat network at the time τ, meters of water gauge; s_i – coefficient of flow friction of branches of the ith section of the heat network (mh^2/t^2).

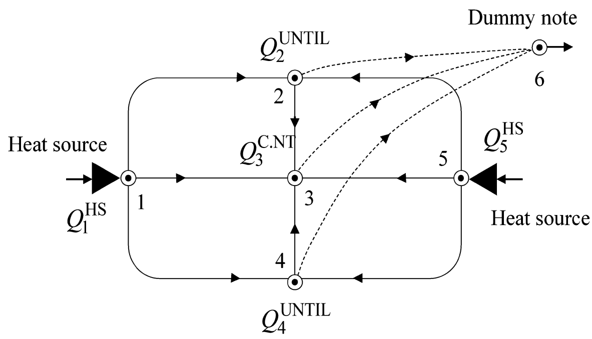


FIGURE 6.14 Construction of a redundant flow diagram of the heating system.

Solving the problem of finding the optimal load flow in the HN in the market environment is more complicated than in conventional problems of their engineering and economic analysis [67], since the loads of industrial consumers are represented as functions of the price of heat. To solve this problem, an approach based on the construction of redundant DHS design flow diagrams has been proposed [13]. The redundant flow diagram is formed on the basis of the original equivalent flow diagram of the DHS by introducing a dummy node and dummy sections connecting this node to consumer nodes, as shown in Fig. 6.14.

In the flow diagram shown in Fig. 6.14, nodes 1 and 5 represent the HS, nodes 2 and 4 correspond to consumers with a given heat load, and node 3 corresponds to the consumer, whose heat load depends on the price of heat energy. By connecting nodes 2, 3, and 4 with the dummy node 6, we obtain a redundant heating flow diagram. The flow rates at branches 2-6 and 4-6 correspond to the given loads of consumers at nodes 2 and 4, respectively, and the flow rate at the branch 3-6 is an optimized parameter. As an additional condition to the problem (6.18)–(6.25) it is necessary to introduce the equation of material balance of total heat production and consumption:

$$\sum_{j \in J_{HS}} Q_{j\tau}^{HS} - \sum_{j \in J_C} Q_{j\tau}^{C} = 0. \tag{6.26}$$

In a formalized description of a redundant flow diagram, the set of nodes J is expanded by including the dummy node $j = m + 1$. As a result, the set of nodes will have the following form:

$$J = J_{HS} \cup J_C^{C.HN} \cup J_C^{UNTIL} \cup J_C^{C.HS} \cup j_{m+1}.$$

The set of sections I of the redundant flow diagram, unlike the conventional equivalent flow diagram, is supplemented by a subset of dummy links I_{m+1} connecting the consumer nodes to the dummy node. Thus, the set of sections of the heat network will be written as follows:

$$I \cup I_{m+1}.$$

New parameters of the redundant flow diagram of DHS extended by a dummy node are as follows: number of nodes $M = m + 1$; number of sections $N = n + n_d$ (n_d – number of dummy sections in the flow diagram); number of loops $C = c + n_d - 1$. Here m, n, and c are the number of nodes, sections, and loops in the redundant flow diagram before its expansion.

After calculating the optimal load flow (system of Eqs. (6.18)–(6.26)), the network costs are determined. According to [67], the costs of heat networks are determined by the following formula, rubles:

$$Z_\tau = F_1 + F_2 \cdot \sum_{i=1}^{n} x_{i\tau}^2 \cdot |x_{i\tau}| s_i, \tag{6.27}$$

$F_1 = n_g^{-1} \cdot f_c \cdot \sum_{i=1}^{n} [a_i + b_i \cdot {\chi_i}^{u_i} \cdot {s_i}^{-0.19 \cdot u_i} \cdot {l_i}^{0.19 u_i}] \cdot l_i$ – semi-fixed costs, rubles; $f_c = 0.075$ - the share of semi– fixed operating (maintenance) costs of the heating network a_i (rubles/m), b_i (rubles/m^{u_i+1}), (dimensionless quantity) coefficients, which are obtained as a result of approximation of real (tabulated) values of the cost of pipelines of different diameters; χ_i – coefficient, depending on the roughness of the pipeline (dimensionless quantity); l_i – length of network section i, m; n_g – number of hours per year, h/year; $F_2 = \frac{C_{el}}{367.2 \cdot \eta}$ – coefficient of semi-variable costs of the HN, rubles; C_{el} – electricity price, rubles/kWh; $\eta \in (0; 1)$ - efficiency factor of the pumping unit.

Mathematical model for the management of supplying heat to consumers. When forming a mathematical model of supplying heat to consumers in the regulated monopolistic district heating market, it is necessary to formulate the statement of the problem itself, which is as follows. It is required to find such a state of the regulated monopolistic district heating market, in which HSs taken together would produce such a total volume of heat that would cover a given demand of consumers, based on the condition that they receive the maximum profit subject to the available capacity of HS and physical and engineering limitations of the HN. In this case, the price of heat for industrial consumers is determined based on their given demand functions (i.e., their willingness to pay for a unit of volume of heat supplied to them, provided that they are supplied a certain volume of heat by its producers), and the regulator sets a fair heat tariff for consumers of the utilities sector.

To model the behavior of the regulator, it is necessary to formalize its criterion. Let us assume that the regulator, defending the interests of consumers of the utilities sector, seeks to determine the minimum heat tariff for them. Let us consider the economic balance of the DHS:

$$\sum_{j\in J_{HS}} w_{j\tau}^{HE}\cdot Q_{j\tau}^{HS}+\sum_{j\in J_{HS}} w_{j}^{POW}\cdot Q_{jmax}^{HS}+Z_\tau=$$
$$w_\tau^{UNTIL}\cdot \sum_{j\in J_C^{UNTIL}} Q_{j\tau}^{UNTIL}+\sum_{j\in J_C^{C.HN}} w_{j\tau}^{C.HN}\cdot Q_{j\tau}^{C.HN}+\sum_{j\in J_C^{C.HS}} w_{j\tau}^{C.HS}\cdot Q_{j\tau}^{C.HS}. \tag{6.28}$$

Let us express from (6.28) the price of heat for consumers of the utilities sector:

$$w_\tau^{UNTIL}=\frac{1}{\sum\limits_{j\in J_C^{UNTIL}} Q_{j\tau}^{UNTIL}}\Big(\sum_{j\in J_{HS}} w_{j\tau}^{HE}\cdot Q_{j\tau}^{HS}+\sum_{j\in J_{HS}} w_{j}^{POW}\cdot Q_{jmax}^{HS}+Z_\tau-$$
$$-\sum_{j\in J_C^{C.HN}} w_{j\tau}^{C.HN}\cdot Q_{j\tau}^{C.HN}-\sum_{j\in J_C^{C.HS}} w_{j\tau}^{C.HS}\cdot Q_{j\tau}^{C.HS}\Big). \tag{6.29}$$

Thus, the mathematical model of regulated monopolistic market management of district heating will be written in the following form.

Find

$$w_\tau^{UNTIL}\to \min, \tag{6.30}$$

subject to the conditions and constraints (6.13)–(6.27).

The search for the optimal solution of the above problem is based on the application of the method of coordinate relaxation (the method of coordinate descent) [68] followed by the use of methods of redundant design flow diagrams and simple iteration inside the loop. The essence of the methodology developed is to reduce the problem of multi-dimensional optimization to the one-dimensional one, with a step-by-step procedure to improve the solutions with respect to the volume of heat production by all sources.

The calculation algorithm is as follows:

Step 1. The calculation time $\tau=\tau_0$ is set.

Step 2. The loads of consumers of the utilities sector ($Q_{j\tau}^{HS}$) are calculated according to the Rossander equation (6.15).

Step 3. $e=1$ is assigned (the cycle of the coordinate descent).

Step 4. The vector $Q_\tau^{HS(0)}=(Q_{1,\tau}^{HS(0)},Q_{2,\tau}^{HS(0)},\ldots\ldots,Q_{n,\tau}^{HS(0)})$ of the initial approximation of the volume of heat production by the sources is set.

Step 5. The value of the tariff for consumers of the utilities sector $w_\tau^{UNTIL(0)}=+\infty$ is set.

Step 6. Form a redundant flow diagram of HNS by introducing a dummy node and subsets of dummy links connecting it to all consumer nodes.

Step 7. Assign $j = 1$, $k' = 1$, where $j \in J_{HS}$, and k' is the step in the downward direction for the function of the tariff for consumers of the utilities sector.

Step 8. The optimal load flow in the network (6.18)–(6.26) is calculated.

Step 9. The network costs are calculated as per the formula (6.27).

Step 10. Heat flow rates obtained at the dummy links connecting industrial consumers to the dummy node are taken as current loads.

Step 11. Based on the obtained values of loads of industrial consumers, heat prices are calculated according to their demand functions (6.16), (6.17).

Step 12. The tariff is calculated according to the expression:

$$\tilde{w}_{k',\tau}^{UNTIKL(e)} = \frac{1}{\sum\limits_{j \in J_C^{UNTIL}} Q_{j\tau}^{UNTIL}} \Big(\sum_{j \in J_{HS}} w_{j\tau}^{HE} \cdot Q_{j\tau}^{HS(e-1)} + \sum_{j \in J_{HS}} w_j^{POW} \cdot Q_{j\_max}^{HS} + Z_\tau - \sum_{j \in J_C^{C.HN}} w_{j\tau}^{C.HN} \cdot Q_{j\tau}^{C.HN} - \sum_{j \in J_C^{C.HS}} w_{j\tau}^{C.HS} \cdot Q_{j\tau}^{C.HS} \Big).$$

Step 13. If $\tilde{w}_{k,\tau}^{UNTIL(e)} < \tilde{w}_{k,\tau}^{UNTIL(e-1)}$, then $Q_{j,\tau}^{HS(e)} = Q_{j,\tau}^{HS(e)} + \Delta Q_j^{HS(e)}$, $k = k + 1$, go to step 8. Otherwise $w_\tau^{UNTIL(e)} = \tilde{w}_{k,\tau}^{UNTIL(e)}$, $j = j + 1$, of $j < m$ go to step 8.

Step 14. Perform a convergence check: if $\left| Q_{j,\tau}^{HS(e)} - Q_{j,\tau}^{HS(e-1)} \right| \leq \varepsilon$ for all $j = 1, \ldots, m$, then $\tau = \tau + 1$ and then go to step 2, otherwise $e = e + 1$ and then go to step 6.

Step 15. The end of the algorithm.

The flowchart of this algorithm is shown in Fig. 6.15.

Practical implementation of the developed mathematical model of management of supplying heat to consumers. The calculations were performed for the DHS of one of the Russian cities, which in its aggregated form consists of 1,273 sections and 1,242 nodes (Fig. 6.16). The number of aggregate consumers in the flow diagram is represented by 534 nodes, of which 533 nodes correspond to consumers with fixed heat loads (consumers of housing and communal services), and one node is represented by an industrial enterprise (IE) connected to the headers of CHPP-1 and CHPP-2 with a heat demand function related only to the price of heat generation.

Modeling of the DHS of the municipality was carried out in the GAMS (General Algebraic Modeling System) computing environment

The calculations were performed for a time interval of 1 year. Calculated metrics of the municipality's DHS are presented in Table 6.7.

Table 6.7 shows that under the conditions of the arrangement of supplying heat to consumers within the UHO framework, CHPP-2 covers 57.3% of the total heat load, the share of CHPP-1 is 22.6% and that of CHPP-3 is 20.1%.

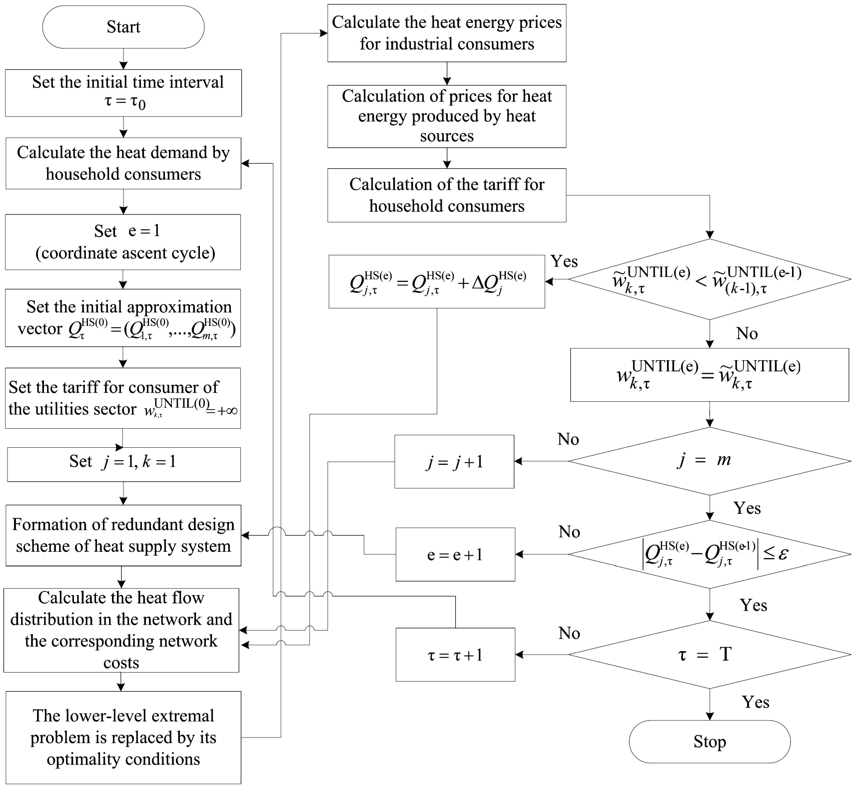


FIGURE 6.15 Flowchart of the algorithm developed.

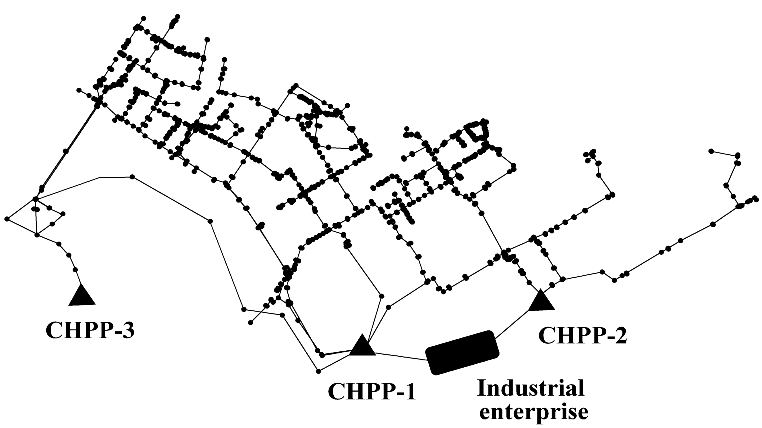


FIGURE 6.16 Equivalent flow diagram of the municipality's DHS.

TABLE 6.7 Estimated integral technical and economic performance metric of the municipality's DHS.

Metrics		Value
Volume of heat production, mln. Gcal, including:		6.85
	CHPP-1	1.55
	CHPP-2	3.92
	CHPP-3	1.38
Heat production costs (fuel costs), bln. rubles, including:		3.30
	CHPP-1	0.78
	CHPP-2	1.91
	CHPP-3	0.61
Semi-fixed (operating) costs, bln. rubles, including:		2.19
	CHPP-1	0.43
	CHPP-2	1.05
	CHPP-3	0.71
Price of heat production, rubles/Gcal:		
	CHPP-1	647.6
	CHPP-2	646.8
	CHPP-3	649.7
Price of capacity, rubles/Gcal		
	CHPP-1	29.4
	CHPP-2	36.0
	CHPP-3	42.3
Profit, bln. rubles, including:		1.02
	CHPP-1	0.22
	CHPP-2	0.62
	CHPP-3	0.18
Costs of heat networks, bln. Rubles		1.22
Price of heat energy for consumers of utilities sector, rubles/Gcal		862.7
Price of heat energy for the IE, ruble/Gcal		1,350.5
Volume of heat energy consumption of the IE, mln. Gcal		2.10
Volume of heat consumption by consumers of the utilities sector, mln. Gcal		4.75

The main heat consumer in the city is the utilities sector, accounting for 69.3% of all heat produced by the district heating system, and 30.7% is consumed by the industrial enterprise process facilities.

The average annual minimum tariff for consumers in the utilities sector will be 862.7 rubles/Gcal (excluding VAT), and for the IE it will be 1,350.5 rubles/Gcal. The total revenue of the UHO from the sale of heat to consumers will amount to 5,65 bln. rubles, and its total profit of heat sources during the reviewed period – 1,22 bln. rubles, from which 0,22 bln. rubles are accounted for by CHPP-1, 0,62 bln. rubles – by CHPP-2, and 0,18 bln. rubles by CHPP-3. The costs of heat transport (costs of the heat networks) amounted to 1.22 billion rubles, which is about 178.1 rubles/Gcal.

On the basis of the review of the published research and the analysis of the current situation in the heating sector, we have presented a new statement of the problems of development of district heating systems for the conditions of the organizational model in the form of a regulated monopolistic market, the requirements to the mathematical models and methods used for their solution, the conceptual considerations on interaction of the participants of the process of delivering heat to consumers in the form of a hierarchical vertically-integrated system. The developed mathematical model of the district heating system is focused on a two-level management system when the regulator controls tariffs for consumers of the utilities sector, industrial consumers buy heat energy in accordance with the demand function, and heat sources cover a given total demand of consumers under the condition of obtaining the maximum profit. For such a statement of the problem, we have proposed a criterion for optimizing the regulator. We calculated the technical and economic performance metrics of the municipal heating system using a two-level approach.

The bilevel mathematical model best reflects the real conditions that are formed in the local heat markets. It reasonably well accommodates the established "rules of conduct" in the heat market, as well as the physical, engineering, and economic constraints of the system in question.

The scientific and methodological basis we have developed is universal and allows one to model heating systems of any scale and capacity, taking into account multiple heat sources and consumers of different types.

6.5 Review on the methods for the hierarchical reliability analysis of district heating systems

The main provisions and current state of the problem. DHSs are currently a topologically complex structure with multiple HSs and consumers distributed over a large territory. These systems are constantly developing and undergoing technological modernization. The issue of assessment and ensuring a high level of reliability of DHSs called for the creation of a science-based effective methodology for its solution.

The first studies of the reliability of heating systems operation with application of mathematical methods of the reliability theory are date back to the period of the most active development of district heating of cities (1960s–1970s) on the basis of cogeneration-based district heating, or the technology of heat and electricity production at CHPP. Subsequently, a significant amount of research in this area was carried out, various methods and models for solving the problems of analysis and synthesis of reliability of subsystems of DHS, i.e. HS and HN were developed [69], standards for RI were substantiated, and a database of statistical data on equipment failures was created. At present, theoretical and applied problems of reliability of heating systems not only have not lost their relevance but are getting more and more in demand in connection with the increase of the structural complexity of systems, their innovative transformations, and the active participation of consumers in the process of power supply management.

A new aspect of the problem of reliability and efficiency of heating system operation arises in connection with their innovative and technological development in the transition to the so-called 4th generation DHS [70–73], a number of studies already consider the 5th generation DHS. This transition is consistent with the global trend of energy development, in which integrated power systems with intelligent control are being formed [74–76]. Active consumers (prosumers) [77–79] have a special function in this process, having their own HS and heat storages. This allows the most efficient combination of district and distributed heating systems in the urban infrastructure.

At the same time, the objective process of development of heating systems leads to the need to revise existing approaches to the study of their reliability, taking into account new aspects associated with the introduction of modern technologies, the emergence of new structural objects and connections, changes in structure, properties, and operating conditions. New methods and models for heating reliability analysis should be aimed, first of all, at comprehensive consideration of all technological processes affecting the reliability of heating of consumers, starting from fuel supply of the heating system to heat distribution to consumers. This approach implies both hierarchical representation and modeling of the object of the study, combining different systems, and hierarchical structuring of reliability problems and methods of solving them.

Methods for the reliability analyzing of fuel supply to HSs. The totality of fuel production, transportation, and storage facilities at the HS is formed FSS. These systems vary in fuel type (coal, oil, gas, etc.), structure, and scale. As a rule, the aggregated structure of the FSS allows allocating within its structure two main subsystems – fuel extraction and transport systems. Analysis of the reliability of the FSS that are characterized by the distributed structure of facilities and the presence of many intra-system and external factors (including stochastic ones), affecting the volume of fuel supplies and fuel requirements, is a rather complex scientific and methodological problem [80]. The main external factor affecting fuel consumption at the HS is the climatic factor, which is related to fluctuations in ambient air temperature [81,82]. Changes in wind loads and the intensity of solar radiation have a less significant effect. Intra-system factors are determined by the structure and technological processes of fuel production, transport, and consumption, as well as the interchangeability of fuels between HSs of one system, the volume of fuel storage, etc.

All of these factors have a complex effect on the volume of HS fuel supply and consumption, causing regular and random fluctuations on a daily, seasonal, and multi-year basis. In addition, the issue of lack of statistical information about failures of elements is more relevant for the FSS than for other subsystems of the heating system (this applies to a greater extent to coal systems). At the same time, for the majority of HS operating as part of heating systems, there are multi-year statistics on the volume of fuel supplies and consumption. This allows the simulation algorithms based on the use of the statistical testing method (Monte Carlo method) to be employed as an apparatus for the FSS reliability study (as concerns the fuel supply of the HS under consideration). One such approach to analyzing the reliability of fuel supply to the HS is considered in [83], which presents a methodology for determining possible coal shortages at the HS arising from a malfunction of the FSS. It is based on the use of probability distributions of random values of fuel demand and supply over a certain period of time, based on a statistical analysis of the actual dynamics of these metrics. The algorithm for solving the problem consists in carrying out multivariate procedures for generating these random variables, taking into account the density of their distributions. These procedures form 'scenarios' that simulate the annual or multi-year process of fuel supply, consumption, and creation and use of its stocks. As a result of the calculations, different RI are calculated: the frequency of occurrence and the average value of shortage and/or excess of fuel, the probabilities of occurrence of shortage, and the expected value of fuel shortage.

The considered methodology and other similar developments are aimed at analyzing the reliability of fuel supply at the level of a given fuel supply system as a whole. The obtained RI make it possible to estimate the level of the overall reliability of the system studied for the entire calculation period without its differentiation by fuel consumption nodes. Such estimates are useful in analyzing the operation of the energy sector but do not allow them to be interpreted to assess the impact of disruptions in the DHS on the reliability of supplying heat to consumers within an individual heating system. In this regard, a dedicated methodology of localized analysis of FSS reliability is needed. Its results could be used when analyzing the reliability of supplying heat to consumers and take into account the impact of possible fuel shortages on the under-supply of heat from the HSs that operate as part of the given heating system.

To analyze the reliability of pipeline FSS, along with the methods of statistical modeling one widely uses methods based on combining deterministic network models of operating conditions (mainly hydraulic) and random process models for probabilistic description of the states of these systems [84]. This approach is one of the most effective and versatile for solving the reliability problems of pipeline systems and a number of other systems of the energy industry that have network features [85–88].

Methods of HS reliability analysis. In the established scientific and design methodology, the process of solving reliability problems of heating systems is divided at the level of their subsystems, i.e., the HS and HN [69]. Accordingly, a review of reliability analysis methods is also conducted separately for the HS and HN. To date, significant scientific, methodological and practical experience has been accumulated in the field of HS reliability analysis and assurance. The objects of reliability research of HS of different types and capacities have a number of common features, which allows the process flow diagram of any HS to be presented in the form of separate modules with certain functions and specified parameters, combined into unified reliable flow diagrams.

Methods of HS reliability analysis can be divided into two main groups: analytical methods and statistical modeling methods. The methods of the former group are based on the use of Markov models [69,89–96], semi-Markov random processes [69,97,98], and other deterministic logical and probabilistic approaches and algorithms [62,99–101]. Solving of reliability problems, in this case, is carried out based on the equivalent flow diagrams of HS with the specified parameters of reliability of components. The degree of aggregation (merging) of the initial component flow diagram is determined by the goals and the required detailing of the results of the reliability calculation. The typical methodology of HS reliability analysis based on the application of Markov random processes includes the following stages: formation of the set of possible states corresponding to failures of various components; construction of the structure of events associated with failures and recoveries of components of the equivalent flow diagram (usually in the form of a directed graph of states and connections between them); solving of the system of equations of a Markov random process that describes the formed structure of events, so as to determine the probabilities of HS states; evaluation of RI that characterize some or other properties of the reliability of the HS under study. Application of semi-Markov random processes allows modeling the change of reliability parameters of components in time and, consequently, the probabilities of HS states, which can increase the validity of reliability analysis by taking into account some additional factors inherent in the operation of the facilities studied (for example, the time reserve associated with passive accumulation of thermal energy, the availability of hot water reserves, etc.). This approach involves integrating deterministic models of thermophysical processes with a system of equations for the random process of HS operation. This significantly complicates the computational mathematical model, so the choice of semi-Markov processes to solve the problems of HS reliability should be based on the optimal balance of labor intensity of calculations and the accuracy of the results obtained.

The methods of the second group of HS reliability analysis (statistical modeling methods) are based on simulation algorithms that usually employ the method of statistical tests (Monte Carlo method) to simulate possible states of the facility [102,103]. Such algorithms do not require a detailed flow diagram of components of the HS, and the input information for modeling is statistical data on failures of the facility studied (or a similar facility) for a certain period of time. Some such techniques are presented in [69,104–108]. The method of statistical tests, widely used in the study of the reliability of energy systems, allows one to obtain very reliable estimates of the reliability of HS operation, but it requires a large amount of preliminary work on the collection and preparation of the input information. In this regard, in many cases, the use of such an approach in practice is impossible due to the lack of the necessary array of statistical data to form a representative sample of modeling parameters.

Methods of HN reliability analysis. The methodological approaches used in the analysis of HS reliability are largely applicable to solving similar problems for the HN operating as part of the heating system. The existing HN of large district heating systems are topologically complex multi-loop pipeline structures connecting centralized HS with heat consumers and distributed over many kilometers (the length of the HN in large district heating systems reaches hundreds of kilometers). This imposes special requirements to the methods of their reliability analysis associated with the need for thermal-hydraulic modeling of emergency modes in combination with the stochastic description of the corresponding states. Such a systematic approach to HN reliability analysis was first proposed in [109], where the basic principles of calculating the reliability and redundancy of HN were laid out. As a result of the subsequent development of this approach, a methodology for the analysis of nodal reliability of HN was developed at the Melentiev Energy Systems Institute of SB RAS [67,69]. In this methodology, we apply the methods of the Theory of hydraulic circuits [13] to calculate the emergency operating conditions in the HN, corresponding to failures of its components (sections), and the probabilities of states corresponding to these failures are determined using simplified models of a random Markov process. Reliability assessment is performed on the basis of nodal RI as defined for each consumer node. This is the main advantage of nodal reliability analysis. It is aimed at identifying consumers with the lowest level of heating reliability, which subsequently allows taking the most effective measures to improve system reliability through the optimal redistribution of available reserves.

Along with the nodal approach to HN reliability assessment, there is another concept based on the use of the integrated (overall) RI [110–112]. This approach does not require multivariate calculations of emergency modes and it is reasonable to use it for express reliability analysis. The integrated RI quantitatively evaluates the level of performance of the given functions and reflects some property of reliability for the whole HN during the calculation period, but it is not interpreted in terms of quality of performance of the functional purpose of the heating system in relation to the consumers. This does not allow using the results of the overall reliability analysis for its decomposition with the highlighting of ‘bottlenecks’ in the system and the identification of possible failures, leading to prolonged disconnection from heating to individual groups of consumers. Ensuring overall reliability across the system does not guarantee the required level of reliability at all of its nodes. As part of this study, a nodal approach to the reliability analysis is employed, so the concepts of 'reliability of heating system operation' and 'reliability of heating to consumers', in fact, are interchangeable. However, in the general case, these concepts are not identical, because in the first case the overall (system) reliability is meant, and in the second case it is the nodal reliability.

6.6 General methodological provisions of the hierarchical and comprehensive reliability analysis of district heating system

Statement of the problem of hierarchical and comprehensive reliability analysis of DHS. Based on the review and analysis of the published research, we can conclude that the existing methods, as well as the experience gained in the design and operational practices, are usually aimed at assessing the reliability of heating systems separately: i.e., at the level of the HS and HN. This separation of problems leads to isolated results that do not allow us to determine the level of reliability of heating of consumers, taking into account the total contribution of heating system subsystems and their mutual influence (system emergence effect), which is largely manifested when several sources work for a single centralized network. In this case, the assessment of the reliability of different types of systems is carried out with different RI reflecting certain properties of their reliability but not allowing them to be used together to assess the overall impact. In addition, the analysis of the reliability of heating fails to take into account the possible disruption of fuel supply to the HS. Assessment of fuel shortages in the FSS is usually performed at the level of energy security analysis of the energy sector. The results of such analysis obtained at this hierarchical level cannot be used at the level of individual heating systems to quantify the impact of fuel supply failures on the reliability of heating from the HS and the reliability of heating of consumers.

Technological connectivity, continuity, and mutual influence of the processes of fuel extraction and supply, production, distribution, and consumption of heat energy are the basis for a comprehensive hierarchical approach to the study of the reliability of their operation. This approach involves joint modeling, calculation, and analysis of the entire process chain of heat production and distribution. Aggregation of the corresponding technological processes allows us to present them as two relatively independent systems: the FSS, consisting of subsystems of extraction and transport of fuel, and the heating system, combining HS and HN. Together, they form the HC. Fig. 6.17 shows the hierarchical structure of the HC divided into 3 levels: the upper level (the level of the HC as a whole), the middle level (the level of the FSS and HS), and the lower level (the level of division of the FSS and fuel transport system into subsystems).

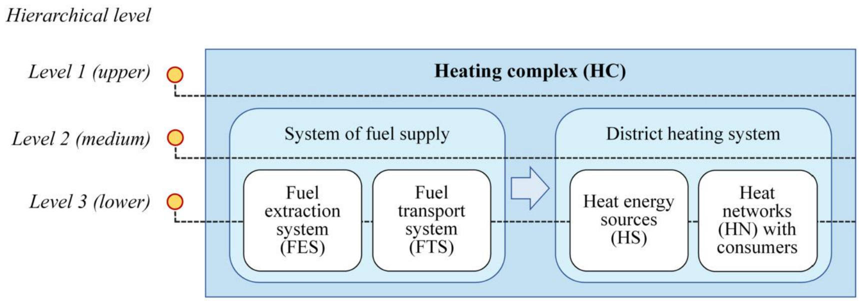


FIGURE 6.17 Hierarchical structure of the HC as an object of comprehensive reliability analysis of heating to consumers.

The main problem of the comprehensive hierarchical analysis of the HC reliability is to determine the integral impact of all subsystems on the reliability of heating to consumers. From the methodological standpoint, this problem consists in determining the RI relative to each heat consumer (nodal approach), accounting the influence of all technological stages of fuel supply and heating at the level of HC subsystems, as well as a lot of internal and external factors. Another important problem of reliability analysis and synthesis is the decomposition of the level of reliability of heating in relation to each system (component) of the HC and quantitative assessment of the degree of their influence on the level of reliability of delivering heat to consumers.

The solution to the stated problem is a methodologically complex and composite problem related to both the solving of the key tasks of reliability calculation, aimed directly at calculating RI, and the support of many auxiliary tasks, providing accumulation and processing of information about the properties of the components of systems under study, assessment of the impact of external factors on performance metrics of subsystems, the development of regulatory requirements, etc. Many of these particular questions constitute the subject of separate studies, and the methodological considerations set forth below are the basis for their statement and solution.

Methodology of hierarchical comprehensive analysis of district heating systems (heating reliability). An overall workflow of the methodology is outlined in Fig. 6.18. Its main tenets are differentiated with respect to hierarchical attributes into two groups by systems and by the problems to be solved. The hierarchy of systems is structured according to the object of research (see Fig. 6.17) at the level of FSS, DHS, and the entire HC as a whole. The set of problems of reliability analysis and methods for solving them is divided into three main subproblems: probabilistic modeling of HC operation; analysis (calculation) of operating conditions of its subsystems; direct evaluation of RMs. A separate module contains the results obtained at some steps of the method and used at some other steps. The final result is the nodal RI calculated using the previously obtained intermediate results (Fig. 6.18).

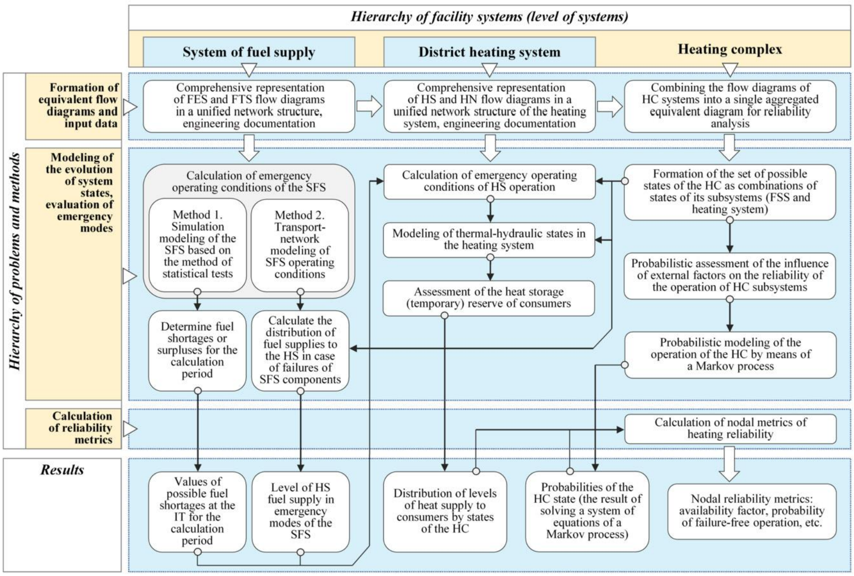


FIGURE 6.18 Methodology for a comprehensive analysis of the reliability of heating – Hierarchy of systems, problems, and methods of solving them.

The topological basis for solving a group of problems associated with probabilistic modeling of HC states is its functional equivalent flow diagram, formed by combining the flow diagrams of its subsystems with a uniform representation of their structure and relationships of elements. Multiple options of separate consideration of FSS and heating system flow diagrams with different methodological approaches to the assessment of emergency operating conditions of their operation are possible. The set of states of the HC (or at the level of individual systems) is formed as a combination of states of its subsystems, taking into account the technological possibility of their implementation (more details provided below). This set can also take into account an array of external (not related to the failure of elements) factors, which requires prior research and statistical analysis of their impact on the performance of the systems under consideration. The estimation of the probabilities of HC states is performed taking into account the given reliability parameters of elements (failure and restoration rates) based on the Markov random process model, which describes the evolution of the facility states. In this case, it is possible to take into account additional conditions associated with the uncommonness and dependence of events.

Methods of analysis of emergency operating conditions of HC subsystems are based on the application of various mathematical models that take into account their process specifics. Assessment of the FSS emergency operating modes can be carried out on the basis of one of the two proposed methodological approaches (Fig. 6.18): simulation modeling based on the method of statistical tests; transport network modeling of the FSS operating conditions. The first approach implies, in fact, a comprehensive analysis of the reliability of the FSS. It is usually used for coal systems, which are difficult or almost impossible to present in the form of an equivalent flow diagram, taking into account all the transport flows, components, and parameters of their reliability. Since the application of this approach does not involve the construction of the FSS component flow diagram, its comprehensive representation and probabilistic modeling are carried out as part of a combination of heating system subsystems (HS and HN). In this case, the levels of fuel availability of the HS (shortage and surplus), obtained at the stage of FSS simulation, determine their performance for the design period (heating season). These metrics are both are important in their own right for the FSS reliability analysis and are used in modeling the load flow in the HN, taking into account possible failures of HS and HN equipment. Based on their results, the levels of emergency heating of consumers in all states of the HC are estimated, taking into account the disturbances in the operation of all its subsystems. The second method of assessment of emergency operating conditions of fuel supply is used for pipeline FSS that have a given flow diagram with known reliability parameters of components. This flow diagram is used to calculate the distribution of fuel supplies by nodes of its consumption (including the HS) under various failures. This study uses the first approach, according to which a methodology for analyzing the reliability of HS fuel supply based on simulation modeling has been developed.

The results of modeling the evolution of states of HC subsystems (probabilities of states), modeling emergency modes in these states (levels of heating of consumers) are jointly used to determine the nodal RI which characterize the reliability of the whole complex operation relative to each consumer. In determining these figures, the time excess in the system due to the heat storage effect is also taken into account.

The methodology of comprehensive hierarchical reliability analysis of DHS (or reliability of the heating to consumers) and its practical applications are described in studies [113–119]. Based on a comprehensive approach to the reliability analysis of the heating system we have developed a methodology for ensuring its component reliability [120,121]. In what follows we consider the main models and methods of solving various tasks of the overall analysis of the reliability of heating in accordance with the hierarchical structure shown in Fig. 6.18. To test the methods developed we perform a comprehensive and decomposition analysis of the existing DHS of one of the Russian municipalities while taking into account possible disturbances of fuel supply of the district HS.

6.7 Simulation modeling of FSS operation based on statistical test method for the reliability analysis of fuel supply to HS

Initial provisions. The reliability of the FSS operation is determined by the proportions between the levels of demand and fuel supply during the time period in question. The discrepancy between these levels determines the shortage or surplus (accumulated stock) of fuel. In this study, a simulation algorithm based on the application of the statistical testing method is used to quantify the availability of fuel supplies to the HS. The choice of this approach is due to the practical complexity of obtaining the reliability parameters of the FSS components [80,83].

Levels of fuel supplies to the HS depend on many factors of both intrasystem and external origin: emergencies at production sites and on fuel transport routes caused by both equipment failures and environmental impacts; economic risks caused by the relationship between fuel suppliers and consumers, etc. The required amount of fuel consumed for HSs is also determined by multiple factors, among which the main one is the change in ambient air temperature. A beyond-design decrease in its annual average value leads to an increase in heat loads and heat consumption, and, accordingly, an increase in the required amount of fuel. Compensation of fuel shortages arising due to beyond-design fall in temperature is made from annual and current reserves calculated based on the conditions of a series of readings from previous years on the average value of ambient air temperature. This reserve is limited by the capacity of fuel-producing enterprises and the available capacity of fuel storage facilities. In this regard, it is possible that the ambient temperature may decrease or increase its duration, at which the demand for fuel may exceed the current production volumes and reserves. Assessment of the probability of occurrence of such an event should be based on statistical data of multiple-year observations, their analysis, processing, and analytical presentation for considering in calculations.

Building mathematical models describing the conditions of fuel supply and consumption at the HS and taking into account the influence of these and other factors on them appears to be quite a difficult problem. At the same time, statistical processing of data on changes in fuel supply and demand caused by the impact of the most significant disturbances allows us to obtain distributions of random values of fuel supply levels and demand for each HS of the investigated heating system. The obtained distributions are used in the simulation modeling of the FSS operation based on the method of statistical tests. This approach allows us to take into account a priori the specific features and conditions of operation of the system under a set of external disturbances affecting it and compensate for the lack of input information on the reliability parameters of its components. The positive experience of using such approaches in modeling fuel supply is confirmed by a number of studies performed on this topic and referred to above.

The FSS reliability assessment model proposed herein is focused on determining the demand and supply of fuel by given time intervals of the heating season (or the distribution of fuel shortages and surpluses by intervals of this period). This provides an opportunity to consider the states of the heating system under various conditions of the HS fuel supply, including its possible disturbances.

Thus, the levels of fuel demand and supply for some i-th HS in a certain time interval n are given by the values a_n^i and b_n^i, respectively, (t e.f., i.e. tons of equal fuel, other dimensions can also be used). Discrete or continuous distributions of these quantities are given as initial data for modeling (generating of corresponding random values). In this case, the following conditions must be met [83,125]:
for discrete distributions:

$$\sum_{a_n^{i\min}}^{a_n^{i\max}} p\{a_n^i\} = 1, \sum_{b_n^{i\min}}^{b_n^{i\max}} p\{b_n^i\} = 1, \tag{6.31}$$

for continuous distributions:

$$\int_{a_n^{i\min}}^{a_n^{i\max}} f(a_n^i)da_n^i = 1, \int_{b_n^{i\min}}^{b_n^{i\max}} f(b_n^i)db_n^i = 1, \tag{6.32}$$

under conditions:

$$f(a_n^i) = 0, f(b_n^i) = 0, \text{if}\, a_n^i \notin [a_n^{i\min}, a_n^{i\max}], b_n^i \notin [b_n^{i\min}, b_n^{i\max}], \tag{6.33}$$

where $p\{a_n^i\}$ and $p\{b_n^i\}$, $f(a_n^i)$ and $f(b_n^i)$, $a_n^{i\min}$, $a_n^{i\max}$ and $b_n^{i\min}$, $b_n^{i\max}$ – probabilities, distribution densities and ranges of values of random variables a_n^i and b_n^i respectively. Calculated time period τ_0 (h), is taken, as a rule, equal to the heating season. This period is divided into time intervals of duration τ_n (h), $n \in N$, where N is the set of time intervals. The total number of considered HSs is combined by a set I. The modeling takes into account the possibility of substituting (interchangeability) fuel between sources (if such possibility exists for a type of fuel and transport infrastructure) by compensating for fuel shortages at some HSs due to surpluses at others.

Algorithm for reliability analysis of FSS. Here is considered Algorithm for reliability analysis of FSS based on statistical test method accounting the initial provisions provided above.

Stage 1. Formation of initial information for each time interval n:

a) average fuel demand by the i-th source $\bar{a}_n^i$ (t e.f.), $i \in I$, calculated from the average outdoor temperature for interval in accordance with the productivity of the source;

b) average value of fuel supply to the i-th source $\bar{b}_n^i$ (t e.f.), $i \in I$, accepted based on retrospective data;

c) distributions of random variables of fuel demand and supply a_n^i and b_n^i respectively, as well as their ranges $a_n^i \in [a_n^{i\,\min}, a_n^{i\,\max}]$, $b_n^i \in [b_n^{i\,\min}, b_n^{i\,\max}]$, in accordance with conditions (6.31) or (6.32);

d) for each i-th source for the initial interval, the seasonal fuel reserve c_n^i (t e.f.), $n = 1$; also, if available, the values of current reserves for each interval can be taken into account as some standard level;

e) other conditions and parameters.

Stage 2. Determining the fuel demand and supply for each i-th HS at each interval n. In accordance with the previously obtained distributions of random variables a_n^i and b_n^i, their values are generated using a statistical test model (random number generator). Repeating these procedures multiple times allows us to increase the number of possible ‘scenarios’ for the functioning of the studied FSS. As for all algorithms based on multivariate calculations using the statistical data, the reliability of the result increases with increasing the number of times tested and the correctness of the initial data on the functioning of the modeling fuel supply system.

Stage 3. Distribution of fuel flows in FSS. For each considered time interval and source the following sequence of logical procedures and calculations is carried out which consists in distribution the fuel reserves in the system, accounting the possible substitution of fuel between HSs.

1. Checking the relation of demand and fuel supply values generated in Stage 2. There are two options: (a) $a_n^i \le b_n^i$ and (b) $a_n^i > b_n^i$.

2. Option (a): $a_n^i \le b_n^i$. The amount of used fuel is equal to its demand, i.e. $a_{n(\text{use})}^i = a_n^i$, fuel shortage $d_n^i = 0$, and the possible surplus of fuel generated at source is equal to:

$$a_{n(\text{sur})}^i = b_n^i - a_n^i. \tag{6.34}$$

3. At zero surplus, i.e. at $a_n^i = b_n^i$, its entire value is used to cover the demand, and the reserve for the next interval c_{n+1}^i (t e.f.) is at the current level c_n^i.

4. With a nonzero surplus, i.e. at $a_n^i < b_n^i$, and provided that its value exceeds some necessary (standard) current reserve $a_{n(\text{res})}^i$ (t e.f.), i.e. at

$a^i_{n(\mathrm{sur})} > a^i_{n(\mathrm{res})}$, then a part of this surplus $c^i_{n(\mathrm{dn})}$ (t e.f.) is used by 'deficient' HSs from the group $i \in I'_n$:

$$c^i_{n(\mathrm{dn})} = a^i_{n(\mathrm{sur})} - a^i_{n(\mathrm{res})}. \tag{6.35}$$

Otherwise, if $a^i_{n(\mathrm{sur})} \le a^i_{n(\mathrm{res})}$, the entire surplus goes into the reserve for the next calculation interval:

$$c^i_{n+1} = c^i_n + a^i_{n(\mathrm{sur})}. \tag{6.36}$$

5. Option (b): $a^i_n > b^i_n$. The used fuel $a^i_{n(\mathrm{use})}$ is the sum of supplied and additional reserve $c^i_{n(\mathrm{add})}$ (t e.f.):

$$a^i_{n(\mathrm{use})} = b^i_n + c^i_{n(\mathrm{add})}. \tag{6.37}$$

6. The required volume $c^i_{n(\mathrm{add})}$ is estimated:

$$c^i_{n(\mathrm{add})} = a^i_n - b^i_n. \tag{6.38}$$

7. Next, it is checked whether the available reserves at the source are sufficient to compensate for the undersupply of fuel. Accordingly, two options are possible: (a) sufficient if $(a^i_n - b^i_n) \le c^i_n$, and (b) insufficient if $(a^i_n - b^i_n) > c^i_n$.

8. Option (a) corresponds to a zero shortage, while 2 scenarios are possible:

1) the available reserve exceeds the required additional fuel, i.e. $c^i_{n(\mathrm{add})} < c^i_n$, in this case, the reserve for the next interval is formed from the balance:

$$c^i_{n+1} = c^i_n - c^i_{n(\mathrm{add})} = c^i_n + b^i_n - a^i_n; \tag{6.39}$$

2) the available reserve is fully used, i.e. $c^i_{n(\mathrm{add})} = c^i_n$, in this case the reserve for the next interval $c^i_{n+1} = 0$.

9. Option (b) involves the use of system operating reserves, which are formed with fuel surpluses from other sources from the group of substitution fuel type. There are 2 scenarios, depending on the volume of the system fuel reserve $c^i_{n(\mathrm{ac})}$ (t e.f.):

1) if it is enough to cover the shortage, i.e. $c^i_{n(\mathrm{ac})} \ge c^i_{n(\mathrm{add})} - c^i_n$, in this case the shortage is equal to zero;

2) if it is not enough to cover the shortage, i.e. $c^i_{n(\mathrm{ac})} < c^i_{n(\mathrm{add})} - c^i_n$, in this case, a shortage is formed, defined as follows:

$$d^i_n = a^i_n - b^i_n - c^i_n - c^i_{n(\mathrm{ac})}. \tag{6.40}$$

The presented computations are performed sequentially for each i-th source. As a result, we obtain the values of fuel shortages and reserves for the next calculation interval $n+1$, for which the calculation is made according to the above stages. The algorithm described above is shown in Fig. 6.19.

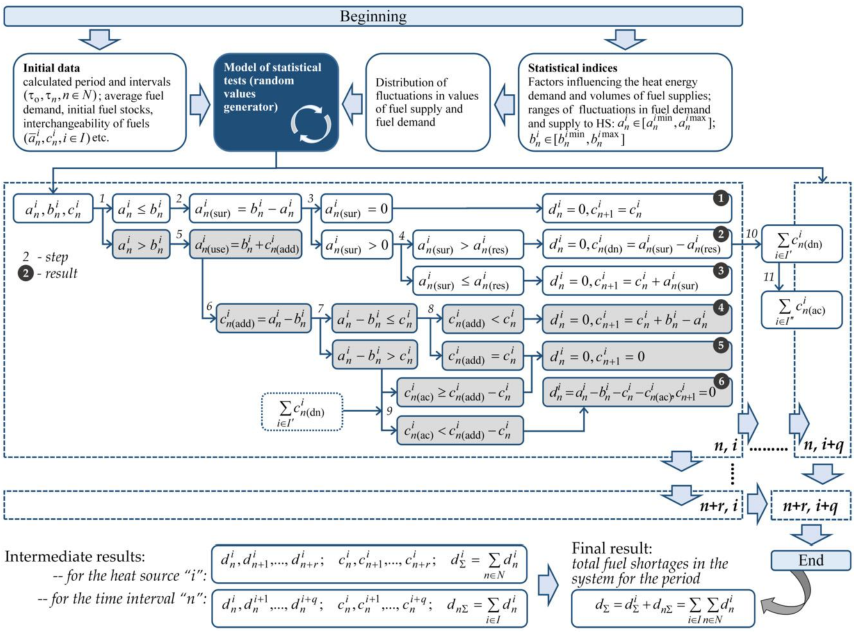


FIGURE 6.19 A methodological scheme for the reliability analysis of fuel supply of heat sources in district heating systems.

Integral assessment of fuel shortages. Fuel shortages at each considered source are used as reliability indices. As a result of multivariate calculations carried out according to the presented algorithm, N pair of shortage and reserve values is formed for each HS. The average summary assessment of fuel shortages was performed for each HS and for the system as a whole (t e.f.):

$$d_\Sigma^i = \sum_{n \in N} d_n^i;\ d_{n\Sigma} = \sum_{i \in I} d_n^i; \tag{6.41}$$

$$d_\Sigma = \sum_{i \in I} \sum_{n \in N} d_n^i. \tag{6.42}$$

The results obtained are both of independent importance for assessing the reliability of the functioning of studied FSS, and can be used to determine the possible undersupply of thermal energy from considered HSs caused by fuel shortages. In this case, the assessment can be made for each interval and for the entire period. There are various options for interpreting the fuel shortages to assess the impact of the fuel component on the reliability of heating to consumers in DHS accounting different system states of component failures.

6.8 Probabilistic modeling of DHS functioning based on the Markov random processes

Formation of the system state set for the probabilistic modeling. Operation of DHS in terms of its probabilistic description is characterized by a sequence of events of failures and recoveries of their elements, occurring with a certain frequency at all process stages of production and distribution of heat energy. To describe this sequence, we employ a Markov random process model, which is one of the most well-grounded and versatile apparatuses for assessing the reliability of restorable systems [69,125–128]. The evolution of states in DHS in the simplest case (with maximum assumptions) is described by the simplest flow of events, which corresponds to the conditions of stationarity of reliability parameters of elements and probabilities of states, exponential laws of distribution of the system time spent in different states, conditions of ordinariness and independence of events [69,122–126].

Formation of the set of heating system states is carried out in accordance with the overall hierarchical approach to the analysis of the reliability of delivering heat to consumers. This approach is based on the hypothesis that there is no superposition of the evolution of heating systems events over time, according to which the interrelation of states realized during the operation of heating system subsystems (HS and HN) is such that the resulting consequence from several independent transitions between them (failures and recoveries as well other internal and external disturbances) does not correspond to the sum of the consequences caused by each impact separately. As a result, the maximum effect of the emergence of the studied processes of production and distribution of heat energy is achieved. In accordance with this principle, complex (composite) states of the heating system are formed, which are combinations of failure states of HS and HN in a single structure of events. In this case, it is recommended to use methods of optimization of the number of modeled states, taking into account the possibility of their grouping by consequences and cutting off the disruptions that are deemed insignificant for delivering heat to consumers. Such a procedure can significantly reduce the dimensionality of the equivalent flow diagram of the heating system and the model of the evolution of its states.

The principle of formation of a set of complex states can be considered on the example of a district-distributed DHS, consisting of system district HS and HN, distributed HS and HN of the prosumer. The issues of the functioning of prosumers in the DHS are considered in many publications, in particular, some methodological aspects are given in [77–79]. The complete set of states for such system consists of 4 subsets: one of the simple states corresponding to the failure of one element of each subsystem and three groups of complex states corresponding to combinations of failures of 2, 3, and 4 elements from different subsystems (states of simultaneous failure of several elements of one subsystem are unlikely). On Fig. 6.20 shows a state graph illustrating the formed set of states of a district-distributed TSS. In accordance with the accepted conditions, the graph has 4 levels of states: simple ones with a failure of the 1st element and 3 levels of complex ones. Each element of the graph of the first level is a subset of simple states of one or another subsystem (E_{ds}, E_{dn}, E_{ps}, E_{pn}), and the subsequent levels are their combinations. The transitions between the states are indicated in Fig. 6.20 by bidirectional lines corresponding to ordinary events, i.e. either single failures or restoration.

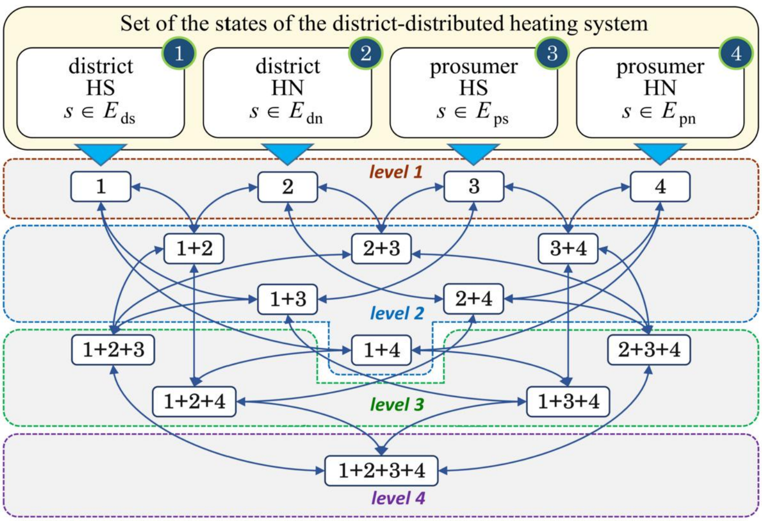


FIGURE 6.20 Graph of states of a district-distributed DHS (in aggregated form).

Basic Markov model. According to the conditions of the simplest flow of events and on the basis of the generated set of states of the heating system, the stationary Markov model of its operation is represented by the following system of linear algebraic equations:

$$p_s \sum_{m \in M_s} (\lambda_m + \mu_m) = \sum_{z \in E_s} p_z \sum_{m \in M_z} (\lambda_m + \mu_m), s \in E, \tag{6.43}$$

provided that:

$$\sum_{s \in E} p_s = 1, \tag{6.44}$$

where p_s, p_z – probabilities of the system states s and z, respectively, $\lambda_m,\ \mu_m$ – rates of failures and recoveries of the component m, respectively $(1/h)$; E – set of the system states; E_s – subset of the system states from which the direct transition (without intermediate states) to the state s is possible; M_s – subset of the system components whose failure or recovery corresponds to the direct transition from the state s to some other state z; M_z– subset of the system component whose failure or recovery corresponds to the direct transition from the state z to some state s.

The condition of stationarity of reliability parameters of components corresponds to the real systems within the time frame of the calculation period (heating season), during which these parameters practically do not change, and consideration of aging and depreciation of equipment proves significant in a longer period of time and is considered at the level of formation of input data [69,126]. In addition, wear and tear should be partially compensated by running and overhaul repairs, the timely performance of which should not allow their reliability parameters to go beyond critical levels. The stationary character of the probabilities of the heating system states is assumed on the basis of the constancy of the reliability parameters of its components.

The condition of exponentiality of distribution of the dwell time of the heating system in its various states in the general case must be justified within each subsystem (HS and HN), since the reliability parameters (failure and restoration rates) of their elements and operating conditions can vary significantly. In the modeling of a number of real-life systems, the exponential distribution of time between transitions of system states is assumed based on the constancy of the value of the failure flow parameter, which assumes an exponential distribution of the operating time between them [69,126]. The restoration time of the elements of heating system subsystems, as a rule, is much (by two orders of magnitude) less than the mean time before failures [69], so the non-exponential distribution of the time periods associated with the recovery processes does not significantly alter the results of reliability calculations. An additional basis for this assumption is due to the specific features of large complex systems consisting of a large number of recoverable components. The failure rate of such a system is a superposition of the failure rates of individual components [122,128], and the sum of a large number of independent random flows is reduced to a Poisson process, for which the distribution of the time intervals between failures agrees fits well the exponential distribution.

The condition of ordinariness and independence of the flow of events in the probabilistic modeling of the heating system for most real systems is generally satisfied [69,126]. At the same time, to assess some properties of reliability (stability, resilience, etc.) it seems necessary to take into account the non-ordinariness and dependence of events. Possible methodological approaches to taking these factors into account when modeling the evolution of heating system states are discussed in [129].

A model of the evolution of DHS states, taking into account the non-ordinariness of the flow of events. When operating structurally complex heating systems, many different technological processes can occur in parallel, so failures or recoveries of several elements simultaneously appear to be more likely events than within individual subsystems of the heating system, such as the HS and HN. Accordingly, in the overall modeling of HS and HN operation, the combination of failures and restorations becomes more probable than in their separate modeling. The non-standard nature of the recovery process is more realistic, as emergency repairs are often performed simultaneously at several failed facilities. The additional time required for such work can be taken into account when assigning restoration rates of elements with some margin.

The coincidence of events can be accounted for at the level of probabilistic modeling of heating system operation based on the following approach. In the case of mutually independent events, the probability of their coincidence is the product of their probabilities [122–124]. Accordingly, the intensity of non-ordinary transitions between states is defined as the product of the failure and recovery intensities of components provided their compatibility and independence:

$$\nu_{sw} = \prod_{m \in M_w} \lambda_m \prod_{m \in M_s} \mu_m, \quad s \in E, \ w \in E_1^*, \tag{6.45}$$

where ν_{sw} is the intensity of a non-ordinary transition from the state s to the state w, to which several failed elements correspond $(1/h)$; E_1^* is a subset of states into which the system can move from the state s due to simultaneous realization of several events (failures and/or recoveries); M_w is a subset of elements in the state of failure during realization of the state w; M_s is a subset of elements in the state of failure during realization of the state s.

The principle of forming a graph of non-ordinary transitions is shown in Fig. 6.21-a for the state '1+2', where lines indicate rates of 'twice' transitions connecting this state with others. Fig. 6.21-b shows a graph showing the structure of non-ordinary events for the system under consideration of four subsystems (see Fig. 6.20). Each line of the graph of 'twice' transitions in one direction assumes one of three combinations: two failures, two restorations, and simultaneously one failure and one restoration of elements. In combination with the graph of the base model presented in Fig. 6.20, they form a complete structure of states, taking into account the non-ordinary events.

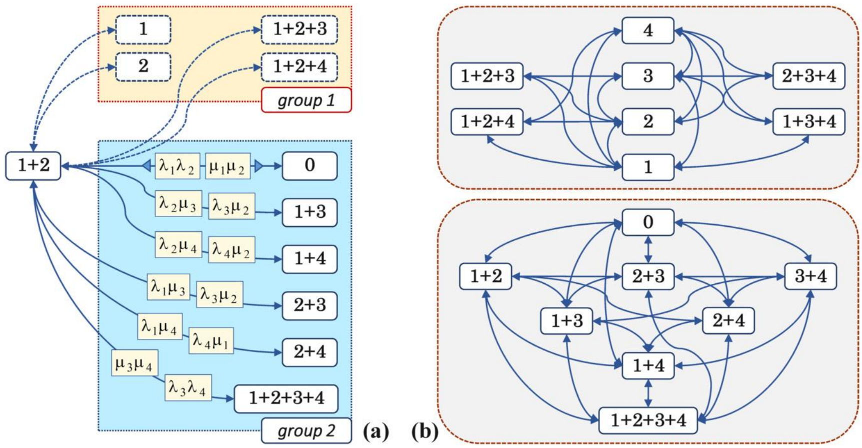


FIGURE 6.21 To modeling a random process of functioning of district-distributed DHS, taking into account the non-ordinary events: (a) a scheme for formation a graph of non-ordinary transitions using the example of the state '1+2' (group 1 – single transitions, group 2 – 'twice' transitions); (b) graph of system states with 'twice' transitions between them.

Depending on the number of concurrent events considered, several levels of non-ordinariness are considered, each of which corresponds to a particular group of states and the connections between them. The set E_1^* is formed for each such level separately. Taking these conditions into account, the model of the random process for the non-ordinary flow of events can be represented in general form as follows:

$$p_s\left(\sum_{z\in E_1} \nu_{sz} + \sum_{u\in U}\sum_{w\in E_1^*} \nu_{swu}\right) = \sum_{z\in E_2} p_z \nu_{zs} + \sum_{u\in U}\sum_{w\in E_2^*} p_w \nu_{wsu},\ s\in E, \quad (6.46)$$

where ν_{swu} and ν_{wsu} are intensities of non-ordinary transitions from the state s to the state w and back for the u-th level of non-ordinary events $(1/h)$; U is a set of considered levels of non-ordinary events; p_w and E_2^* are the probability and subset of states from which the system can move to the state s due to concurrent realization of several events.

A model of the evolution of DHS states with regard to dependent events. Dependent events (mainly failures) in subsystems of the heating system can occur, but they are very rare events and occur, as a rule, under extreme operating conditions and are characterized by large disturbances with cascading development of accidents and mass disturbances of delivering heat to consumers. When calculating the reliability of the heating system, dependent events can be considered at the level of probabilistic models using the rules of probability theory [122–124]. For this purpose, the formation of the set of heating system states is performed using conditional probabilities. Let us consider the component m with the failure rate λ_m, given the failure of which the conditional probability of failure of the component k is equal to $\zeta_{k/m}$. Obviously, the conditional probability of failure varies within the limits $0 \le \zeta_{k/m} \le 1$ depending on the operating conditions and the connection flow diagram of the components. Dependent failure of the component k given the failed component m will occur with the rate $\lambda_{k/m}$ determined by the value of the conditional probability $\zeta_{k/m}$:

$$\begin{cases} \lambda_{k/m} = \lambda_k(1+\zeta_{k/m}) \quad \text{given} \quad 0 \le \zeta_{k/m} < 1, \\ \lambda_{k/m} = \lambda_m \quad \text{given} \quad \zeta_{k/m} = 1. \end{cases} \tag{6.47}$$

The rate of a non-ordinary failure $\lambda_{mk/m}$, provided that the rate of the dependent failure is described by the expressions (6.47), is defined as for two independent events:

$$\begin{cases} \lambda_{mk/m} = \lambda_m \lambda_k(1+\zeta_{k/m}) \quad \text{given} \quad 0 \le \zeta_{k/m} < 1, \\ \lambda_{mk/m} = \lambda_m \quad \text{given} \quad \zeta_{k/m} = 1. \end{cases} \tag{6.48}$$

Fig. 6.22 shows a fragment of the graph of DHS states that reflects construction process of the events structure under availability of dependent failures and restorations on the example of considered components (k and i).

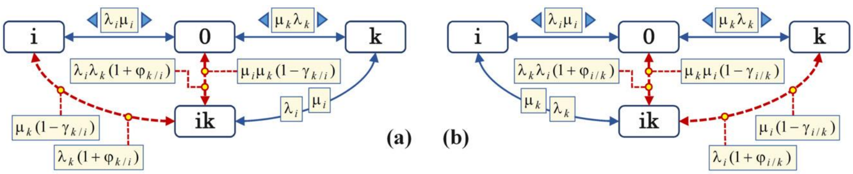


FIGURE 6.22 Scheme of forming a graph of states with dependent events on the example of some two elements i and k: (a) – in case of dependence of the failure of element k in case of failure of element i; (b) – with the dependence of the failure of element i with the failure of element k.

The joint use of the model for non-ordinary events (6.46) with the expressions for determining the rates of dependent events (6.47)–(6.48) allows us to present a model of the random process of DHS operation taking into account both of these factors:

$$p_s\left(\sum_{z\in E_1} \nu_{sz}(2\pm\zeta_{z/s}) + \sum_{u\in U}\sum_{w\in E_1^*} \nu_{swu}(2\pm\zeta_{w/s})\right) = \sum_{z\in E_2} p_z \nu_{zs}(2\pm\zeta_{s/z}) + \tag{6.49}$$

$$+\sum_{u\in U}\sum_{w\in E_2^*} p_w \nu_{wsu}(2\pm\zeta_{s/w}), \quad s\in E;$$

$$\begin{matrix} 0\le\zeta_{z/s}<1,\ \nu_{sz}>\nu_{sz/s}; & 0\le\zeta_{w/s}<1,\ \nu_{swu}>\nu_{swu/s}; \\ 0\le\zeta_{s/z}<1,\ \nu_{zs}>\nu_{zs/z}; & 0\le\zeta_{s/w}<1,\ \nu_{wsu}>\nu_{wsu/w}; \end{matrix} \tag{6.50}$$

where $\zeta_{z/s}$ and $\zeta_{s/z}$ – conventional probabilities of ordinary transitions of a set from states z to s and back, accordingly; $\zeta_{w/s}$ and $\zeta_{s/w}$ – conventional probabilities of non-ordinary transitions of a set from states w into s and back, accordingly; $\nu_{sz/s}$ and $\nu_{zs/z}$ – rates of dependent transitions from state s into state z and back; $\nu_{swu/s}$, $\nu_{wsu/w}$ – similar indicators for non-ordinary transitions. Each value of $\zeta_{z/s}$ is associated either with a failure or restoration.

A number of computational experiments were carried out using the developed probabilistic models to describe the random process of functioning of test aggregated schemes of district-distributed DHS. Characteristics are obtained that make it possible to determine some modeling conditions that take into account the change in the results of reliability analysis depending on the factors described above – non-ordinary and dependent events. The generalized results of numerical modeling based on a test calculation scheme of DHS with dependent events (failures) are shown in Fig. 6.23.

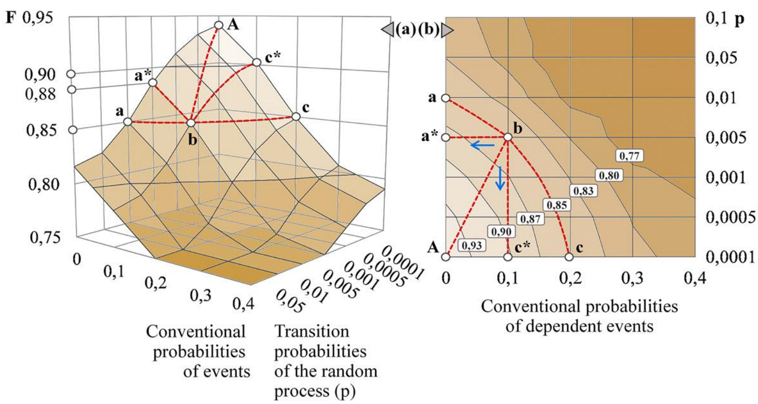


FIGURE 6.23 Results of numerical modeling based on the test calculation scheme of DHS: (a) dependence of the reliability function F on the values of conventional transition probabilities between dependent events for different values of transition probabilities p (failure rates); (b) gradient of the reliability function F (projection of the diagram shown in part 'a').

The diagram shown in Fig. 6.23-a, is the dependence of the reliability function (F) of the system under study on the values of the conventional probabilities of transitions between dependent events at different values of the transition probabilities of a random process describing the evolution of the system states (in the example under consideration, the failure rates of elements were used as transition probabilities). This diagram reflects the degree of possible decrease in the reliability of the system (function F) from some calculated initial level (point A) under the influence of the dependency factor between failures of a group of system elements. On this surface, it is possible to single out the range of F values, limited by some minimum allowable level, for example, $F = 0.85$ (line a–b–c on Fig. 6.23-a). The figure cut off by this curve, projected onto the horizontal plane of the diagram, contains the ratios of the initial values of the parameters, under which the specified reliability requirements are met. The corresponding projection of the diagram shown in Fig. 6.23-b is the gradient of index F. This diagram can be used to determine the initial parameters necessary to ensure some level of reliability. So, for example, the point c^* enters the area of an acceptable level of reliability (F not less than 0.85) with the values of the conventional probability of dependent events 0.1 and the transition probability of a random process of functioning $p = 0.0001$. Obviously, an increase in p, which in this example is interpreted as an increase of probabilities of element failures, the function F also decreases (point b). An increase in the conventional probability of dependent events (failures) also leads to a decrease in the level of reliability (point c).

6.9 Final assessment of the reliability of DHS based on the nodal reliability indices accounting the emergency hydraulic conditions

Modeling of post-emergency operating conditions of the heating system taking into account possible fuel shortages at the HS. These studies are necessary to determine the level of delivering heat to consumers in each of its possible states, which correspond to failures of various elements of its subsystems (HSs and HNs), as well as their combinations. At the same time, the assessment of the consequences of the realization of heating system states is carried out taking into account the potential disruption of the HS fuel supply. The levels of HS fuel availability (shortage and surplus), obtained at the FSS modeling stage described above, allow us to determine the probable decrease in their performance in different states of the system. These metrics are used in modeling the load flow in the HN, taking into account the expected failures of HS and HN equipment.

Determination of the level of heat carrier supply to each j the consumer in different states of the heating system (s) is carried out using a model for calculating the hydraulic states of the HN (load flow model) that was developed within the framework of the Theory of hydraulic circuits [13]. The model of load flow in HN in the matrix nodal form for some state s is represented by the following system of equations [13]:

$$\mathbf{A}_s \mathbf{x}_s = \mathbf{g}_s, \tag{6.51}$$

$$\overline{\mathbf{A}}_s^{\mathrm{T}} \mathbf{p}_s = \mathbf{h}_s - \mathbf{H}_s, \tag{6.52}$$

$$\mathbf{S}\mathbf{X}_s \mathbf{x}_s = \mathbf{h}_s, \tag{6.53}$$

where $\mathbf{A}_s$ is a matrix of connections of linearly independent HN nodes under conditions of the emergency state s of the system (taking into account failure of any component); $\mathbf{x}_s$ – vector of flow rates at the network branches (t/h); $\mathbf{g}_s$ – vector of flow rates at the network nodes (t/h); $\overline{\mathbf{A}}_s^{\mathrm{T}}$ – full transposed matrix of connections of network nodes and branches; $\mathbf{p}_s$ – vector of network node pressures (Pa); $\mathbf{h}_s$ – vector of pressure losses at the network branches in the system state s (Pa); $\mathbf{H}_s$ – vector of effective pressures (differential pressure) of pumping stations under conditions of the emergency state s of the system (Pa); $\mathbf{S}$, $\mathbf{X}_s$ – diagonal matrices of coefficients of flow friction of branches, composed of values of flow friction of branches and absolute values of flow rates.

Modeling of each post-emergency operating condition of the heating system (after localization of the failed component) in the state s corresponding to the failure of some component is performed by its exclusion from the equivalent flow diagram or by designating a reduced capacity in accordance with the considered state. As a result of calculating the whole system of Eqs. (6.51)–(6.53) for each of the heating system states (s), we determine the values g_{sj} (t/h): heat carrier flow rates at each consumption node j, with the help of which the heating levels q_{sj} (MW), are calculated as per the following dependence [130]:

$$q_{sj} = g_{sj} c \Delta t_{\mathrm{hn}}, \tag{6.54}$$

where c – heat capacity of the heat transfer fluid (MWh/(t°C)); Δt_{hn}– temperature difference of the district water in the supply and return pipelines of the HN (°C).

The final assessment of the reliability of heating to consumers based on nodal reliability indices accounting the thermal inertia effect. The results of probabilistic modeling of heating system operation (probabilities of system states) and the obtained levels of delivering heat to consumers serve as a basis for calculating the final quantitative assessment of HC reliability by means of nodal RIs of delivering heat to each consumer. According to the HN reliability assessment methodology presented in [69], the reliability of the design (first) level is determined by nodal AF, denoted as K_j. It corresponds to the period within the heating season, during which the design value of indoor air temperature is provided ensured at the given consumer j. The reliability of the reduced (second) level is estimated by nodal PFFO, denoted as R_j. This index is the probability of the internal air temperature at the consumer during the heating period not falling below its specified boundary value. On the basis of the initial formulas for calculating the nodal AF and PFFO, presented in [69], the Rossander equation, describing the profile of changes in heat loads during the heating season [67,131], simplified models of thermophysical processes describing the cooling of the air inside the premises [130], we have obtained the dependencies for calculating nodal RIs for the assessment of the reliability of heating of the HC consumers, which have the following form:

$$K_j = 1 - \sum_{s\in E} p_s \left[\frac{1}{1-\omega_j} \left(1 - \frac{1}{q_{\mathrm{hd}j}} \left(\varphi_j t_{sj} - \varphi_j \left(\frac{C_1 - C_2 \exp B_j}{C_3(1-\exp B_j)} \right) - q_{\mathrm{hw}j} \right) \right) \right]^{\alpha_j}, \tag{6.55}$$

$$R_j = \exp\left[-\sum_{m\in M} \lambda_m p_{\mathrm{o}} \tau_{\mathrm{o}} \left(\frac{1}{1-\omega_j} \left(1 - \frac{1}{q_{\mathrm{hd}j}} \left(\varphi_j t_{sj} - \varphi_j \left(\frac{C_1 - C_2 \exp B_j}{C_3(1-\exp B_j)} \right) - q_{\mathrm{hw}j} \right) \right) \right)^{\alpha_j} \right], \tag{6.56}$$

$$C_1 = t_{\mathrm{o}j}(1-\bar{q}_{sj}),\ C_2 = t_{j\,\mathrm{min}} - t_{\mathrm{o}j}\bar{q}_{sj},\ C_3 = 1-\bar{q}_{sj},\ B_j = 1/\beta_j \mu_j^{\mathrm{max}}, \tag{6.57}$$

$$\omega_j = q_{\mathrm{bg}j}/q_{\mathrm{hd}j},\ \delta_j = q_{\mathrm{avg}j}/q_{\mathrm{hd}j},\ \alpha_j = (1-\delta_j)/(\delta_j - \omega_j), \tag{6.58}$$

where ω_j, δ_j, α_j – coefficients of irregularity of the heat load profile [69,130]; $q_{\mathrm{hd}j}$, $q_{\mathrm{bg}j}$, $q_{\mathrm{avg}j}$ – heating loads: the calculated value as corresponding to the beginning of the heating period and the average for the heating period (MW); $q_{\mathrm{hw}j}$ – heat load of hot water supply (MW); $\bar{q}_{sj} = q_{sj}/q_{\mathrm{o}j}$ – relative reduction of heating in the state s, here $q_{\mathrm{o}j}$ – total calculated heating load of the consumer (MW); φ_j – constant factor, depending on the thermophysical properties of the building of the consumer j [130]; p_{o} – probability of the fully operational state of the system; τ_{o}– duration of the heating period (h); $t_{\mathrm{o}j}$ – design indoor air temperature for the consumer j (°C); t_{sj} – indoor air temperature at the consumer j in the state s (°C); $t_{j\,\mathrm{min}}$ – minimum allowable indoor air temperature for the consumer j (°C); β_j – heat energy accumulation factor (thermal inertia) for the consumer j (h); μ_j^{max}– maximum possible rate for state s of the transition to an operable state for the consumer j (1/h). The obtained values of RIs for each consumer shall meet their standardized levels, ensuring comfortable living conditions for the population.

6.10 Case study: the hierarchical and comprehensive reliability analysis of a municipal district heating system

The developed methodology of the comprehensive hierarchical analysis of the reliability of heating was tested in practice and demonstrated high efficiency. The results of its work will be illustrated by studies of the real-life DHS of a municipality. The system includes a CHPP and a peak boiler house with a total heat capacity of 512 MW, heat networks with a length of 15.7 km of main lines, and numerous consumers [132]. The schematic diagram of the heating system under consideration is given in Fig. 6.24 'a', its calculated (aggregated) view, obtained by aggregation of system components, is given in Fig. 6.24 'b'. In accordance with the overall approach to the analysis of the reliability of the heating systems, its aggregate equivalent flow diagram is formed by combining the equivalent flow diagrams of the HN and HS. The thus obtained aggregated equivalent flow diagram of the heating system consists of 89 components, of which 41 components correspond to sections of the HN and 48 components correspond to the main process nodes of the HS.

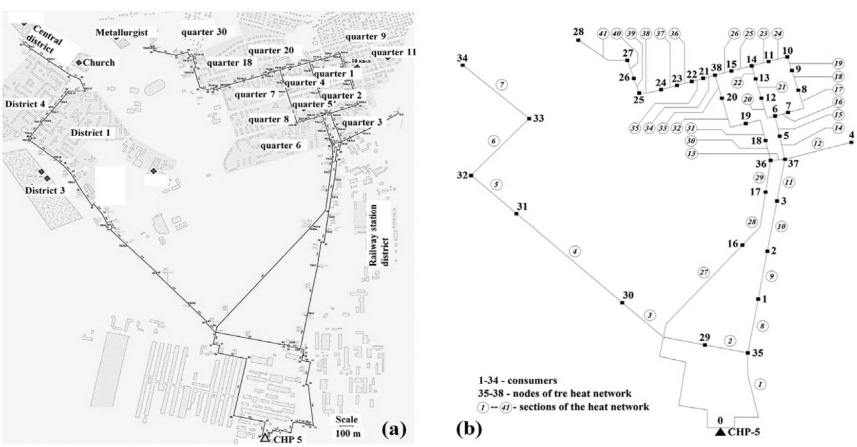


FIGURE 6.24 The schematic flow diagram of the municipal heating system: (a) the real flow diagram of the heating systems as represented on the city plan; (b) an aggregated equivalent flow diagram (as used for calculation) of the heating system with generalized consumers.

On the basis of the resulting equivalent flow diagram, we form the state graph of the heating system shown in Fig. 6.25. The structure of its states and events formed according to the conditions of the Poisson flow of events. The number of the graph element corresponds to the number of the failed components of the system under study. The set of states in the graph are grouped as follows: to the left of the fully operational state '0' is a subset of failure states of HN components (1–41), to the right – a subset of failure states of HS components (42–89), and their combinations are given below as composite simultaneous failure states of HS and HN components, which are designated by corresponding numbers with the sign '+'.

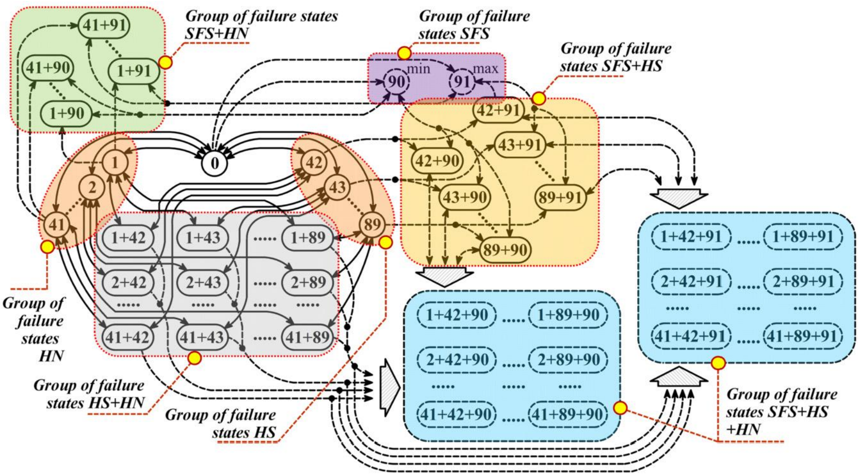


FIGURE 6.25 The graph of the states of the city's heating system given the fuel supply of the HS (states corresponding to fuel shortages at the HS correspond to numbers 90 and 91 and their combinations with failures of components of heating system subsystems).

The structural mix of events also takes into account the state of the HS fuel supply system, i.e., possible disturbances in the FSS operation. To account for the expected fuel shortages at the HS (FSS failures), two additional states with numbers 90 and 91 (see Fig. 6.25) corresponding to the range of fuel shortage values, were added to the general structure of the heating system states. According to the methodology described above for the comprehensive analysis of the reliability of the heating system, these shortages are determined by the results of simulation modeling of the HS fuel supply system, carried out using the statistical testing method based on actual data on fuel supplies and demand. These states of possible fuel shortages are combined with HS and HN failures and expand the graph with new groups of corresponding states (see Fig. 6.25). This is how the fuel supply to the HS is taken into account when assessing the reliability of the system.

Probabilistic modeling of the operation of heating system operation to assess its reliability was carried out using a Markov model in accordance with the structure of states and events, displayed by the presented graph. The set of states is described by a corresponding system of linear steady-state equations of the type (6.46) containing more than 3,000 variables. As a result of solving it, the probabilities of all considered states are

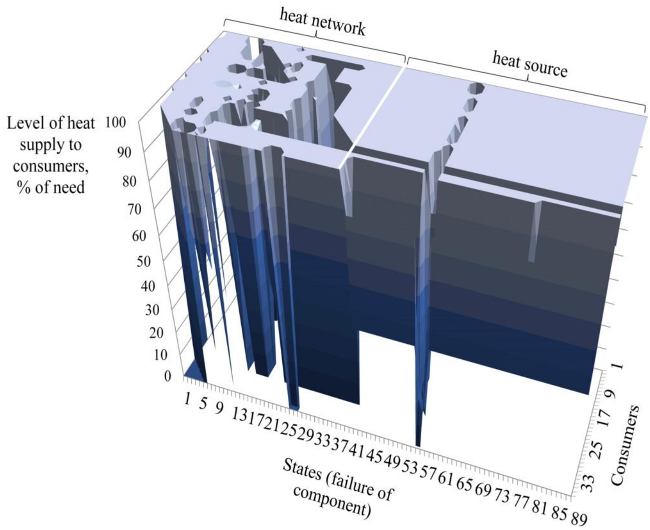


FIGURE 6.26 Levels of heating of consumers in case of failures of components of heating system subsystems (HS and HN).

determined, which together with the results of calculations of the post-emergency operating conditions are used to determine the RIs. Estimation of post-emergency operating conditions in the heating system was obtained by carrying out multivariate calculations of the load flow using the model (6.51)–(6.53). Fig. 6.26 shows a diagram illustrating the ratio of levels of delivering heat to consumers in the states corresponding to failures of HS and HN components.

The results of the reliability analysis of the system are presented in Table 6.8 and Fig. 6.27, where the values of nodal RIs (AF and PFFO), calculated according to (6.55)–(6.56) for each considered generalized consumer of the system are presented (see Fig. 6.24). The table also shows the values of the additional RI coupled with the main ones (AF and PFFO), including the average total time of reducing the indoor air temperature during heating season Z_j (h) and the number of failures F_j (1/year) [69].

Comparison of the obtained indices against the standardized values [69,133] showed that the requirements for the AF are not met for all consumers of the system, and those for the PFFO – for 32% of consumers of the system. Based on the decomposition of the nodal RI, the degrees of influence of each of the subsystems on the final level of reliability of delivering heat to consumers was determined. Table 6.9 and Fig. 6.28 summarize the results of the overall and decomposition analysis of the reliability of the heating system, where the ranges of values of the nodal metrics of the AF and PFFO (Figures 'a' and 'b', respectively) are given for their comparative analysis. Fig. 6.27 shows the results both for the overall solution

TABLE 6.8 The results of a comprehensive analysis of the reliability of the municipal heating system considering fuel supply of the HS – nodal RIs.

Consumer (Fig. 6.26)	K	R	Z, h	F, 1/year	Consumer (Fig. 6.26)	K	R	Z, h	F, 1/year
1	0.948	0.962	300	0.04	18	0.937	0.935	366	0.07
2	0.943	0.940	328	0.06	19	0.934	0.933	383	0.07
3	0.939	0.935	351	0.07	20	0.934	0.924	383	0.08
4	0.935	0.931	374	0.07	21	0.926	0.908	428	0.10
5	0.935	0.937	377	0.07	22	0.923	0.906	445	0.10
6	0.934	0.935	383	0.07	23	0.921	0.900	457	0.11
7	0.933	0.933	388	0.07	24	0.914	0.893	496	0.11
8	0.932	0.937	394	0.07	25	0.907	0.886	535	0.12
9	0.932	0.937	394	0.07	26	0.900	0.879	574	0.13
10	0.931	0.941	400	0.06	27	0.894	0.872	613	0.14
11	0.931	0.941	400	0.06	28	0.887	0.866	653	0.14
12	0.938	0.933	360	0.07	29	0.913	0.910	501	0.09
13	0.938	0.932	360	0.07	30	0.906	0.900	541	0.11
14	0.941	0.935	337	0.07	31	0.899	0.891	583	0.12
15	0.942	0.929	331	0.07	32	0.892	0.882	625	0.13
16	0.949	0.946	291	0.06	33	0.884	0.873	667	0.14
17	0.947	0.944	303	0.06	34	0.877	0.864	708	0.15

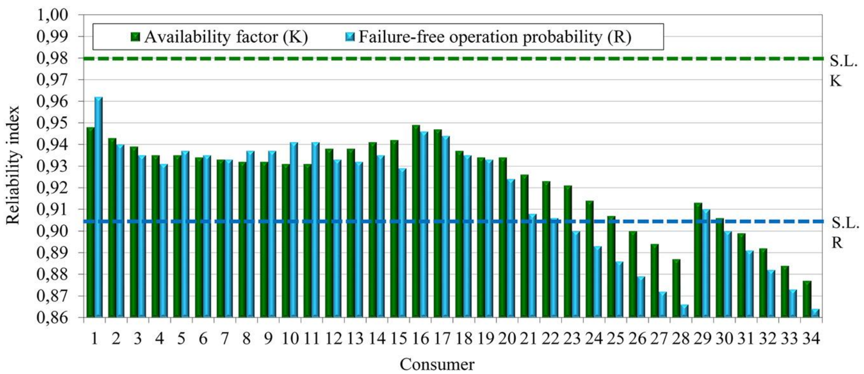


FIGURE 6.27 The results of a comprehensive analysis of the reliability of the municipal heating system considering fuel supply of the HS – nodal RI (SL – standardized levels of values of metrics).

and separately for the considered subsystems. The RI ranges shown in the diagrams contain their values for all consumers of the system under consideration. The changes in the nodal RI for the heating system subsystems with respect to the level of the overall evaluation are shown in Fig. 6.28-c.

The analysis of the presented results allows us to formulate the following conclusions about the preliminary general directions of increasing the reliability of the considered municipal heating system.

TABLE 6.9 Generalized results of a comprehensive and decomposition-based analysis of the reliability of the studied heating system.

System level	Ranges of values of the nodal RI								Increase in the RI for subsystems relative to the initial value, %		Part of consumers with a standard level of the RI, %	
	K		R		Z, h		F, 1/year		K	R	K	R
	min	max	min	max	min	max	min	max				
DHS+SFS	**0.877**	**0.949**	**0.864**	**0.962**	**708**	**291**	**0.15**	**0.04**	**-**	**-**	**0**	**68**
SFS	0.896	0.969	0.889	0.985	602	179	0.12	0.02	2.1	2.6	0	88
DHS	0.902	0.976	0.873	0.967	564	138	0.14	0.03	2.8	0.7	0	74
HS	0.926	0.994	0.904	0.987	428	36	0.1	0.01	5.1	4.6	9	56
HN	0.911	0.987	0.883	0.983	513	75	0.12	0.02	3.9	2.2	0	53

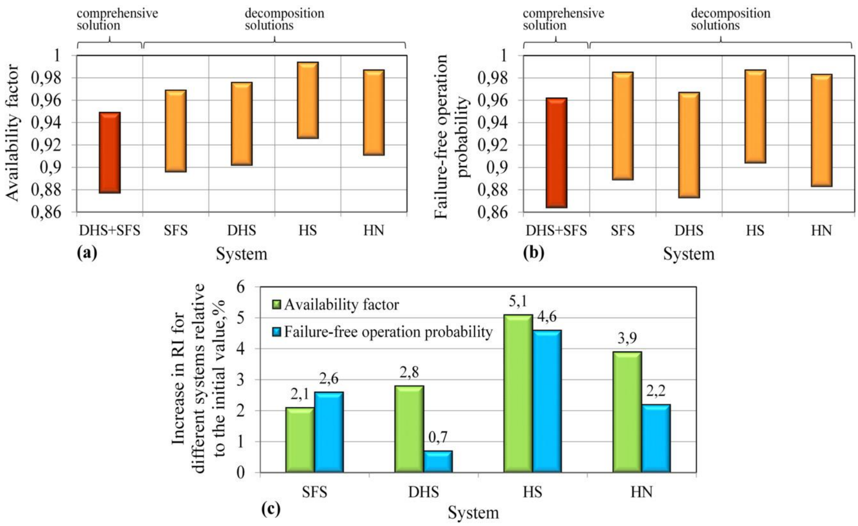


FIGURE 6.28 Generalized results of overall and decomposition-based analysis of the reliability of the municipal heating system: (a) ranges of nodal AF values; (b) ranges of values of nodal PFFO; (c) changes in the nodal RI for the FSS and subsystems of the heating system by to the overall level of indices (the ratio of indices of decomposition-based and comprehensive reliability assessment).

1. Fuel supply failures of the HS in the system reduce the reliability of the calculated delivery of heat to consumers to a greater extent than failures of components of the HS and HN. This is confirmed by the lower AF values for FSS compared to the system (Figs. 6.26 and 6.27). The range of increasing its values to the standardized level is from 1 to 9.3%. Improving

the reliability of the FSS is achieved by optimal control and increasing fuel reserves, the formation of additional sources of backup fuel.

2. The AF index, calculated relative to the HS, has the highest values, and for some consumers corresponds to the standardized value. To achieve this metric with required values relative to other consumers it will require taking measures to improve the functional and structural redundancy of the HS. The reliability of the reduced level of delivering heat to consumers, characterized by the PFFO metric, is affected to a greater extent by failures of elements of the heating system (Figs. 6.27 and 6.28). The decomposition of this RI shows that the least reliable subsystem is the HN. In this regard, one of the main directions of increasing the reliability of the heating system is associated with the implementation of a set of measures for component-wise and structural redundancy of the HN. Additional shunt pipes and duplication of some network sections will ensure the required level of reliability of reduced heating of consumers in emergency modes. Replacement of HN elements with more reliable ones in the most 'bottleneck' and reduction of their restoration time will lead to an increase of both nodal RI.

4. The presented results of the reliability analysis of the system are aimed at forming recommendations for making further decisions on the search for the optimal ratio of measures to improve the reliability of this system. Rational distribution of reliability both by subsystems of the system and by methods of ensuring it is an array of special problems of reliability synthesis, which is the subject of dedicated studies in the field of heating reliability. For example, the papers [120,121] present a methodology for solving one of the problems of heating system reliability synthesis, that of determining the optimal reliability parameters of the system components. The studies presented in [134–136] are devoted to some methodological issues of optimization and improvement of reliability of heating systems when introducing prosumers with their own heat generation.

Acknowledgments

The study was carried out under State Assignment Project No. FWEU-2021-0002 of the Fundamental Research Program of Russian Federation 2021–2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038). Sections 6.7 and 6.8 are based on research supported by the Russian Science Foundation grant No. 22-29-01252.

References

[1] N.N. Novitsky, Intelligent pipeline systems: the arguments for and against, content, and prospects, in: Kommunal'noe Khozyaystvo Gorodov, 2011, Ukraine, Kharkov, in: Seriya Tekhnicheskie Nauki i Arkhitektura, vol. 101, 2011, pp. 456–464 (in Russian).

[2] V. Sakalkar, P. Hajela, Multilevel decomposition based nondeterministic design optimization for structural systems, Advances in Engineering Software 42 (1–2) (2011) 1–11.

[3] Jie Lu, Jialin Han, Yaoguang Hu, Guangquan Zhang, Multilevel decision-making: a survey, Information Sciences 346 (2016) 463–487.
[4] A. Lazzaretto, A. Toffolo, M. Morandin, M.R. Spakovsky, Criteria for the decomposition of energy systems in local/global optimizations, Energy 35 (2) (2010) 1157–1163.
[5] Armando Di Nardo, Alberto Cavallo, Michele Di Natale, Roberto Greco, Giovanni Francesco Santonastaso, Dynamic control of water distribution system based on network partitioning, Procedia Engineering 154 (2016) 1275–1282.
[6] G. Schweiger, P.-O. Larsson, F. Magnusson, P. Lauenburg, S. Velut, District heating and cooling systems – framework for Modelica-based simulation and dynamic optimization, Energy 137 (2017) 566–578.
[7] M. Vesterlund, J. Dahl, A method for the simulation and optimization of district heating systems with meshed networks, Energy Conversion and Management 89 (2015) 555–567.
[8] E. Guelpa, C. Toro, A. Sciacovelli, R. Melli, E. Sciubba, V. Verda, Optimal operation of large district heating networks through fast fluid-dynamic simulation, Energy 102 (2016) 586–595.
[9] M. Vesterlund, A. Toffolo, J. Dahl, Optimization of multi-source complex district heating network, a case study, Energy 126 (2017) 53–63.
[10] E. Guelpa, A. Sciacovelli, V. Verda, Thermo-fluid dynamic model of large district heating networks for the analysis of primary energy savings, Energy 184 (2019) 34–44.
[11] B.S. Gilani, M. Bachmann, M. Kriegel, Evaluation of the temperature regimes of multilevel thermal networks in urban areas through exergy analysis, Energy Procedia 122 (2017) 385–390.
[12] V.Y. Khasilev, Elements of the theory of hydraulic circuits, Izvestiya AN SSSR. Energetika i Transport 11 (1964) 69–88 (in Russian).
[13] A.P. Merenkov, V.Y. Khasilev, The Theory of Hydraulic Circuits, Nauka, Moscow, 1985, p. 278 (in Russian).
[14] A.P. Merenkov, E.V. Sennova, S.V. Sumarokov, N.N. Novitsky, et al., Mathematical Modeling and Optimization of Heating, Water-, Oil-, and Gas Supply Systems, Nauka, Novosibirsk, 1992, p. 407 (in Russian).
[15] N.N. Novitsky, Development of the hydraulic circuit theory for solving the problems of controlling the operation of heating systems, Teplotekhnika 56 (12) (2009) 1024–1029 (in Russian).
[16] N.N. Novitsky, A.V. Alekseev, State of the art and directions in development of the hydraulic circuit theory methods for modelling and technological control of water supply systems, in: The Eleventh International Conference on Computing and Control for the Water Industry, vol. 3, University of Exeter, UK, 2011, pp. 901–906.
[17] A. Merenkov, N. Novitsky, V. Sidler, Direct and Inverse Problems of Flow Distribution in Hydraulic Circuits, Soviet. Techno. Rev. Sec. Energy Rev., vol. 6, Harwood Academic, New York, NY, USA, 1994, pp. 33–95.
[18] A.V. Alekseev, N.N. Novitsky, V.V. Tokarev, Z.I. Shalaginova, Principles of design and software implementation of information and computing environment for computer modeling of piping and hydraulic systems, in: Pipeline Energy Systems: Methods of Mathematical Modeling and Optimization, in: Coll. Scientific Papers, Nauka, Novosibirsk, 2007, pp. 221–229 (in Russian).
[19] N.N. Novitsky, V.V. Tokarev, Z.I. Shalaginova, A.V. Alekseev, Experience gained with development and application of informational-computation systems for calculating and organizing the operating conditions of large heat supply systems, in: Proc. of the International Scientific Conference Power Engineering and Market Economy, Ulaanbaatar, Mongolia, 2005, pp. 323–329.
[20] N.N. Novitsky, V.V. Tokarev, Z.I. Shalaginova, A.V. Alekseev, O.A. Grebneva, S.Yu. Barinova, Information and computing system "ANGARA-HS" for the automation of calculation and analysis of operating conditions in the management of large multiple-loop heating systems, Vestnik IrGTU 22 (11) (2018) 126–144 (in Russian).

[21] N.N. Novitsky, A.V. Alekseev, State of the art and directions in development of the hydraulic circuit theory methods for modelling and technological control of water supply systems, in: Proceedings of the Eleventh International Conference Computing and Control for the Water Industry, vol. 3, University of Exeter, UK, 2011, pp. 901–906.
[22] A.V. Alexeev, N.N. Novitsky, The information and computing complex "ANGARA-VS" for end-to-end modeling of water supply systems when developing development schemes, scheduling modes, and dispatching management, in: Proceedings of 2018 International Scientific Conference "Investment, Construction, Real Estate: New Technologies and Special-Purpose Development Priorities" (icre 2018), in: Matec Web of Conferences, vol. 212, 2018, pp. 107–111, https://doi.org/10.1051/matecconf/201821206001.
[23] N.N. Novitsky, V.P. Frolov, S.P. Epifanov, Methods and software for the calculation and optimization of operating modes of reservoir pressure maintenance systems, Neftyanoe Khozyaystvo 11 (2003) 71–73 (in Russian).
[24] V.V. Tokarev, Decomposition and equivalenting of heating systems design flow diagrams for operation and supervisory control problems, in: N.N. Novitsky (Ed.), Energy Pipeline System, in: Mathematical Modeling and Optimization, Nauka, Novosibirsk, 2010, pp. 379–390 (in Russian).
[25] V.V. Tokarev, Z.I. Shalaginova, Technique of multilevel adjustment calculation of the heat-hydraulic mode of the major heat supply systems with the intermediate control stages, Thermal Engineering 63 (1) (2016) 68–77.
[26] Z.I. Shalaginova, Methods for the thermohydraulic analysis of operating conditions of large heat supply systems, Thermal Engineering 56 (12) (2009) 1016–1023.
[27] Z.I. Shalaginova, V.V. Tokarev, O.A. Grebneva, Technique for commissioning calculation for centralized hot water supply distribution networks, Vestnik IrGTU 3 (98) (2015) 165–174 (in Russian).
[28] N.N. Novitsky, Z.I. Shalaginova, V.V. Tokarev, O.A. Grebneva, Technology for the development of large heating systems operating conditions based on methods of multilevel thermo-hydraulic modeling, Izvestiya RAN. Energetika 1 (2018) 12–24 (in Russian).
[29] Z.I. Shalaginova, Mathematical model for calculation of the heat-hydraulic modes of heating points of heat-supplying systems, Thermal Engineering 63 (3) (2016) 222–232.
[30] N.N. Novitskii, Development of the hydraulic circuit theory for solving problems of controlling the operation of heat supply systems, Thermal Engineering 56 (12) (2009) 1010–1015.
[31] V.V. Tokarev, Z.I. Shalaginova, Experience in the use of new technologies for the arrangement of operating conditions of heating systems, Vestnik IrGTU 59 (12) (2011) 240–248 (in Russian).
[32] Z.I. Shalaginova, V.V. Tokarev, Applied problems and methodological approaches to planning and implementation of operating conditions at district heating systems, Thermal Engineering 66 (10) (2019) 714–729.
[33] A.I. Yufa, D.R. Nosulko, Integrated Heating Optimization, Tekhnika, Kyiv, 1988, p. 135 (in Russian).
[34] G.K. Voronovskii, Improvement of Operational Management Practices of Large District Heating Systems in the New Economy, Kharkiv, 2002, p. 239 (in Russian).
[35] R.L. Keeney, H. Raiffa, Decisions with Multiple Objectives–Preferences and Value Tradeoffs, Cambridge University Press, Cambridge & New York, 1993, 569 p. ISBN 0-521-44185-4 (hardback), 0-521-43883-7 (paperback).
[36] N.N. Novitsky, A.V. Lucenko, Discrete-continuous optimization of heat network operating conditions in parallel operation of similar pumps at pumping stations, Journal of Global Optimization 66 (1) (2016) 83–94.
[37] I.I. Dikin, Determination of internal feasible point, in: Proc. 13th Intern. Simp. on Mathematical Programming, Tokyo, 1988, p. 230.

[38] N.N. Novitsky, A.V. Lutsenko, Problems and methods of multi-criteria optimization study of hydraulic states of distribution heat networks, Nauchnyi Vestnik NSTU 64 (3) (2016) 131–146 (in Russian).
[39] A.V. Lutsenko, N.N. Novitsky, Modified method of dynamic programming for optimization of hydraulic states of distribution heat networks, Vychislitel'nye Tekhnologii 23 (6) (2018) (in Russian).
[40] A.V. Lucenko, N.N. Novitsky, Optimization of hydraulic conditions of radial district heating systems with pumping stations, Energy Systems Research 2 (1(5)) (2019) 34–41.
[41] S. Frederiksen, S. Werner, District Heating and Cooling, Lund Studentlitteratur AB, 2013.
[42] A.I. Bashmakov, Analysis of the main trends in the development of heating systems, Novosti Teplosnabzheniya 2 (2008) 6–9 (in Russian).
[43] S. Wenren, District heating and cooling in Sweden, Energy 126 (2017) 419–429.
[44] L. Belyaev, Electricity Market Reforms: Economics and Policy Challenges, Springer, New-York, 2011.
[45] S. Stoft, Power System Economics: Designing Markets for Electricity, Wiley-IEEE Press, 2002.
[46] S. Paiho, H. Saastamoinen, How to develop district heating in Finland?, Energy Policy 122 (2018) 668–676.
[47] M. Wissner, Regulation of district-heating systems, Utilities Policy 31 (2014) 63–73.
[48] Barriers to district heating development in the Netherlands: a business model perspective, https://essay.utwente.nl/73054/1/Osman_BA_BMS.pdf. (Accessed 20 January 2023).
[49] K. Wojdyga, M. Chorzelski, Chances for Polish district heating systems, Energy Procedia 116 (2017) 106–118.
[50] District Heating and Cooling, Combined Heat and Power and Renewable Energy Sources, http://basrec.net/wp-content/uploads/2014/06/Appendix%20-%20country%20survey.pdf. (Accessed 20 January 2023).
[51] J. Ziemele, G. Vigants, V. Vitolins, D. Blumberga, I. Veidenbergs, District heating systems performance analyses. Heat energy tariff, Environmental and Climate Technologies 13 (2014) 32–43.
[52] U. Sarma, G. Bazbauers, District heating regulation: parameters for the benchmarking model, Energy Procedia 95 (2016) 401–407.
[53] District Heating in Norway. An Analysis of Shifting from Individual Electric Heating to District Heating, https://projekter.aau.dk/projekter/files/260084106/Master_thesis_Askeland_Bozhkova.pdf. (Accessed 20 January 2023).
[54] J. Šommet, Sustainable development in Estonian mining, Environmental and Climate Technologies 11 (2013) 34–40.
[55] The Netherlands Authority for Consumers and Markets, https://www.acm.nl/en/about-acm/our-organization/the-netherlands-authority-for-consumers-and-markets. (Accessed 20 January 2023).
[56] Energy Regulatory Office, https://www.ure.gov.pl/en/about-us/presidents-duties/22,Presidents-duties.html. (Accessed 20 January 2023).
[57] National Commission for Energy Control and Price, https://www.regula.lt/en/Pages/default.aspx. (Accessed 20 January 2023).
[58] Sabiedrisko pakalpojumu regulēšanas komisijas, https://www.sprk.gov.lv/content/siltumenergija. (Accessed 20 January 2023).
[59] Norwegian Water Resources and Energy Directorate, https://www.nve.no/energy-market-and-regulation/?ref=mainmenu. (Accessed 20 January 2023).
[60] Estonian competition authority, https://www.riigiteataja.ee/en/eli/ee/Riigikogu/act/520062017016/consolide. (Accessed 20 January 2023).
[61] Federal Law No. 190-FZ, "On Heating" of July 27, 2010.
[62] Jing Lin, Boqiang Lin, Heat tariff and subsidy in China based on heat cost analysis, Energy Economics 71 (2018) 411–420.

[63] S. Dempe, Foundations of Bi-Level Programming, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2002.
[64] A.V. Penkovskii, et al., Search for a market equilibrium of Cournot-Nash in the competitive heat market, Energy 161 (2018) 193–201.
[65] A. Rossander, A. Die, Anwendung von symbolischen Belastungskurven fur Elektrizitatswerk, ETZ 18 (2013) 7–9 (in German).
[66] A. Penkovskii, V. Stennikov, Mathematical modeling and optimization of the monopoly heating market, International Journal of Energy Economics and Policy 10 (2020) 342–351.
[67] E.V. Sennova, V.G. Sidler, Mathematical Modeling and Optimization of Heating Systems Development, Nauka, Novosibirsk, 1987 (in Russian).
[68] E. Shoup, A Practical Guide to Computer Methods for Engineers, Prentice-Hall, England, 1979.
[69] E. Sennova, A. Smirnov, A. Ionin, et al., Reliability of Heating Systems, Nauka, Novosibirsk, 2000 (in Russian).
[70] H. Lund, N. Duic, P. Østergaard, B. Mathiesen, Smart energy systems and 4th generation district heating, Energy 110 (2016) 1–4.
[71] H. Lund, S. Werner, R. Wiltshire, et al., 4th Generation District Heating (4GDH): integrating smart thermal grids into future sustainable energy systems, Energy 68 (2014) 1–11.
[72] H. Lund, P. Østergaard, M. Chang, et al., The status of 4th generation district heating: research and results, Energy 164 (2018) 147–159.
[73] J. Ziemele, A. Gravelsins, A. Blumberga, D. Blumberga, Combining energy efficiency at source and at consumer to reach 4th generation district heating: economic and system dynamics analysis, Energy 137 (2017) 595–606.
[74] H. Lund, P. Østergaard, D. Connolly, B. Mathiesen, Smart energy and smart energy systems, Energy 137 (2015) 556–565.
[75] P. Mancarella, MES (multi-energy systems): an overview of concepts and evaluation models, Energy 65 (2014) 1–17.
[76] N. Voropai, V. Stennikov, E. Barakhtenko, et al., A model for control of steady state of intelligent integrated energy system, Energy Systems Research 1 (1) (2018) 57–66.
[77] L. Brange, J. Englund, P. Lauenburg, Prosumers in district heating networks – a Swedish case study, Applied Energy 164 (2016) 492–500.
[78] L. Brand, A. Calvén, J. Englund, et al., Smart district heating networks – a simulation study of prosumers' impact on technical parameters in distribution networks, Applied Energy 129 (2014) 39–48.
[79] H. Kauko, K. Kvalsvik, D. Rohdeb, et al., Dynamic modeling of local district heating grids with prosumers: a case study for Norway, Energy 151 (2018) 261–271.
[80] A. Nekrasov, A. Reznikovsky (Eds.), Reliability of Power Plant Fuel Supply: Research Methods and Models, Nauka, Moscow, 1990 (in Russian).
[81] Y. Mazur, Problems of Maneuverability in Energy Industry Development, Nauka, Moscow, 1986 (in Russian).
[82] V. Zorkaltsev, E. Ivanova, Intensity and synchronicity of fluctuations of fuel demand for heating by economic regions of the country, Izvestiya AN SSSR. Energetika i Transport 6 (1990) 14–22 (in Russian).
[83] V. Zorkaltsev, Y. Kolobov, Simulation model to study the reliability of fuel supply of heat-generating units, Trudy Komi Filiala Akademii Nauk SSSR (1984) 33–39 (in Russian).
[84] M. Sukharev, S. Babayev, A. Beilin, et al., Reliability of Gas and Oil Supply Systems (Book 1), Nedra, Moscow, 1994 (in Russian).
[85] S. Rimkevicius, A. Kaliatka, M. Valincius, et al., Development of approach for reliability assessment of pipeline network systems, Applied Energy 94 (2012) 22–33.

[86] A. Amirat, A. Mohamed-Chateauneuf, K. Chaoui, Reliability assessment of underground pipelines under the combined effect of active corrosion and residual stress, International Journal of Pressure Vessels and Piping 83 (2) (2006) 107–117.
[87] T. Adefarati, R. Bansal, Reliability assessment of distribution system with the integration of renewable distributed generation, Applied Energy 185 (2017) 158–171.
[88] J. Ramirez-Marquez, D. Coit, Multi-state component criticality analysis for reliability improvement in multi-state systems, Reliability Engineering & Systems Safety 92 (2007) 1608–1619.
[89] A. Lisnianski, D. Elmakias, B. Hanoch, A multi-state Markov model for a short-term reliability analysis of a power generating unit, Reliability Engineering & Systems Safety 98 (2012) 1–6.
[90] A. Shahhosseini, J. Olamaei, An efficient stochastic programming for optimal allocation of combined heat and power systems for commercial buildings using, Thermal Science and Engineering Progress 11 (2019) 133–141.
[91] M. Haghifam, M. Manbachi, Reliability and availability modelling of combined heat and power (CHP) systems, International Journal of Electrical Power & Energy Systems 33 (3) (2011) 385–393.
[92] H. Sabouhi, A. Abbaspour, M. Fotuhi-Firuzabad, P. Dehghanian, Reliability modeling and availability analysis of combined cycle power plants, International Journal of Electrical Power & Energy Systems 79 (2016) 108–119.
[93] P. Kumar, L. Kumar Singh, C. Kumar, Performance evaluation of safety-critical systems of nuclear power plant systems, Nuclear Engineering and Technology 52 (3) (2020) 560–567.
[94] J. Jiang, L. Zhang, Y. Wang, et al., Markov reliability model research of monitoring process in digital main control room of nuclear power plant, Safety Science 49 (6) (2011) 843–851.
[95] J. Wang, C. Fu, K. Yang, et al., Reliability and availability analysis of redundant BCHP (building cooling, heating and power) system, Energy 61 (2013) 531–540.
[96] A. El-Nashar, Optimal design of a cogeneration plant for power and desalination taking equipment reliability into consideration, Desalination 229 (1–3) (2008) 21–32.
[97] S. Woo, Z. Nam, Semi-Markov reliability analysis of three test/repair policies for standby safety systems in a nuclear power plant, Reliability Engineering & Systems Safety 31 (1991) 1–30.
[98] V. Korolyuk, A. Turbin, Semi-Markov Processes and Their Applications, Nauk. Dumka, Kyiv, 1976 (in Russian).
[99] J. Jiang, W. Gao, X. Wei, et al., Reliability and cost analysis of the redundant design of a combined cooling, heating and power (CCHP) system, Energy Conversion and Management 199 (2019) 111988.
[100] J. Wang, S. You, Y. Zong, et al., Flexibility of combined heat and power plants: a review of technologies and operation strategies, Applied Energy 252 (2019) 113445.
[101] C. Frangopoulos, Effect of reliability considerations on the optimal synthesis, design and operation of a cogeneration system, Energy 23 (3) (2004) 309–329.
[102] M. Claudio, S. Rocco, A rule induction approach to improve Monte Carlo system reliability assessment, Reliability Engineering & Systems Safety 82 (2003) 85–92.
[103] A. Naess, B. Leira, O. Batsevych, System reliability analysis by enhanced Monte Carlo simulation, Structural Safety 31 (2009) 349–355.
[104] N. Buslenko, Modeling of Complex Systems, Nauka, Moscow, 1978 (in Russian).
[105] N. Buslenko, V. Kalashnikov, I. Kovalenko, Lectures in Complex Systems Theory, Sov. Radio, Moscow, 1983 (in Russian).
[106] A. Smirnov, Functional and Process Approach to Reliability of Heat Sources in Heating Systems, Heat and Energy Saving, Thermometry, Institute of Energy Saving Problems of the Academy of Sciences of the Ukrainian SSR, Kyiv, 1990 (in Russian).
[107] L. Shua, L. Chena, J. Jina, et al., Functional reliability simulation for a power-station's steam-turbine, Applied Energy 80 (1) (2005) 61–66.

[108] H. Ahn, D. Rim, G. Pavlak, J. Freihaut, Uncertainty analysis of energy and economic performances of hybrid solar photovoltaic and combined cooling, heating, and power (CCHP+PV) systems using a Monte-Carlo method, Applied Energy 255 (2019) 113753.

[109] V. Khasilev, M. Takaishvili, On the basis of the methodology of calculation and creating redundancy of heating networks, Teploenergetika 4 (1972) 14–19 (in Russian).

[110] A. Ionin, Criteria for assessing and calculating the reliability of heat networks, Vodosnabzhenie i Sanitarnaya Tekhnika 12 (1978) 9–10 (in Russian).

[111] A. Ionin, Reliability of Heat Network Systems, Stroyizdat, Moscow, 1989 (in Russian).

[112] M. Valincius, I. Zutautaite, G. Dundulis, et al., Integrated assessment of failure probability of the district heating network, Reliability Engineering & Systems Safety 133 (2015) 314–322.

[113] V. Stennikov, I. Postnikov, Methods for the integrated reliability analysis of heat supply, Power Technology and Engineering 47 (6) (2014) 446–453.

[114] V. Stennikov, I. Postnikov, Development of methods for analyzing the reliability of heating, Problemy Energetiki 5–6 (2010) 28–40 (in Russian).

[115] V. Stennikov, I. Postnikov, Comprehensive analysis of the reliability of supplying heat to consumers, Izvestiya RAN. Energetika 2 (2011) 107–121 (in Russian).

[116] V. Stennikov, I. Postnikov, Methodological support for a comprehensive analysis of fuel and heat supply reliability, Chapter 5, in: P. Vasant, N.I. Voropai (Eds.), Sustaining Power Resources Through Energy Optimization and Engineering, Hershey PA, 2016, Engineering science reference (an imprint of IGI Global).

[117] V. Stennikov, I. Postnikov, Methods for comprehensive analysis of heat supply reliability, International Journal of Energy Optimization and Engineering 2 (4) (2013) 120–142.

[118] I. Postnikov, V. Stennikov, Reliability of heating systems, Chapter 2, in: N.I. Voropai (Ed.), Reliability of Energy Systems: Problems, Models and Methods for Solving Them, Nauka, Novosibirsk, 2014 (in Russian).

[119] I. Postnikov, Application of the methods for comprehensive reliability analysis of district heating systems, Environmental and Climate Technologies 24 (3) (2020) 145–162.

[120] I. Postnikov, V. Stennikov, E. Mednikova, A. Penkovskii, Methodology for optimization of component reliability of heat supply systems, Applied Energy 227 (2018) 365–374.

[121] I. Postnikov, V. Stennikov, Ensuring parametric reliability of heating systems, Problemy Energetiki 3–4 (2017) 20–30 (in Russian).

[122] O. Linton, Probability theory, Chapter 1, in: Probability, Statistics and Econometrics, University of Cambridge, Elsevier Inc., United Kingdom, 2017.

[123] S. Garrett, Probability theory, Chapter 9, in: Introduction to Actuarial and Financial Mathematical Methods, Academic Press, Elsevier Inc., 2015.

[124] Sheldon M. Ross, Introduction to Probability Models, twelfth edition, University of Southern California, Los Angeles CA, 2019.

[125] R. Barlow, F. Proschan, Mathematical Theory of Reliability, John Wiley and Sons, New York, 1965.

[126] G. Antonov, V. Zorkaltsev, L. Krivorutsky, et al., Handbook on General Models of Analysis and Synthesis of Reliability of Energy Systems, Energoatomizdat, Moscow, 1994 (in Russian).

[127] Yu. Rudenko, I. Ushakov, G. Cherkesov, Theoretical and methodical aspects of reliability analysis of energy systems, Energy Reviews Scientific and Engineering Problems of Energy System Reliability 3 (1984) 82–94.

[128] A. Polovko, S. Gurov, Fundamentals of Reliability Theory, BHV-Peterburg, St. Petersburg, 2006 (in Russian).

[129] I. Postnikov, V. Stennikov, Modifications of probabilistic models of states evolution for reliability analysis of district heating systems, Energy Reports 6 (2) (2020) 293–298.

[130] V. Sokolov, Cogeneration-Based District Heating and Heat Networks, Publishing House of Moscow Power Engineering Institute, Moscow, 1999 (in Russian).

[131] E. Sklovskaya, et al., Mathematical description of the heating loads profile by their duration for calculation of technical and economic performance metrics of heating systems, Izvestiya Vuzov. Energetika 1 (1982) 75–77 (in Russian).
[132] F. Bukher, M. Ermakov, et al., Study of operating conditions and a feasibility study of the reconstruction of heat networks in the municipality of Shelekhov with prospective loads factored in, Report on the research work, Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, Irkutsk, 2008 (in Russian).
[133] SP 124.13330.2012 “Heat Networks”, Ministry of Construction and Housing and Communal Services of the Russian Federation, Moscow, 2012 (in Russian).
[134] I. Postnikov, V. Stennikov, A. Penkovskii, Prosumer in the district heating systems: operating and reliability modeling, Energy Procedia 158 (2019) 2530–2535.
[135] I. Postnikov, Methods for optimization of time redundancy of prosumer in district heating systems, Energy Reports 6 (2) (2020) 214–220.
[136] I. Postnikov, Methods for the reliability optimization of district-distributed heating systems with prosumers, Energy Reports 9 (1) (2022) 584–593.

This page intentionally left blank

CHAPTER

7

Hierarchy of mathematical modeling and optimization problems of advanced co-generation systems and fuel coproduction power generation systems

A.M. Kler, E.A. Tyurina, Yu.M. Potanina, E.L. Stepanova, P.V. Zharkov, A.Yu. Marinchenko, A.S. Mednikov, and N.O. Epishkin

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

7.1 Hierarchy of optimization problems of flow diagrams and parameters of co-generation systems and fuel co-production power generation systems

It should be noted that in almost all cases process flow diagrams (PFD) of co-generation systems and fuel co-production power generation systems have hierarchical structures. In the PFDs of the plants, one can isolate the PFDs of individual modules or plants. For example, the PFD of the coal-fired steam turbine power unit includes the PFD of the coal-fired steam boiler and the PFD of the steam turbine and the system of regenerative heating of feed water. The PFD of the natural gas-fired CCGT includes PFDs of the gas turbine plant, heat recovery steam generator, and steam turbine plant. The PFDs of coal-fired fuel co-production power generation

Hierarchical Modeling of Energy Systems
https://doi.org/10.1016/B978-0-44-313917-8.00016-X

systems include PFDs of the coal gasification unit, liquid fuel synthesis unit, and power unit. The PFDs of these lower-level subsystems are characterized by a large number of "internal" process links between components of the subsystem and a small number of "external" process links with components of other subsystems. It should be emphasized that the process flows of the lower-level subsystems can include their "internal" subsystems. For example, a fuel co-production power generation system power plant can include a gas turbine plant, a heat recovery steam generator, and a steam turbine plant. In some cases, there are even lower hierarchical levels. Thus, high-pressure heaters of a regenerative feed water heating system of a steam turbine plant consist, as a rule, of three zones (heaters): steam cooling zone, condensation zone, and condensate cooling zone. The above hierarchical structures of co-generation systems and fuel co-production power generation systems give rise to their hierarchically organized mathematical models. The hierarchy of such models is shown in Fig. 7.1. Each plant subsystem has its corresponding mathematical model, which includes mathematical models of lower hierarchical level subsystems. In all cases, at the lower hierarchical level are mathematical models of the simplest "indivisible" components.

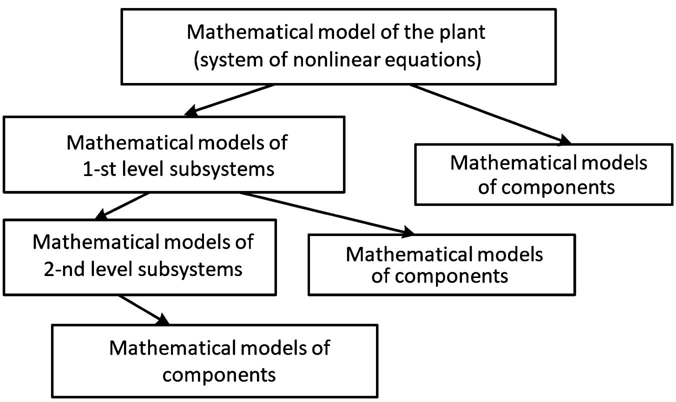


FIGURE 7.1 Hierarchical structure of mathematical models of co-generation systems and fuel co-production power generation systems.

When it comes to the calculation of steady-state conditions of plant operation, the problem is reduced to solving systems of nonlinear algebraic and transcendental equations. In the case of a hierarchical structure of mathematical models of plants, there is a conventional approach as to the arrangement of the computational process of solving the specified systems of equations. It consists in arranging an "internal" iterative process of solving the corresponding system of equations in a mathematical model of any hierarchical level. And, at each iteration of solving the system that is related to the model of the n-th hierarchical level, solving of all the systems of equations of the $n + 1$ hierarchical level related to this model is performed. It should be noted that most of the systems of equations describing components and subsystems of the co-generation systems are non-linear systems. It is well known that such systems cannot be solved exactly in a finite number of iterations of any known method of solving them. This leads to the appearance of "noises" that have a strong influence on the determination of derived functions by finite-difference methods. Most pronounced is the effect of the specified "noises" on the efficiency of gradient methods of optimization.

Due to the complexity of PFDs, considered plants, and the variety of external conditions of their operation, there are several problems of their structural and parametric optimization, and one can notice a hierarchical relationship between these problems when it is required to repeatedly solve the problems of the lower hierarchical level so as to solve the problems of the upper level of the hierarchy. In accordance with such a representation, the problems of optimization of continuous-variable parameters of the plant should be classified as the problems of the lower hierarchical level. And here we can distinguish two types of problems.

1. For plants where the external operating conditions change only slightly (e.g., power plants operating within the baseline part of the electrical load profile), optimization of continuous-variable parameters can be performed taking into account only one characteristic mode of operation.
2. For plants where the external operating conditions vary significantly (e.g., plants with combined heat and electricity generation for which the heat load significantly depends on the ambient temperature, or plants generating electricity only and operating at the peak part of the electrical load profile), optimization should be carried out taking into account several characteristic modes of operation.

At a higher hierarchical level are the problems of joint optimization of discrete- and continuous-variable parameters. Optimization of the composition of components for working components of maximum redundancy PFDs also comes down to the same type of problems.

At the highest hierarchical level are the problems of evolutionary optimization of PFDs of co-generation systems and fuel co-production power generation systems. In this case, structural and parametric optimization of the plant is carried out using the optimization problems mentioned above. For the obtained optimal structural and parametric solution, we perform an analysis of the efficiency of additional flows of thermal energy or working medium between the given points of the PFD. The efficiency of such flows (their effect on the objective function) is evaluated either on the basis of the duality theory in nonlinear mathematical programming or by the results of solving special linear programming problems. On the basis of this analysis, the evolution of the PFD is determined, its mathematical model is built, and optimization studies are conducted. As a result of several iterations of the described "evolutionary" process, it is possible to achieve a noticeable improvement in the efficiency of the optimized plant. The hierarchy of structural and parametric optimization problems is shown in Fig. 7.2.

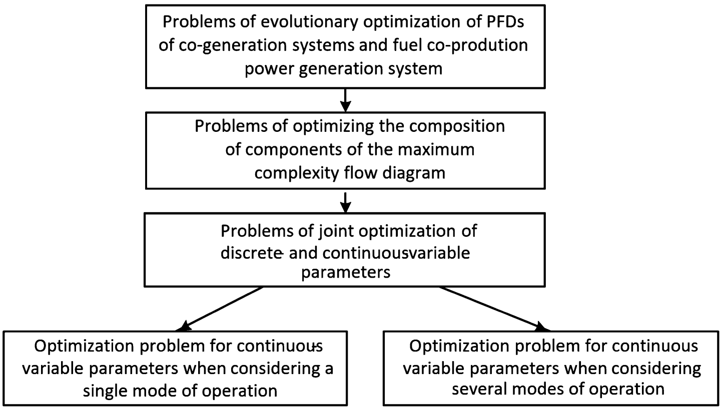


FIGURE 7.2 The hierarchical structure of process flow and parametric optimization problems of co-generation systems and fuel co-production power generation systems.

Below we consider the efficient approach developed at the Melentiev ESI, SB RAS, to build mathematical models of complex plants and solving problems of optimization of continuous-variable parameters. In addition, we consider the approaches to the optimization of PFDs of co-generation systems and fuel co-production power generation systems.

7.2 An efficient approach to the optimization of continuous-variable parameters of co-generation systems and fuel co-production power generation systems and the arrangement of their mathematical models

The only efficient approach to the study of complex co-generation systems and fuel co-production power generation systems is the approach based on the use of mathematical modeling and optimization methods. Quite a number of studies are devoted to the application of these methods to the study of co-generation systems.

In [1], for optimization studies of power plants with respect to increased steam parameters, the authors used software developed for thermodynamic analysis (exergic and exergy-based economic analysis) and optimization, based on methods that do not require calculating gradients of the objective function and constraints (exergy-based economic approach, Nelder-Meade method, and evolutionary algorithms) of energy conversion systems, and they solve a mixed problem of nonlinear mathematical programming with continuous-variable and discrete-variable parameters to be optimized. In [2], optimization of thermodynamic parameters of a power plant for supercritical steam parameters (SCP) in Indian climatic conditions was performed on the basis of neural networks and genetic algorithms (neuro-genetic optimization). In [3], non-gradient methods were used to optimize the parameters of a 900 MW power plant for advanced ultra-supercritical steam conditions (A-USC), namely the Nelder-Meade, Hooke-Jeeves, and Rosenbrock methods. In [4], the authors carried out the optimization of structural parameters of a low-pressure economizer that uses waste heat recovery from the exhaust flue gas before it enters a flue gas desulfurizer to heat the feed water in the path of the low-pressure heater group of a 600 MW coal-fired power plant. The particle swarm method was used for this purpose. The genetic algorithm of non-dominated sorting II was used in [5] to optimize the power plants. To optimize a 250 MW coal-fired power plant, the fuzzy logic method was used in [6].

It should be noted that in the above studies, to determine the rational parameters, various methods of a directed exhaustive search of parameters are used, which are efficient only when selecting a small number of them (no more than 10–15). With a larger number of parameters, the methods do not guarantee a good approximation with respect to the optimal solution. At the same time, a reasonable optimization of such complex engineering systems as the co-generation system and fuel co-production power generation system requires a coordinated choice of several dozens of parameters of process connections between PFD components and internal parameters of individual components.

To all intents and purposes, the only efficient tool for solving such optimization problems are gradient methods of nonlinear optimization. The MESI SB RAS, has long been involved in the development of such methods with their application to the problems of optimization of parameters of various power plants [7,8].

It should be noted that the processes of co-generation system operation in steady-state operating conditions are described by nonlinear systems of algebraic and transcendental equations of high dimensionality. These systems of equations are solved by iterative methods (Newton method, Seidel method, etc.), and the exact solution cannot be obtained in a finite number of iterations. When solving nonlinear optimization problems of continuous-variable parameters of the co-generation system, one uses the approach [7], according to which all variables calculated from the system of equations are represented as implicit functions of independent optimized parameters. As a result, the optimization problem is reduced to a problem with constraints that are in the form of inequalities only. In this case, the calculation of implicit functions consists in solving a system of nonlinear equations. Such a calculation must be performed each time one refers to the calculation of the process flow diagram of the plant. Since the calculation of partial derivatives of the objective function and inequality constraints for complex co-generation systems when using efficient gradient optimization methods can be carried out only by finite-difference methods, at each iteration of the optimization process it is necessary to repeatedly solve nonlinear systems of equations of large dimension, which creates major computational difficulties in optimization. At the same time, as noted above, due to the hierarchical structure of the mathematical model of the plant, all subsystems of equations of the $n + 1$ hierarchical level should be solved at each iteration of the computational process of the n-th hierarchical level.

A significant disadvantage of this approach is that at the "starting" point of the iterative optimization process there must necessarily exist a solution to the system of equations defined by the inequality constraints. Another notable shortcoming of the approach is related to the errors in calculating partial derivatives of the objective function and constraints by the finite-difference method, due to errors in solving systems of nonlinear equations, which compromises the convergence of iterative processes.

In this regard, it seems promising to arrange the optimization process in such a way that the solution to the system of equations is achieved with the required accuracy not at all points of the iteration process but only at the final point. The optimization process is combined with the process of solving systems of nonlinear equations. This applies to systems of all hierarchical levels. This approach was covered in the works by the MESI SB RAS [9,10]. Its essence is that the process of solving systems of nonlinear equations is taken from the level of mathematical modeling to the level of optimization. In this case, each equality is replaced by two inequalities bounding the value of the relative residual of the corresponding equation (the relative residual is equal to the absolute residual divided by the required accuracy of solving the equation). One inequality is violated if the absolute value of the relative residual exceeds a given value when the residual is positive, and the second inequality is violated when it is negative. The specified limit value of the absolute values of the residuals is given through one auxiliary variable, which is included in the inequalities corresponding to all equations of the system. In addition, one introduces an estimate of the optimal value of the objective function and the required accuracy of the objective function calculation.

Let us consider the mathematical statement of the proposed method. The initial optimization problem has the form

$$\min_{x,y} f(x, y) \tag{7.1}$$

subject to the following conditions:

$$H(x, y) = 0, \tag{7.2}$$
$$G(x, y) \geq 0, \tag{7.3}$$
$$\underline{x} \leq x \leq \overline{x}, \tag{7.4}$$
$$\underline{y} \leq y \leq \overline{y}. \tag{7.5}$$

Let us replace the system of equalities (7.2) by a system of inequalities of the form

$$\frac{x^v - h_k(x, y)}{\varepsilon_k} \geq 0, \tag{7.6}$$
$$\frac{x^v + h_k(x, y)}{\varepsilon_k} \geq 0, \tag{7.7}$$
$$k = 1, \ldots, K, \; x^v \geq 0, \tag{7.8}$$

where h_k is the k-th absolute residual of the system (7.2); ε_k is the required accuracy for the k-th residual; the system (7.2) is solved if $\varepsilon_k \geq h_k$; x^v is the auxiliary variable, $\theta_k = h_k/\varepsilon_k$ is the relative k-th residual.

Obviously, the inequalities (7.6) and (7.7) hold simultaneously if $x^v \geq |h_k(x, y)|/\varepsilon_k$. If this condition is violated given $h_k(x, y) > 0$, then the inequality (7.6) is violated, otherwise, ($h_k(x, y) < 0$) the inequality (7.7) is violated.

We introduce a constraint on the relative residual of the objective function of the form

$$x^v + \frac{f^c - f_{cur}}{\sigma} \geq 0, \tag{7.9}$$

where f^c is the lower estimate of the optimal value of the objective function; f_{cur} is the current value of the objective function; σ is the acceptable discrepancy between the estimate of the objective function and its current value.

If the inequality (7.9) is satisfied given $x^v < 1$, then f_{cur} approaches the optimal value of the objective function f^* with the required accuracy. This follows from the inequality $f_{cur} \geq f^* \geq f^c$, where f^* is the value of the objective function at the point of the solution to the problem (7.1)–(7.5). Similarly, given $x^v \leq 1$ the conditions $\varepsilon_k \geq h_k(x, y)$ and $\varepsilon_k \leq -h_k(x, y)$ will be satisfied. This ensures the correctness of the inequality $\varepsilon_k \geq |h_k(x, y)|$. Thus, all the residuals of the system (7.2) will have the required accuracy.

As an estimate of the objective function f^c, one can use its value at the solution point of the next problem (Problem I):

$$\min_{x,y} f(x, y)$$

subject to the conditions (7.3)–(7.8).

When solving Problem I x^v is fixed at some value of $\bar{x}^v > 0$. Let us denote the objective function at the solution point of Problem I by f^I. Obviously, the set of values of x, y meeting the conditions (7.6)–(7.8) includes the set of values of x, y meeting the condition (7.2). Therefore $f^I \leq f^*$ and f^I can be used as a lower estimate f^c for f^*.

An efficient modification of this method was proposed in [10]. In this modification, two steps are taken at each iteration.

The first step solves Problem I. As a result, the optimal value of the objective function f^c is determined, which is certainly less than the optimal value of the solution to the original problem.

At the second step, the value of f^c obtained at the first step is substituted into the inequality (7.9) and Problem II is solved having the following form:

$$\min_{x^v, x, y} x^v,$$

subject to the conditions (7.3)–(7.9).

After that we move on to the second iteration. This process continues until x^v decreases to the value at which the specified accuracy of the calculation of the residuals and approximation to the optimal value of the objective function is achieved.

The advantages of the above method are that it can start from a point where the system of equations has no solution with the required accuracy and that the solution of the system of equations is reached only at the optimal point.

The solving of practical problems showed drastically better convergence and greater accuracy in approaching the optimum as compared to the conventional optimization approach when systems of equations are repeatedly solved at each iteration. It should be noted that when using the conventional approach, a significant part of the work effort associated with the development of mathematical models of co-generation system and fuel co-production power generation system components is aimed at arranging efficient computational processes for solving subsystems of nonlinear algebraic and transcendental equations that describe the processes occurring in the corresponding components. In the proposed approach, all computational processes are taken out of mathematical models. This greatly simplifies the models and makes them consistent.

As an example of employing the proposed approach, we consider the optimization of continuous-variable parameters of a coal-fired power plant for increased steam parameters.

For the purpose of optimization studies, we adopted the PFD of the power unit for increased steam parameters (Fig. 7.3), which includes a once-through steam boiler with one live-steam reheater (SG), 660 MW steam turbine, three high-pressure heaters (FWH5-FWH7), deaerator (DEA), and four low-pressure heaters (FWH1-FWH4). The equivalent heat balance diagram of the considered power unit includes not only the turbine with the regeneration system but also a detailed diagram of the steam boiler. In the convective shaft of the steam boiler, there are three steam superheater stages (SH1-SH3), two live-steam reheater stages (RH1, RH2), maximum heat capacity zone (TZ), as well as two water economizer stages (WE1, WE2) and air heater stages (AH1, AH2).

To solve the optimization problems of the coal-fired power plant parameters, we built a mathematical model of the considered power plant, and the model included 1127 specified parameters and 1202 calculated parameters. And we isolated 32 residuals and the same number of parameters in the system of equations describing the PFD of the plant; changing the latter allows one to minimize the above residuals. In the mathematical models of the components, 73 residuals and the same number of balancing parameters were identified, changing them allows one to minimize these residuals. The power plant model was built with the aid of the software package "Machine Program Building System" developed at the MESI SB RAS [7], which, based on the graphically specified process flow diagram of the plant and mathematical models of its components builds a program for calculating the plant and allows forming problems for optimization of its parameters.

It should be noted that the following is characteristic of power plants burning solid fuel. A part of the components of the specific capital expenditures increases with the efficiency of the plant, i.e., with the growth of its energy efficiency, while the other part - decreases. The former part includes the cost of heating surfaces of the steam boiler, high and medium pressure cylinders of the steam turbine, regenerative heaters, and condensers. The latter part includes capital expenditures in the fuel supply, dust preparation, ash removal, flue gas treatment and removal, and thermal discharge systems. In [8], it is shown that the dependency of minimum specific capital expenditures of coal-fired power plants as a function of net efficiency has a minimum at a certain efficiency. The value of efficiency, at which the minimum is achieved, depends on the ratio of the costs of various components of the equipment of the power plant. Obviously, the optimal power unit efficiency according to the criterion of economic efficiency should be within the range between the efficiency, which achieves the minimum specific capital expenditures, and the maximum efficiency.

Taking this into account, the optimization problems of power plant parameters as nonlinear mathematical programming problems have the following statements:

1) Maximizing energy efficiency (Problem 1)

$$\max \frac{W - W_{own}}{m_{coal} \cdot Q_l^p} \tag{7.10}$$

subject to the following conditions:

$$H(x, y, z) = 0, \tag{7.11}$$

$$G(x, y, z) \geq 0, \tag{7.12}$$

$$m_{coal} = f_m(x, y, z), \tag{7.13}$$

$$W = f_W(x, y, z), \tag{7.14}$$

$$W_{own} = f_{own}(x, y, z), \tag{7.15}$$

$$TCI = f_{TCI}(x, y, z, W, m_{coal}), \tag{7.16}$$

$$W^{min} \leq W \leq W^{max}, \tag{7.17}$$

$$\underline{x} \leq x \leq \overline{x}, \tag{7.18}$$

where W – the full power of the power unit; W_{own} – auxiliary power; m_{coal} – fuel consumption; Q_l^p – lower calorific value of fuel; H – l-dimensional function of inequality constraints; x – n-dimensional vector of independent parameters to be optimized; y – l-dimensional vector of parameters to be calculated (dependent parameters); z – vector specifying the external conditions of the power unit operation and some design parameters that are not to be optimized; G – m-dimensional vector function of inequality constraints; TCI – total capital expenditures; $\underline{x}$, $\overline{x}$ – vectors whose components specify lower and upper bounds of the variation range of the corresponding components of the vector x.

2) Minimization of specific capital expenditures (Problem 2)

$$\min \frac{TCI}{W - W_{own}} \tag{7.19}$$

subject to the conditions (7.11)–(7.18).

3) Minimization of specific capital expenditures for fixed values of net efficiency (Problem 3).

To solve this problem, an additional constraint of the following form is introduced into Problem 2

$$\frac{W - W_{own}}{m_{coal} \cdot Q_l^p} = \eta^z, \tag{7.20}$$

where η^z is the fixed value of net efficiency.

4) Minimizing the price of electricity at a given internal rate of return on investment (Problem 4)

$$\min COE = f_{COE}(x, y, z, FC, TCI, CRF, W_{net}, N) \tag{7.21}$$

subject to the conditions (7.11)–(7.18), where COE is the electricity price; FC is annual fuel costs; CRF is the internal rate of return on investment; W_{net} is useful capacity; N is the number of hours of the utilization of installed capacity.

Herein, as a criterion of economic valuation of compared options of engineering solutions for the power plant we use the minimum price of electricity (COE) that ensures a given value of the internal rate of return on investment (CRF). This criterion is more convenient than the maximum net present value (NPV) because it does not require bringing the compared options to the same useful energy output. In addition, it is preferable to the criterion of maximum internal rate of return for a given electricity price because it is easier to set an acceptable level of CRF than the price of electricity.

When determining COE for a coal-fired power unit, the following assumptions can be made, which have almost no effect on the accuracy of COE calculation [10].

1. Capital expenditures are distributed evenly over the years of construction of the power unit.

2. Useful annual electric power output for all years of operation of the power unit E_{year} is assumed to be the same and is determined from the following expression

$$E_{year} = W_{net} \cdot N. \tag{7.22}$$

3. Annual fuel costs (FC) for all years of power unit operation are assumed to be the same and are determined from the expression

$$FC = 3.6 \cdot m_{coal} \cdot c_{coal} \cdot N, \tag{7.23}$$

where c_{coal} is the specific cost of fuel.

4. The annual semi-fixed operating costs (AFOC), which do not depend on the number of hours of use of useful capacity, and the annual depreciation (AD), constant for all years of the calculation period, are determined from the expressions

$$AFOC = TCI \cdot \alpha_{AFOC}, \tag{7.24}$$

$$AD = TCI \cdot \alpha_{AD}, \tag{7.25}$$

where α_{AFOC} and α_{AD} are the share of annual semi-fixed and depreciation costs, respectively.

With these assumptions, the price of electricity at which a given level of CRF is achieved is determined from the equation

$$\sum_{t=1}^{NYC} \left[\left(\frac{TCI}{NYC} \right) \left(\frac{1}{1+CRF} \right) \right]^{t-1} + \sum_{t=NYC+1}^{NYC+NYO} \left[\left(FC + AFOC + AD - E_{year} \cdot COE \right) \left(\frac{1}{1+CRF} \right) \right]^{t-1} = 0, \tag{7.26}$$

where NYC is the number of years of construction; NYO is the number of years of operation.

It is easy to show that the COE such that makes Eq. (7.17) satisfied can be found from a fairly simple expression

$$COE = (TCI \cdot A + FC + AFOC + AD)/E_{year}, \tag{7.27}$$

where

$$A = \frac{\sum_{t=1}^{NYC} \left(\frac{1}{1+CRF}\right)^{t-1}}{NYC \cdot \sum_{t=NYC+1}^{NYC+NYO} \left(\frac{1}{1+CRF}\right)^{t-1}}.$$

When calculating the capital expenditures of the plant, the cost of the main components of the boiler and turbine were taken into account. In this case, the cost of heat-exchange equipment was taken directly proportional to the weight of the heat-exchange tubes, taking into account the price of steel these tubes were made from. Capital expenditures were determined in proportion to the weight of steel for the conduits of superheated steam, live reheated steam, and feed water. Costs of pumps and blower fans were determined in proportion to their capacities, taking into account the parameters of the working medium. Costs of the systems of fuel supply, dust preparation, ash removal, cleaning and disposal of combustion products were determined in proportion to fuel consumption. Costs of design, installation, and construction were assumed to be proportional to the cost of the main equipment.

In general, capital expenditures are determined by the expression

$$TCI = \left(C_{mb} + C_{fc} + 3.6 m_{coal} \cdot c_{fuel} + c_{ee} W_{net} + C_{channels} + C_{chillers}\right) k_{uc}, \tag{7.28}$$

where C_{mb} – cost of the main shell; $C_{fc} = 290$ mln. USD – fixed costs independent of equipment cost for the 660 MW unit; $c_{fuel} = 0.24$ mln. USD/(t/h) – specific cost of systems that depend on fuel consumption; $c_{ee} = 192 \cdot 10^{-6}$ mln. USD/kW – specific cost of electrical equipment; $C_{channels}$ – cost of channels and pipelines of process water supply systems; $C_{chillers}$ – cost of chillers of process water supply systems; $k_{uc} = 1.03$ – coefficient that accounts for contingencies.

The cost of the main shell is determined as

$$C_{mb} = PEC \cdot k_{oc} \cdot k_{cc} \cdot k_{pa}, \tag{7.29}$$

where PEC is the cost of equipment; $k_{oc} = 1.3$ is the coefficient that takes into account other costs; $k_{cc} = 1.6$ is the coefficient of accounting for construction and installation costs; $k_{pa} = 1.62$ is the present value index of equipment prices (the prices of 2007 are converted to 2018 prices).

The cost of the equipment is determined as

$$PEC = (PEC_{HES} + PEC_{turbine} + PEC_{GEN} + PEC_{pumps} + PEC_{own} + PEC_{pipes})\,k_{ue}, \quad (7.30)$$

where PEC_{HES} is the cost of heat-exchange surfaces of a steam boiler, regenerative heaters, and a condenser; $PEC_{turbine}$ is the cost of a steam turbine; PEC_{GEN} is the cost of a generator; PEC_{pumps} is the cost of pumps; PEC_{own} is the consumption for in-house needs; PEC_{pipes} is the cost of main pipelines; $k_{ue} = 1.1$ is the coefficient that takes into account the cost of unaccounted equipment.

In [1,11,12], the cost of a steam turbine is presented as a function of the turbine power and the temperature of the superheated steam, the temperature of the reheated steam, and the internal relative efficiency of the cylinders. The disadvantage of this approach is the possibility of using the dependency in a fairly narrow range of parameter changes and lacking the consideration of the effect of the pressure of superheated steam and reheated steam.

Herein, the cost of a steam turbine is represented as the sum of the costs of its cylinders. For high-pressure (HPC) and medium-pressure (MPC) cylinders, the cost is presented as a function of the inlet steam flow rate, its temperature, and pressure. The cost of a low-pressure cylinder (LPC) is presented as a function of its total exhaust cross-section.

By analogy with [13], the values of the HPC and MPC are represented as power functions of the ratio of the corresponding cylinder parameters to the parameters of the base variant. The following expressions are used

$$PEC_{turbine} = C_{HPC} + C_{MPC} + C_{LPC}, \quad (7.31)$$

$$C_{HPC} = C_{HPC}^{const}\left(\frac{t_0}{t_0^{const}}\right)^3\left(\frac{p_0}{p_0^{const}}\right)^{0.07}\left(\frac{m_0}{m_0^{const}}\right)^{0.4},$$

$$C_{MPC} = C_{MPC}^{const}\left(\frac{t_{rs}}{t_{rs}^{const}}\right)^3\left(\frac{p_{rs}}{p_{rs}^{const}}\right)^{0.07}\left(\frac{m_{rs}}{m_{rs}^{const}}\right)^{0.4},$$

$$C_{LPC} = c_{LPC}^{const}\left(\frac{m_{out}\cdot v_{out}}{c_x}\right),$$

where $C_{HPC}^{const} = 11163.6$ and $C_{MPC}^{const} = 13821.6$ – base costs of the turbine HPC and MPC, respectively (thous. USD); $c_{LPC}^{const} = 1740$ – base specific cost of the turbine LPC (thous. USD/m^2); t_0, p_0, m_0 – temperature, pressure, and flow rate of the superheated steam, $t_0^{const} = 535°C$, $p_0^{const} = 16.6$ MPa, $m_0^{const} = 247.5$ kg/s; t_{rs}, p_{rs}, m_{rs} – temperature, pressure, and flow rate of reheated live-steam; $t_{rs}^{const} = 535°C$, $p_{rs}^{const} = 3.7$ MPa, $m_{rs}^{const} = 224.1$ kg/s; m_{out}, v_{out}, c_x – flow rate, specific volume and circumferential velocity of working medium at the outlet of the last turbine compartment. The exponents in the expressions are determined on the basis of the analysis of the data presented in [14,15].

The PFD of the considered power unit for increased steam parameters with a capacity of 660 MW is shown in Fig. 7.3.

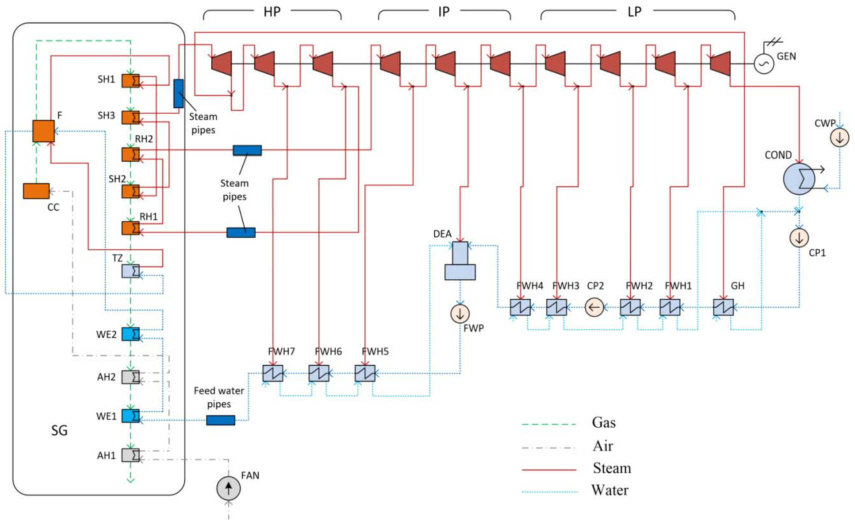


FIGURE 7.3 The PFD of the power plant with a capacity of 660 MW for increased steam parameters. FAN – blower fan; SG – once-through steam boiler; CC – combustion chamber of the steam boiler; F – furnace of the steam boiler; SH1–SH3 – convective superheaters; RH1, RH2 – live-steam reheaters; TZ – maximum heat capacity zone; WE1, WE2 – water economizers; AH1, AH2 – air heaters; HP – high-pressure cylinder compartment group; IP – intermediate pressure cylinder compartment group; LP – low-pressure cylinder compartment group; GEN – electric generator; COND – steam turbine condenser; CWP – circulating water pump; CP1, CP2 – condensate pumps; GH – gland heater; FWH1–FWH4 – low-pressure heaters; DEA – deaerator; FWP – feed water pump; FWH5–FWH7 – high-pressure heaters.

Four types of optimization problems were solved for the power unit: maximization of net efficiency (Problem 1), minimization of specific capital expenditures (Problem 2), minimization of specific capital expenditures at fixed values of net efficiency (Problem 3), and minimization of electricity price at a given internal rate of return on investment (Problem 4). At the same time, 116 parameters were taken as independent parameters to be optimized. They include the following: pressure and temperature of superheated steam and reheated steam, superheated steam flow rate, steam pressure in the extractions for regeneration and in turbine condenser, enthalpy of heat transfer fluid at the outlet of the heat-receiving surfaces of the steam boiler heating, thickness and pitch of tubes of these surfaces, etc. 164 inequality constraints were taken into account during optimization. They include the following: constraints on the temperature and mechanical stress of heat exchanger tubes steel, the temperature of combustion products at the boiler furnace outlet, the dew point for the first stage of the air heater, the end temperature pressures of heat exchangers, constraints on humidity at the outlet from the last turbine compartment, etc. For the tubes of the boiler heating surfaces, we assumed ultimate stresses providing $2 \cdot 10^5$ hours of operation at the appropriate temperature of the steel of the tube walls.

The following steels were considered for the power unit, which are used for manufacturing boiler heating surfaces. In the convective superheater of the first, second, and third stages, the live-steam reheater of the second stage and the main steam conduits, high-alloyed austenitic steel of grade 10H16N16B2MBR (EP-184) with a limit operating temperature of 700°C was used, and we considered heat-resistant steel grade 15H1MF, limit temperature 575°C and carbon steel 20, limit temperature 450°C as materials for the manufacture of other heating surfaces of the boiler unit. The rated allowable stresses of the steels used with a design life of 200000 h [16,17] are shown in Fig. 7.4.

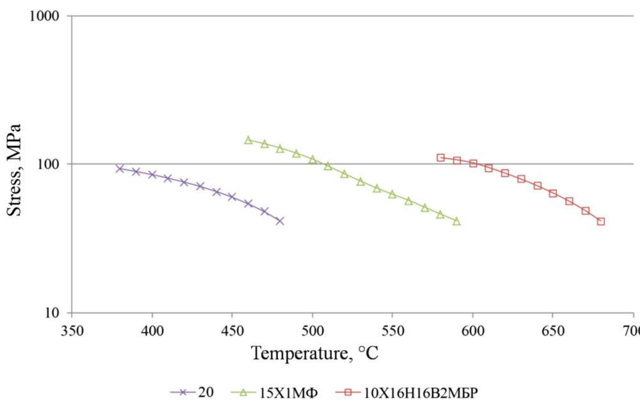


FIGURE 7.4 Rated allowable stresses of steels with service life of $2 \cdot 10^5$ h.

The following input engineering and economic information was used to calculate the capital expenditures of the power unit. The specific cost of heat exchanger tubes, made of carbon steel 20 is taken as equal to 21 thous. USD/t, that of heat-resistant steel 15Kh1MF – 30.6 thous. USD/t, and that of austenitic steel 10Kh16H16V2MBR – 53 thous. USD/t.

The following values of relative internal efficiencies of compartments (along the steam flow) were accepted for the steam-turbine plant, % – 90; 92; 94; 94; 94.5; 95.5; 94.5; 95; 90; 90.5; 86.

The Berezovsky lignite (Krasnoyarsk region, Russia) of the 2BR grade was considered as a fuel, its characteristics are presented in Table 7.1.

TABLE 7.1 Specifications of the Berezovsky coal.

W^p, %	A^p, %	S^p, %	C^p, %	H^p, %	N^p, %	O^p, %	Q_l^p, kJ/kg
33.0	4.7	0.2	44.3	3.0	0.4	14.4	15648.2

A number of optimization calculations were carried out and the dependency of the minimum specific capital expenditures on the net efficiency of the power unit was obtained (Fig. 7.5).

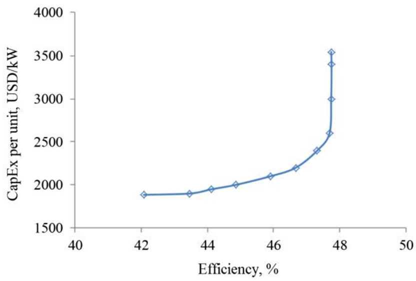


FIGURE 7.5 Dependency of minimum specific capital expenditures (CapEx per unit) on the net efficiency of the power plant.

Table 7.2 presents an iterative process of solving the optimization problem of maximizing the net efficiency of the power unit at a fixed value of the specific capital expenditures of $2,200/kW using the efficient gradient method.

The first iteration of solving the optimization problem begins with the problem of maximizing net efficiency at a fixed value of the auxiliary parameter equal to 8. As a result of solving it we obtain a net efficiency of 50.84%. We take this value as a "given" value and solve the problem for the minimum value of the auxiliary parameter. As a result, we get the value of the auxiliary parameter of 3.5482 and the current net efficiency of 48.36%. The first step of the second iteration starts at the specified value of the auxiliary parameter. The optimal efficiency value at the first step of the second iteration is 48.62%. At the second step of the second iteration, we obtain the value of the auxiliary parameter of 2.3747 and the current net efficiency of 48.06%. The iterative process of solving the optimization problem continues until the value of the auxiliary parameter becomes less than 0.001. At the 18th iteration, we obtain the value of the auxiliary parameter of 0.0097 and the net efficiency value of 46.51%.

Table 7.3 presents the key findings of optimization studies of the power plant of 660 MW for increased steam parameters. The table shows that the optimal initial parameters of the power plant fall within the range of 15.5 MPa, 613/540°C to 35.4 MPa, 657/613°C, their corresponding efficiency is within the range of 42.08% to 47.74%, and the specific capital expenditures range from 1884.6 to 3545.7 USD/kW. It should be noted that

TABLE 7.2 Iterative process for solving the optimization problem.

Iteration number	Step number	Value of the auxiliary parameter		Value of the objective function (net efficiency), %	
1	1	Fixed	8.0000	Optimal	50.84
	2	Optimal	3.5482	Set	
				Obtained	48.36
2	1	Fixed		Optimal	48.62
	2	Optimal	2.3747	Set	
				Obtained	48.06
3	1	Fixed		Optimal	48.07
	2	Optimal	2.2513	Set	
				Obtained	47.99
4	1	Fixed		Optimal	48.09
	2	Optimal	1.8636	Set	
				Obtained	47.57
5	1	Fixed		Optimal	47.65
	2	Optimal	1.1881	Set	
				Obtained	47.19
6	1	Fixed		Optimal	47.38
	2	Optimal	0.9212	Set	
				Obtained	47.08
7	1	Fixed		Optimal	47.25
	2	Optimal	0.4958	Set	
				Obtained	46.91
8	1	Fixed		Optimal	46.92
	2	Optimal	0.4582	Set	
				Obtained	46.79
9	1	Fixed		Optimal	46.87
	2	Optimal	0.2276	Set	
				Obtained	46.73
10	1	Fixed		Optimal	46.76
	2	Optimal	0.1793	Set	
				Obtained	46.64
11	1	Fixed		Optimal	46.86
	2	Optimal	0.1435	Set	
				Obtained	46.62
12	1	Fixed		Optimal	46.62
	2	Optimal	0.1045	Set	
				Obtained	46.56
13	1	Fixed		Optimal	46.63
	2	Optimal	0.0749	Set	
				Obtained	46.55

continued on next page

TABLE 7.2 (*continued*)

Iteration number	Step number	Value of the auxiliary parameter		Value of the objective function (net efficiency), %	
14	1	Fixed		Optimal	46.58
	2	Optimal	0.0694	Set	
				Obtained	46.54
15	1	Fixed		Optimal	46.54
	2	Optimal	0.0693	Set	
				Obtained	46.53
16	1	Fixed		Optimal	46.58
	2	Optimal	0.0321	Set	
				Obtained	46.52
17	1	Fixed		Optimal	46.63
	2	Optimal	0.0182	Set	
				Obtained	46.51
18	1	Fixed		Optimal	46.67
	2	Optimal	0.0097	Set	
				Obtained	46.51

TABLE 7.3 Main results of optimization calculations.

Parameters	Maximum efficiency	Minimum specific capital expenditures	Minimum electricity price			
Fuel cost, USD/kg	–	–	50	100	150	200
Electricity price, $/MWh	–	–	86.0	100.5	114.6	128.4
Net efficiency, %	47.74	42.08	42.58	42.83	43.14	43.47
Exhaust gas temperature, °C	115	147	135	132	125	121
Superheated steam flow rate, kg/s	478.6	516.6	514.0	511.3	505.6	502.1
Superheated steam pressure, MPa	35.4	15.5	16.7	17.0	17.3	18.1
Superheated steam temperature, °C	657	613	615	617	619	622
Feed water temperature, °C	317	262	262	263	262	262
Reheated steam pressure, MPa	7.6	3.6	4.1	4.1	4.1	4.2

continued on next page

TABLE 7.3 (*continued*)

Parameters	Maximum efficiency	Minimum specific capital expenditures	Minimum electricity price			
Reheated steam temperature, °C	613	540	537	540	544	545
Temperature of gases at the furnace outlet, °C	927	927	923	926	926	926
Boiler efficiency, %	95.21	93.68	94.31	94.50	94.89	95.10
Useful electrical power of the plant, MW	620.8	636.6	634.5	634.3	634.3	634.9
Specific fuel consumption, tons of fuel equivalent/kWh	258	292	289	287	285	283
Fuel consumption, kg/s	83.1	96.6	95.2	94.6	93.9	93.3
Power, MW	662.5	669.5	668.2	668.2	668.1	668.6
Capital expenditures of the plant, thous. USD.	2201244.0	1199827.8	1215004.7	1218914.2	1219295.3	1221638.7
Specific capital expenditures per installed capacity. $/kW	3545.7	1884.6	1915.0	1921.7	1922.3	1924.3

during optimization according to the criterion of minimum specific capital expenditures and minimum electricity price, the optimal pressure of superheated steam turned out to be quite low (15.5 to 18.1 MPa), while the temperature of superheated steam takes a very high value (613 – 622°C). This is due to the fact that the superheated steam pressure significantly affects the wall thickness and weight of the steel of the tubes of the heat exchange surfaces of the boiler. Therefore, an increase in pressure, on the one hand, makes it possible to increase the efficiency, but, on the other hand, it increases the capital expenditures. It should be noted that, in this case, optimal engineering solutions can be determined only as a result of joint optimization of the cycle parameters and design parameters of the components.

It should be noted that the values of pressure and temperature of reheating for all considered options are selected so that the humidity of steam at the outlet of the last turbine compartment was near the maximum allowable value of 13%. This ensures a reduction of heat loss in the condenser.

This example shows the effectiveness of the developed method of gradient optimization. According to this method, iterative processes of solving nonlinear systems of algebraic and transcendental equations describing the entire plant and its individual components are taken from the level of mathematical models to the level of optimization. This allows one to simplify and make consistent mathematical models of components and plant. They calculate only the residuals of the corresponding subsystems of equations. It is important to note that the calculation of the residuals is possible with such combinations of initial data, in which there are no solutions to the corresponding systems of equations. This allows one to start from the points where there are no solutions to systems of equations. And the exact solution is achieved only at the optimal point.

The essence of the proposed method is that at each iteration two optimization problems are solved: minimization of the objective function with a given maximum value of the absolute value of the relative residuals (Problem I); minimization of the maximum value of the absolute value of the relative residuals when the increment of the objective function is limited (problem II). Initially, a large absolute value of the maximum of relative residuals is specified. This value decreases from iteration to iteration, and the optimal value of the objective function in the solution points of Problem I increases from iteration to iteration. This results in a sequence of optimal solutions to Problem I, which converge to the optimal solution of the original problem (7.1)–(7.5). Since in this case, from iteration to iteration, the objective function is increasing stepwise for minimization problems or decreasing stepwise for maximization problems, it is reasonable to call the proposed method a nonlinear stepwise optimization method.

The use of the proposed approach made it possible to obtain a smooth dependency of the minimum specific capital expenditures on the efficiency for the coal-fired power plant considered herein. The obtained dependency showed that when approaching the point of maximum efficiency, the specific capital expenditures of the power plant increase sharply.

Optimal solutions were obtained with respect to the criteria of maximum efficiency, minimum specific capital expenditures, and minimum electricity price.

It is shown that when optimizing with respect to the criteria of minimum specific capital expenditures and minimum electricity price, one obtains rather low optimum pressures of steam at its high optimum temperatures.

7.3 Methods for selecting the optimal composition of components and connections of process flow diagrams of co-generation systems and fuel co-production power generation systems

The efficiency of the co-generation system is determined by its process flow structure, values of thermodynamic cycle parameters, and design parameters of components. The PFD is determined by the composition of the components and the structure of the material and energy flows connecting them. Optimization of plant parameters for a given PFD is reduced to the problem of nonlinear mathematical programming. In this case, most of the optimized parameters can take any real value that falls within some specified limits. Such parameters are called continuous-variable parameters. These include the flow rates of working media and heat transferring fluids, their pressures, temperatures, geometric dimensions of the components. A minor share of the parameters can only take discrete values that fall within specified limits. These are such design characteristics of components as the number of heat exchange tubes connected in parallel, the number of nozzles and buckets at the turbine stage, etc. Such parameters are called discrete-variable parameters. It should be emphasized that with the values of these parameters that do not meet the requirements of discreteness and do not have a physical meaning, calculations of the co-generation system can be carried out, i.e., one can solve the system of equality constraints, determine the inequality constraints, and find the criteria of energy and economic efficiency.

To solve problems with continuous-variable parameters that are to be optimized, a significant number of studies use various directed search methods. These methods have fairly simple algorithms and are robust. But they allow one to optimize only a small number of parameters. As examples of their use to optimize the parameters of power plants, we can refer to the following studies.

The article [18] compares two optimization methodologies based on energy-economic and exergoeconomic analysis. As an example, we consider a combined cycle plant with different heat recovery steam generator configurations and different gas turbines. A genetic algorithm was used in the calculations.

The article [19] presents the results of thermo-economic optimization of the heat recovery steam generator for a range of gas turbine exhaust temperatures and the study of the effect of electricity price on its optimal design parameters. The particle swarm optimization method was used in the calculations.

The article [20] presents the CGAM problem as a test case for comparing thermo-economic optimization methodologies and shows its conventional solution. As such an example, we considered a natural gas-fired cogeneration plant with an electric capacity of 30 MW and a steam capacity of 14 kg/s. The following articles discuss the application of various methodological approaches to this problem, such as thermo- economic functional analysis [21], engineering functional analysis [22], and exergetic cost theory [23].

The article [24] deals with multi-objective optimization of coal-fired power plants using differential evolution. As an example, we present a coal-fired plant for ultra-supercritical steam parameters. The efficiency criteria were maximum efficiency and minimum electricity price.

As can be seen from the analysis of the above studies, as well as many others on this topic (e.g., [25–31] etc.), this problem is of considerable interest to researchers. It should be noted that, due to the complexity of co-generation systems, it is advisable to study ways to improve the efficiency of plants as based on more detailed mathematical models, and the number of optimized parameters should be much larger.

Some works use gradient methods [9,32], which allow optimization of a large number of parameters (100 or more). It should be noted that these methods have the following disadvantage. If an optimization problem has several local extrema, the optimization process can get "stuck" in one of them and fail to reach the global extremum. However, all the other methods considered have this disadvantage as well. The remedy is to start the optimization process from different starting points. From the solutions obtained in this way, the solution with the highest efficiency is chosen.

If it is impossible to refuse to take into account the discrete nature of the series of optimized parameters of the co-generation system, then we have to solve the mixed problem of nonlinear programming (NLP) with continuous- and discrete-variable optimized parameters. The main method for solving such problems is the branch and bound method [33]. Examples of its use are presented in [34,35]. In [36], a simplified method based on the construction of a tree of potentially optimal options is used to solve a mixed NLP problem. The continuous-variable parameters of the coal-fired steam turbine unit and discrete-variable parameters specifying the composition of steels for the production of steam boiler heating surfaces were optimized.

The problems of the PFD optimization lend themselves to some known mathematical problems much less naturally than parameter optimization problems. The only problem that lent itself to full formalization is the problem of optimizing the system of heat exchanger units. In [37,38] it is reduced to the assignment problem and in [7] – to the transport problem of linear programming.

The authors of [39] consider a sequential structure for synthesizing a network of heat exchangers. An approach to minimizing the number of subproblems (heat exchangers) is presented. The paper [40] discusses the automated synthesis of a network of heat exchangers using genetic algorithms, the particle swarm method, and parallel processing. The paper [41] proposes a methodology for the synthesis of a network of heat exchangers with a large number of uncertain parameters while combining several heuristic methods.

The optimization problems of complex steam turbine, combined heat and power and other thermal power plant PFDs could not be fully formalized. The following approaches were used to solve them.

1. Preliminary assignment of the set of PFDs under consideration.

For each of these PFDs, a parameter optimization problem is formed. One compares the values of the adopted criterion of effectiveness at the decision point of these problems for different PFDs and chooses the one for which the criterion takes the best value. The main advantage of the method is its simplicity, and the disadvantage is the inability to consider a large number of options.

2. Evolutionary methods of optimization.

The essence of these methods is that they set the initial PFD and form the problem of optimizing its parameters. At the point where this problem is solved, an analysis is carried out to find such changes to the original process flow that can lead to an improvement with respect to the performance criterion. In [7] such an analysis was based on the duality theory in NLP and allowed one to estimate how the optimal value of the efficiency criterion would be affected by the arrangement of additional small heat or material flows between different points in the PFD. In [42], the authors no longer considered "small" flows, but those that provide the maximum improvement of the efficiency criterion without violating the linearized process constraints. Such analysis is reduced to solving special linear programming problems. Evolutionary methods include an informal step of the transition from the recommendations of the original PFD analysis to the new PFD, which can lead to ambiguity of the optimization results.

3. Methods for optimization of the maximum complexity process flow. Their essence is to form the most complex PFD, from which, by excluding "superfluous" components, it is possible to obtain any variant of the PFD of the plant that is interesting for research. These methods fall into two groups.

a) Methods for forming a particular PFD by setting logical variables, each of which is responsible for the inclusion of a single component. If the value of such a variable is "true", then the corresponding component is included in the PFD. Its cost is taken into account, the parameters of its operation modes and design parameters are introduced into the array of the optimized parameters, the constraints on the component parameters are included in the array of the inequality constraints. If the value of the logical variable is "false", then the parameters and constraints associated with the component are not taken into account [43]. As a result, a specific

PFD and the corresponding problem of optimization of plant parameters are formed according to the specified composition of logical variables. The advantage of this group of methods is that there is no need to develop a separate mathematical model for each version of the PFD. Their disadvantage is the need to solve for each version of the PFD its own problem of optimization of continuous-variable parameters.

b) Methods for optimizing the maximum complexity PFD, based on the use of discrete-variable parameters. Each component, which may be present or absent in the PFD, is assigned a discrete-variable parameter z taking the value of 0 (component in the PFD is absent) or 1 (component in the PFD is present). Calculations of the values of the objective function, equality constraints, and inequality constraints can be performed for any real values of the parameter z in the range from 0 to 1 but only the values belonging to the set {0, 1} are admissible.

The advantage of the methods of the second group is that the optimal PFD is determined as a result of solving a single mixed NLP problem. The above approach was used in [43] to select the composition of the operating equipment of the co-generation system, where instead of individual PFD components, which may be present or absent, groups of components connected in parallel, identical, and equally loaded components were considered. Groups of cogeneration units were considered as such groups in the PFD of the co-generation system. The problem was to determine the number of units of each group included in operation in a particular mode. The relationship between the extensive parameters (steam, water, and electric capacity) of the group and the individual unit was as follows

$$Y_{bl} = \frac{Y_{gr}}{z_{gr}}, \tag{7.32}$$

where Y_{bl}, Y_{gr} are extensive parameters of the block and group, z_{gr} is the number of components of the group included in the operation. In this case Y_{gr} us the parameter that characterizes the material and energy flows linking the group of components with the rest of the PFD, and Y_{bl} is the parameter that characterizes the energy flows linking the individual unit with the PFD.

All extensive flow parameters of one unit must take such values, at which an allowable mode of operation of the unit is possible. It should be noted that the intensive flow parameters (pressures, enthalpy temperatures, etc.) of the group and similar flow parameters corresponding to one component should be equal.

In [44], an approach similar to the maximum complexity PFD optimization method is used for the overall optimization of the flue gas treatment system of a coal-fired power plant. However, this did not take into account the requirement of integrability of the optimized parameters.

As can be seen from the presented analysis of previously carried out studies, most of them employ, as already noted, methods of directed exhaustive search for the optimization of continuous parameters of the co-generation system utilization that allow optimization of a small number of parameters. It is possible to perform a joint optimization of the parameters of the cycle of a co-generation system and the design parameters of its components only by using gradient methods of nonlinear mathematical programming. This is due to the need to optimize several dozen and sometimes more than a hundred parameters. The efficiency of directed search methods decreases sharply with increasing dimensionality of the optimization problem.

It is possible to formalize the problem of optimizing the PFD only for individual subsystems, in particular, heat exchanger subsystems. A promising enough approach to the optimization of PFDs of co-generation systems in general is an approach based on the method of optimization of the maximum complex PFD. This is especially relevant for newly designed plants.

Herein, the approach to optimizing the number of working components of the group outlined in [43] is applied to the optimization of the maximum complexity PFD containing components that may be present or absent in the PFD of the plant [50]. Let us refer to such components as "includable". As mentioned above, for an includable component we introduce the parameter z, which can take two permissible discrete values: 1 – the component is present in the PFD, 0 – the component is absent. However, the operation of the includable component at the extensive parameters of the flow close to 0 that link this component with other components of the PFD is impossible. Minimum safe load constraints and other constraints will not be met. Therefore, in the proposed approach, the "external" flows linking the component to the PFD and the "internal" flows, in which the component is calculated, are separated (similarly to the presented separation of component and group flow parameters).

The relationship between the extensive parameters of these flows is as follows:

$$Y_{ijl}^{in.int} = \frac{Y_{ijl}^{in.ext}}{z_i}, \tag{7.33}$$

$$Y_{ikl}^{out.int} = \frac{Y_{ikl}^{out.ext}}{z_i}, \tag{7.34}$$

where i – the component number, z_i – the parameter specifying the inclusion of the i-th component, $Y_{ijl}^{in.int}$, $Y_{ijl}^{in.ext}$ – the l-th extensive parameter of the j-th external and internal input flows of the i-th component, $Y_{ikl}^{out.int}$, $Y_{ikl}^{out.ext}$ – the l-th extensive parameter of the k-th external and internal output flows of the i-th component.

Similar intensity parameters of the corresponding external and internal input and output flows should be equal to

$$X_{ijl}^{in.ext} = X_{ijl}^{in.int}, \tag{7.35}$$

$$X_{ikl}^{out.ext} = X_{ikl}^{out.int}, \tag{7.36}$$

where $X_{ijl}^{in.ext}$, $X_{ijl}^{in.int}$ is the l-th intensive parameter of the j-th external and internal input flows of the i-th component, $X_{ikl}^{out.ext}$, $X_{ikl}^{out.int}$ is the l-th extensive parameter of the k-th external and internal output flows of the i-th component.

It should be noted that given that $z = 0$ in the expressions (7.33), (7.34) there will be a division by 0. Therefore, instead of 0, it is proposed to equate the smaller discrete value of the parameter z with a small positive value ε. This value must be chosen such that given $z = \varepsilon$ the energy and material "external" flows are small and do not affect the results of the PFD analysis. In this case, the "internal" material and energy flows must be within acceptable limits.

In the considered PFD optimization problem, the includable component is connected in the PFD through nodes (points) of flow splitting or mixing. At flow splitting points, some initial flow going from one PFD component to another is divided into two flows. One of them still goes to the corresponding PFD component, and the other goes to the includable component. At the mixing points, the flow from one PFD component to the other is added by the flow from the includable component.

At the point of flow separation, from which the j-th input flow of the i-th component comes out, the equations of material balance and equality of intensive parameters of the flows are satisfied.

$$G_{ij}^{out.pfd} = G_{ij}^{in.pfd} - G_{ij}^{in.ext.comp}, \tag{7.37}$$

$$P_{ij}^{out.pfd} = P_{ij}^{in.pfd}, \tag{7.38}$$

$$P_{ij}^{in.ext} = P_{ij}^{in.pfd}, \tag{7.39}$$

$$T_{ij}^{out.pfd} = T_{ij}^{in.pfd} \left(\text{or } H_{ij}^{out.pfd} = H_{ij}^{in.pfd}\right), \tag{7.40}$$

$$T_{ij}^{in.ext} = T_{ij}^{in.pfd} \left(\text{or } H_{ij}^{in.ext} = H_{ij}^{in.pfd}\right), \tag{7.41}$$

where the superscript "pfd" marks the parameters of the flows between the components of the PFD.

Furthermore, the constraint on non-negativity of the flow rate at the point of splitting of the flow that follows from the splitting point to the next component of the PFD

$$G_{ij}^{out.pfd} \geq 0. \tag{7.42}$$

At the point of mixing of flows, which receives the k-th output flow of the i-th component, the equations of material and energy balances and the identity for the pressures of flows between the components of the PFD hold true

$$G_{ik}^{out.pfd} = G_{ik}^{in.pfd} + G_{ik}^{out.ext.comp}, \tag{7.43}$$

$$G_{ik}^{out.pfd} H_{ik}^{out.pfd} = G_{ik}^{in.pfd} H_{ik}^{in.pfd} + G_{ik}^{out.ext.comp} H_{ik}^{out.ext.comp}, \tag{7.44}$$

$$P_{ik}^{out.pfd} = P_{ik}^{in.pfd}. \tag{7.45}$$

In addition, at this point we take into account the equality constraints requiring that the flow pressure from the includable component be at least as high as the pressure $P_{ik}^{in.pfd}$

$$P_{ik}^{out.ext} \geq P_{ik}^{in.pfd}. \tag{7.46}$$

Only when this condition is met is it possible to arrange the flow between the includable component and the mixing point of the PFD without using additional pumps or compressors.

It should be noted that the includable component is described by a system of equations linking the above-mentioned parameters of input and output flows of the component, and its internal parameters. Some of these internal parameters are specified and some are calculated from the specified system of equations. In turn, some of the specified parameters are determined by external conditions, and some can vary within certain limits and are subject to optimization. Let us call the last group of parameters the internal optimized parameters of the component. The calculated internal parameters of a component must satisfy a system of inequality constraints. Let us call these constraints internal inequality constraints.

When calculating the criteria of the economic efficiency of the plant, it is necessary to determine the external and internal capital expenditures in the PFD component. The internal capital expenditures of a component are determined by its calculation, and the external ones, as used in the calculation of the total capital expenditures of the plant, are determined from the expression

$$K_i^{ext} = K_i^{int} \cdot z_i. \tag{7.47}$$

It should be noted that conditions the (7.45) and (7.46) are easily satisfied for some of the components considered in optimization and do not limit optimal solutions. This applies to components for which the flow rates of all flows connecting the component to the PFD become small given $z_i = \varepsilon$ (Fig. 7.6).

Using the inequality (7.46) for the mixing point is not always possible. This applies to the case where the separation point and the mixing point are located on the same flow of the working medium or heat transfer fluid.

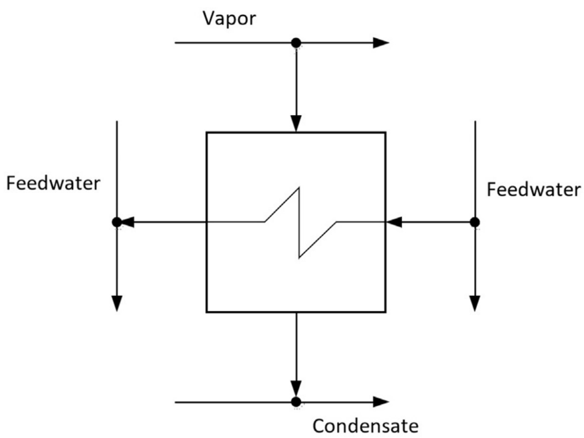


FIGURE 7.6 An "includable" component of the PFD that is connected in parallel to existing flows.

This situation occurs if there is a material flow in the PFD, which in the absence of the i-th includable component goes from the component l to the component k. When the i-th component ($z_i = 1$) is included, the entire flow is directed from the component l to the component I, and from the component i to the component k.

One can imagine that the specified flow is broken, and a new component is included in this break. It should be noted that in the general case one component can be included in the break of not one but several flows. The components included in this way include additional steam coolers installed on the steam flows from the steam turbine to the regenerative heaters. The additional heating surfaces, installed in the break of the flow of combustion products of the steam boiler can be another example of such components. In order to smoothly transition from the state when the new component is present in the PFD to the state when it is absent, a bypass line is provisionally introduced into the calculation PFD, which comes out of the point of flow separation and enters the point of flow mixing (Fig. 7.7). This line is considered to have no flow friction.

It should be noted that in the presence of even small internal flow friction of the component, the conditions (7.38), (7.45), and (7.46) cannot be simultaneously satisfied.

For such components, in order to eliminate the above contradiction at the point of mixing the flows, in the break of which the new component is installed, it is proposed to use the model of *an ideal mixer*. In this model, as in the above one, the equations of material (7.43) and energy (7.44) balances are taken into account. However, instead of the conditions (7.45) and (7.46), the following conditions are taken into account.

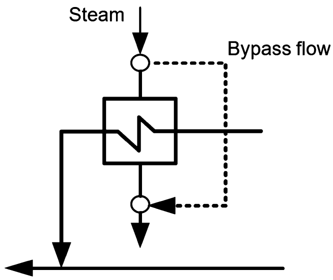


FIGURE 7.7 An "includable" component that is connected into the break of the steam flow.

It is assumed that the flow entering the mixer with higher pressure (bypass flow) expands during the isentropic process to some pressure P_{mix}, and the flow entering the mixer with lower pressure (flow passing through the component) is compressed during the isentropic process to the same pressure P_{mix}. And the pressure P_{mix} is selected so that the work of expansion of the bypass flow equals the work of compression of the flow passing through the component. The pressure at the outlet of the mixer $P^{out.sc}$ is assumed to be equal to the pressure P_{mix}. Obviously, the pressure P_{mix} is within the range determined by the pressures of the flows entering the mixer.

In the general case, one can imagine that the pressure P_{mix} is determined from the equality

$$\begin{aligned} &N^{prs}_{comp_{ij}}\left(P^{out.ext.comp}_{ij}, G^{out.ext.comp}_{ij}, H^{out.ext.comp}_{ij}, P^{mix}_{ij}\right) \\ &\quad = N^{exn}_{byp_{ij}}\left(P^{byp}_{ij}, G^{byp}_{ij}, H^{byp}_{ij}, P^{mix}_{ij}\right), \end{aligned} \tag{7.48}$$

where $N^{prs}_{comp_{ij}}$ is the compression power of the external output flow j of the component I, $N^{exn}_{byp_{ij}}$ is the bypass expansion power of the j-th flow of the i-th component.

It should be noted that the use of this condition allows one to accurately determine the pressure downstream the mixer when $z_i = 1$ (the entire flow goes through the component, $G^{in.pfd} = 0$), and with a small error when $z_i = \varepsilon$ and the flow through the component is small and almost all the flow goes through the bypass. At intermediate values of z_i, the proposed approach provides a smooth change in pressure between extreme values, which yields good convergence of the computational process.

At the point of flow separation, to which the external flow to the component is connected, the material balance equation is written in the form

$$G^{in.pfd}_i = G^{in.pfd} \cdot z_i, \tag{7.49}$$

$$G_i^{byp} = G_i^{in.pfd} \cdot (1 - z_i), \tag{7.50}$$

where G_i^{byp} is the flow through the bypass line.

At the mixing point of the flows, the material balance equation will be

$$G_i^{in.ext.comp} = G_i^{in.ext.comp} + G_i^{byp}. \tag{7.51}$$

The internal flow rate of the PFD component is determined from the expression

$$G_i^{in.int.comp} = \frac{G^{in.ext.comp}}{z_i}. \tag{7.52}$$

In the PFD, these flows can be designated as follows (Fig. 7.8).

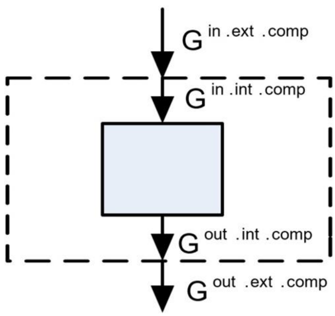


FIGURE 7.8 The relationship between the internal and external flows of a component.

Taking into account the above descriptions of the points of splitting and mixing of flows, as well as the relationships between the parameters of internal and external flows, the mixed problem of optimization of the maximum complexity PFD will take the following form.

To find

$$\min F\left(x^H, y, U, \widetilde{Q}_1^{ext.comp}, \ldots, \widetilde{Q}_I^{ext.comp}, \widehat{Q}_1^{ext.comp}, \ldots, \widehat{Q}_I^{ext.comp}\right) \tag{7.53}$$

given the conditions

$$W_{pfd}\left(x^{cont}, y, U, \widetilde{Q}_1^{ext.comp}, \ldots, \widetilde{Q}_I^{ext.comp}, \widehat{Q}_1^{ext.comp}, \ldots, \widehat{Q}_I^{ext.comp}\right) = 0, \tag{7.54}$$

$$V_{pfd}\left(x^{cont}, y, U, \widetilde{Q}_1^{ext.comp}, \ldots, \widetilde{Q}_I^{ext.comp}, \widehat{Q}_1^{ext.comp}, \ldots, \widehat{Q}_I^{ext.comp}\right) \geq 0, \tag{7.55}$$

$$\underline{x}^{cont} \leq x^{cont} \leq \overline{x}^{cont}, \tag{7.56}$$

$$\widetilde{Q}_i^{ext.comp} = z_i \cdot \widetilde{Q}_i^{int.comp}, \tag{7.57}$$

$$\widehat{Q}_i^{ext.comp} = \widehat{Q}_i^{int.comp}, \tag{7.58}$$

$$w_i\left(\widetilde{Q}_i^{int.comp}, \widehat{Q}_i^{int.comp}, y_i, u_i, x_i^H\right) = 0, \tag{7.59}$$

$$v_i\left(\widetilde{Q}_i^{int.comp}, \widehat{Q}_i^{int.comp}, y_i, u_i, x_i^{cont}\right) = 0, \tag{7.60}$$

$$\varepsilon \le z_i \le 1,\ i = 1, \ldots, I, \tag{7.61}$$

where F – optimality criterion (objective function), which can be: energy efficiency criterion (specific fuel consumption per unit of electricity output), economic efficiency criterion (discounted costs, electricity price at a given value of the internal rate of return, etc.), x^{cont} – vector of continuous-variable parameters of constant part of the PFD of the co-generation system, y – vector of variables calculated (from the general system of equations), P – a vector of input data specifying external conditions for the constant part of the PFD, $\widetilde{Q}_i^{ext.comp}$, $\widehat{Q}_i^{ext.comp}$ – vectors of extensive and intensive parameters of external flows of the i-th "includable" component, W_{pfd} – a system of equations describing the constant part of the PFD; this includes the above presented equations of points of separation and mixing of external flows of "includable" components, V_{pfd} – a system of inequality constraints of the constant part of the PFD; this includes the above described inequality constraints for points of mixing and separation, $\underline{x}^{cont}$, $\overline{x}^{cont}$ – vectors, the components of which set lower and upper constraints on the components of the vector x^{cont}, z_i – discrete variable parameter to be optimized that determine the presence ($z_i = 1$) or absence ($z_i = \varepsilon$) in the co-generation system PFD of the i-th "includable" component, I – number of "includable" components in the maximum complexity PFD, $\widetilde{Q}_i^{int.comp}$, $\widehat{Q}_i^{int.comp}$ – vectors of extensive and intensive parameters of internal flows of the i-th "includable" component, w_i – subsystem of equations of the i-th "includable" component, v_i – subsystem of inequality constraint of the i-th "includable" component. Vectors relating to the i-th "includable" component have the same designation as the corresponding vectors related to the constant part of the PFD, but with the subscript i.

In the above description, for simplicity, it is assumed that all the optimized parameters of the PFD x and the internal optimized parameters of the components x_i "includable" are continuous variables.

The equations of the points of separation and mixing of the external flows of "includable" components belong to the system of equations W_{pfd}. The inequality constraints for the mixing and separation points are included in the system V_{pfd}. Let us call the problem (7.53)–(7.61) problem I.

To solve the mixed problem of nonlinear mathematical programming one uses the method of branches and bounds [33].

The overall procedure of application of this branch and bound method is as follows. The set of all possible options of the values of discrete-variable parameters to be optimized is divided into non-intersecting subsets. In this case, for all options of one subset, a part of the optimized discrete-variable parameters takes fixed discrete values, the same for all options of the subset. The other discrete-variable parameters are optimized without discreteness constraints. For each subset, a lower estimate (bound) of the optimal value of the objective function is determined. This estimate should have the following properties.

The optimal value of the objective function of any option of a subset (with fixed values of discrete-variable parameters and optimal values of continuous-variable parameters to be optimized) should be not lower than the bound.

2. If the bound of the objective function of some subset coincides with the value of the objective function for a completely discrete solution belonging to this subset, then the bound is exactly equal to the minimum value of the objective function in the specified subset of options.

The subset with the minimum bound is selected. Let us call it a "subset of potentially optimal options" because it seems reasonable to look for the optimal options, first, in this subset. If the boundary value of the objective function of a given subset is reached for the option with discrete values of all parameters z_i, then this option will be optimal. Otherwise, the subset of potentially optimal options is divided (branched) into several (at least two) subsets, for each of which the bounds of the objective function are found. This process continues until the above optimality condition is satisfied. The branch and bound method will converge if, when branching, the boundary of the objective function of a subset will approach its minimum value.

The application of the general workflow of the method to specific problems requires the definition of the way to construct the boundary of the objective function and the way to partition the set of options of discrete-variable parameters into subsets.

In the problem in question, for the construction of the bound of the objective function of the initial set of options of Problem I we introduce the set J^q made up of i components. Each component of the set J_i^q can have three values: 1, 0, and -1. If $J_i^q = 1$, then z_i is fixed at the value of 1. If $J_i^q = -1$, then z_i is fixed at the value of ε. If $J_i^q = 0$, then z_i is optimized within the range $[\varepsilon, 1]$.

We introduce a system of additional conditions of the form

$$J_i^q = 1 \rightarrow z_i = 1,\ J_i^q = 0 \rightarrow \varepsilon \le z_i \le 1,\ J_i^q = -1 \rightarrow z_i = \varepsilon,\ i = 1, \dots, I. \tag{7.62}$$

The problem (7.53)–(7.60), (7.62) is solved to find the bound of the objective function of options as defined by the composition of fixed discrete-variable parameters given by the set J^q. Let us refer to this problem as Problem II.

If Problem II has no admissible solution, then the number D greater than any possible admissible value of the objective function is taken as the bound of the objective function.

In the considered Problem I, any discrete-variable parameter can take only two discrete values. At each step of the branch and bound method, the set of potentially optimal options is divided into two subsets by taking one discrete-variable parameter out of those to be optimized. For all options of one subset this parameter should take the maximum discrete value, and for all options of another subset - the minimum discrete value. Let us call this parameter *a branching parameter*.

At each step, one is prompted to select this parameter as follows. Among discrete-variable optimized parameters that were optimized when determining the lower estimate of the objective function (their corresponding component $J^q = 0$), we look for the parameter whose optimal value is the furthest from the nearest allowable discrete value. This parameter is taken as a branch parameter at the current step.

If for the set of potentially optimal options chosen at the next step, all values of discrete-variable parameters are close to the admissible discrete values with some accuracy at the point of solving the problem of determining the bound of the objective function, then they can be rounded to these values. Given these values, the additional Problem II is solved. Note that the set J^q, corresponding to this problem, has no components equal to 0. The resulting discrete solution is considered optimal for the given set of options.

Rounding the values of discrete-variable parameters allows one to reduce the number of branches and the amount of calculations needed to solve the mixed problem.

To illustrate the branch and bound method, a tree of sets (subsets) of options of discrete-variable parameters can be used.

The tree of options is built according to the following rules. Each vertex of the tree with the number q corresponds to its option of fixing a part of discrete-variable parameters and its corresponding optimization Problem II. The root vertex of the tree (the one having number 0) corresponds to the option with none of the discrete-variable parameters fixed. Each vertex is mapped to the set J^q, the value of the objective function F^q and the vector of discrete-variable parameters Z^q obtained as a result of optimization. If a tree vertex has no branches outcoming, it is called a pendant vertex. At each t-th step of the branch and bound method, the pendant vertex of the tree is searched for, which corresponds to the minimum bound. Let us denote the number of this vertex as m_t. The number V_t of the branching parameter is searched for, such that $J_{V_t}^{m_t} = 0$ and meets the condition

$$\min\left[\left(z_{V_t}^{m_t} - z_{V_t}^{min}\right), \left(z_{V_t}^{max} - z_{V_t}^{m_t}\right)\right] = \max_{\forall i \in \left\{j/\left(J_j^{m_t}=0\right)\right\}} \left\{\min\left[\left(z_i^{m_t} - z_i^{min}\right), \left(z_i^{m_t} - z_i^{max}\right)\right]\right\} \tag{7.63}$$

where z_i^{min}, z_i^{max} – minimum and maximum discrete values of the parameter $z_{V_t}^{m_t}$, $z_{V_t}^{m_t}$ – optimal value of the parameter z_i at the solution point of the optimization problem, corresponding to the vertex m_t.

Two branches coming out of the vertex m_t are introduced into the tree. The first corresponds to the minimum value of the parameter z_{V_t}, and the second to the maximum. The first branch enters the vertex tA, and the second branch enters the vertex tB. When solving problems corresponding to these vertices, the components of the sets J_i^{tA} and J_i^{tB} are defined as follows

$$J_i^{tA} = \begin{cases} J_i^{m_t}, & \text{if } i \neq V_t, \\ -1, & \text{if } i = V_t, \end{cases} \tag{7.64}$$

$$J_i^{tB} = \begin{cases} J_i^{m_t}, & \text{if } i \neq V_t, \\ 1, & \text{if } i = V_t. \end{cases} \tag{7.65}$$

If at any vertex of the tree with the number N when solving the optimization problem corresponding to this vertex the following condition is met

$$\gamma \geq \max_{\forall i \in \left\{j/(J_j^N=0)\wedge(j=1,I)\right\}} \left\{\min\left[(z_i^N - z_i^{min}), (z_i^{max} - z_i^N)\right]\right\}, \tag{7.66}$$

where γ is a given accuracy of approximation of parameters z_i to discrete values, then rounding of all parameters z_i to the nearest discrete values is carried out and an additional optimization problem is solved, in which the values of all discrete parameters are fixed. A new vertex N' and a branch leading from the vertex N to the vertex N' are introduced into the tree. The vertex N' is mapped to the set $J^{N'}$, all components of which are not equal to 0. The value of the objective function at the solution point of the additional problem is taken as the lower bound of this vertex. This vertex will correspond to one option of values of discrete-variable parameters.

It should be noted that at each optimization step the set of pendant vertices of the tree of options defines all non-overlapping combinations of discrete-variable parameters. Three types of vertices can be distinguished. If Problem II at the vertex q has no admissible solution ($F^q = D$), then all options of the set represented by the vertex q have no admissible solution. Let us introduce the set Q_D^t, which will include the numbers of all pendant vertices of the specified kind present in the tree at the step t. If all optimized discrete parameters at the optimal point of Problem II corresponding to the pendant vertex q are close to discrete values with required accuracy (satisfying the condition (7.66)), then the best of all options represented by the vertex q is the option with discrete values of optimized parameters corresponding to the vertex N'. It is assumed that if Problem II corresponding to the vertex q has an admissible solution, then the latter also exists for Problem II corresponding to the vertex q'. Let us introduce the set Q_0^t, which will include the numbers of all pendant vertices that correspond to vectors of discrete optimized parameters with completely discrete values available in the tree at the step t.

Let us introduce the set Q_B^t, which includes the numbers of all pendant vertices present in the tree at step t that are not included in the sets Q_D^t and Q_0^t. These are the numbers of vertices for one of which a branching procedure can be performed at the step t.

If Q_0^t is not empty at some step t, then let us find the number of the pendant vertex S that belongs to Q_0^t with the best value of the objective function. This number meets the following condition

$$F^S(S \in Q_0^t) = \min_{\forall i \in Q_0^t} F^i. \tag{7.67}$$

If the set $Q_B^t = \emptyset$, then the vertex with number S corresponds to the optimal discrete solution. If $Q_B^t \neq \emptyset$, then let us find the number of the vertex $m \in Q_B^t$, which corresponds to the best value of the objective function

$$F^n = \min_{\forall i \in Q_B^t} F^j. \tag{7.68}$$

If the condition $F^S \leq F^n$ is satisfied, then the number S corresponds to the optimal discrete solution.

It should be noted that solving optimization problems happens with some error. Therefore, if the difference between the value of the objective function for the optimal discrete solution F^{opt} and the lower bound for some set, in which not all discrete-variable parameters take values close to discrete with the required accuracy F^c, meets the condition

$$F^{opt} + \varphi \geq F^c, \tag{7.69}$$

where φ is the error of the optimization problem, then the set is branched. This process is repeated as long as there are many options for which the above condition is true. As a result, several discrete solutions can be found, in which the difference between the objective functions and the optimal solution is less than the optimization error. We can assume that these solutions form a set of optimal options.

As a demonstration example of the proposed approach, we consider a CCGT plant with integrated coal gasification combined cycle. A number of works, such as [45–49], are devoted to studies of such plants.

A mathematical model of the plant that focuses on its design calculation was developed (Fig. 7.9).

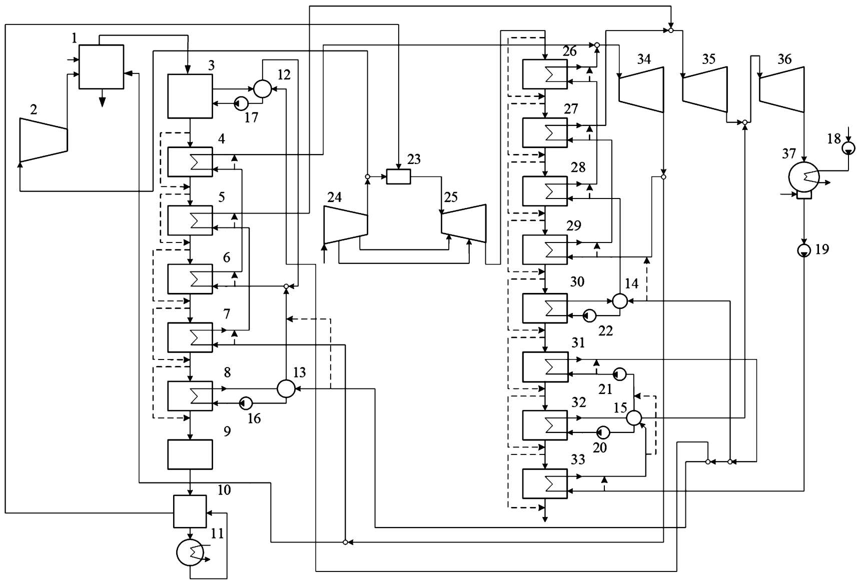


FIGURE 7.9 Equivalent PFD: 1 – gas generator, 2 – booster compressor, 3 – gas generator furnace, 4–8 – gasification product heat exchangers, 9, 11 – gas treatment devices, 10 – regenerative heater, 12–15 – drum separators, 16–22 – pumps, 23 – gas turbine combustion chamber, 24 – air compressor, 25 – gas turbine, 26–33 – combustion product heat exchangers, 34–36 – steam turbine compartments, 37 – condenser.

The dashed lines in the figure indicate the bypassing points of the "includable" components for different heat transfer fluids (steam, combustion products, feed water, condensate). The model provides for the ability to switch off both a single component and a group of components of different types, which are switched off in a coordinated manner. For example, the evaporator heating surface is switched off together with the pump and the separator drum. A total of 11 switchable components are considered in the PFD: heat exchangers that run on gasification products and combustion products (high-pressure evaporators are not switched off).

Mathematical models of components include equations of heat and material balances, heat transfer, descriptions of expansion and compression of the working medium, etc. The coal gasification process is calculated taking into account the thermodynamic equilibrium conditions. This makes it possible to determine the design characteristics of the plant. Technical and economic performance metrics are calculated by individual software modules. The calculation was carried out with the aid of the software package

"Machine Program Building System SMPP-PK" developed at the MESI SB RAS [23,28].

The mathematical model of the plant contains 802 information-input parameters, 918 information-output parameters, and 22 parameters whose values are subject to refinement during the iteration process. The following parameters were optimized: flow rate, pressure, and enthalpy of superheated steam, pressure and enthalpy of reheated steam. Enthalpy of the medium to be heated at the outlet from all economizer and evaporator heating surfaces. Internal diameters of convective heat exchanger tubes, as well as a number of other operating conditions parameters and design parameters. The parameters determining the presence of a component in the PFD and the number of parallel flows of heat exchangers running on the gasification products, which varied in the range from 1 to 2, were also optimized. As inequality constraints, we considered the constraints on the maximum temperature of the outer walls of the tubes of heat exchangers, the mechanical stress of the pipe steel, the maximum diameter of the bodies of convective gasification product heat exchangers, non-negativity of the end temperature heads, etc. In addition, the minimum allowable number of tubes along the gas flow was taken into account for convective heat exchangers. The introduction of these constraints does not allow reducing the optimization of the PFD to an NLP problem with continuous-variable parameters only. A total of 127 parameters were optimized (of which 12 were considered to be discrete variables) and 169 constraints were taken into account. Lignite was assumed to serve as fuel with the following design characteristics: $Q_i^r = 17291$ kJ/kg, $W_i^r = 22\%$, $A^r = 15.6\%$, $S^r = 0.9\%$, $C^r = 46\%$, $H^r = 3.6\%$, $N^r = 0.9\%$, $O^r = 11\%$.

The minimum electricity price at a given IRR value and the maximum net plant efficiency were used as efficiency criteria in the optimization. Determination of the capital expenditures of the plant and the description of the cost-efficiency criterion were discussed earlier in Section 7.2. It should be noted that the method used to solve the optimization problem is classified as an inner point method. Therefore, the values of the parameters z_i determining the inclusion of the component in the PFD obtained at the optimal point cannot strictly belong to their boundary values of ε and 1 and are taken equal to 0.00001 and 0.99999. At these values of the specified parameters an additional optimization problem is solved.

Optimization with respect to the criterion of minimum electricity price was carried out at two values of the fuel price: USD 50 and USD 100 per ton of fuel equivalent. The value of the specified accuracy γ was taken as 0.05. As a result of solving the optimization problem at the point 0 for both options the values of all discrete-variable parameters turned out to be close given the specified accuracy to their nearest integer values, so the branching procedure by the branch and bound method was not used. To refine the optimal values of continuous-variable parameters and the

TABLE 7.4 Optimization results for discrete-variable parameters (efficiency criterion: minimum price of electricity).

Name	Parameter designation, z_i	Value of the parameter at different fuel prices	
		50 USD/ton of fuel equivalent	**100 USD/ton of fuel equivalent**
Number of parallel flows of gasification products in the convective gas generator shaft	z_1	1.000	1.001
Parameters determining the inclusion of components in the PFD			
Heat exchangers of heat recovery steam generator running on gasification products			
Convective second-stage steam superheater	z_2	0.999	0.997
Second-stage live-steam reheater	z_3	0.999	0.999
Convective first-stage superheater	z_4	0.996	0.998
First-stage live-steam reheater	z_5	0.992	0.967
Heat exchangers of heat recovery steam generator running on combustion products			
Convective second-stage steam superheater	z_6	0.999	0.998
Second-stage live-steam reheater	z_7	0.999	0.999
Convective first-stage superheater	z_8	0.0001	0.0002
First-stage live-steam reheater	z_9	0.0001	0.0001
Second stage water economizer	z_{10}	0.999	0.999
Low pressure evaporator	z_{11}	0.00009	0.0001
First stage water economizer	z_{12}	0.999	0.999
Objective function			
Electricity price. cents/kWh	–	7.767	8.971

objective function, an additional optimization problem 0* was solved. The optimal values of discrete-variable parameters at the point 0 obtained by solving the problem (7.53)–(7.60) are presented in Table 7.4.

The values of the objective function at the point 0* were 7.749 and 8.966 cents/kWh, respectively. As can be seen, in both options the first stages of the convective and live-steam reheaters and the low-pressure evaporator are switched off). The optimal electricity prices at points 0* in both variants were slightly less than the optimal values at points 0. This is due to the fact that at point 0 the values of discrete-variable optimized parameters have a small deviation from their optimal discrete values due to the use of the method of internal points in the optimization.

When solving the optimization problem with respect to the criterion of maximum plant efficiency at point 0. The values of a number of parameters of the component inclusion in the PFD turned out to be far from their nearest integer values (i.e., failed to satisfy the condition (7.66)). To find the optimal discrete-continuous solution. A tree of potentially optimal options was constructed (Fig. 7.10).

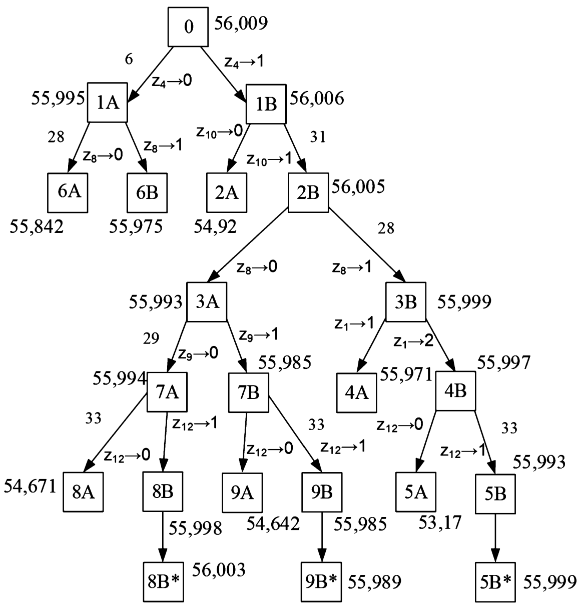


FIGURE 7.10 The tree of potentially optimal options for the considered plant.

The search required nine branching operations. Heat exchangers are designated by their numbers on the tree branches in the PFD (Fig. 7.9). They have discrete values assigned at the corresponding step. The values of the objective function (efficiency) are given at the points of the tree. At the branches 3B-4A and 3B-4B, the choice was made for the number of parallel flows of heat exchangers.

As a result of optimization, we obtained three options, the difference between which is less than the specified accuracy (0.02), and they can be considered indistinguishable. Having a similar value of efficiency, they have different capital expenditures.

At the vertices 5B, 8B, and 9B the values of all discrete-variable parameters satisfy the condition (7.66), so additional problems of optimization of 5B*, 8B*, 9B* were solved. Tables 7.5 and 7.6 show values of parameters z_i at the points corresponding to all points of the tree.

TABLE 7.5 Optimization results for discrete-variable parameters (heat exchangers that recover heat from gasification product.

Vertex number	Name				
	Parameters determining the inclusion of a component in the PFD				Number of parallel gasification product streams z_1
	z_2	z_3	z_4	z_5	
0	0.999	0.995	0.517	0.007	1.932
1A	0.999	0.999	0	0.004	1.994
1B	0.999	0.997	1	0.011	1.897
2A	0.999	0.998	1	0.002	1.981
2B	0.999	0.998	1	0.005	1.871
3A	0.999	0.997	1	0.005	1.971
3B	0.999	0.998	1	0.001	1.903
4A	0.999	0.998	1	0.007	1
4B	0.999	0.992	1	0.003	2
5A	0.999	0.999	1	0.669	2
5B	0.999	0.997	1	0.003	2
6A	0.994	0.878	0	0.067	1.471
6B	0.999	0.998	0	0.001	1.983
7A	0.999	0.998	1	0.007	1.945
7B	0.999	0.998	1	0.003	1.954
8A	0.999	0.997	1	0.003	1.856
8B	0.999	0.999	1	0.005	1.977
9A	0.999	0.999	1	0.001	1.993
9B	0.999	0.999	1	0.002	1.981
5B*	1	1	1	0	2
8B*	1	1	1	0	2
9B*	1	1	1	0	2

Parameters of the plant at the optimal points given various efficiency criteria are presented in Table 7.7. For options with maximization of efficiency, the price of fuel equal to 100 USD/t of fuel equivalent was assumed when calculating the price of electricity.

As can be seen from Table 7.7, the plant efficiency increase is achieved by reducing the temperature of flue gases, which leads to a decrease in temperature heads in the convective heat exchangers of the heat recovery steam generator and an increase in the area of heating surfaces. This, in turn, leads to a significant increase in the capital expenditures of the plant and the price of electricity.

Thus, for the first time, the proposed methodological approach to flow diagram and parametric optimization of co-generation systems, based on a combination of the optimization method of the maximum complexity PFD and the branch and bound method has been proven to be effective. The authors are not aware of any other works, in which the optimization

TABLE 7.6 Optimization results for discrete-variable parameters (heat exchangers that recover heat from combustion products).

Vertex number	Name						
	Parameters determining the inclusion of a component in the PFD						
	z_6	z_7	z_8	z_9	z_{10}	z_{11}	z_{12}
0	0.999	0.999	0.471	0.023	0.873	0.006	0.917
1A	0.999	0.999	0.382	0.164	0.668	0.009	0.884
1B	0.998	0.999	0.987	0.004	0.714	0.003	0.92
2A	0.999	0.999	0.445	0.003	0	0.999	0.976
2B	0.999	0.999	0.492	0.011	1	0.002	0.791
3A	0.999	0.999	0	0.277	1	0.004	0.861
3B	0.999	0.999	1	0.002	1	0.002	0.94
4A	0.999	0.999	1	0.003	1	0.007	0.907
4B	0.999	0.999	1	0.002	1	0.002	0.975
5A	0.003	0.998	1	0.0001	1	0.999	0
5B	0.999	0.999	1	0.004	1	0.006	1
6A	0.991	0.993	0	0.211	0.848	0.05	0.759
6B	0.999	0.999	1	0.007	0.709	0.001	0.965
7A	0.999	0.999	0	0	1	0.005	0.922
7B	0.999	0.999	0	1	1	0.004	0.873
8A	0.999	0.999	0	0	1	0.999	0
8B	0.999	0.999	0	0	1	0.001	1
9A	0.999	0.999	0	1	1	0.999	0
9B	0.999	0.999	0	1	1	0.001	1
5B*	1	1	1	0	1	0	1
8B*	1	1	0	0	1	0	1
9B*	1	1	0	1	1	0	1

of the PFD of the co-generation system would be reduced to the problem of nonlinear mathematical programming.

By way of illustration, we considered a CCGT plant with coal gasification. We constructed its mathematical model suitable for the joint optimization of the composition of the components of the PFD, its working and design parameters.

Optimization calculations were carried out with respect to the criterion of the minimum price of electricity at a given internal rate of return on investment and the maximum net efficiency of the plant. We obtained options that have the values of the considered discrete-variable parameters as close as possible to their bounds. For options with discrete values, additional optimization calculations were performed. It is shown that when solving the maximum efficiency problem, several optimal solutions with close values of efficiency, but different capital expenditures of the plant, are possible.

In the future, the proposed approach can be used to optimize the PFD and parameters of other power plants.

TABLE 7.7 Plant parameters at optimal points under different criteria of efficiency).

Name	Efficiency criterion				
	Min C_el. cents/kWh		Maximum efficiency		
	Pf=50 USD/ton of fuel equivalent	Pf=100 USD/ton of fuel equivalent	5B*	8B*	9B*
Fuel consumption in the gas generator, kg/s	48.0	48.0	48.0	47.96	47.97
Gas temperature at the gas generator outlet, °C	1297.0	1297.0	1297.0	1297.0	1297.0
Air temperature at the gas generator inlet, °C	335.0	341.0	447.0	447.0	447.0
Air pressure in the gas generator, MPa	1.13	1.18	2.01	2.01	2.01
Superheated steam pressure, MPa	9.7	9.8	11.9	11.96	11.96
Superheated steam temperature, °C	512.0	513.0	523.0	524.0	524.0
Superheated steam flow rate, kg/s	146.1	146.9	137.6	137.5	137.5
Reheated steam pressure, MPa	0.97	1.02	1.95	1.94	1.92
Reheated steam temperature, °C	455.0	456.0	474.0	475.0	475.0
Steam pressure of the low-pressure circuit, kg/cm^2	0.83	0.89	0.99	0.99	0.99
Exhaust gas temperature, °C	142.0	128.0	100.0	100.0	100.0
Weight of carbon steel heat exchangers, t	289.1	336.4	3775.3	3152.4	3410.1
Weight of pearlitic steel heat exchangers (with shells), t	155.2	156.2	815.3	897.1	843.9
Weight of austenitic steel heat exchangers, t	5.9	5.8			
Number of parallel gasification product streams	1	1	2	2	2
Useful power of the plant, MW	403.6	409.1	452.2	452.0	451.9
Annual consumption of fuel equivalent per plant, thous. tons of fuel equivalent.	694.6	694.6	694.6	694.1	694.2
Specific fuel equivalent consumption for the plant, g fuel equivalent/t.	246.2	242.8	219.6	219.6	219.6
Electricity generation, mln. kWh	2825.2	2863.7	3165.4	3164.0	3163.3

continued on next page

TABLE 7.7 (*continued*)

Name	Efficiency criterion				
	Min C_el. cents/kWh		Maximum efficiency		
	Pf=50 USD/ton of fuel equivalent	Pf=100 USD/ton of fuel equivalent	5B*	8B*	9B*
Specific capital expenditures, USD/kW	2084.9	2118.7	4935.6	4596.7	4589.0
Net efficiency, %	49.96	50.64	55.99	56.003	55.989
Electricity price, cents/kWh	7.795	9.098	17.73	16.67	16.64

Conclusion

In the chapter, we presented an idea of the organization of hierarchical structures of mathematical models of cogeneration systems and fuel co-production power generation and optimization problems for their schemes and parameters. An effective method of gradient optimization is considered, which allows one to simultaneously take into account several tens of parameters during optimization, and provides a more accurate solution of equations, in comparison with previously used methods. The main idea of the method is that the exact solution of the set of equations describing the one of the considered system is achieved only at the optimal point.

The use of this approach made it possible to obtain a dependence of the minimum specific capital investment on the efficiency of the considered coal-fired power unit, which has a smooth character. The resulting dependence showed that when the point of maximum efficiency is being reached, the specific investment in the power unit increases dramatically. Optimal solutions were obtained according to the criteria of maximum efficiency, minimum specific capital investment, and minimum price of electricity.

An original methodical approach to the circuit parametric optimization of thermal power plants based on a combination of the optimization method for the most complex circuit and the branch-and-bound method is presented. As an example, a combined-cycle plant with coal gasification is considered. Its mathematical model is constructed, suitable for the joint optimization of the composition of the elements of the technological scheme, the operating parameters, and the design parameters. Optimization calculations were carried out according to the criteria for the minimum price of electricity and the maximum net efficiency of the installation. It is shown that when solving the problem for maximum efficiency, several optimal solutions with close values of efficiency are possible, but different capital investments in the installation.

In the future, the proposed approaches can be used to optimize the schemes and parameters of other power plants.

Acknowledgments

The research was carried out under the grant of the Russian Science Foundation (no. 16-19-10174), State Assignment Project (no. FWEU-2021-0005) of the Fundamental Research Program of Russian Federation 2021–2030 using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] L. Wang, Y. Yang, C. Dong, T. Morosuk, G. Tsatsaronis, Parametric optimization of supercritical coal-fired power plants by MINLP and differential evolution, Energy Conversion and Management 85 (2014) 828–838.

[2] M.V.J.J. Suresh, K.S. Reddy, A.K. Kolar, ANN-GA based optimization of a high ash coal-fired supercritical power plant, Applied Energy 88 (2011) 4867–4873.

[3] J. Kowalczyk, W. Elsner, P. Niegodajew, M. Marek, Gradient-free methods applied to optimization of advanced ultra-supercritical power plant, Applied Thermal Engineering 96 (2016) 200–208.

[4] C. Wang, B. He, S. Sun, Y. Wu, N. Yan, L. Yan, X. Pei, Application of a low pressure economizer for waste heat recovery from the exhaust flue gas in a 600 MW power plant, Energy 48 (2012) 196–202.

[5] F.A. Boyaghchi, H. Molaie, Advanced exergy and environmental analyses and multi objective optimization of a real combined cycle power plant with supplementary firing using evolutionary algorithm, Energy 93 (2015) 2267–2279.

[6] M. Baghsheikhi, H. Sayyaadi, Real-time exergoeconomic optimization of a steam power plant using a soft computing-fuzzy inference system, Energy 114 (2016) 868–884.

[7] A.M. Kler, N.P. Dekanova, T.P. Shchegoleva, et al., Methods of Optimization of Complex Heat Power Plants, Nauka, Novosibirsk, 1993 (in Russian).

[8] A.M. Kler, N.P. Dekanova, E.A. Tyurina, Co-Generation Systems: Optimization Studies, Nauka, Novosibirsk, 2005 (in Russian).

[9] A.M. Kler, P.V. Zharkov, N.O. Epishkin, An effective approach to optimizing the parameters of complex thermal power plants, Thermophysics and Aeromechanics 23 (2) (2016) 289–296.

[10] A.M. Kler, P.V. Zharkov, N.O. Epishkin, Parametric optimization of supercritical power plants using gradient methods, Energy 189 (2019) 116230.

[11] J. Xiong, H. Zhao, C. Zhang, C. Zheng, P.B. Luh, Thermoeconomic operation optimization of a coal-fired power plant, Energy 42 (2012) 486–496.

[12] C. Carcasci, L. Cosi, R. Ferraro, B. Pacifici, Effect of a real steam turbine on thermoeconomic analysis of combined cycle power plants, Energy 138 (2017) 32–47.

[13] A.M. Kler, Y.B. Zakharov, Y.M. Potanina, Coordinated optimization of the parameters of the cooled gas-turbine flow path and the parameters of gas-turbine cycles and combined-cycle power plants, Thermophysics and Aeromechanics 21 (3) (2014) 383–392.

[14] D. Pauschert, Study of equipment prices in the power sector, ESMAP Technical Paper 122 (2009) 121.

[15] I.I. Komarov, N.D. Rogalyev, A.N. Rogalyev, O.V. Zlyvko, I.V. Lyvov, Effect of the initial steam parameters on the financial and economic performance of high-temperature steam turbine power units, Novoye v Rossiyskoy Elektroenergetike 9 (2016) 23–40 (in Russian).

[16] Stationary boilers and pipelines for steam and hot water. Strength analysis standards, General provisions for justifying wall thickness. OST 108.031.08-85, http://tehnorma.ru/normativbase/8/8981/index.htm, 2018. (Accessed 6 August 2018) (in Russian).
[17] L.M. Pike, Development of a fabricable gamma-prime (γ') strengthened superalloy, in: Superalloys, Wiley, 2008, pp. 191–200.
[18] R. Carapellucci, L. Giordano, A comparison between exergetic and economic criteria for optimizing the heat recovery steam generators of gas-steam power plants, Energy 58 (2013) 458–472.
[19] M. Nadir, A. Ghenaiet, C. Carcasci, Thermo-economic optimization of heat recovery steam generator for a range of gas turbine exhaust temperatures, Applied Thermal Engineering 106 (2016) 811–826.
[20] A. Valero, M.A. Lozano, L. Serra, G. Tsatsaronis, J. Pisa, C.A. Frangopoulos, et al., CGAM problem: definition and conventional solution, Energy 19 (3) (1994) 279–286.
[21] C.A. Frangopoulos, Application of the thermoeconomic functional approach to the CGAM problem, Energy 19 (3) (1994) 323–342.
[22] M.R. von Spakovsky, Application of engineering functional analysis to the analysis and optimization of the CGAM problem, Energy 19 (3) (1994) 343–364.
[23] A. Valero, M.A. Lozano, L. Serra, C. Torres, Application of the exergetic cost theory to the CGAM problem, Energy 19 (3) (1994) 365–381.
[24] L. Wang, Y. Yang, C. Dong, T. Morosuk, G. Tsatsaronis, Multi-objective optimization of coal-fired power plants using differential evolution, Applied Energy 115 (2014) 254–264.
[25] E. Godoy, N.J. Scenna, S.J. Benz, Families of optimal thermodynamic solutions for combined cycle gas turbine (CCGT) power plants, Applied Thermal Engineering 30 (2010) 569–576.
[26] A. Lazzaretto, A. Toffolo, Energy, economy and environment as objectives in multi-criterion optimization of thermal systems design, Energy 29 (2004) 1139–1157.
[27] E. Martelli, T.G. Kreutz, M. Gatti, P. Chiesa, S. Consonni, Numerical optimization of steam cycles and steam generators designs for coal to FT plants, Chemical Engineering Research and Design 91 (2013) 1467–1482.
[28] X.J. Liu, X.B. Kong, G.L. Hou, J.H. Wang, Modeling of a 1000 MW power plant ultra super-critical boiler system using fuzzy-neural network methods, Energy Conversion and Management 65 (2013) 518–527.
[29] R. Arora, S.C. Kaushik, R. Kumar, Ra. Arora, Soft computing based multi-objective optimization of Brayton cycle power plant with isothermal heat addition using evolutionary algorithm and decision making, Applied Soft Computing 46 (2016) 267–283.
[30] M. Liu, X. Zhang, Y. Ma, J. Yan, Thermo-economic analyses on a new conceptual system of waste heat recovery integrated with an S-CO2 cycle for coal-fired power plants, Energy Conversion and Management 161 (2018) 243–253.
[31] C. Wang, Y. Zhao, M. Liu, Y. Qiao, D. Chong, J. Yan, Peak shaving operational optimization of supercritical coal-fired power plants by revising control strategy for water-fuel ratio, Applied Energy 216 (2018) 212–223.
[32] N.P. Dekanova, A.M. Kler, L.F. Moskalenko, T.P. Shchegoleva, Mathematical modeling and study of integrated gasification and combined-cycle power plants, in: Proceedings of the International Centre for Heat and Mass Transfer, 1990, pp. 829–842.
[33] A.H. Land, A.G. Doig, An automatic method for solving discrete programming problems, Econometrica 28 (1960) 497–520.
[34] J.I. Manassaldi, N.J. Scenna, S.F. Mussati, Optimization mathematical model for the detailed design of air-cooled heat exchangers, Energy 64 (2014) 734–746.
[35] Si-D. Oh, H.-J. Lee, J.-Y. Jung, H.-Y. Kwak, Optimal planning and economic evaluation of cogeneration system, Energy 32 (5) (2007) 760–771.
[36] A.M. Kler, Y.M. Potanina, An approach to optimization of the choice of boiler steel grades as to a mixed-integer programming problem, Energy 127 (2017) 128–135.
[37] V.V. Kafarov, V.P. Meshalkin, L.V. Gur'eva, Optimization of Heat Transfer Processes and Systems, Energoatomizdat, Moscow, 1988 (in Russian).

[38] M.G. Kesler, R.O. Parker, Optimal networks of heat exchange, Chemical Engineering Progress. Symposium Series 65 (92) (1969) 111–120.
[39] R. Anantharamana, I. Nastad, B. Nygreen, T. Gundersen, The sequential framework for heat exchanger network synthesis - the minimum number of units sub-problem, Computers and Chemical Engineering 34 (2010) 1822–1830.
[40] L.V. Pavão, C.B. Borba Costa, M.A. da Silva Sá Ravagnani, Automated heat exchanger network synthesis by using hybrid natural algorithms and parallel processing, Computers and Chemical Engineering 94 (2016) 370–386.
[41] Z. Novak Pintarič, Z. Kravanja, A methodology for the synthesis of heat exchanger networks having large numbers of uncertain parameters, Energy 92 (2015) 373–382.
[42] A.M. Kler, A.S. Maximov, N.O. Epishkin, Methods for analysis and synthesis of technological schemes of thermal power plants based on solving auxiliary problems of linear programming, Thermophysics and Aeromechanics 24 (5) (2017) 787–798.
[43] A.M. Kler, N.P. Dekanova, S.K. Skripkin, et al., Mathematical Modeling and Optimization in Problems of Operational Control of Thermal Power Plants, Nauka, Novosibirsk, 1997 (in Russian).
[44] L.S. Guerras, M. Martin, Optimal gas treatment and coal blending for reduced emissions in power plants: a case study in Northwest Spain, Energy 169 (2019) 739–749.
[45] A. Ryzhkov, T. Bogatova, S. Gordeev, Technological solutions for an advanced IGCC plant, Fuel 214 (2018) 63–72.
[46] V. Tola, A. Pettinau, Power generation plants with carbon capture and storage: a techno-economic comparison between coal combustion and gasification technologies, Applied Energy 113 (2014) 1461–1474.
[47] F. Emun, M. Gadalla, T. Majozi, D. Boer, Integrated gasification combined cycle (IGCC) process simulation and optimization, Computers and Chemical Engineering 34 (2010) 331–338.
[48] R. Hoya, C. Fushimi, Thermal efficiency of advanced integrated coal gasification combined cycle power generation systems with low-temperature gasifier, gas cleaning and CO2 capturing units, Fuel Processing Technology 164 (2017) 80–91.
[49] M. Gharaie, M. Jobson, M.H. Panjeshahi, N. Zhang, R. Smith, Techno-economic optimization of IGCC integrated with utility system for CO2 emissions reduction— simultaneous heat and power generation from IGCC, Chemical Engineering Research and Design 94 (2015) 428–439.
[50] A.M. Kler, Y.M. Potanina, A.Y. Marinchenko, Co-optimization of thermal power plant flowchart, thermodynamic cycle parameters, and design parameters of components, Energy 193 (2020) 116679.

Index

0–9

A

B

C

F

I

N

O

P

T

U

V

W

Hierarchical Modeling of Energy Systems

Hierarchical Modeling of Energy Systems presents a comprehensive methodology for hierarchical modeling of large-scale complex systems with the focus on energy systems, their expansion planning, and control. The general methodological principles of hierarchical modeling are laid out, and on the basis of them, a generalized technology for the hierarchical approach is provided.

The scope of the book also covers the mathematical foundations of decomposition and bilevel programming, as well as the applications of information technology in energy modeling. Theoretical propositions are supplemented with practical examples of hierarchical modeling. These mini-case studies address the issues of planning the development of the energy sector and expansion of energy systems through analysis, optimization, and control of their operation. Algorithm descriptions and sample simulations are included.

Hierarchical Modeling of Energy Systems proves an invaluable guide for researchers, engineers, and all those working in the field of development, control, and management of energy systems, while the summary of fundamental principles and concepts in energy modeling makes this book an accessible learning tool for graduate students of any subject related to energy systems or energy modeling.

Key features

- Summarizes hierarchical modeling principles and methods
- Critically examines all energy systems, including electric power systems, heating systems, gas and coal supply systems, integrated and cogeneration systems, their interrelations, and more
- Investigates expansion planning, development and operation, control, and management of energy systems
- Provides detailed mathematical descriptions of models, computation algorithms, and optimization problems

About the Editors
Dr. Nikolai I. Voropai
Professor, Dr. of Eng., Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Corresponding Member of Russian Academy of Sciences, Russia

Dr. Valery A. Stennikov
Professor, Dr. of Eng., Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Academician of Russian Academy of Sciences, Russia

ISBN 978-0-443-13917-8
9 780443 139178

ELSEVIER
elsevier.com/books-and-journals