Energy Systems Research

Volume 2 • Number 4 • 2019

Published by
Melentiev Energy Systems Institute
Siberian Branch of Russian Academy of Sciences

Available online: esrj.ru

ISSN 2618-9992

Energy Systems Research

Volume 2 • Number 4 • 2019
International scientific peer-reviewed journal
Available online: http://esrj.ru

About the journal

Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

Energy systems research methodology is based on a systems approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of systems analysis.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

The journal welcomes papers on advances in heat and electric power industries, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technologies.

Energy Systems Research is also concerned with energy systems challenges related to the applications of information and communication technologies, including intelligent control and cyber security, modern approaches of systems analysis, modeling, forecasting, numerical computations and optimization.

The journal is published by Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences. The journal's ISSN is 2618-9992. There are 4 issues per year (special issues are available). All articles are available online on English as Open access articles.

Topics

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- Integrated energy systems
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- International, regional, local energy systems
- Energy system protection, control and management
- Smart energy systems, smart grids
- Energy systems reliability and energy security
- Electricity, heating, cooling, gas and oil systems
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- Demand-side management
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- Distributed energy systems
- Sustainable energy transitions
- System problems of power and thermal engineering
- Artificial intelligence in energy systems
- Information and communication technologies in energy systems
- Energy systems analysis and modelling
- Computational methods and optimization in energy systems

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PREFACE

Introduction to hierarchical modeling of complex systems

The energy sector is a totality of interrelated energy industries within the fuel and energy complex. Each of the industries represents a technically and organizationally sophisticated energy (electricity, heat, gas, oil, etc.) system that produces, transports, stores, and distributes a certain type of energy (electricity, heat, gas, etc.) to the consumer. Energy systems are characterized by a complex multiply-connected spatially distributed network structure integrating energy production and consumption plants into a single whole. They play an essential infrastructure role in reliably providing the consumer with the energy of desired quality.

Effective expansion and operation of each energy system; integrated systems, including several jointly operating and developing energy systems; as well as the entire energy; sector require informed decisions on their expansion and control to meet the efficiency criteria set. Given that the tools for making such decisions and control actions are computer-based decision-support systems and automated control systems, modeling of the studied object (energy system, integrated energy systems, and energy sector, i.e. complex energy system) appears to be of paramount importance in terms of the adequacy of decisions to be obtained for the real states and processes in the systems at issue.

The multidimensionality of the studied systems and the complexity of the processes that occur in them, however, often make the original problems of expansion planning and control of complex energy systems, hard to implement for a variety of reasons. These are the time limit for solving the original general problem, the lack of observability required for modeling the system, the uncertainty of the model parameters, and others. Oversimplification, on the other hand, or “emasculation” of the original detailed model of the system can deprive the model of its representative properties necessary to adequately represent the object to be studied. In these contradictory contexts, a real solution for such an insurmountable situation is a hierarchical approach to planning the expansion and control of the complex energy systems and their components. Generally, the hierarchy of problems and decisions based on solutions to these problems is considered in spatial, temporal and functional dimensions. The hierarchy of solutions, in turn, predetermines the hierarchy of interrelated models of the corresponding system and models of operations (decision-support criteria). Hierarchical modeling is also instrumental as a technique for solving complex multidimensional problems.

The collected papers contain a systematized presentation of the experience gained by the Melentiev Energy Systems Institute SB RAS (ESI SB RAS) in the development of a hierarchical approach to modeling the complex energy systems to provide their expansion planning and control. The papers present the results of the studies on the hierarchy in complex energy systems, which mainly summarize the developments of ESI SB RAS in recent years.

A focus is also made on the specific features of modern energy systems as objects of hierarchical modeling and some trends in their development. Existing general methodological approaches to hierarchical modeling of complex systems are analyzed. The generalized methodology of hierarchical modeling of complex energy systems is described. The mathematical methods of hierarchical modeling of complex systems exemplified by the energy sector are considered. The hierarchical modeling for different problems of complex energy systems is demonstrated.

N.I.Voropai
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Energy Systems as Objects of Hierarchical Modeling

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***Abstract* — The paper covers the trends in changing of the structure and properties of the energy systems of the future that are innovations-driven in their development. The role of intelligent technologies in the transformation of energy systems is analyzed. The main directions and findings of the published research on intelligent power systems are presented.**

***Index Terms* — Energy systems, innovative intelligent technologies, transformation of energy systems, substantiation of development, operating modes control.**

I. Introduction

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 internal for the energy sector (intensive development of energy technologies, a qualitative 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 fundamental change in the paradigm of development and functioning 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 power, heating and gas supply systems with developed transportation and distribution network infrastructure. In a sense, the infrastructure includes oil and petroleum product supply systems, although they 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 operating modes.

The scale of the energy systems and the expansion of the areas served by them 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 individual low-rise residential buildings construction. Furthermore, the status and standard of living will continue to increase in medium and small towns. All this 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 of quality of life and labor productivity [1-3].

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 adjusting 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 makeup 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. Let us consider in more detail the features and challenges of future energy systems.

II. Innovations-driven electric power systems of the future

The widespread adoption of distributed generation units in electric power systems is responsible for several distinctive features. Many small generating units that make use of gas turbine technologies operate at higher

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http://dx.doi.org/10.25729/esr.2019.04.0001
Received August 12, 2019. Revised October 21, 2019.
Accepted November 07, 2019. Available online January 25, 2020.

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-regulating effect of generation diminishes. Distributed generation units have small permanent rotor inertia if compared to conventional high-capacity generators and and also have 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 power 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].

Due to the trends in the development and location of electric power generation and consumption, the power grid 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 power transmission grid. At the same time, the widespread adoption of devices that form flexible AC power transmission systems (FACTS) on the basis of power electronics will radically increase the controllability of the AC transmission grid [4]. New technologies, including the use of FACTS devices, will significantly improve the reliability and controllability of the power distribution grid.

Growth of electricity consumption under scattered generating sources and consumers across the territory leads to an increase in the density of power transmission and distribution grids. In general, taking these factors into account, future electric power systems will increasingly acquire the functions and properties of infrastructure systems (think "the electric power Internet"), which will, in theory, 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 a reasonable 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 changes in the voltage of the power mains (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, and 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 power distribution grid, which results in relatively stable voltage levels on the consumers' buses and the compliance with regulatory requirements, but in case of emergency in the mains and the power distribution grid 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 power supply grid.

Another problem is that an increasing number of receivers are keeping their power consumption constant when the frequency in the mains changes. 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 mains (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 operating 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 operating modes using the controlling capabilities of consumers is 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 [5]. Characteristically, 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 energy storage is expected to be based on electric vehicles, that, when used on a mass scale, will significantly change the appearance and operating modes of future electric power systems.

Taking into account the indicated tendencies of increasing adoption of electric receivers and electric power

storage systems supplied with direct current through converter elements, one can expect transition to the establishment of electric power supplying DC distribution gridswith shared AC to DC converter units placed at supplying substations [6, 7].

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

Almost all countries around the world have declared the concept of the intelligent energy 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 production to electricity consumption, namely [8, etc.]:

- Innovative technologies and installations for the production, 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, a full-scale digitalization of all stages of the information and control subsystem will be carried out, ranging from measuring the current values of the operating 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 changing 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 operating modes of electric power systems at various levels, improve control efficiency, and ensure the reliability of the system of control over the operating 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 acute [9, 10, etc.].

III. Innovative technological transformations of future heat supply systems

Important conditions determining the development of heat supply at the present stage and in the oncoming future are the following [11]:

- 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 own energy sources will have a significant impact on the structure and demand for thermal energy, as well as on the makeup of generating capacity;
- Energy saving, application of energy efficient technologies in production, changes in the structure of industrial production, use of heat-saving structures of buildings, introduction of systems of metering and controlling of heat supply and consumption contribute to a significant 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, emergence of the market of efficient heat generating equipment of small capacity increase the role of decentralized (distributed) systems:
- Growth of the cost of electricity, higher prices for fuel and its transportation, more expensive equipment and materials, and, as a result, higher tariffs for heat energy, contribute to the adoption of energy-saving measures in the processes of production, transportation, and consumption of heat, as well as 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 efficiency of large heat sources, limits the spans 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, transition of heat supply 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 of 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 measures of forcing consumers into using certain types of heat supply without providing economic incentives and encourage them to behave actively.

These 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 application 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 heat energy;
5. increasing the use of renewable heat sources;
6. interest in making really 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 adequately to changes in heat demand and other external challenges.

The new trends emerging in the heat supply industry will determine the technological transformation of heat supply 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 under way 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 and power 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 diagrams 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 regulation devices;
d) Creation of an automated control system for technological processes of production, transport, and consumption of the thermal energy.

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

– Joint operation of heat sources, which actually meets 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 regulation 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 coolant, 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-houses, 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 heat supply and will ensure extension of the working life of the equipment;
– Reduced coolant pressure due to the fact that in the independent circuits of heat and power system elements it is necessary to provide only coolant circulation, while leakage of coolant reduces and working life of equipment extends.

Technical re-equipment of the systems includes a set of measures without which it is impossible to implement the above-mentioned directions. Among them are 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 heat supply system operating mode to the implementation of control actions;
- Wide-scale application of the automated heat points with plate heat exchangers and control and regulation systems for sources, heat networks, and heat inputs of consumers.

A promising technological platform for the heat supply of the future, that is 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 unified automated system [12]. This will provide it with the necessary flexibility and adaptability to changing operating conditions, increase efficiency, reliability, and quality of heat supply, facilitate decrease in heat losses, and smooth out the unevenness of heat consumption schedules, etc. Availability of an opportunity to monitor and control in real-time the operating 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 heat market. This will ensure bilateral and mutually coordinated interaction between the consumer and the heat and power system.

IV. 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 the regions, further urbanization of the country, the "overgrowth" of cities with townhouse villages and suburban settlements with the 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 building 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 reinvigorates the processes of mass application of more efficient and higher quality gas dispenser valves, gas consuming devices, automatic means of control in 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 operating modes that are either non-standard or even beyond-design.

This in turn serves as an incentive for the following:

- Introduction of new highly adaptable energy-saving compressor and power equipment with 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 the 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 [13], 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 commercial metering complexes of 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 technological parameters: inlet and outlet gas pressure, pressure drops on 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, 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 indicators.

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 operation of metering stations of gas distribution stations. This subsystem enables to see the status of the main parameters of the gas distribution station, such as gas pressure at the outlet, hourly gas flow rate, 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 mode of a periodic automatic request.

The next, as per the order of the process of gas transportation in the gas distribution system, is the subsystem of control over gas regulating points of the enterprise. This subsystem is built on the basis of a software and hardware system that allows online monitoring of the following gas regulating points parameters via radio communication channels:
– Inlet and outlet gas pressure;
– Temperature inside the gas regulating points room;
– Level of gas content in the gas regulating points process rooms and those of consumers within the gas regulating points 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 online redistribution of gas flows in the gas distribution network, optimizing (to the necessary and possible extent) the gas flows through its branches.

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

The covered innovative tendencies in electric power, heat supplying and gas supplying systems are in many respects characteristic of water supply systems, and also, of oil supplying systems 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 under consideration, expansion of the territories served by them.
2. Increasingly complex structure of power systems due to increased diversity of power 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 under emergency conditions, 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 final energy types.
5. The active nature of consumer behavior in terms of managing their own energy consumption at the pace that matches that of the process, 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 presentation of current information for monitoring and control of operating 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 of their operating modes.
9. Creation of conditions for the making up 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 CHPPs that produce 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., heating that comes either from a district heating system or an electric heater) [14].

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

VI. The current state of the research in the field of intelligent 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 [15-19, etc.]. Under the auspices of international organizations, international conferences are held annually on the problems 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 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 (CIRED), 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 language, such as "Contemporary directions in the development of the systems of power-system protection", "Electric power engineering through the eyes of the youth", "Methodological issues of research of 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 to create a 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 grid and consumer activity [15, 16]. In China, emphasis is placed on the high-voltage transmission grid 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 creation of large-scale systems of monitoring (WAMS) and control (WACS) of the operating modes of electric power systems [20, 21]. In Russia, the concept of the active and adaptive grid is being developed, referring, first of all, to the transmission electric power grid, but also to the distribution grids [17, 18]. Active and adaptive grid, 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 grid and influence the generation and consumers, real-time control systems that allow to respond 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 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 of the Russian Academy of Sciences, and the Scientific and Technical Center of the Federal Grid Company (FGC UES), with the participation of a number of organizations and experts, developed the Concept of the intelligent electric power system of Russia with an active and adaptive grid [22]. On the basis of this concept, the above organizations have developed and systematized theoretical foundations, methods, and models of control of intelligent power systems [23]. 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 under the coordination of the Melentiev Energy Systems Institute, SB RAS, and with the participation of the Institute of Control Sciences, RAS, and a number of other organizations, the project "Knowledge-based coordination of operational and emergency control of interconnected power utilities of the European Union and Russia" was implemented [24]. These fundamental works have served as a methodological basis for the development of research in Russia in the field of intelligent technologies and intelligent electric power systems.

In 2011-2013, Irkutsk National Research Technical University (INRTU) with 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 Gehrike 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, according to which INRTU established an advanced research infrastructure within the framework of the project. 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 [25-27 et al]. The main research and their 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 [27]. In Russia, the process of using the Smart Grid ideology is still at its infancy [28, 29].

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

thermak 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, Geneva, Cologne, London, Rotterdam [30]. 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 heat supply systems are being implemented in a number of other European cities, such as Marstal and Copenhagen (Denmark) [31, 32, 33] Bietigheim-Bissingen and Crailsheim (Germany) [30], Malmö (Sweden) [34], Delft and Heerlen (Netherlands) [34, 35], 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 published abroad on the subject of intelligent heat supply systems are primarily related to the definition of their properties, the shaping of the technological concept of the intelligent heat supply system (smart thermal grids) [36, 37], a general mathematical description of such systems, taking into account the storage and alternative production of thermal energy on the consumer side [38, 39]. The mathematical model of optimal control of the system operation that ensures reconciling energy balances at the minimum cost of heat production is proposed [39], the problem of optimizing the system operating modes at the minimum fuel consumption for heat production were stated and solved [40, 41]. The problems of real-time forecasting of the demand for heat and its distribution among sources, including renewable ones, were formulated [42]. The main feature of these projects is that they focus on the application in systems with a high degree of automation of technological processes. However, they do not cover the entire range of new challenges that arise. In Russia, the issue of "smart thermal grids" have 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 works on solving the problems of optimal distribution of heat loads between heat sources [43, etc.], on the ideology, principles of design, and control of operating modes [44, etc.]. They can lay the methodological foundation for intelligent heat supply systems.

On the basis of the analysis of problems of designing and operation of pipeline systems of heat, water, oil and gas supply, as well as current trends of innovative development of energy systems the tasks of construction and control of intelligent pipeline systems were formulated at the Melentiev Energy Systems Institute, SB RAS [12, 45]. A new content was elucidated for the problems of analysis and synthesis of hydraulic circuits, which are 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.[46-48, etc.]. 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 problem of standardization of smart meters of electricity, gas, heat, water (Mandate M/4416, 2009) [26, 27]. The smart metering system is considered a key link in the implementation of integrated intelligent power 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, micro-turbines, 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 [49,50].

VII. Conclusion

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 abroad. 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.

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General Methodological Approaches to Hierarchical Modeling of Complex Systems

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***Abstract* — Based on the analysis of features inherent in any complex system, including modern energy systems, this study argues for the necessity of adopting hierarchical principles of modeling of such systems when solving the tasks of substantiating their development and the way their operation is controlled. The study also provides a concise overview of general methodological research contributions that further the development of the technology behind hierarchical modeling of complex systems.**

***Index Terms* — Complex systems, hierarchical modeling, general methodological approaches.**

I. Introduction

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 stipulates that any theory that claims to study complex systems should do so by operating the models, the structure of which reflects this complexity [1 - 3, etc.]. Treating energy systems as complex large systems was typical of this period with respect to the energy sector problems as well [4 - 6, etc.].

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 multivariance 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, is 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 stipulated 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.

II. 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

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http://dx.doi.org/10.25729/esr.2019.04.0002
Received July 30, 2019. Revised August 25, 2019.
Accepted November 07, 2019. Available online January 25, 2020.

implements the solutions obtained. A unique and one-of-a-kind book by M. D. Mesarovic, D. Macko and Y. Takahara dwells at great depth on this cornerstone idea [1]. 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 elucidaded as stratified, multi-layered, and multiechelon 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" [7] 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 [8] 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 [8] 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 formulation 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 [8] supplements Manheim's book [7] in terms of methods of building a hierarchical structure for the design process and the use of 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 [9-11]. 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 insoluble due to the huge dimensionality of the model and the multiplicity of preference relations, which oftentimes prove contradictory. Therefore, in [9-11] 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 studio (CB), 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 studio 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-problems of the uppermost level of aggregation as a problem of the external designing.

The challenges related to information aggregation are addressed in [12] 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 decentralisation 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 article 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 [13]. 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 multicriteria evaluation and optimization tasks 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 [14, 15] offers hierarchical game-theoretical principles of how to study and control hierarchical systems. In [14], within the framework of the game-theoretical model of hierarchical control, which takes into account the requirements of sustainable development of the system, formalization of the required methods of hierarchical controls as specific instances of principles of optimality is performed. 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. In [15] 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.

III. Conclusion

The research findings by various authors as expounded in this study detail in a sufficiently comprehensive way 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.

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Generalized Technology of Hierarchical Modeling of Complex Energy Systems

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***Abstract* — This study aims at investigating the technology of hierarchical modeling of large energy systems when substantiating their development and control over their operation. To build the hierarchy of models of an energy system, we rely on the property of heterogeneity of the structure of complex systems. As a proof of concept of the technology, we present a two-level hierarchy of models employed for solving the problem of substantiating the development of the Unified Energy System of Russia.**

***Index Terms* — Large energy systems, hierarchical technology, expansion, operation.**

I. Introduction

Modern large organizational and engineering systems, that include 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 proof 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 throughput capacity 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 loose 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 control over their operation.

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 control over operation of the system. Multicriteriality, 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 multicriteria 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 control over operation of a large system in the form of a general operations research problem proves insoluble 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 stipulate 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 control over the operation of such systems [1, 2].

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http://dx.doi.org/10.25729/esr.2019.04.0003
Received June 11, 2019. Revised August 01, 2019.
Accepted October 29, 2019. Available online January 25, 2020.

II. Hierarchical technology

The problem of substantiation of the development of a large energy system consists, firstly, in the choice of the most preferable, in terms of 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 variant. Building a set of alternatives (variants) that represent as a whole a given area of 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); $x_i=\{x_{i1},x_{i2},\ldots\}$ — a set of parameters for variant i of the system; $PR = \{PR_1, PR_2, \ldots\}$ a set of preference relations for making a choice. Then the problem of rational choice in a rather general form can be formulated as

$$X_o = opt(X, \Phi);\ x_o=opt(x, X_o, PR), \quad (1)$$

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

Let's 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:

$$PR^m \to PR^{m-1} = V_{m-1}\left(PR^m\right) \to \ldots \to PR^0 = V_0\left(PR^1\right) \quad (2)$$

The arrows in (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 subproblems 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 (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 (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:

$$x^0 \to x^1 = opt\, f_1\left(x^0, PR^1\right) \to \ldots \to x^m = opt\, f_m\left(x^{m-1}, PR^m\right) \quad (3)$$

To follow the arrows in (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 (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 (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 loose couplings of subsystems. This is well-justified, since loose coupling (sections) in almost all cases are usually the "culprits" of emergency situations as a result of overloading of these links during changes in flow distribution in the system, violations 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 loose sections in its structure, so it is expedient to leave loose couplings and sections intact during aggregation.

In fact, transformations (2) and (3) serve as preliminary in the overall process of hierarchical modeling and studies of large systems. Subsequent actions represent a sequence of subproblems for choosing solutions, which can be formalized as follows:

$$\begin{aligned} &x_o^m = opt(f'_m(x^m, PR^m);\ F_m(X, PR^m)) \\ &\qquad\qquad \downarrow \\ &x_o^{m-1} = opt\big(f'_{m-1}(x_o^m, PR^{m-1});\ F_{m-1}(X^m, PR^{m-1})\big), \\ &\qquad\qquad \downarrow \\ &\qquad\qquad \vdots \\ &\qquad\qquad \downarrow \\ &x_o^0 = opt(f'_0, (x_o^1, PR^0);\ F_0(X^1, PR^0) \end{aligned} \quad (4)$$

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 subproblems of the overall hierarchical problem of a choice of solutions. In the process of "moving" the top-down way in (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:

$$X^m = X \to X^{m-1} = F_{m-1}(X^m) \to \ldots \to X^o = F_o(X^1). \quad (5)$$

In the case of sequential solving of subproblems of choice in accordance with (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:

$$\begin{aligned} &x^m \to x^{m-1} = opt\big(f'_{m-1}(x^m, PR^{m-1})\big) \to \\ &\to \cdots \to x^0 = opt\big(f'_0(x^1, PR^0)\big). \end{aligned} \quad (6)$$

Here the *opt* operation has the same meaning as in (3). The "prime" superscript in the functional relation marks

the disaggregation operation of the model as an inverse of aggregation. Subscript o in ratios (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 (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 of the initial problem (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). Here, 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).

III. Case study of applying the hierarchical technology

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 main power grid, 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 subproblem of choosing the structure of generating capacity units and their location, while at the lower level it will be the subproblem of choosing the structure and parameters of the main power grid 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 power lines, the levels of reliability of power supply to consumers and the stability of the UES. Let us set the acceptability requirements for the operating 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:

$$PR^1 = \{PR_{cg}^1, PR_e^1\};\ PR^0 = \{PR_{cn}^0, PR_r^0, PR_s^0\} \quad (7)$$

where the indices *"cg"* and *"cn"* correspond to capital expenditures for generation capacity and the grid; while *"e"*, *"r"*, *"s"* corresponds to criteria of environmental impact, reliability, and sustainability. The interrelation between the sets of criteria at the two considered levels of the problem description is provided through capital expenditures, since $PR_c = PR_{cg} + PR_{cn}$ and it is usually necessary to find the minimum of PR_c, while the ratio between its components can be adjusted in the transition from the top-level subproblem to the entire set of the lower level subproblems by refining the requirements for generation, taking into account the introduction of additional power 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 operating 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 power 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 subproblem, 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. 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 loose coupling within such integrated energy systems.

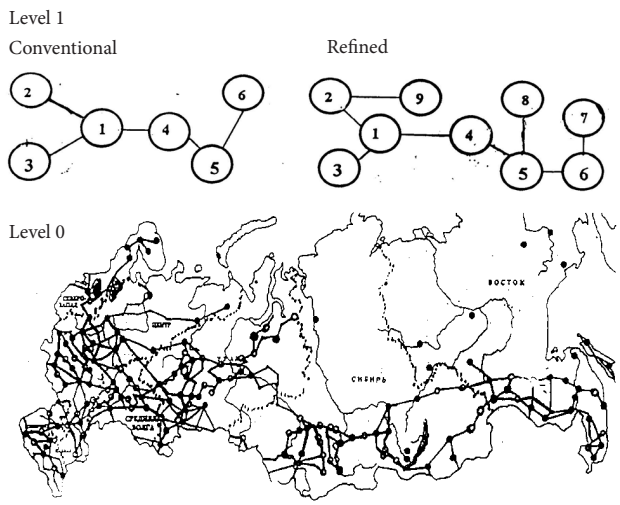

Fig. 1. Two-level representation of the UES of Russia

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 subproblems of type (4) formally following the proposed hierarchical choice procedure, but with respect to their content the composition of these subproblems, 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 subproblems, 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.

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Hierarchical Modeling in Projection Studies of the National Energy Sector Development

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***Abstract* — The focus of the paper is the evolution of methodological tools for long-term projections of the national energy sector development. The research highlights the importance of considering the growing uncertainty of the future when determining the rational hierarchy of employed economic and mathematical models. We propose adjusting their composition and the degree of aggregation depending on the projection time frame.**

***Index Terms* — energy sector, projections, uncertainty, models, hierarchy.**

I. Introduction

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, 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. Long-term projections are 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 improvement 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 (Table 1), appears more promising.

An important role in factoring in the uncertainty when making long-term projections 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.

II. The evolution of the applied models for projection of the energy sector development

The recognition of the important part played by long-term projections in developing strategic decisions was instrumental in the development of projections methodology 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, SB of the Russian Academy of Sciences), where in the

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http://dx.doi.org/10.25729/esr.2019.04.0004
Received July 27, 2019. Revised October 10, 2019.
Accepted October 29, 2019. Available online January 25, 2020.

Table 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. Projections 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 the 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: 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: models for the analysis of the sensitivity of options to changes in the imposed constraints and requirements, 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 indicator 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.

1970s, the energy sector optimization model, the first 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 consumption, 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 projections 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 the 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 macroeconomic 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 the 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 the energy 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 Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, where the experience accumulated over several decades helps to adapt the models sensibly and build their combinations catered to specific projections. 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 U.S. 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 dozen models (modules), including but not limited to the following: the macroeconomic 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 U.S.

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, fuel and 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 technology enables 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; 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 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 research 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 (Figure 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 Figure 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 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 composition 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 modeling 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 period 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 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 Melentiev Energy Research Institute 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:

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

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 determined 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):

$$\sum_t [\sum_r (\sum_{e,p} c^t_{epr} X^t_{pr} + \sum_{e,r'} c^t_{er'r} Y^t_{er'r} + \sum_{e,r'} c^t_{err'} Y^t_{err'} + \sum_{e,s,d} z^t_{esd^r} S^t_{esd^r} +$$
$$+ \sum_e v^t_{er} I^t_{er} + \sum_{e,a,p} \eta^t_{eapr} A^t_{eapr} - \sum_e q^t_{er} E^t_{er}) Dis^t] \to \min,$$

where $c^t_{epr}, c^t_{er'r}, c^t_{err'}, z^t_{esd^r}$ – 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]. Unlike the energy sector models, they allow more comprehensively for the modes of power production and consumption, constraints on inter-regional power exchanges, 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.

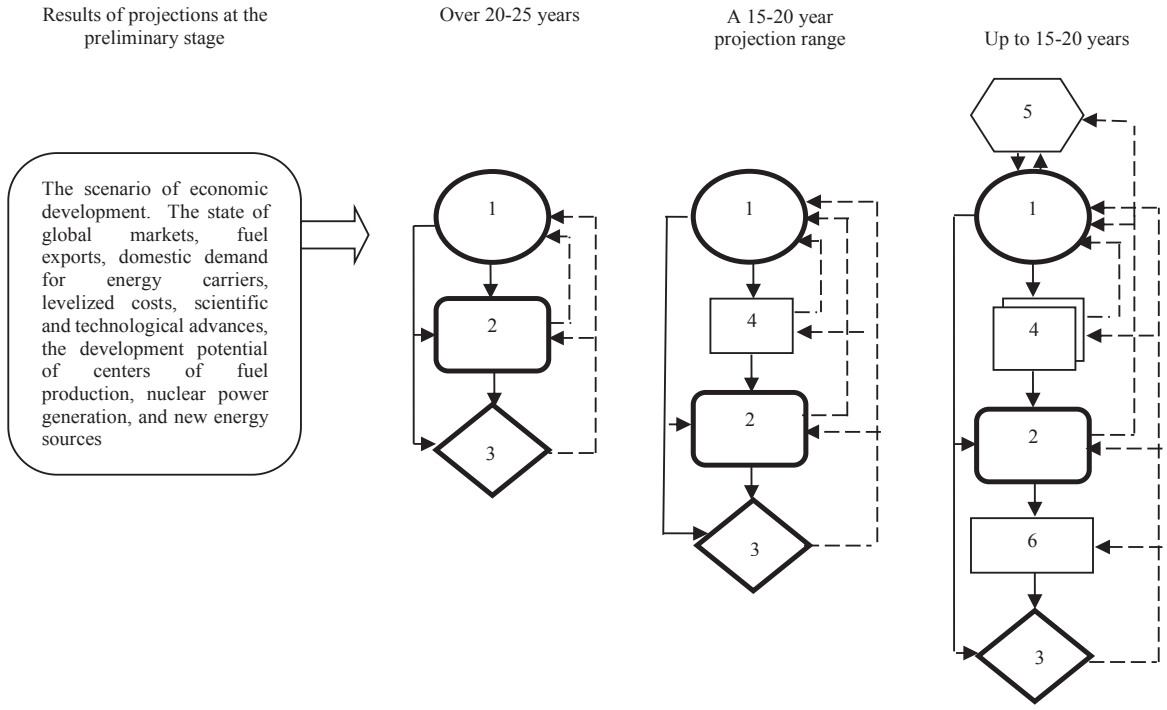

Figure 1. Hierarchy of problems and models at various temporal stages of working out and studying the options of long-term development of the energy sector
1 - The energy sector; 2 - state of regional energy markets (demand and prices); 3 - barriers and threats; 4 - industries of the energy sector; 5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

Table 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, macroeconomic models, models of demand for energy carriers and their aggregated region-wise cost dynamics	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 indicators thresholds. Price elasticity of demand for fuel and electricity. Development prospects of regional energy systems and new sources of electric energy. Risk analysis of large-scale projects and programs

III. Problems of a great number of criteria and aggregation in the hierarchy of models employed for the 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 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 real 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 modeling projection studies. This allows specifying the limits set on possible new capacity additions while optimizing the development of energy systems.

Optimization models used in the 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 do not take into account the likelihood of such changes. The scenario approach, which is widely used in real-life projection studies, 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 it does not arrive at the likelihood of other scenarios and does not 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, operating and development conditions of the modeled object are presented by random variables. The main parameters of such models are defined not deterministically, but as governed by the laws of their probability distribution [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 Melentiev Energy Systems Institute, SB RAS (MISS-EL models) [13] for a comprehensive assessment and risk analysis of energy supply options for individual aggregated regions.

In the projection studies 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 most significant problems within each time frame segment (Table 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 interconnected 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.

IV. Conclusion

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 projections: a dynamic macroeconomic 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.

Acknowledgements

The research was carried out under State Assignment III.17.5.2 (reg. no, AAAAA-A17-117030310432-7, project subject No. 0349-2016-0012) of the basic research program of the Siberian Branch of the Russian Academy of Sciences.

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Hierarchy of Models for the Study of National and Regional Energy Security

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***Abstract* — This paper focuses on the specific features of the hierarchical approach in the en-ergy security studies for modeling the processes of functioning and development of in-dustry-specific energy systems within a single energy sector. The experience of devel-oping and using hierarchical modeling in the study of reliability and survivability of energy systems is analyzed using the example of the unified gas supply system, oil sys-tem, oil product system, and the unified power system of Russia. In the paper, the hier-archy of models in the energy security studies is considered in terms of territory and structure.**

***Index Terms* — hierarchical modeling, energy security, energy systems, the energy sector.**

I. Introduction

The system of mathematical models used to study the national and regional energy security (EB) problems is largely based on mathematical models designed to study reliability. At the same time, reliability, being a complex index of 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 the 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, the 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 world region, various groups and unions of states, individual countries, their regions, territorial and industrial entities, etc. [12]. Thus, energy security as a subject of research is not so much of a state of the energy sector itself but 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 on the energy system reliability based on hierarchical modeling, with the emphasis on the specifics of energy security research.

II. The principles of the energy system reliability study

The reliability of energy systems, following [3], 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 index, includes the feature of “survivability” or the ability of energy systems to withstand large disturbances, preventing their cascade development with mass outages of consumers [4]. 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 the energy systems themselves and represent predominantly technical categories, which have an economic sense only because their decrease 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 determination of such capabilities of individual industry-

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http://dx.doi.org/10.25729/esr.2019.04.0005
Received September 17, 2019. Revised October 27, 2019.
Accepted November 30, 2019. Available online January 25, 2020.

specific systems, including those in case of large-scale disturbances. The subject of research here is the process of disturbance occurrences, the reaction of energy systems, the consequences for end energy consumers, and the method of compensation for undesirable consequences [5]. The need to study the operation of energy systems under emergencies is dictated by the general methodological principle formulated in [6]: 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, especially, to the hierarchical modeling in the study of these issues, for example [7-12]. The Energy Systems Institute SB RAS (ESI) has gained extensive experience in studying various aspects of interconnected operation of the 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 [13-17].

III. Methodological features of the energy security studies

In the mid-1990s, the ESI (the then Siberian Energy Institute) SB RAS 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 energy sector state and 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.

Considering the methodological aspects of the energy research in the context of energy security, one should keep in mind the following important features [1]:

- 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;
- The research requires that the energy systems 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 in terms of energy security and the justification of measures to increase the survivability of energy systems and to ensure energy security. Composition of the studied scenarios, among other things, is determined by the specific threats to energy security, whose materialization is considered possible in the research. The analyzed set of disturbances in specific conditions can be quite large. Since the scale of the considered disturbances is large, the occurrence of possible energy security threats will inevitably result in fuel and energy shortage for consumers, and energy consumption limitations, which are associated with economic damage to industry, agriculture, other sectors of the economy, the public utilities sector, and the energy sector itself (lower profit, increase in fines, etc.). The sizes of these shortages, energy consumption limitations, and damages are indicators, which 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.

IV. Modeling principles of the assessment of technical consequences for the energy consumer in case of large-scale energy system failures

A general scheme has been designed to assess the technical consequences of disruptions in the energy system operation within the energy sector for energy consumers. 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 [4]:

1. ***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 in a wide territory around 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.
2. ***The operating conditions of energy systems***. Under normal operating conditions, energy facilities perform the functions assigned to them according to their production characteristics. In emergencies, when their production characteristics decrease 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 insufficient. In this case, the resulting power shortage will cause a limitation of power supply to consumers. Consideration of such situations in the research necessitates sufficiently detailed modeling of the energy system operation.
3. ***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 violations of their production processes. The detailed structural representation of energy systems makes it possible to show each major consumer given 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 equipment operating in the system and its loading [4]. Thus, at the level of energy systems under various types of emergencies, there is a "point-in-time" modeling of their operating conditions [4].

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 [18]. The simulation approach is the main methodological principle of energy research in terms of providing continuous fuel and energy supply to the consumer and the rationale for measures to improve the survivability of the energy systems. A general scheme for studying the survivability of energy systems, representing the relationship between the main tasks, is shown in Fig. 1 [1].

Building a set of disturbance scenarios that reflect the most representative or characteristic combinations of external conditions for the development and functioning 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 generates the need to make a reasonable choice of the most representative set of characteristic situations, which are called calculation ones. The resulting estimates and solutions must be invariant for different combinations of the conditions.

The next two tasks – identification of "bottlenecks" in the fuel and energy supply to consumers and assessment of the effectiveness of measures for specific disturbance

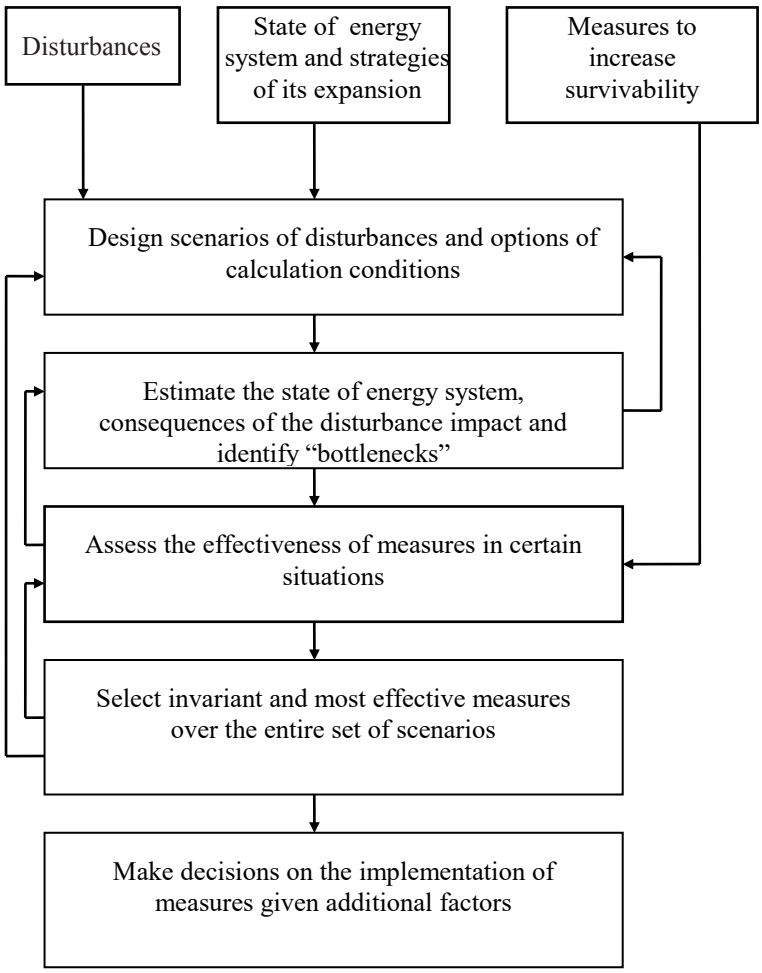

Fig. 1. The relationship between the main tasks in the research into the energy systems survivability

scenarios – have their specific features in terms of object modeling. As already mentioned, the study of the energy system survivability performs a set of subtasks 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 studied system are 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 task 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 selection of measures when the optimizing functional 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 economically should be considered when analyzing the economic efficiency of the measures. The economic effectiveness 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, the measures that can prevent them and do not require large additional costs can only 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 estimates of 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.

V. A two-level approach to the energy security study

To study the energy security problems, ESI SB RAS 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 energy sector operation and development meeting the energy security requirements. The study is based on the linear optimization models of the energy sector and individual industries. It also relies on the technical and economic characteristics of energy facilities, reported data on the state of energy systems, and the findings of the energy development studies that provide grounds for the selection of a long-term strategy and formulation of an energy policy. Based on the adopted socio-economic development program 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, which is carried out in the stage of quantitative analysis. Based on the presented hierarchy of problems to be solved

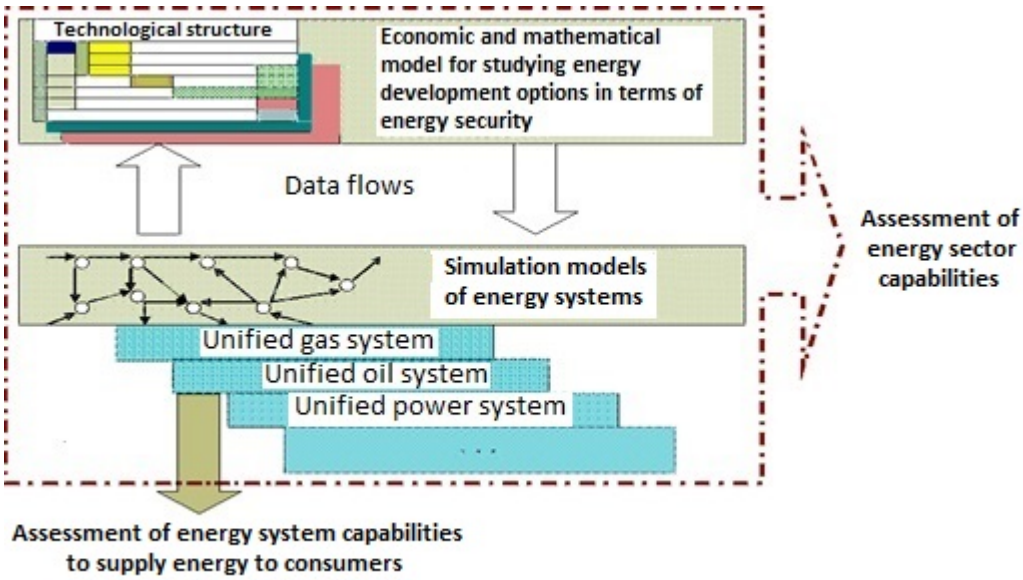

Fig. 2. The relations of linear optimization models for the study of energy security problems.

and models developed for this kind of research, a two-level system of models was proposed [19]. 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.

In this approach, the upper-level models are constructed by adequate 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 state of the energy sector in case of possible disturbances and their impact on the fuel and energy supply to consumers from the energy security perspective [20]. These models are interconnected by balance and technological (structural) relationships but differ in the duration of the considered time interval, Fig. 3:

- a model for estimating the current state of the energy sector under normal and emergency operating conditions;
- a model for optimizing the territorial-production structure of the energy sector (based on the adopted energy development strategies given the possibility of emergencies).

In the models used, the territory of the country is presented in detail with the emphasis on federal districts and federal subjects of the Russian Federation. The industry-specific energy systems including backup facilities are presented with a sufficient degree of detail. The models are designed to indicate seasonal unevenness and provide yearly, quarterly, and daily consideration. They are also aimed at determining the directions and scales of the optimal energy development (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 at consumers. The objective function includes not only the costs of energy development but also the fines for possible energy undersupply to consumers.

Mathematically, the problem of the optimization of fuel and energy balances in the Russian regions under possible disturbances, which is solved using the indicated models, is a classical linear programming problem. Conceptually, the approach is based on the territorial-production model of the energy sector with the blocks of electric power-, heat-, gas-, coal supply, and oil refining (fuel oil supply).

Formalized constraints of the above optimization problem are written as a system of linear equations and inequalities:

$$S_н + AX - \sum_{t=1}^{T} Y^t - \sum_{h=1}^{H} S_k^h = 0 \quad (1)$$

$$0 \le X \le D \quad (2)$$

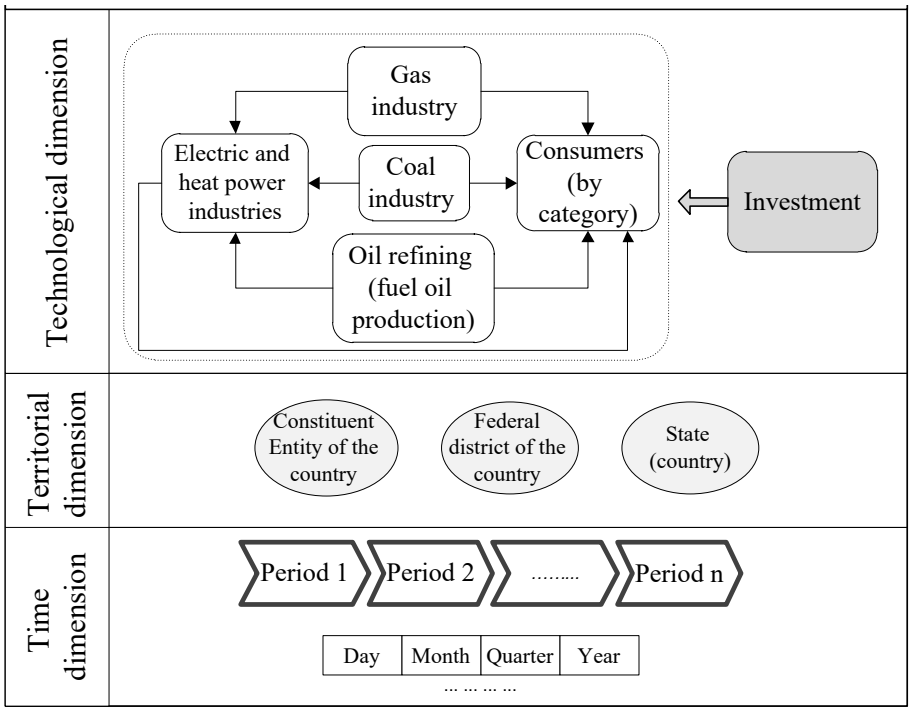

Fig. 3. The structure of the energy sector model.

$$0 \le Y^t \le R \quad (3)$$

$$0 \le S_k^h \le \overline{S^h} \quad (4)$$

$$\sum_{h=1}^{H} \overline{S}^h \le S \quad (5)$$

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^h_k is the desired vector characterizing the volumes of fuel reserves of a considered category (h) at the end of the studied period; $S_н$ 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 has the following form:

$$(C,x)+\sum_{t=1}^{T}(r^t,g^t)+\sum_{h=1}^{H}(q^h,\overline{S}^h-S_k^h) \to \min \quad (6)$$

The first component of the objective function reflects the costs associated with the operation of the energy sector industries. Here C is the vector of unit costs for individual methods of operation of existing, reconstructed or modernized, 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 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 transfer capability of energy transmission tie lines;
- rational volumes of 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 [13-16], which make it possible to assess the potential capabilities of gas, oil, and oil product systems, and also the capabilities of the electric power system to satisfy consumers with appropriate energy resources under various operating conditions, including normal and emergency ones. The major principle of the models of the Unified oil and oil product system (UOS) and the Unified Gas Supply System (UGSS) of Russia is shown below in this section. The model of the electric power industry 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 formulation and using the simulation flow models of the corresponding industries. In addition to the production and transport blocks, the models include the blocks of gas, oil and oil 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 oil product system under extreme situations is presented in detail in [13]. The UOS is understood as both the oil system and the oil 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 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 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 [21]. Two dummy nodes are added to the graph simulating the oil and oil product system: O is the total source, S is the total sink. 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:

$$\text{Max } f \quad (7)$$

subject to

$$\sum_{i \in N_j^+} x_{ij} - \sum_{i \in N_j^-} x_{ji} = \begin{cases} -f, \ j = O \\ 0, \ j \neq O, S \\ f, \ j = S \end{cases} \quad (8)$$

$$0 \leq x_{ij} \leq d_{ij}, \text{ for all } (i, j) \quad (9)$$

Here N_j^+ is a subset of arcs entering node j; N_j^- is a subset of arcs outgoing from node j; f is the value of the total flow throughout the network; x_{ij} is a flow in the arc (i, j); d_{ij} are constraints on the flow in the arc (i, j).

The maximum flow problem (7)-(9) 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:

$$\sum_{(i,j)} C_{ij} x_{ij} \to \min \quad (10)$$

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 oil products. The specificity of the UOS study is that it is necessary to find out the production capabilities of the system on three interrelated graphs (oil, light oil products, and fuel oil). This requires two stages of the research. Stage 1 suggests 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 arcs and production capabilities of sources (fields) and consumers (refineries, export points). Stage 2 is aimed at solving a similar problem in the oil product system (sources are refineries and oil product import points; consumers are federal subjects of the Russian Federation, large industrial centers and points of export).

The comprehensive approach to solving the stated problems along the entire UOS process flow from oil production to oil 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 industry.

The model for assessing the production capabilities of the UGSS under various kinds of disturbances [14] is considered as a combination of three subsystems: gas sources, main transmission network, and consumers. The listed facilities also include underground gas storages (UGS), which, depending on the situation, 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 heating period), gas is withdrawn from 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 tool is used in a network formulation. 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 gas shortage at the consumption nodes.

The calculation results obtained using the industry-specific models serve as input data for the energy sector models whose output can be used to comprehensively assess the possibilities for the industries and energy sector to cope with the considered situation and serve as the basis for the formulation of the energy security requirements. Experimental calculations using a two-level system of models were mainly carried out to assess the consequences of the emergencies in the industry-specific energy systems and to identify directions for energy development from the perspective of energy security. An example of such research can be an analysis of the situation with the disconnection of a major intersection of gas pipelines in the north of the Urals Federal District. 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 the industry-specific energy systems, gas shortages throughout the country in this situation 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 in the amount of 3% of the total quarterly demand for them.

VI. Models of electric power system operation to determine power and electricity shortage in case of the energy security threat occurrence

The energy security factor is extremely important to make control decisions in the electric power industry. It is, however, 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 applied, the time of its application and, most importantly, on 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 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, load flow calculations, etc. As already noted, one of the critical infrastructures that impacts on energy security is the electric power system. Given the specificity of the electric power system operation, which consists in simultaneous production, transmission, distribution, and consumption of electric energy and power, the occurrence of threats to energy supply has an instant effect on electricity consumers.

The spatial and temporal decomposition of the problems of the energy security research dictates the conditions for hierarchical construction of the models. The general trend in the construction of the electric power system models corresponds to the following principles: the closer the horizon of consideration of the power system operation to the present date, the more detailed presentation of the model is required; 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:

4. Form a set of input data. The input data in the general case may include the topology of the design scheme of electric power system; values of available generation capacities; values of transfer capabilities of power lines included in the inter-zone tie lines; 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 sufficiently accurately reflect the actual operating conditions of the power system, given planned maintenance of equipment as well).
5. Build a scenario for the case of a disturbance.
6. Model operating conditions of an electric power system. In this case, each condition characterizes the operation of the electric power system for one hour.
7. Determine electricity and power shortages due to the disturbance.

The model [22] can be used to model the electric power system operating conditions for the energy security study. At the same time, it is necessary to minimize the power shortage arising in the electric power system due to the energy security threat occurrence:

$$\sum_{i=1}^{I}(\bar{y}_i - y_i) \rightarrow min, \tag{11}$$

Given the balance constraints

$$x_i - y_i + \sum_{j=1}^{J}(1 - a_{ij}z_{ji})z_{ji} - \sum_{j=1}^{J} z_{ij} = 0, i - 1, \dots, I, j = 1, \dots, J, i \neq j, \tag{12}$$

and linear inequality constraints on variables

$$0 \leq y_i \leq \bar{y}_i, i = 1, \dots, I, \tag{13}$$

$$0 \leq x_i \leq \bar{x}_i, i = 1, \dots, I, \tag{14}$$

$$z_{ij} \leq \bar{z}_{ij}, z_{ji} \leq \bar{z}_{ji}, i = 1, \dots, I, j = 1, \dots, J, \tag{15}$$

$$y_i \geq 0, x_i \geq 0, z_{ij} \geq 0, z_{ji} \geq 0, i = 1, \dots, I, j = 1, \dots, J, i \neq j \tag{16}$$

where: $\bar{y}_i$ is the value of load maximum at a node of electric power system, MW (depending on electric power system aggregation, a node can be represented by the buses of the

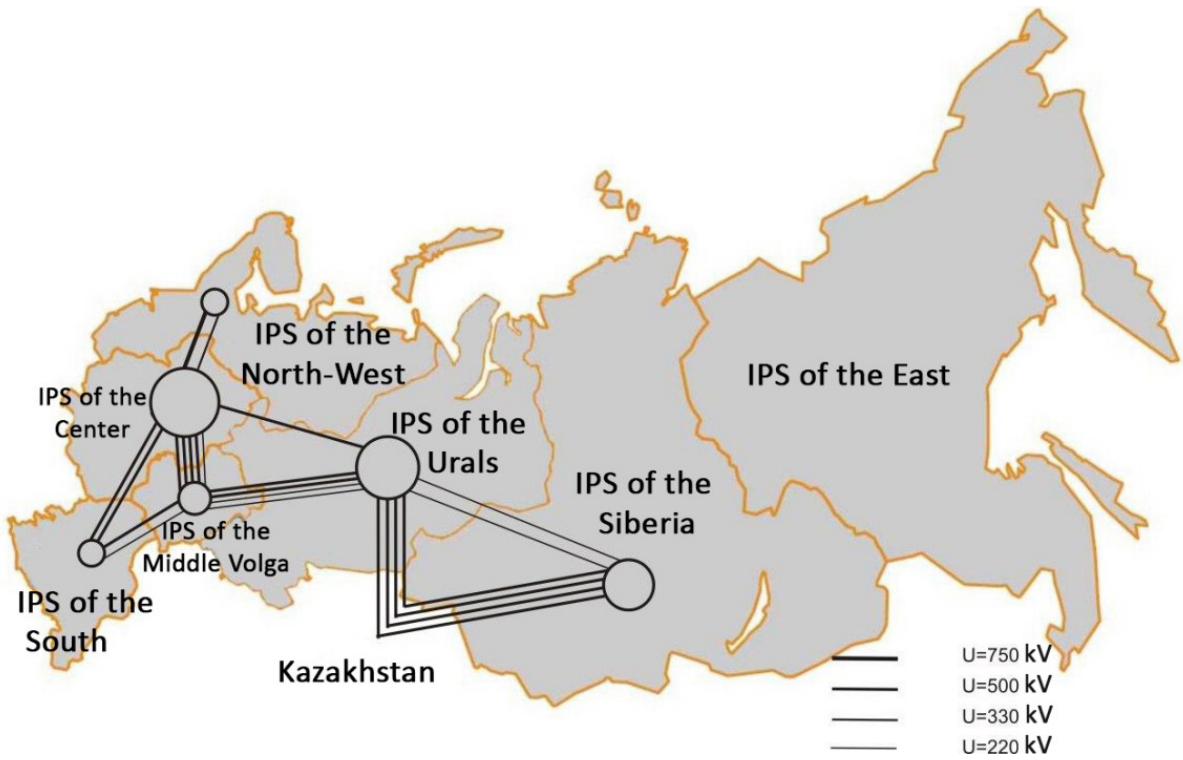

Fig. 4. Representation of Russia's unified power system for long-term energy security study.

substation and electric power plant or an area, including 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 transfer capability of tie-line between nodes i and j, MW; $\overline{z}_{ij}$ is transfer capability of tie-line between nodes j *and* i, MW; z_{ij} is power flow from node i to node j, MW; z_{ij} 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 made up only for active power, but the statement of this problem with quadratic power transmission losses is a fairly accurate approximation to the balance of active and reactive powers [23].

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 example, to develop an energy strategy, a national power system (e.g. the unified power system of Russia) can be aggregated according to the interconnected power systems (Fig. 4).

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 the representation of the unified power system of Russia where the zone can be represented by the constituent entity of the Russian Federation. Figure 5 shows such a model.

The electric power systems can be divided into zones according to other criteria, for example, the system operator of electric power system controls the cutsets that limit power transmission within the UES of Russia. Thus, the partition can be done according to these controlled cutsets, 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 can shift. As to the regional aspect of the EPS modeling for the energy security study, the regional energy system model can be based on the full topology of the power system, the zones can be represented by load substations and power plants, and internal power lines can act as inter-zone tie lines. Depending on the structure of the electric power system and the specific features of its operation, the level of its stability also changes. Some disturbances in different power systems can lead to a cascading development of the emergency. In model (11) – (16), this situation is not considered. In this case, the occurrence of this threat and its consequences should be factored in by the models aimed at assessing the dynamic stability of the electric power system and the development of cascading failures.

VII. Conclusion

The system of mathematical models employed in the study into the 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 today is considered in terms of two main aspects:

- spatial – from regions and aggregated centers of energy consumption to federal entities at the level of districts, countries, their unions and regions of the world;
- structural – covering the whole structure of the energy economy: from industry-specific energy facilities, included in the unified production and functional complex, and the links between them to large-scale (federal and interstate) technologically connected

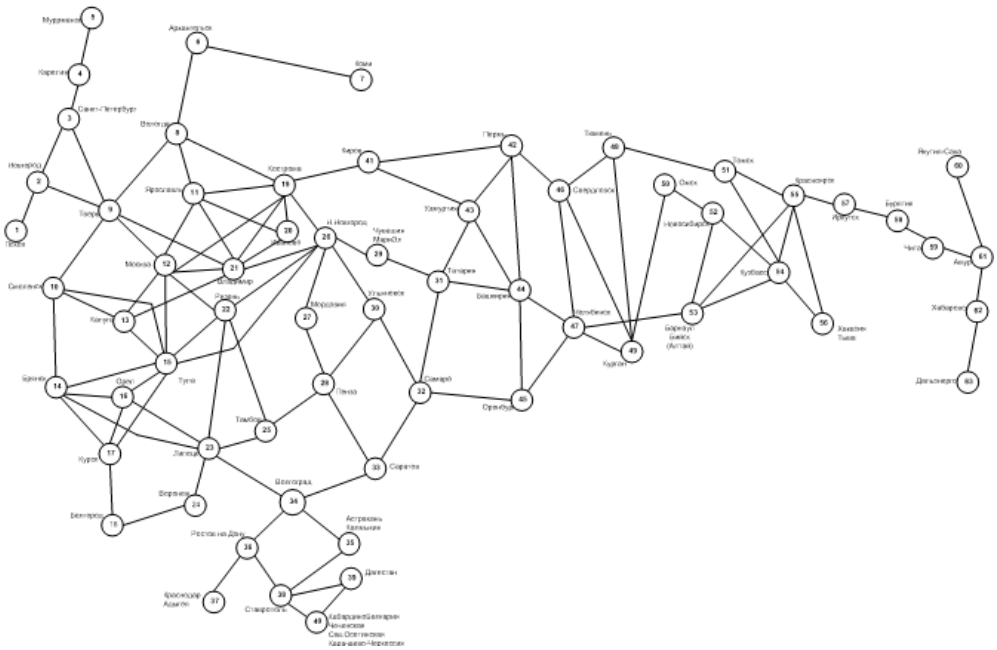

Fig. 5. Representation of Russia's unified power system for the medium- and short-term planning horizon in the energy security study.

energy systems and further to unified energy sectors of countries and regions of the world, in which industry-specific energy systems are interconnected.

This paper demonstrates the principles of hierarchical modeling on the example of the main technologically connected large-scale energy systems including a unified oil and oil product supply system; a unified gas supply system; and a unified power system of the country. The findings indicate that individual regional energy systems can also be studied in terms of the energy security of corresponding regions using the principles of hierarchical modeling, both in spatial and structural dimensions.

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Intelligent Technologies and Tools to Support Hierarchical Research for Justification of Strategic Decisions on Energy Development

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***Abstract* — The paper is concerned with a general scheme of hierarchical studies aimed at substantiating the energy development. It also considers an approach to integrating the software, information support and intelligent information technologies required for research. The concept of knowledge management is proposed for the semantic integration of data, knowledge and software components. It can also be used as a methodological, fractal approach to knowledge structuring. In addition to a two-level research technology, which integrates semantic and mathematical modeling, and intelligent IT-environment supporting them, including semantic modeling tools and the ability to integrate with traditional software systems, we consider the concepts and content of semantic modeling.**

The architecture of a multi-agent intelligent environment (MAIE) is proposed as the development of the IT-environment. It integrates the levels of information analysis (semantic modeling), development and substantiation of decisions (using mathematical modeling), and representation of the proposed decisions. We demonstrate the proposed methodological multi-agent approach to MAIE development; the main components (agents) of MAIE and their scientific prototypes developed under the guidance of the authors are defined.

***Index Terms* — Hierarchical studies of the energy sector, intelligent information technologies, mathematical and semantic modeling, knowledge management, fractal stratified model, intelligent IT-environment, multi-agent systems.**

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http://dx.doi.org/10.25729/esr.2019.04.0006
Received June 13, 2019. Revised August 31, 2019
Accepted Otober 03, 2019. Available online January 25, 2020.

I. Introduction

The spread of the concepts of Smart Grid [1-2] and Digital Energy [3-5] in Russia generates the need to take into account the fact that their adoption distinguishes two 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. Melentiev Energy Systems Institute of SB RAS (MESI SB RAS) has traditionally 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, which are developed by the team under the guidance of the authors and used to create intelligent systems to support the strategic decision-making in the energy sector. An approach to the construction of such an intelligent system (multi-agent tool environment) is proposed. It integrates mathematical and semantic methods and models, and software tools for their support developed at the MESI SB RAS.

II. Hierarchical systems studies of the energy sector

The MESI SB RAS is one of the leaders in the field of systems research in the energy sector of Russia [6]. The main scientific areas of the Institute include the theory of the creation of energy systems, complexes and plants, and their control; scientific foundations and mechanisms for implementing the energy policy of Russia and its regions. The studies within the framework of these areas focus on the energy systems (electricity, gas, oil, oil products, heat), Russia's energy security; regional energy issues; the interactions between energy and economy; promising

energy sources and systems; and studies in the applied mathematics and computer science [6].

Until recently, the main tool for the studies has been mathematical modeling and computational experiment. In the context of the new development trends in the Russian 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 think 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 first area in more detail. A major role in making the strategic decision- should be played by their scientific justification, which can employ the scientific achievements of the institute.

Traditionally, the MESI SB RAS uses a hierarchical research scheme, in which economic and mathematical models are used at the aggregated level of researches of the energy sector and industry-specific energy systems, whereas physical and mathematical models are used at the next levels (Fig. 1). These models must be coordinated. Research on projecting energy development is carried out at the top level, based on the results obtained in the studies on the development of industrial energy systems at the following 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 [7].

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

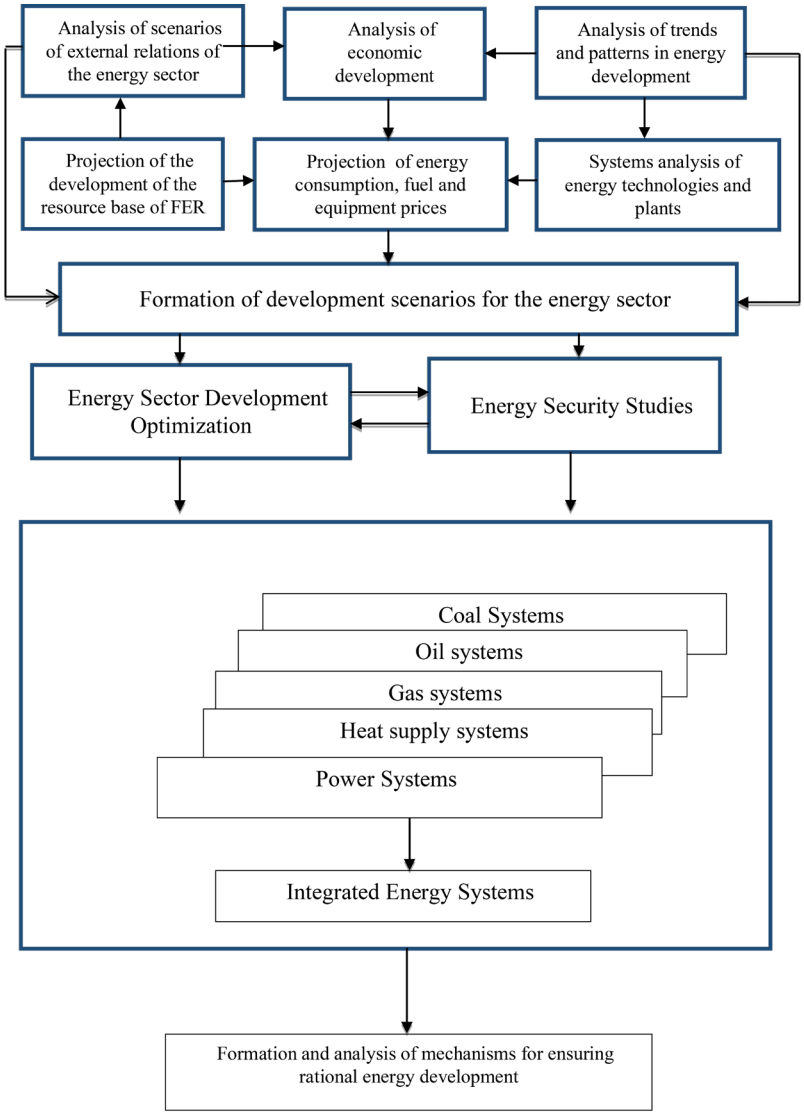

Fig. 1. A general scheme of hierarchical studies to substantiate the development of the energy sector

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.

III. The proposed approach to solving the integration problem 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 situational management and semantic modeling.

The 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 [8].

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 [9].

The main idea of the fractal approach is that the concepts of information space and information worlds (subspaces) are introduced. 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 introduced from any stratum to each. 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 the selected disciplines when we study the real world. The application of the FS-model is illustrated in Fig. 4.

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) [10].

In the framework of the latter approach, 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. are used. 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 the energy sector development. Below we consider the concepts and content of semantic modeling.

Table 1. Comparison of ontological, cognitive, event and probabilistic modelling

Technology	Purpose of Use	Formalization apparatus	Use in energy security (ES) research
Ontology modeling	To describe declarative pieces of knowledge	Ontologies (Special languages (OWL, RDF, XML, etc.))	For identification, classification, and specification of basic concepts in energy research
Cognitive modeling	To identify causal relationships of concepts	Cognitive maps (graph theory)	For analysis of energy security threats
Event modeling	To build behavioral models. Identification of the development dynamics of emergency	Event Maps (Joiner Networks Theory)	For analysis of the development and consequences of emergencies
Probabilistic modeling	To construct probabilistic models. Assess the risk of ES threat occurrence	Bayesian Trust Network	For assessment of risks of emergencies

A semantic model in a generalized form is an information model that reflects the concepts of the subject area and the relationship between them. The authors consider semantic modeling on the example of ontological, cognitive, event and probabilistic (based on Bayesian trust networks) models [11, 12]. Table 1 shows a comparison of semantic modeling technologies applied for energy security research.

Ontological modeling is the construction of ontologies, in both a graphical form and a formalized form. Ontologies are defined as a knowledge base of a special kind, or as a «specification of a conceptualization» of a subject domain [13]. The latter means the classification of the basic terms of the subject area with the definition of basic concepts (concepts) and the establishment of relations between them. In turn, the specification process consists in describing the ontology in a graphical form ("light" or heuristic ontologies) or in one of the formal languages (XML, RDFS, OWL, etc.) ("heavy", or logical ontologies). To work with experts, the team represented by the author uses a graphical representation of ontologies; Ontologies are stored using their representation in XML.

Cognitive modeling is the construction of cognitive models, or, in other words, cognitive maps (oriented graphs), in which the vertices correspond to factors (concepts) and the arcs correspond to the connections between factors (positive or negative), depending on the nature of the causal relationship. In the simplest case, the weights of the connections can have the values +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 [14].

Event modeling is the construction of behavioral models, and both people and technical objects can act as modeling objects. The essence of the event modeling method is to track the sequence of events on 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 reaction to the occurrence of an initiating 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 [15].

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 have combined the results of the studies carried out mainly in the 1980s. The results of the authors applying this approach in the energy sector using Bayesian trust networks are considered, for example, in [16].

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

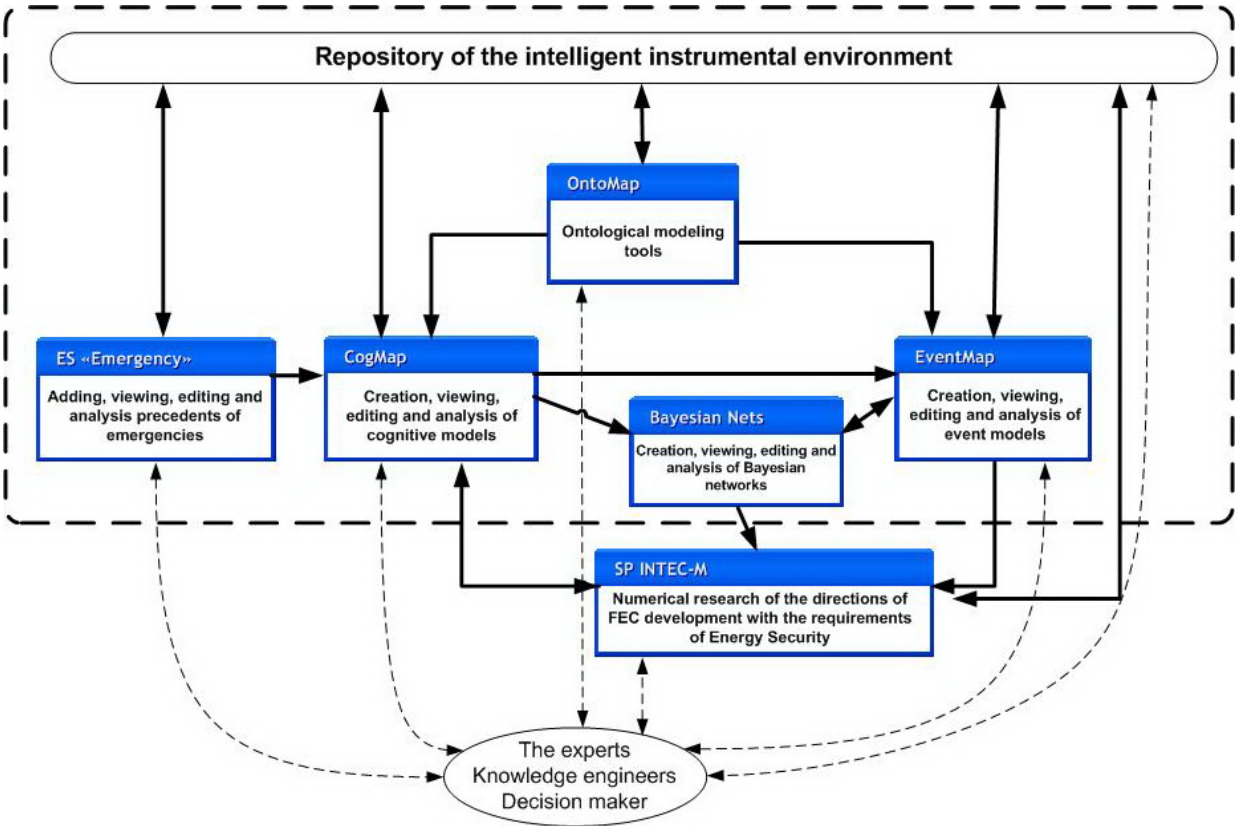

Fig. 2. Tools interaction in intelligent IT-environment

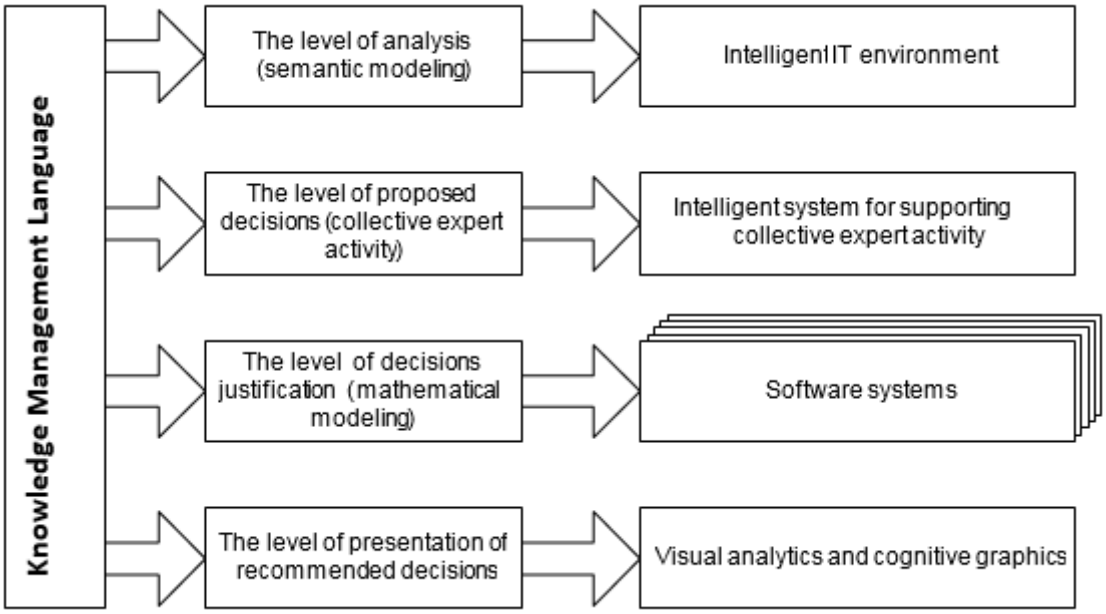

Fig. 3. Levels (stages) of energy systems research and tools supporting them.

display causal relationships can be used to describe and analyze scenarios of external relations of the fuel and energy complex, 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 variants using semantic models, traditional software systems that implement mathematical models of industry-specific energy systems and the energy sector are used and optimization problems are solved to justify the recommended solutions.

In our study, the situational management concept is used following the works by D.A. Pospelov and his students [17]. Recently, some researchers have proposed using this concept for operational control but we believe it can be applied in the field of substantiation of strategic decisions. We use a modern interpretation of situational management, considered in [18]. The situational management concept is used to justify and support decision-making to ensure energy security. This is considered, in particular, in [19].

The integration of mathematical and semantic modeling tools is proposed to justify strategic decisions in the energy sector [20]. In this case, both basic technologies are used: agent-oriented and cloud computing, and 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 provides the ability to integrate with traditional software systems (Fig.2) [12].

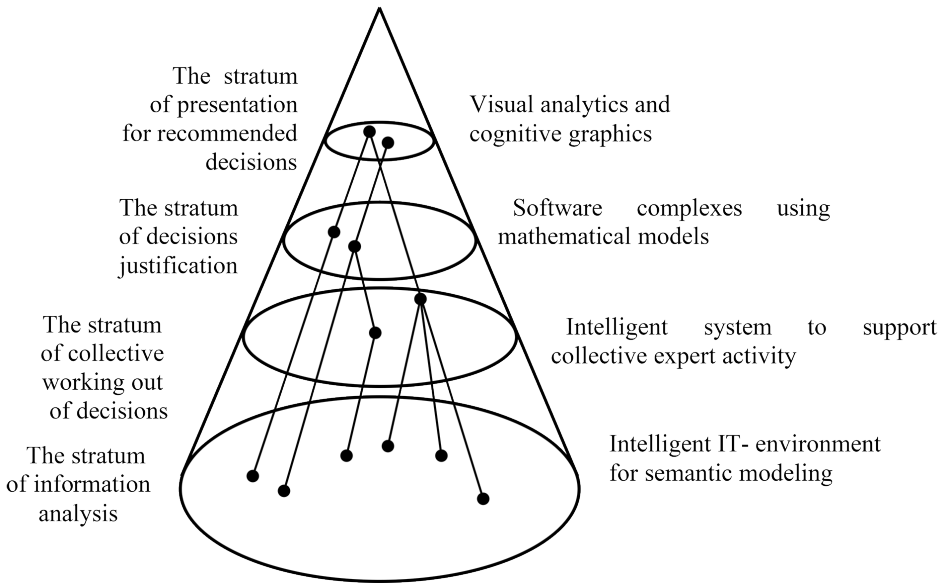

Fig. 4. FS-model of strata (stages) of research (left) and tools supporting them (right).

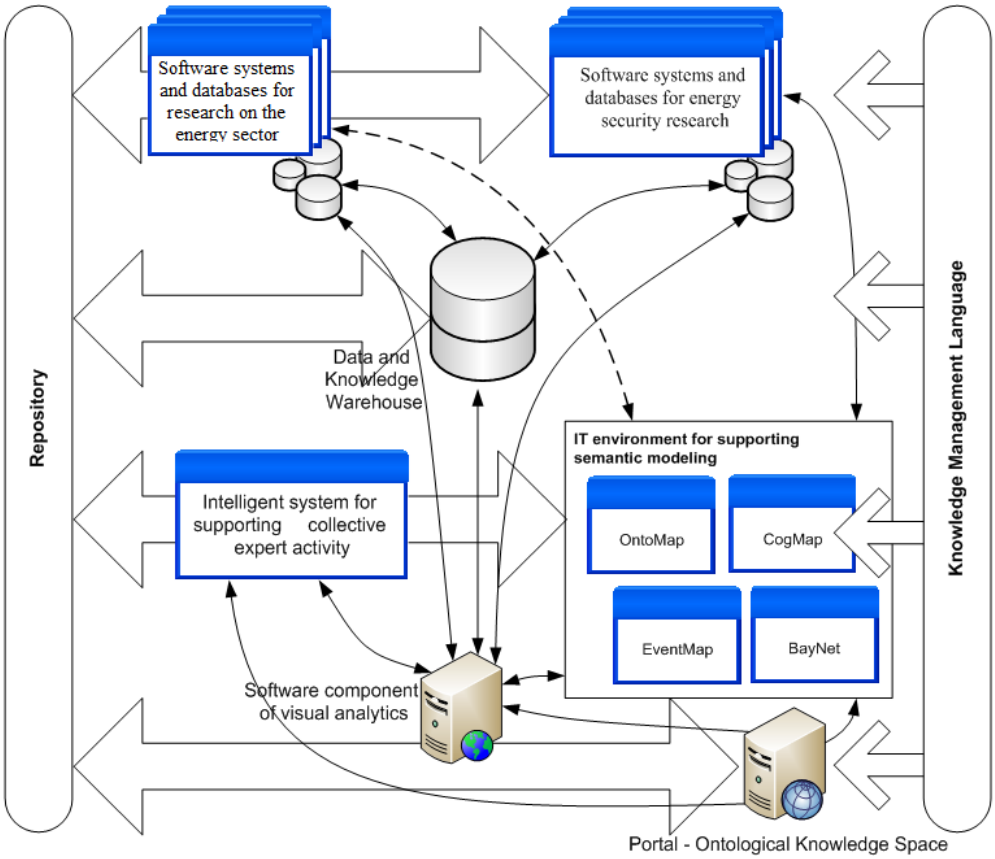

Fig. 5. The architecture of the multi-agent intelligent environment (MAIE).

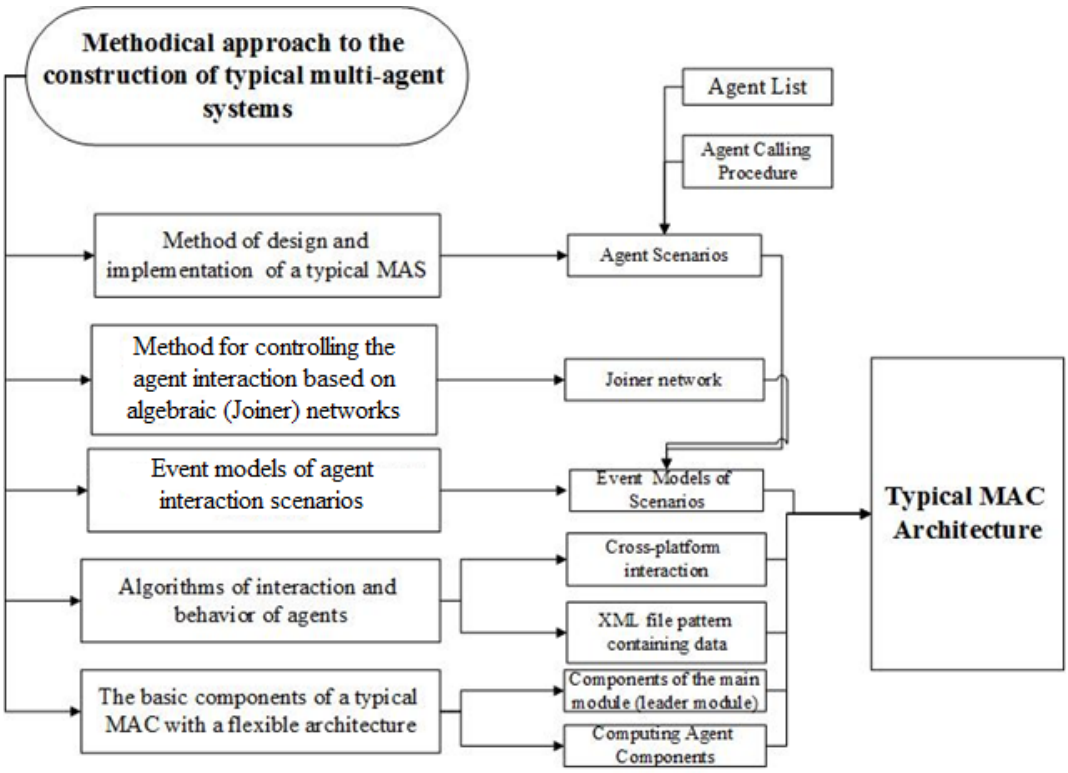

Fig. 6. Methodical approach to the construction of multi-agent systems.

Tools supporting the upper quality 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 expert system Emergency contains precedents for extreme situations in the energy sector, which can be used in the construction of semantic models. The Geocomponent is a 3D-geovisualization tool. The block bottom left shows the multi-agent software system INTEC-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 considered as a prototype Multi-Agent Intelligent Environment (MAIE) to support hierarchical research, a diagram of which is shown in Fig. 1. The following research levels (stages) and the supporting tools are identified for this scheme (Fig. 3). Their stratification using the FS model is illustrated in Fig. 4.

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 others) supported by the Intelligent Support System for Collective Expert Activity [20].
3. The level of substantiation of decisions (the options proposed at the previous stage are calculated using traditional software systems for research on 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 [21] (Fig. 5).

The main components (agents) of MAIE are:

1. Software Systems and Databases for research of the energy sector together with Software and Databases, for example, for energy security research;
2. Data and Knowledge Warehouse;
3. Intelligent IT-environment for supporting semantic modeling;
4. An intelligent system for supporting collective expert activity;
5. Software component for visual analytics (GEO-visualization component);
6. Repository for storage of descriptions of all intelligent and information resources supported by MAIE.
7. Knowledge Management Language (KML) to ensure the interconnection and interaction of all components (agents) of MAIE.
8. Portal supporting Ontological Knowledge Space in the field of energy.

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

We have developed a methodological approach to the construction of multi-agent systems and propose it to implement MAIE (Fig. 6). Its novelty is determined by 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 [23].

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

Full inclusion of the software and databases for research on the energy sector and energy systems as agents in the MAIE (p. 1 of the previous list) will require their reengineering since most of them have moved into the category of legacy software. At the first stage, we can limit the inclusion of software and database on the level of information exchange. In this case, the studies are carried out autonomously, their results are transferred to the Data and Knowledge Warehouse, and the fact of 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 cyber vulnerabilities and reflect the current state of cybersecurity tools (preventing cyber attacks); we also have results in this area [24].

IV. Conclusion

The study emphasizes that the concept of digital energy does not pay attention to such issues as intelligent support for strategic decisions on the development of the technological infrastructure of the energy sector, and cybersecurity of critical energy facilities. We propose eliminating these shortcomings by using the results of the hierarchical studies conducted at the MESI SB RAS, which integrate the existing results in mathematical and semantic modeling; situational management; agent, cloud, and intelligent computing. We present the approach to integrating software, information support and intelligent information technologies required for research. The architecture of a multi-agent intelligent environment integrating heterogeneous components is proposed, and the state of the development is considered.

Acknowledgment

The results were obtained as part of the implementation of the MESI SB RAS project no. AAAA-A17-117030310444-2, some aspects were studied as part of projects supported by grants from the Russian Foundation for Basic Research No. 19-07-00351, No. 19-57-04003 and No. 18-07-00714.

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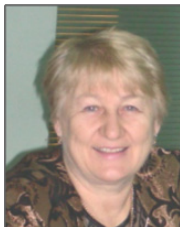

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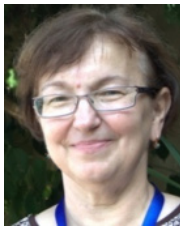

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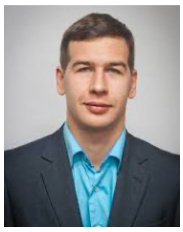

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Multilevel Modeling of Pipeline Energy Systems for Solving their Analysis and Design Problems

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***Abstract* — The complexity and scale of pipeline energy systems (PES) necessitate the use of multilevel (in terms of structure, problems, and methods) modeling for their analysis, calculation, and optimization, which are based on the theory of hydraulic circuits (THC). This theory was originally proposed at the Melentiev Energy Systems Institute, SB RAS, and since then has been undergoing further development. The use of methodological approaches to multilevel modeling described in this paper allows switching from large systems to hierarchically connected systems of lower dimensionality, that is from complex problems to simpler ones. The use of these approaches for PES analysis and development is illustrated with specific examples. The paper provides the findings of our studies on the municipal heat supply system.**

***Index Terms* — pipeline systems, analysis, design, multilevel modeling, decomposition, hierarchy, model, optimization, software package.**

I. Introduction

Modern pipeline energy systems (heat supply, water supply, oil supply, gas supply, etc.) are engineering structures that are unique with respect to their scale and complexity and that are of increasing importance for the energy, economy, industry, public utilities sector, and other spheres of life of the country and society. Solving the problems of their design, reconstruction, operation, and dispatching efficiently is impossible without relying on the appropriate methodological backbone. The theoretical basis for solving problems of design and control over operation of pipeline systems of various types and serving various purposes is the theory of hydraulic circuits (THC) originally proposed at the Melentiev Energy Systems Institute, SB RAS, and successfully undergoing further development there. This theory is the basis for modeling, calculation, evaluation, and optimization of pipeline and hydraulic systems of various types [1]. Within the framework of the THC, the problem of optimal PES design is defined so as to cover a wide range of problems and consists in finding the optimal direction for changing the structure and parameters of systems, identification and elimination of «bottlenecks», replacement of outdated technologies and equipment with new energy-efficient solutions, meeting the requirements of reliability of heat supply and controllability of systems while satisfying the physical and technical conditions of their operation and complying with constraints on operating parameters [2]. The specific feature of solving the problem of optimal PES design is that it involves the development of its own algorithm made up of subproblems (structure optimization, parameter optimization, analysis of reliability of the system, hydraulic analysis, etc.) that vary on the case by case basis as applied to the set of considered PESs, given their specific features. As a rule, it is a complex iterative computational process during which subproblems for various PESs can be solved in different orders and by employing different methods depending on the predefined goal. One of the possible algorithms for solving the problem is presented in Figure 1.

The above problems are solved for the PESs of the real-life size and complexity which is due to their multi-ring structure, availability of multiple control elements (pumping and throttle stations, regulators), and a large number of pipelines. As a result, the calculation of such PESs proves unfeasible within a reasonable amount of time. The means of overcoming the above mentioned difficulties is the application of approaches based on decomposition into simpler subproblems of PES calculation schemes or the problems that are to be solved. Decomposition is a part

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http://dx.doi.org/10.25729/esr.2019.04.0007
Received September 5, 2019. Revised October 18, 2019
Accepted October 30, 2019. Available online January 25, 2020.

of the multilevel modeling methodology, which assumes transition from an initial 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 PESs [3-7]. Abroad, methods based on decomposition of PES calculation models and other energy systems have been widely adopted [8-10]. High dimensionality of PESs and other energy facilities, as well as high complexity of the problems being solved, are successfully overcome by making use of approaches based on aggregation [11-13] and hierarchical modeling [14-16].

II. Fundamental principles of multi-level PES modeling

Mathematical and computer modeling of PES begins with the construction of its model, which describes the configuration of the PES, the composition of its equipment, and the characteristics of the latter, the state of elements and their properties (specifications, hydraulic parameters, and boundary conditions). PESs of different types share structural and topological properties and physical laws that govern the transported medium flow [1], which allows formulating the following general statements characteristic of the methodology of their computer and mathematical modeling:

1. All PESs can be modeled as a graph whose vertices correspond to the nodes (sources, connecting nodes, consumers) while the arcs correspond to the branches (pipelines, active branches with pumping stations, pressure or flow regulators).
2. The problems of mathematical modeling of the PES share their conceptual and mathematical statements, while the methods, algorithms, and dedicated software used to solve them can be universal in their nature (that is, they do not depend on the type of the PES).
3. A computer model of the PES 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 elements.
4. Modern PSs 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 problems by applying multilevel modeling.

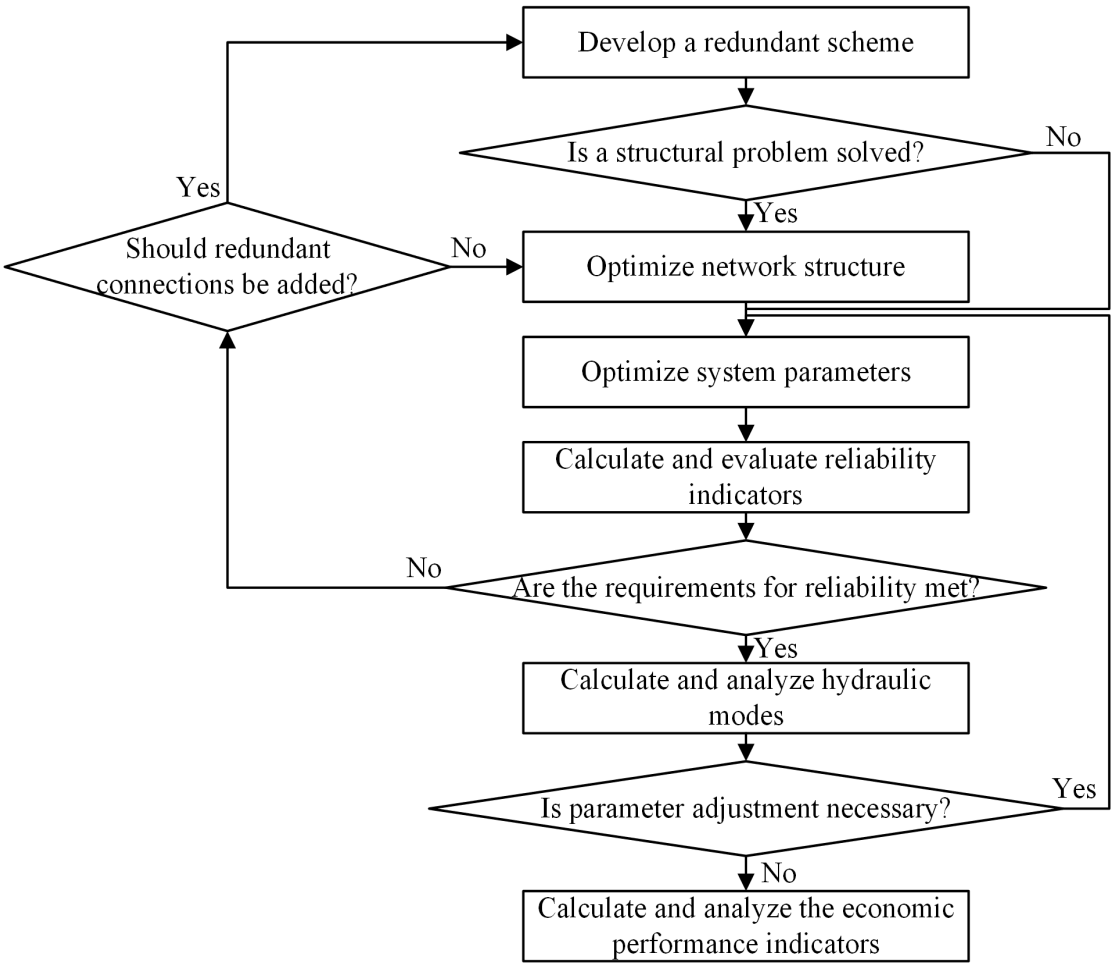

Figure 1. Algorithm for solving the PES design problems

In the case of multilevel modeling the unified model of the PES 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 PSs according to territorial and geographical criteria.
3. The structure of the transport subsystem in the PES:
   - 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 PES:
   - ring subnetworks,
   - tree-shaped branches.

III. Key methodological points of multilevel modeling as illustrated by the case of heat supply systems

A hierarchical model of heat supply systems (HSS) when solving the problems of control over their optimal development and operation with application of multilevel modeling allows treating the following levels individually (Figure 2):

1. HSSs in general;
2. supply and return main lines;
3. ring and tree-shaped parts (dead-end branches) of the supply and return main lines;
4. individual HSS elements (heat sources, consumers, sections, pumping stations, etc.).

The flow distribution model for each level of the HSS hierarchical model, as well as for the system as a whole, is described by the following equations:

$$Ax = G, A \in R^{m\times n},\ G \in R^{m},$$

$$A^{T}P+H = f(s,x)$$

where A - incidence matrix of the calculation scheme; G – vector of nodal outflows and inflows of the transported medium; f – n-dimensional vector-function with elements $f_i(s_i(d_i),x_i) = s_i(d_i)x_i\left|x_i\right|^{\beta-1},\ i \in I,$ capturing the law of pressure drop at network branches, $s_i(d_i)$ - pipeline hydraulic resistance.

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.

To solve system of equations (1)-(2), algorithms based on efficient mathematical methods have been developed [17-18]. Application of methods of multilevel modeling together with these algorithms allows solving problems of real-life dimensionality when studying PSs.

Finding optimal parameters of elements of the HSS is a problem challenging enough to be impossible to solve without hierarchical modeling. The computational procedure for solving this problem is considered to be impossible without applying multilevel modeling and includes the following main stages [19, 20].

1. Multilevel decomposition of the HSS calculation scheme and construction of its hierarchical model.
2. Determination of the optimal parameters of the return main line using an algorithm based on the method of final ratios.
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

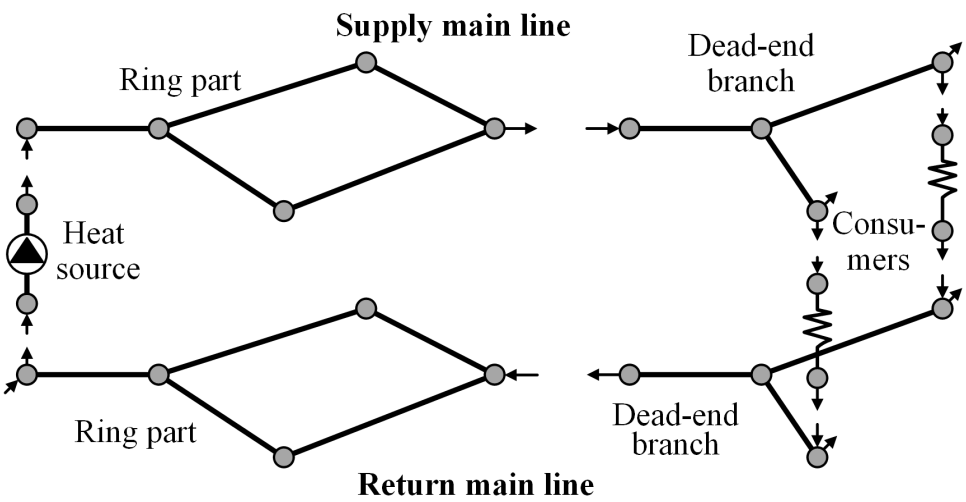

Figure 2. Levels of a hierarchical model of the heat supply system.

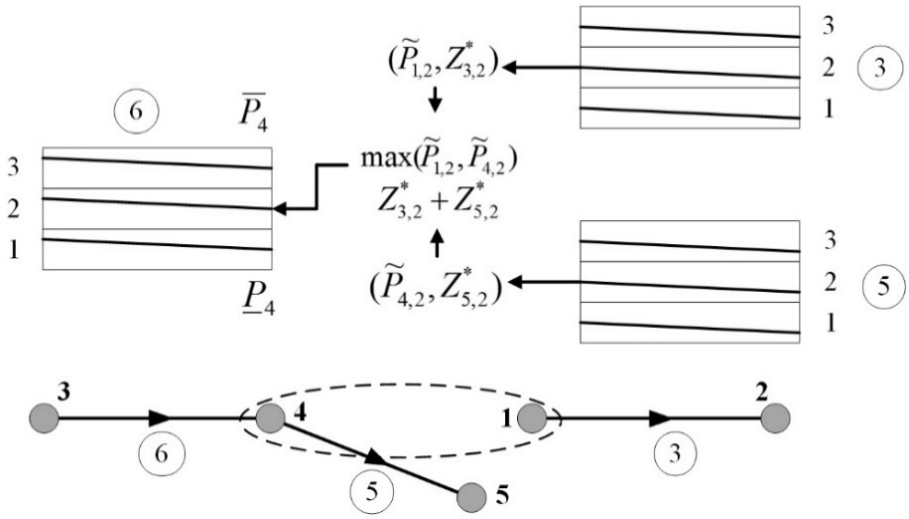

Figure 3. Model for "linking" results between hierarchical levels.

return main line to ensure the necessary heads at the consumers' end.

4. Determination of the optimal parameters of the supply main pipe using an algorithm based on the method of final ratios.
5. Calculation of total costs and capital expenditures for the HSS 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 method of final ratios and with the emphasis on calculation that takes into account hierarchical construction of a model of the HSS. This algorithm consists of the following steps:

1. Defining set J_L of nodes of the scheme, which have incident areas belonging to both ring 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 determination of suboptimal variants of parameters of all dead-end branches.
4. Transferring pressure and cost values of suboptimal variants obtained at the level of dead-end branches to the level of ring networks for all nodes $j \in J_L$.
5. Performing the «forward pass» of the DP method for determination of suboptimal variants of parametres of the ring part of the HSS, 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 variant 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 ending the computational process are not met, the transition to step 5 is performed.

Suboptimal 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 final ratios method. In doing so, the following principle is used. If the node is the initial node both for the sections of the ring part and for the

Table 1 - Parameters of heat network sections before and after the reconstruction.

Section number as per the scheme	L_i	Before the reconstruction				After the reconstruction			
		h_i	x_i	v_i	d_i	h_i	x_i	v_i	d_i
	m	mm/m	t/h	m/s	mm	mm/m	t/h	m/s	mm
63	12.0	61.9	1461.8	2.0	517	6.1	1473.6	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

sections of dead-end branches, then a «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 node j at step i of the computational process. «Linking» the pressure values is done as per expression

$$P_{jz} = \max_{k \in J^{(i)}} \tilde{P}_{kz}, \quad z = 1, \ldots, \mu.$$

Let $I^{(i)}$ denote a set of all sections coming from node j, the costs of which should be taken into account at step i of the computational process. The costs are summed up as per expression

$$Z^*_{iz} = \sum_{r \in I^{(i)}} Z^*_{rz}, \quad z = 1, \ldots, \mu.$$

Figure 3 presents a fragment of the hierarchical model of a heat network. After calculating section 5, one has to determine the parameters of section 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 parameter determination is performed only for the ring part of the network during the iterative process of the method of final ratios . To this end the solutions of the ring part and the dead-end branches are «linked» according to the principles indicated above.

The proposed algorithms implemented in the SOSNA software package are used to solve real-life problems of optimal HSS reconstruction. The calculations of the HSS of the Tsentralny and Admiralteysky districts of St. Petersburg, the city of Bratsk, and the urban locality of Magistralny. The aggregated scheme of the Bratsk HSS is shown in Figure 4. District heating of this system is provided by four heat sources: GDB (Galachinskaya District Boiler House).2, GDB (Galachinskaya District Boiler House).1, IHPP (Irkutsk Heat Power Plant)-6-2, and IHPP (Irkutsk Heat Power Plant)-6-1. The calculation scheme of the heat network contains 632 sections and 613 nodes.

As a result of performing the calculations, we have identified optimal flow distribution in the system; sections of the network with insufficient throughput capacity where an increase in diameters of pipelines is required; required

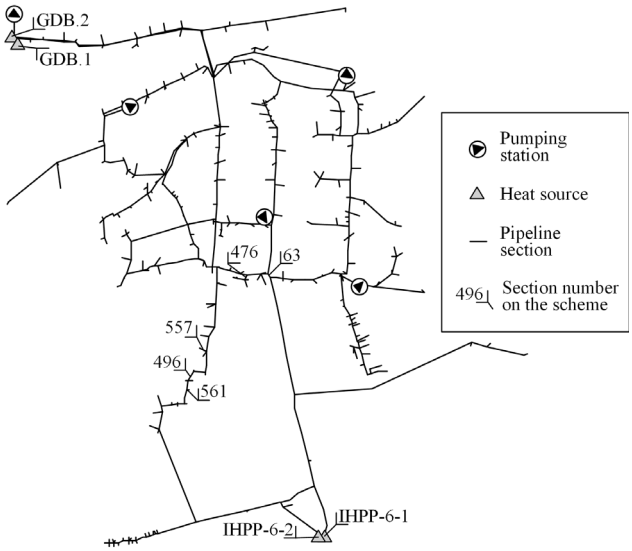

Figure 4. Heat supply scheme of Bratsk.

operating pressure values of pumping stations; rational available heads at the consumers' end, etc. Table 1 shows the parameters of the sections recommended for re-laying (pipeline length values (L_i), specific pressure drop values (h_i), heat transfer medium consumption values (x_i), heat transfer medium velocity values (v_i), pipeline diameters (d_i) before and after reconstruction.

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 obtaining the solution in 1.5 seconds. The SOSNA software package, which had been earlier used at the Melentiev Energy Systems Institute SB RAS for determination of optimal HSS parameters and which does not make u1se of multilevel decomposition of the model arrived at the solution of 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 new versions are given in Table

Table 2. Costs and capital expenditures in the heat network of Bratsk

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

2. It presents the values of the discounted costs of the HSS and the capital expenditures required for the reconstruction of the heat 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 calculation scheme does not lead to compromising the quality of the obtained result.

IV. Conclusion

The existing PESs of the energy industry are engineering facilities that are complex in structure and composition. Solving the problems of their development involves building hierarchical mathematical models, which makes it possible to solve these problems by applying multilevel modeling. The paper lists the aspects according to which hierarchical representation of a unified PES model is carried out. Application of multilevel modeling allows switching from an initial complex problem to a hierarchically connected set of subproblems, each of which has lower dimensionality and complexity compared to the initial problem.

The study provides an example of multilevel modeling of HSS in solving the problem of determining its optimal parameters. The performed calculations attest to the effectiveness of the multilevel modeling for solving practical problems of design of the PES of real-life dimensionality and complexity.

Acknowledgements

The research was carried out under State Assignment, Project 17.4.1 (reg. no. AAAA-A17-117030310432-9) and Project 17.4.3 (reg. no. AAAA-A17-117030310437-4) of the Fundamental Research of Siberian Branch of the Russian Academy of Sciences.

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Modeling the Development Prospects of the Coal Industry of Russia and its Regions

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***Abstract* — The paper is concerned with the approach to modeling the development prospects of the Russian coal industry. A brief overview of the simulation modeling experience is given. A profile of the Russian coal industry and its specific features are given as an object of research. A research workflow is provided. The hierarchy of levels of studying the Russian coal industry and the system of models corresponding to these levels are shown. The system of models is represented by optimization and simulation models corresponding to various hierarchical levels (Russia as a whole, federal districts, federal subjects, and companies). Separate optimization models have been developed to make projections of the development of production, consumption, and supply of steam and coking coal. Consumer costs of coal purchase and transportation are minimized provided that a given demand for coal and other constraints are met. The simulation models are of four types, corresponding to different levels of hierarchy and aspects of consideration. An aggregated diagram of the relationships between the models is studied. We detail the most frequently used types of models that either represent the last option for certain studies or are typical of a given category. To fit each study, either previously developed models were adjusted or new ones were developed. References to the studies carried out using the tools covered in this paper are provided.**

***Index Terms* — Russia, coal industry, modeling, hierarchy, a system of models, research workflow, optimization model, a simulation model.**

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http://dx.doi.org/10.25729/esr.2019.02.0008
Received August 18, 2019. Revised September 11, 2019.
Accepted Novenber 5, 2019. Available online January 25, 2020.

I. Introduction

Modeling the development and operation of the coal industry is presented in the research published in Russia and other countries [1-2 2]. Models were developed to study the prospects for the entire industry, coal-mining regions, and companies. A significant number of publications are concerned with modeling of various aspects and conditions affecting the development of coal mining, i.e. hazardous seismic conditions [5], hydrological conditions [18, 19], coal consumption and coal prices [22], and others.

In their studies of the development prospects for the coal industry, the scholars in Russia and elsewhere most frequently use optimization and simulation models [1, 3, 15, 17], and also logistic, static, and dynamic models [2].

The experience accumulated in Russia in the field of modeling the development of the coal industry spans 70 years [11-17]. The Energy Research Institute (ERI) of the Russian Academy of Sciences has developed a system of simulation models that enables one to identify the most efficient directions of the industry development based on the projected scenarios of the development of the Russian economy [12]. The Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences has investigated and projected the development of the national and regional coal industries as part of the energy sector for over 50 years [2 1]. These studies rely on optimization and simulation models. A research workflow that takes into account the specific features of the Russian coal industry has been developed, and a system of models, software and information support [16,17,23] have been implemented.

The hierarchical approach, also known as the integrated approach, allows considering the coal industry in interaction with other industries of the economy, at the level of individual regions and companies within the model. It is widely used in modeling the development of the coal industry in various countries [1,3,6,7,21]. Multiple links between the coal industry and other industries of the economy and the internal structure of the industry are most comprehensively taken into account in the coal market

module of the U.S. National Energy Modeling System (NEMS) [1]. The Russian government, unfortunately, does not have a tool of this kind.

The conditions for the development of the coal industry vary significantly from country to country. These are social and economic situation; the development of transportation system; the tariff policy for coal transportation; competition with other energy resources (gas, hydropower, etc.); mining and geological, hydrological, and other conditions of coal production. The difference in quality characteristics of coal leads to their use in a variety of fields, the main of which are energy, by-product coke production and, in the long run, the coal chemistry sector. One of the essential features of the Russian coal industry is a large share of the exported coal. In 2018, it accounted for more than 50% of total coal supplies [2 4].

This paper presents an approach to modeling the development of Russia's coal industry and a system of models that take into account the specific features of the coal industry. Both of the above have been developed with the participation of the authors at the Melentiev Energy Systems Institute, SB RAS.

II. Russia's coal industry as an object of study

Modern science views the national coal industry as one of the energy systems that possess certain properties [14, 25]. Such properties of the coal industry as its structural complexity, scale, inertia, dynamism, pro-active nature and limitedness (balance reserves, resources, demand, interchangeability of the product, etc.) predefine the complexity of building the models of the coal industry operation and arranging a computational experiment.

The Russian coal industry, as an object of modeling, is characterized by the following:

- a large number of components, the numerous relationships between which are rather difficult or impossible to define by an analytical function;
- constraints on the resource base, transportation, and other resources, including those related to regional features of coal production and consumption;
- a large number of technical and economic indicators to be factored in;
- a high degree of uncertainty inherent in the projection of economic development scenarios, based on which the demand for coal is calculated, the constraints on the development of the industry are set, and other indicators necessary for research;
- the effect of various factors on the development of the coal industry, which are difficult to consider analytically.

Coal is the marginal fuel, the consumption of which increases or decreases depending on climatic conditions. Coal consumption also depends on whether or not the transportation infrastructure operates or it is constructed

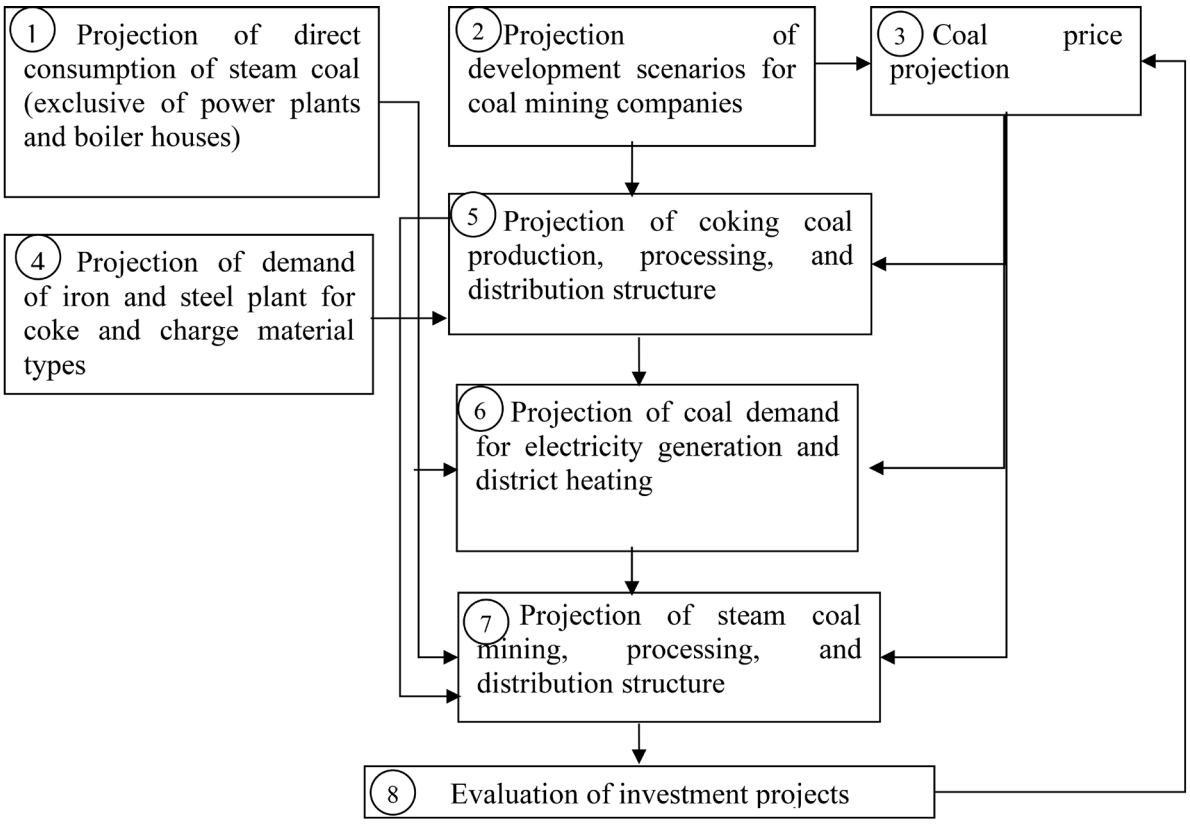

Fig. 1. The workflow of the coal industry development study

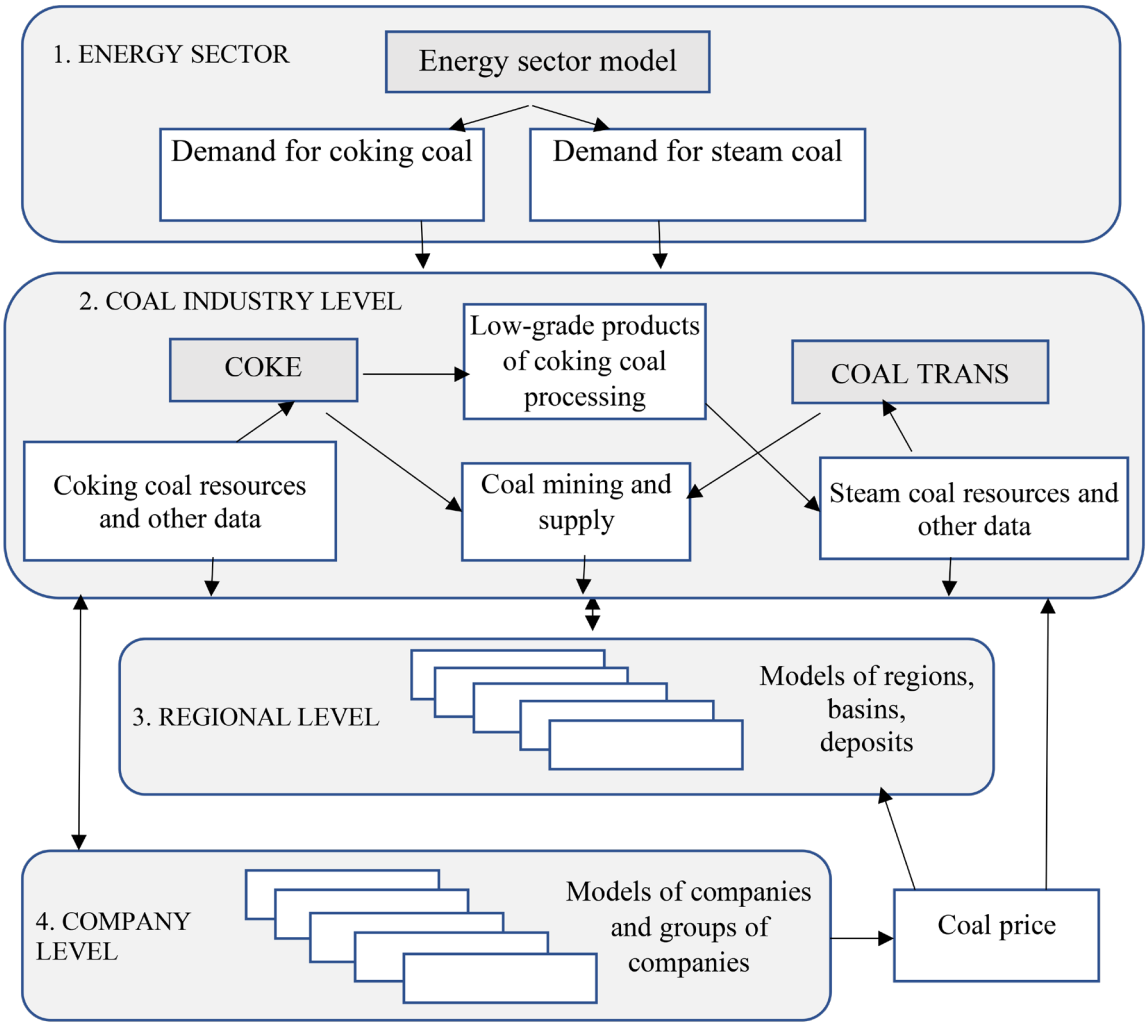

Fig. 2. An aggregated diagram of hierarchical levels and relationships between models in the system of models.

for the implementation of new coal-mining projects. Among the climatic conditions, the most significant effect is due to cold/warm winters and water content of rivers that determine the hydroelectric power plant output in the regions where the hydropower industry is developed.

One of the options to overcome the complexity of the structure, including the existence of multiple links and poorly structured problems in large energy systems, is to construct them using the principle of hierarchy. Hierarchical (multi-stage, multi-step) modeling implies using a hierarchy of mutually complementary models to make a projection of the development and operation of the coal industry.

III. A workflow of the research into the coal industry development in Russia and its regions

Making projections of the coal industry development involves solving the following range of problems:

- assessment of resources and possible volumes of coal production;
- projection of coal demand;
- projection of coal price;
- projection of coal production volumes;
- projections of volumes of inter-regional coal supplies;
- an economic evaluation of investment projects for the development of coal-mining companies.

The above problems are interrelated. The sequence of solving them forms a workflow for studying the development of the coal industry (Fig. 1).

The problems of studying the industry can be described as poorly structured and multi-criteria problems. Poorly structured problems are the problems whose solving process apart from the well- known formalizable procedures also contains components characterized by uncertainty and heterogeneity inherent in them. Formalization of such problems is challenging and they are similar to unstructured ones in terms of the effort to be made by experts. They require human participation to arrive at the most preferable solution. Four levels of the hierarchy have been identified to study the development of the Russian coal industry:

1. the energy sector of Russia;
2. the coal industry of Russia;
3. regions (federal districts and federal subjects);
4. companies (coal-mining and coal-processing companies).

IV. A system of models for researching the coal industry development in Russia and its regions

The system of economic and mathematical models has been developed and used to solve the problems corresponding to different hierarchical levels (Fig. 2):

1. A model of the energy sector development (optimization of the territorial and production structure of the regional energy sector);
2. Models of the development of the coal industry of the country and its regions (optimization of production, inter-regional supplies, and the use of steam coal [COAL TRANS] and coking coal [COKE] by consumers);
3. Simulation models of regions and coal basins;
4. A model of financial and economic analysis of investment projects of coal mining companies and groups of companies.

Mutual alignment of solutions to the above problems can provide an optimal solution to the entire initial problem. Depending on the problem statement, the models can be used jointly or independently. Several problems can be solved using one model.

At the levels of the energy sector and the coal industry, the computational experiment is carried out with the models stated in the form of linear programming problems. The objective function, as a rule, contains financial and economic indicators.

The models used at the levels of individual regions and companies are simulation models.

The energy sector development model is designed to study the dependence of the main parameters of the Russian energy sector development on the level of energy consumption, the extent to which the territories are provided with primary energy resources, etc. for the time horizon of 10-25 years. The energy sector model is used to determine the demand for coal for electric power generation and district heating.

The coal industry development model COAL TRANS is designed to make projections of the structure and volumes of inter-regional supplies of steam coal for the case of changes in prices, transportation tariffs, coal demand and possible constraints on supply volumes. This model quite comprehensively considers the geographical administrative division by distinguishing between over 80 coal consumers in the corresponding federal subjects (territories, regions, and republics) and over 30 suppliers of brown coal and hard coal, and the established supply chain.

The model is built as a linear programming problem. Consumer costs for the purchase and transportation of coal are minimized for a given coal demand by individual federal subjects and available coal resources. The quality of coal is factored in through the heating value and the demand for mandatory supplies. The coal-fired power plants in Russia were designed for a certain quality of fuel or coal from certain deposits, which affects the supply chain. The consumer price is calculated given the current tariff policy for coal transportation, the distance from the site of production to the consumer, and other parameters.

To analyze the development prospects of the coal industry, the results of calculations obtained for the federal subjects and individual companies are aggregated by federal districts, areas of use, mining methods, etc.

The COKE model of the development of coking coal production and consumption is similar to the COAL TRANS model.

The COKE and COAL TRANS models are designed to project the structure and volumes of inter-regional coal supplies for the case of price changes. These models have a similar structure but differ in some parameters. The need to develop individual models is primarily due to significant differences in the calculation of the demand for coking and steam coal, the units of measurement, and the supply chain. In the COKE model, coal is delivered to by-product coke plants, while in the COAL TRANS model the destination is federal subjects. The demand for coking coal at by-product coke plants depends on the composition of coal charge as per coal grades. The coal charge at the Russian by-product coke plants can contain both domestic and imported coking coal grades. The model takes into account the specific features of coking coal mining and processing. For process reasons, mines and open-pit mines can produce several grades of coking coal and run-of-mine steam coal. In the process of coking coal preparation, coke concentrate and low-grade processed products are produced, which are suitable for use only as an energy fuel (Fig. 2). Steam coal resources are formed from steam coal resources proper and coal resources derived from coking coal processing at coal-preparation plants and accompanying steam coal production during coking coal mining. A significant amount of coal mined in Russia is exported [23]. The models allow determining coal resources available for export. The most exported product is coal concentrate. The constraint on resources for coal export is a lack of demand for low-grade products of coal processing in the energy industry.

When modeling the development of the coal industry, it is difficult to take into account the entire set of factors affecting the development of the properties of facilities and links to consumers, including transportation. Optimization models provide projections that need further refinements. Simulation models are the most suitable for refining the solutions. The final solution is obtained with the direct participation of an expert, which allows considering most features of the operation and development of coal production, processing, and consumption.

The specifics of scientific research are such that practically for each of the above processes respective simulation models had to be developed based on the previously developed ones. Lack of opportunity to create tools for simulation models with fixed input and output is due to significant differences (uniqueness) in coal industry facilities; uncertainty inherent in the available source data; the unpredictability of the volume and algorithm of provisional calculations of performance indicators.

Table 1. Characteristics of simulation models.

Model	Level of detail	Coal market participants	Result
INVEST COAL 1) Direct problem 2) Inverse problem	Enterprise or company	Technical and economic performance indicators of the project	1) Efficiency indicators 2) Coal price or other indicators
BALANCES	**Coals**, FD	Groups of companies*	Projection of demanded coal production and delivery in the country and FD
REGIONAL BALANCES	**Coals**, FSs, coal-mining companies, deliveries, exports	Consumers: FDs, export	Projection of demanded coal production, schemes and volumes of coal supply, and coal balances for FSs and FDs
FEDERAL SUBJECT	Companies, coal-preparation plants, marketable products, FD areas	Coal-mining companies	Projection of demanded coal production and processing in FSs, coal deliveries to RF regions, and coal balances in FSs

Four types of simulation models have been implemented, each corresponding to different hierarchical levels and aspects of consideration (Table 1).

The INVEST COAL model is designed to evaluate the economic performance of the operation and development of a company or a group of companies. This model can also be used to solve the inverse problem, i.e. the determination of the coal price or other indicators for a given performance indicator. The model calculates the pre-tax profit; net profit; product profitability and cash flow; and proceeds from the sale of products. Coal production costs include electricity, heat, materials, and labor costs; depreciation; taxes; industrial services; loan interest, and other costs. The indicators that serve as criteria include current account status; discounted current account; net present value; profitability index; product profitability; internal rate of return, and payback period. To improve the reliability of the estimates obtained, a stability analysis is performed, which is a calculation of the dependence of the summarizing financial and economic indicators on certain changes in the initial parameters of the project.

The simulation models “BALANCES”, “REGIONAL BALANCES” and “FEDERAL SUBJECT” differ in their level of detail and some other aspects, without significant differences in their structure. They contain three functional modules: "Production", "Consumption", and "Coal Balances"(Fig.3). Models of the same type created for specific studies differ depending on the composition of the information available and the objectives of the study. Depending on the level of detail, the market participants are types of coal, coal mining and coal processing companies, and regions. Supply volumes and transportation costs represent links between market participants. Coal supply and consumption are projected given the established trends

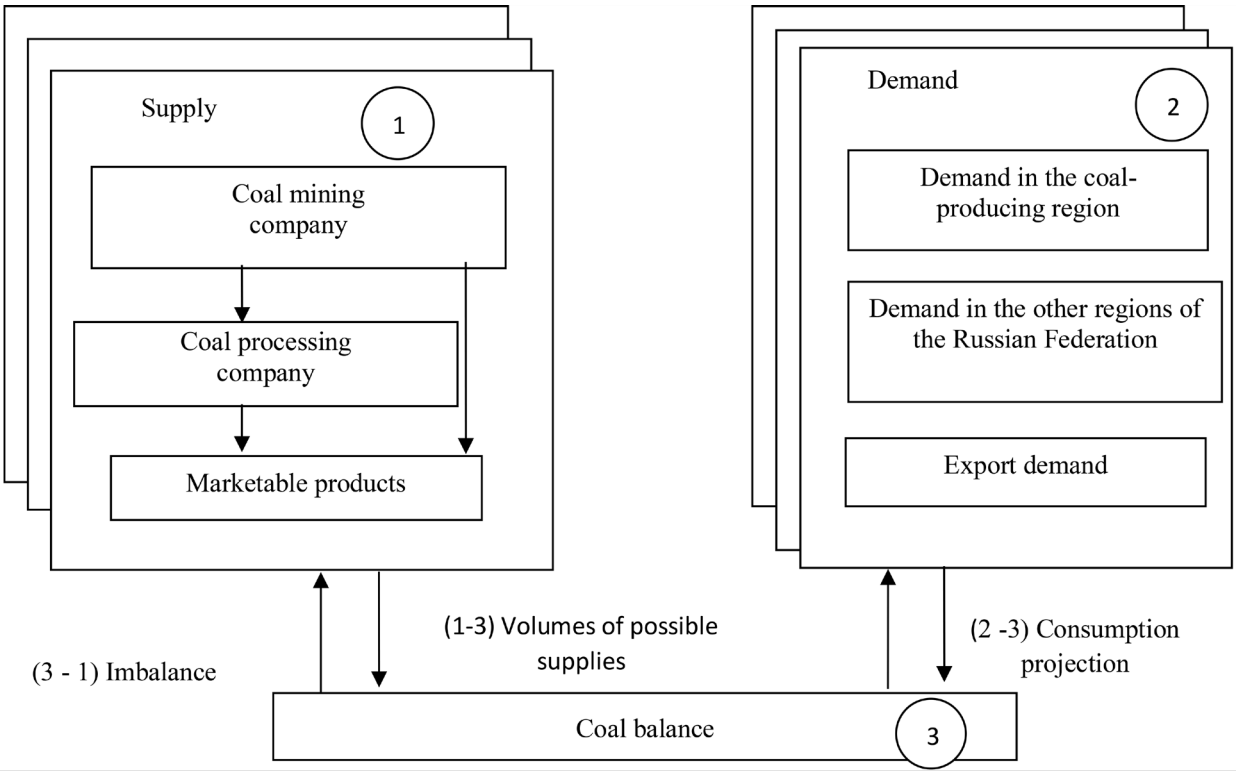

Fig. 3. Structure of the “balances”, “regional balances”, and “federal subject” models.

in coal supply and consumption.

The "BALANCES" model allows projecting the demand for and supply of coal outside the region based on the potential coal mining opportunities and coal demand.

The "REGIONAL BALANCES" model supplements the COAL TRANS optimization production and transportation model of the Russian coal industry, and the "BALANCES" model.

The FEDERAL SUBJECT model is intended for the study of the coal industry development at the level of a federal subject. It provides most completely the details of the indicators for coal-mining companies, coal-preparation plants, consumption of certain coals in the context of the federal subject given its division by any features it has (administrative, transport accessibility, etc.), and so on.

To research the development prospects of the coal industry, an information and model system has been developed, which includes an information system [2 3], a system of models [16, 1 7], projections of constraints and conditions of prospective development, and programs for building models and processing calculation results. The composition and structure of the system take into account the hierarchy of models for the study of the development prospects for the coal industry, corresponding to the second, third, and fourth levels of the hierarchy.

Dual estimates in the LP problem determine the marginal coal prices.

The models make use of the indicators, the main of which are:

- projections based on individual economic development scenarios: demand for coal; constraints on steam coal resources; constraints on the production of steam and coking coal;
- estimates of the opportunities for the development of coal mining companies;
- quality characteristics of coal;
- technical and economic performance indicators of companies;
- data for calculating resource requirements, such as capital expenditures, electricity, heat and labor, and corresponding specific indicators;
- the existing coal supply chain;
- historical data on coal supply and consumption.

The results of the calculations are consistent with the historical data. They contain projected indicators in the form of tables (with varying degrees of detail for different models) in the context of the administrative division of the country and its regions:

- potential opportunities for the development of coal mining and possible volumes of export quality coal production;
- volumes of coal supplies, including those for export;
- volumes of demanded coal production, including those by individual company;
- potential coal resources for the energy industry;
- new capacity additions in the coal industry;
- coal processing volumes;
- output of marketable coal products;
- balances of coal in general and steam coal in particular;
- the demand for resources to maintain and develop coal production: capital expenditures; labor power; electricity and heat;
- directions of the coal industry development (new construction projects, capacity expansion);
- the structure of production (surface mining vs. underground mining; brown coal vs. hard coal; steam coal vs. coking coal) and processing;
- tables and charts to be used in printed matter.

V. Conclusion

The hierarchical approach to the studies of the coal industry development in the country and its regions using the presented system of models allows considering different aspects of the coal industry development, solving many interrelated and stand-alone problems with different development criteria, which would otherwise be difficult to reduce to a single model. The use of simulation models, in addition to optimization models, enables experts to consider the variables that are difficult to factor in analytically. In different years, the presented models were used to make projections of the development of the coal industry of the country, Eastern Siberia, the Far East, and individual federal subjects (Republic of Sakha; Amur, Sakhalin and Irkutsk regions; Chukotka Autonomous Okrug; etc.) [26-3 3].

Acknowledgements

The research was carried out as part of the scientific project XI.174.2. of the program for basic re-search of the Siberian Branch of the Russian Academy of Sciences, reg. No. AAAA-A17-117030310435-0.

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Multi-level Modeling of Optimal Development and Pricing in the Gas Industry

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***Abstract* — This paper studies hierarchical modeling of the optimal development of facilities of multilevel gas supply systems (GSSs), given the general issues of their aggregation and contributes corresponding development and pricing models. The models for the comprehensive development of GSSs are considered at three hierarchical levels: 1) structure optimization and investment processes; 2) optimization of seasonal gas consumption, reliability analysis and synthesis; 3) optimization of parameters of a facility with its reliability factored in, as illustrated by the main gas pipeline. Three pricing models are proposed: determination of retail prices and tariffs for natural gas for certain categories and groups of consumers; determination of wholesale gas price components for federal subjects of Russia; determination of supply and demand equilibrium between natural gas suppliers and consumers. The development and pricing models were put to test to calculate the optimal volume of gas production and transportation taking into account seasonality of consumption and reliability of GSSs equipment performance, as well as to set natural gas prices for federal subjects of Russia.**

***Index Terms* — multi-level modeling, gas supply system, mathematical models, optimal development, pricing issues.**

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http://dx.doi.org/10.25729/esr.2019.04.0009
Received August 10, 2019. Revised September 30, 2019.
Accepted October 30, 2019. Available online January 25, 2020.

I. Notation

1. Network flow model

x_{ij}, y_{ij} – gas flows through existing and new arcs.

d_{ij}, g_{ij} – throughput capacity and increments of arcs.

c_{ij}, k_{ij} – "prices" of gas transportation through existing and new arcs.

λ_{ij} — the arc coefficient that takes into account the changes in gas flow as it passes through the arc. s and t – additional nodes — the shared source and outlet.

U – the set of all nodes. v and w – total flows from node s to node t.

2. Model for selecting the areas of investment activities

x_i — the share of the total cost of implementation of the ith investment option ($X_i = [0;1]$).

U_i — sources of financing

$K_{i,t}$ — the value of the investment in the ith option that is made within the tth segment of the investment period.

T — the number of intervals within the investment period.

B_t — the planned amount of financial resources available within the tth interval.

$f_{j,t,i}$ — total costs of the jth production factor used as part of the ith option (e.g. wages C_{wag}, fixed assets C_{fix}, construction costs C_{con}, transportation costs C_{tr}, etc.).

$F_{j,t}$ — the capacity of the j production factor within the tth interval.

$Q_{i,t}$ — volume of gas supply to consumers as per the ith option within the tth time interval.

Qt_{min} — the minimum required volume of gas supply to consumers within the tth interval.

N — the total number of feasible investment project options.

AC_i — the average cost of the ith investment option.

BP_{pri} — the amount of budget receipts for the ith option at the beginning of the investment period.

TR_{pri}, TC_{pri} — discounted receipts and payments, respectively.

3. Model for determining the structure of financing sources

M — the number of possible financing sources.
$ACY_{j,t}$- specific costs related to the use of the jth source.
$Y_{j,t}$ — sources of financing (own funds, funds received due to the issuance of securities and other funds raised, borrowed funds).
G_t — the amount of government subsidies within the tth interval.
ka — the coefficient capturing the recommended ratio of own funds to other sources.

4. Model for selecting partners

$TCSpr_k$ $TCSpr$ — discounted costs associated with the use of construction company services.
S_k — the set of construction companies.
$PS_{k,t}$ — the capacity of the k the construction company within the tth interval.
$QS_{i,t}$ — the required scope of construction work as per the ith option within the tth time interval.
X_i^0 — the share of the ith investment option in the optimal solution of the first model.

5. Model for regulating the seasonal irregularity in gas consumption

$x_{i\tau}^P, x_{i\tau}^T, x_{i\tau}^{-T}, x_{i\tau}^x, x_{i\tau}^U, x_{i\tau}^b$ — variables of interest for each node i of the calculation scheme and for each season of year τ $\left(\tau = \overline{1,T}\right)$, respectively, reflecting the volume of gas production at the fields, the volume of gas supply to the node and gas output from the node to other nodes through the MGP, the volume of gas storage in underground gas storage facilities, the volume of gas substitution by other fuels and the volume of gas use by buffer consumers.
$z_{i\tau}$ — a dummy variable in node i in time period τ that shows possible misalignment of fuel resources and demand.
L — the number of consumer categories that accept substitution of gas by some other fuel $\left(l = \overline{1,L}\right)$.
$b_{i\tau}$ – gas demand of node i that is mandatory to meet within time period τ.
$a_{i\tau}^P, a_{i\tau}^T, a_{i\tau}^x, a_{i\tau l}^U, a_{i\tau}^b$ — coefficients indicating for each node i within time period τ, respectively, process indicators (losses due to unreliability, gas consumption for auxiliaries, overconsumption of other fuel types when using them to substitute gas, etc.) for the above listed facilities.
$d_{i\tau}^P, d_{i\tau}^T, d_{i\tau}^x, d_{i\tau}^U, d_{i\tau}^b$ — constraints on the production capacity of gas fields, main gas pipelines, underground gas storage facilities, possible maximum volume of gas substitution by other fuels by various consumer categories, respectively. $c_{i\tau}^P, c_{i\tau}^T, c_{i\tau}^x, c_{i\tau l}^U, c_{i\tau}^b$ — discounted levelized cost of gas production, transportation, and storage, consumption of other fuels by consumers of category l and gas buffer units, respectively.
$u_{i\tau}$ — discounted specific damage as shown by individual nodes of the calculation scheme due to possible shortages of energy resources.

6. Model for reliability assessment of the gas supply system

$i \in R$ – nodes in the model network that correspond to the fields $i \in R_1$ consumers $i \in R_2$ underground storage facilities $i \in R_3$ junction points of pipelines $i \in R_4$.
$(i, j) \in U$ – edges connecting nodes i and j.

For each calculated field node $i \in R$ we specify:
$q^o\left[x^o\right]$ – variation series of potential gas supply to the system.
x_i^o, X_i^o – current and maximum possible gas supply from fields to the system, t.c.e.
C_i^o –specific costs of gas production, RUR/t.c.e.
λ_i^o – the coefficient that captures gas consumption for auxiliaries, $\lambda_i^o < 1$

For each calculated consumer node $i \in R_2$ we set:
$M[x_i^I], \sigma[x_i^I]$ – demand by household consumers for gas, represented by a mean value and mean square deviation of the normal law of distribution, t.c.e.
$x_i^I X_i^I$ – current and maximum possible demand for gas for consumer category I (households), t.c.e.
$X_i^{II(III)}$ – demand for gas for consumer category II (III) (industrial consumers, gas–fired boilers, and electric power plants), t.c.e.
C_1, C_2, and C_3 – specific gas cost for consumer categories I, II, III, respectively, $C_1 << C_2 << C_3$, RUR/t.c.e.
x_{0i}, B_i – current and maximum volume of backup fuel, t.c.e.
C_{0i} – specific costs of backup fuel, RUR/t.c.e.
x_i^d – total gas shortage for all consumer node categories, t.c.e.
y_{0i} – specific damage due to gas undersupply, RUR/t.c.e.
$q^{st}[x_i^+], q^{st}[x_i^-]$ – variation series of potential gas withdrawal from the UGS to the system or potential gas injection into the UGS.
x_i^+, x_i^- – potential gas supply from the UGS to the system or gas injection into the UGS, t.c.e.
C_i^+, C_i^- – specific costs of gas withdrawal or injection, RUR/tce.
V_i – storage capacity, t.c.e.
S_i – gas reserve at the beginning of the considered period, t.c.e.
λ_i^+ – the coefficient that captures gas storage losses, $\lambda_i^+ < 1$.

For each main gas pipeline we $(i, j) \in U$ set:
$q^{gp}\left[x_{ij}\right]$ – variation series of capacity.
x_{ij} – main gas pipeline capacity, t.c.e.
C_{ij} – specific costs of gas transportation from node i to node j, RUR/tce.
λ_{ij} – the coefficient that captures gas transportation losses, $\lambda_{ij} < 1$.

7. The model for synthesis of reliability of a complex gas supply system

(i, j) – the arcs connecting the nodes i and j.
x_{ij} – the capacity flow of the graph arc reflecting a source or transportation facility with available redundancy.
y_{ij} – the flow of additional redundant capacity of the graph arc reflecting a source or transportation facility.
z_j – the backup fuel volume.
c_{ij} – the specific cost value with available redundancy of a gas source or transportation facility.
k_{ij} – the specific value of additional redundant cost of a gas source or transportation facility.
P_j – the specific value of redundant fuel cost.
λ_{ij} – the factor that takes into account gas consumption for

auxiliaries and losses due to unreliability.
π_{ij} – the graph arc reliability factor with additional redundant capacity factored in.
α_j – the fuel supply reliability factor.
Q – the total value of gas produced by all its sources.
B – the total value of gas used by all consumers.

II. Introduction

The Unified Gas Supply System of Russia is a unique large-size system that has no equal in the world. The issues of multilevel modeling of its optimal development were reflected in [1, 2], including the works carried out at the ESI SB RAS [2-4]. To a certain extent, hierarchical modeling issues are also dealt in the research published abroad [5-17]. Various problems of making global and national projections of gas supply systems (GSS) development (generally, gas flow models are used) are solved along with those of the interaction of gas markets, and each problem is solved at its own hierarchical level. For example, the world energy models [5-7] study the interrelationships between the industries of the energy sector, including the gas industry. In global gas models [8-14] each country is treated as a standalone gas market. European market models [15, 16] make projections of natural gas production, transportation, consumption, and prices in European markets. National gas models investigate in more detail the gas markets of a particular country as is illustrated in [17]. Gas flows, demand, production, gas prices, required new capacity additions for gas transportation corridors and gas liquefaction plants are projected for different time frames. Data exchange can take place between individual models of different hierarchical levels.

The analysis of models when substantiating the development of the gas industry indicates the necessity of considering it at different hierarchical levels for improving, clarifying, and detailing the use of information base. Therefore, research in the field of multi-level modeling of the gas industry development and pricing issues is a critical task.

The object of the study is the gas industry, which includes gas supply systems that provide consumers with hydrocarbon gases, the most important raw material resource for obtaining chemical products and environmentally friendly energy.

Natural gas is produced by gas producing companies that have their main and auxiliary equipment. This gas is transported by gas transportation companies (main gas pipelines (MGP), including line pipes (LP), and compressor stations (CS)) to gas distribution systems (GDS). Then natural gas is delivered by gas distribution systems to consumer facilities (industry, energy, utilities, transport, households). The great bulk of natural gas is exported. The listed gas production and transportation facilities are complex systems that interact with each other within a single process and time cycle. They are equipped with control, regulation, and metering instruments.

Liquefied natural gas is produced in Russia by two companies (Sakhalin-2, Yamal-LNG), where natural gas is liquefied, stored, and delivered to consumers by water by dedicated tankers (gas carriers).

Hierarchical modeling of optimal development of multi-level gas supply systems is considered in this study while taking into account general issues of utilities systems aggregation, namely: mathematical models of their development, investment models, models for reliability analysis and synthesis, optimization of parameters of facilities with reliability factored in; covered are principles of pricing and methods of calculation of wholesale prices and their components for natural gas as applied to federal subjects of Russia, as well as the model for finding the supply and demand equilibrium between gas suppliers and consumers.

III. General issues of aggregation of gas supply systems companies

The subject of the study of companies producing and transporting gas to consumers is the modeling of their technical and economic performance indicators (constraints on capacity, operating costs, and coefficients reflecting the consumption of gas for auxiliaries and leakages due to unreliability).

The aggregation of the calculation scheme is understood as modeling of the actual scheme of gas supply in a consolidated form [18]. Such a scheme should reflect the actual scheme with certain accuracy while maintaining its required properties. The resulting aggregate scheme is characterized by a smaller number of nodes and links, which facilitates the analysis of results to develop the necessary solutions and use the information for calculations in mathematical models.

The Gas Supply System (GSS) is represented as an oriented graph and treated as a set of three subsystems (companies): gas sources, main transportation networks, and consumers. Source facilities include all companies that supply gas to the main transportation network: comprehensive gas treatment plants, gas chemical facilities, and underground gas storage facilities, if a given time coincides with the withdrawal period the facility operates with. Main transportation network companies consist of sections of main gas pipelines that include line pipes and compressor stations located thereon. Consumption facilities include groups of consumers that take gas from main gas pipelines and underground gas storage facilities, if a given moment coincides with the period of gas injection into a UGS.

Consumption nodes are aggregated according to the administrative and geographic principle, with federal subjects of Russia acting as consumers.

For each subject, we identify a node with the maximum demand; in case the subject has two or more nodes with the same maximum demand, the node closest to the branching node with the maximum number of adjacent nodes is

selected. The demand for natural gas of an aggregate consumer is determined provided the same demand in the original and aggregate schemes.

For each federal subject of Russia we identify the CS that has gas pipelines with maximum aggregate throughput capacity passing through it. In this case, it is its aggregate consumer node.

If the CS does not coincide with the aggregate consumer node, it is denoted in the scheme as a branching node. Such a node is required to correctly reflect the main gas flows in the scheme. There is no demand for gas defined at the branching node. The entire demand of the subject is concentrated at the consumer node.

A gas production company (GPC) is denoted as an aggregate source node associated with the consumer node of the subject of the aggregate network in which the company is located. Gas production in the aggregate subject is the total production by all fields.

Multi-line MGPs are presented as single-line ones. The aggregate arc of the graph between two nodes is characterized by the total throughput capacity of gas pipelines on the border between two subjects and the length of all MGPs coming from one node to another.

To determine the aggregate technical and economic performance indicators of each arc and node of the aggregate calculation scheme, we use statistical data made available by Gazprom PJSC along with the input technical and economic data on existing GPCs and GTCs. The cost of gas production at each field, as well as the tariff for its transportation through a certain gas pipeline, are calculated taking into account the costs of the corresponding gas production and transportation company and the profit required for its internal needs.

The final operation to form a calculation scheme is to "glue" all the aggregate schemes into a single one. "Gluing" is carried out along the borders of gas transportation companies. Thus, the complex multi-line Unified Gas Supply System (UGSS) (see Figure 1) is presented in the form of an aggregate calculation scheme (see Figure 2), (different lines of the scheme delimit the boundaries within which individual gas transportation companies operate).

The aggregate existing GSS scheme is superimposed by existing large-scale projects of gas transportation systems that are at the design or project implementation stage. In addition to this, the calculation scheme is supplemented with links that characterize the projects and scientific developments, as broken down by year of the planned periods, contributed by research and design organizations. Thus, a redundant aggregate calculation scheme is built reflecting the stages of GSS development for the investigated time frame.

The obtained calculation schemes allow studying rational growth rates and proportions in development of the gas supply of individual regions and the country as a

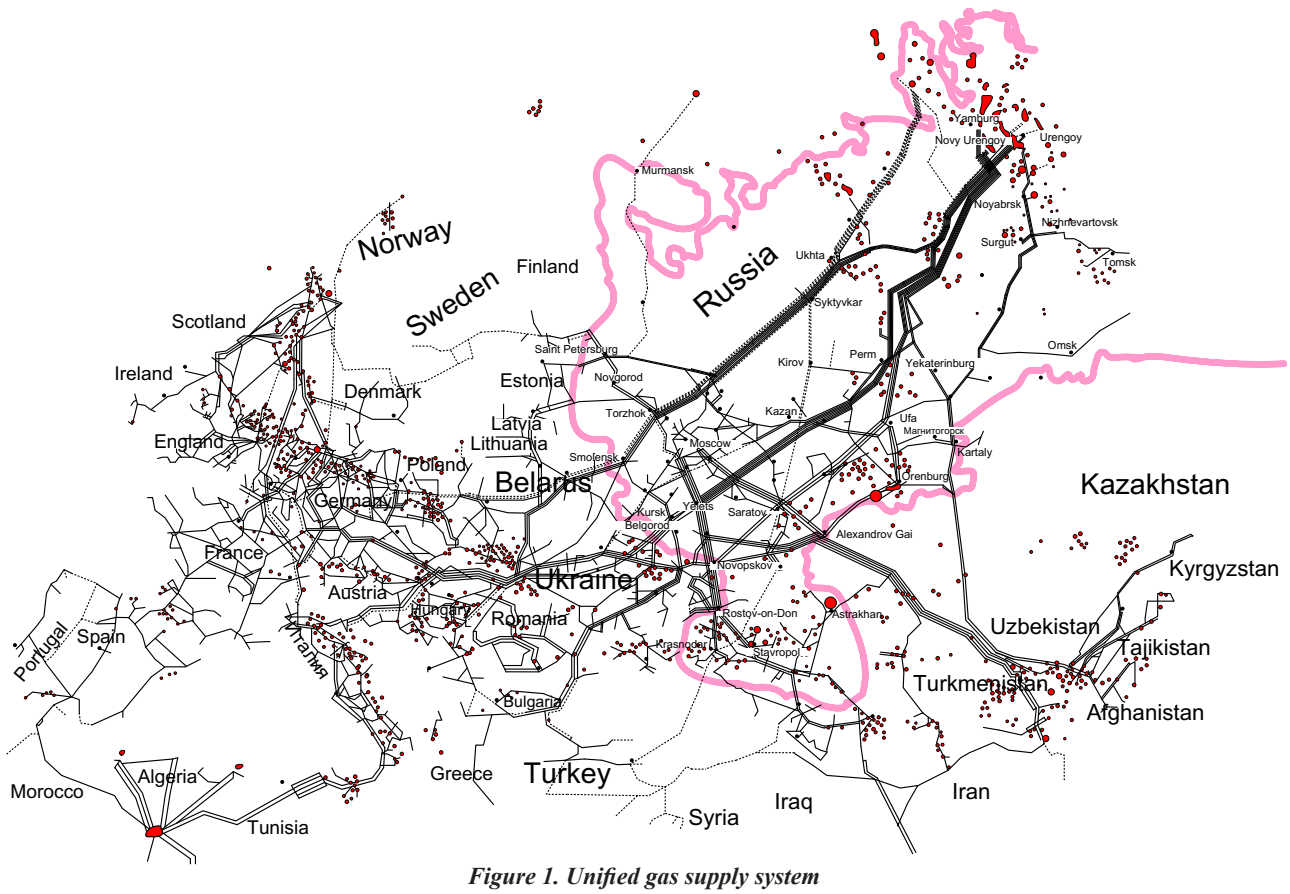

Figure 1. Unified gas supply system

whole taking into account interaction of all industries that are part of the energy sector, while touching upon general energy, economic, environmental, and other cross-industry issues.

Based on the data available in [19] an information base for multi-level modeling of development of gas supply systems in Russia to 2030 was built [4]. It captures the following: demand for gas at the nodes of the scheme, upper limits on production and transportation, as well as costs and coefficients showing gas consumption for auxiliaries and leakage flows. The database includes the following: estimation of natural gas demand dynamics in the Russian Federation and its export deliveries (the current state and prospects of gas supply markets development in federal subjects of Russia); technical and economic performance indicators for existing and new gas producing companies and gas transportation systems.

The subject of the research is the problems of prospective development of complex gas supply systems. The methodological developments that were made allow setting and solving complex problems so as to pursue the following two directions [4]: that of optimal prospective development of gas supply systems and that of pricing for gas supply systems development.

IV. Complex problems of optimal prospective development

Figure 3 shows the models developed at the ESI SB RAS to solve the problems of optimal development of gas supply systems and their interaction at the three levels of their study [4].

1. Integrated development models of GSSs of the first hierarchical level

Model for structural optimization of the gas supply system

This network flow model allows finding a gas supply plan that ensures minimum costs for gas production, transportation, and delivery to consumers when gas demand is fixed.

The generalized task of flow modeling is written down in the following form:

$$\sum_{i,j}\left(c_{ij}x_{ij}+k_{ij}y_{ij}\right)\to\min$$

$$\sum_{i}\lambda_{ij}x_{ij}-\sum_{i}x_{ij}=\begin{cases}-v, & j=s\\ 0, & j\neq s,t\\ w, & j=t\end{cases}$$

$$l_{ij}\le x_{ij}\le d_{ij}+y_{ij},(i,j)\in U$$

$$0\le y_{ij}\le g_{ij}\,(i,j)\in U.$$

Here, the optimality criterion is the minimum cost of gas production, transportation, and delivery to consumers, while the constraints are production capacity of existing and new companies and requirements to meet the minimum demand by consumers, provided that the balance of gas supply and withdrawal at the network nodes is maintained.

This problem of the minimum cost flow, which belongs to the class of LP problems, is solved by the modified Busacker-Gowen algorithm [1].

Based on the data from the information base built, calculations were made showing the optimal volume of gas

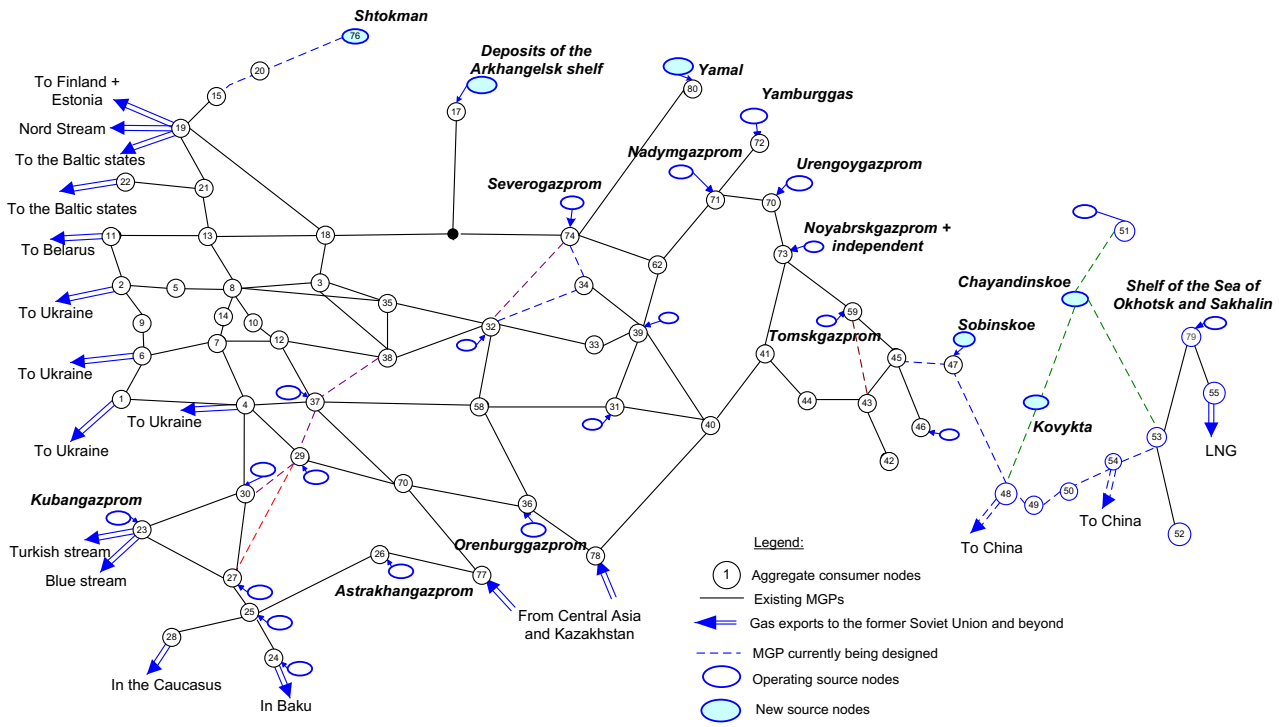

Figure 2. Redundant aggregate calculation scheme of the GSS of the Russian Federation

production and transportation for the averaged scenario of consumption in Russia and exports in years 2020, 2025, and 2030. The calculation result for 2030 is presented in Figure 4 that shows the optimal volume of gas production by gas producing companies and the volume of gas flows through the aggregate gas transportation companies.

As a result of generalization of model calculations for optimization of development of gas supply systems in Russia to 2030 [20], interval estimates of indicators descriptive of gas consumption, exports, consumption for auxiliaries, and leakages were obtained

The dotted line in Figure 4 outlines the scheme of gas supply to the Northwestern Federal District. Using this scheme as an example, in what follows we will show the details of the solutions of the models of problems of lower levels of consideration.

Models of investment processes

These models enable one to plan investments (areas of investment, their volume, and terms of their financing) in such a way that the resulting discounted effect would best satisfy the interests of all subjects [21].

The above can be presented as the following three problems: 1) choice of areas of investment activity; 2) determination of the structure of financing sources; 3) choice of partners (construction and other companies).

The mathematical model for the problem of choosing the areas of investment is as follows:

Criteria: $\sum_{i=1}^{N}[U_i \cdot x_i] \to \min,$

$$\sum_{i=1}^{N}[AC_i \cdot x_i] \to \min,$$

$$\sum_{i=1}^{N}[BPpr_i \cdot x_i] \to \max,$$

Constraints:

$$\sum_{i=1}^{N} K_{it} \cdot x_i \le B_t \left(t = 1,2,...,T\right),$$

$$\sum_{i=1}^{N} f_{j,t,i} \cdot x_i \le F_{j,t} \left(j = 1, 2,..., J\ t = 1,2,..., T\right)$$

$$\sum_{i=1}^{N} Q_{it} \cdot x_i \ge Q_{\min_t}, \left(t = 1,2,...,T\right),$$

$$x_i - x_j \le 0 \text{ при } x_i, x_j = 1 \cup 0, i \ne j \quad \left(i, j = 1,2,...,N\right),$$

$$x_i + x_j \le 1 \text{ при } x_i, x_j = 1 \cup 0, i \ne j \quad \left(i, j = 1,2,...,N\right),$$

$$0 \le x_i \le 1 \text{ или } x_i = 0 \cup 1.$$

It is a multi-criterion problem. The criteria show the minimum average costs and are used when the interests of the state and the national economy as a whole are reflected in the model, maximize budget receipts, and represent the interests of the state and the government, and indicate the maximum profit for the owners.

The constraints show the total financing capability; the capacity of financial resources and the conditions of gas supply to consumers.

The desired solution is a matrix that represents the amount of funding by a source of funding for each interval of the investment period.

The problem of determining the structure of financing sources for the gas supply system can be formulated as follows:

Criterion: $\sum_{j=1}^{M}\sum_{t=1}^{T}\left[ACY_{j,t} \cdot y_{j,t} / \left(1+r\right)^t\right] \to \min$

Constraints: $\sum_{j=1}^{M} y_{j,t} \ge K_t - G_t (t = 1,2,...,T),$

$$\sum_{j=1}^{M}\left[ACY_{j,t} \cdot y_{j,t} + y_{j,t}\right] \le B_t \ (t = 1,2,...,T),$$

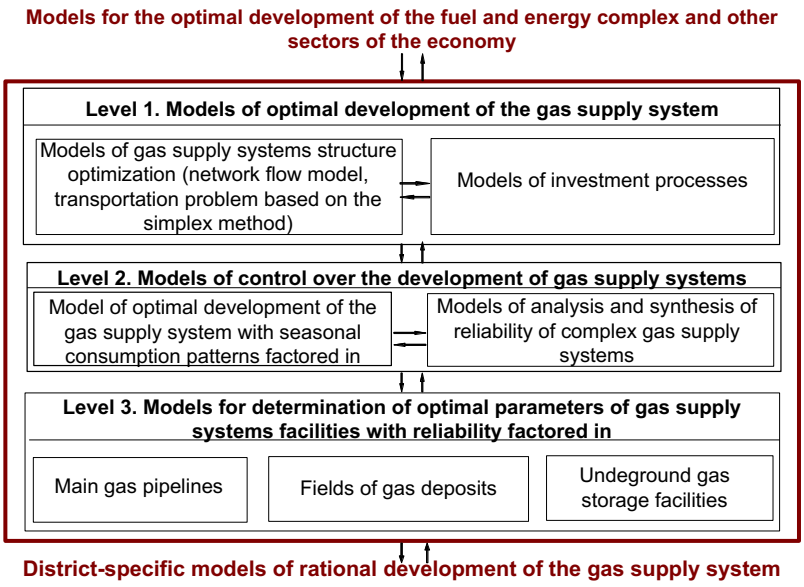

Figure 3. Models for solving problems of optimal development of gas supply systems.

$$\left[\sum_{j=1}^{M1} y_{j,t} \Big/ \sum_{j=M1+1}^{M} y_{j,t}\right] \geq ka\left(t=1,2,...,T\right),$$

$$y_{j,t} \geq 0\left(j=1,2,...,J, t=1,2,...T\right).$$

Constraints show the possibility of financing sources, as well as the coverage of investments and costs by the budget of the company.

The problem statement for the problem of choosing partners, with the latter being construction and other companies, is as follows:

Criterion: $$\left[\sum_{k=1}^{K} TCSpr_k \cdot s_k\right] \rightarrow \min$$

Constraints: $$\sum_{k=1}^{K} s_k \cdot ps_{k,t} \geq \sum_{i-1}^{N} qs_{i,t} \cdot X_i^0 \left(t=1,2,...,T\right),$$

$$s_k = 0 \cup 1 \quad (k=1,2,...,K)$$

Within this problem, out of the available set of partners, one s chooses s^0 those that ensure minimum discounted costs associated with the choice of the kth construction company.

The constraint shows that capacity of the chosen construction company should be not less than it is required as per the investment plan.

The industry average rate of return for construction is used as the discount rate to arrive at the present values of indicators, with the discounting period corresponding to the construction period.

This problem can be extended to cover suppliers providing construction (production) services for the object of investment. In addition, the problem can be modified so as to distribute the utilization of capacity of construction companies and other partners over time.

As a case study, we consider the choice of the optimal investment option for the development of the gas sup-ply system of the Russian Federation. Let us consider three options: Option one. Gazprom PJSC is developing in line with the recommendations set out in the energy strategy of Russia. Option two. The first option is supplement-ed by accelerated development of new gas production companies and construction of gas transportation systems in Eastern Siberia and the Far East. Option three. The second option is supplemented by accelerated development of new gas production companies in the shelf of the Barents and Kara Seas. Our studies provide evidence (see Figure 5) that the second option of development will be the optimal one if the development of gas supply systems in Russia will be carried out by Gazprom PJSC. The option has the lowest average costs for the minimum scenario and the highest discounted profit

2. Models of integrated development models of the GSSs of the second hierarchical level

Model of regulation of seasonal irregularity in gas consumption patterns

The model is a system of linear equations and inequalities that coherently describe the processes of gas

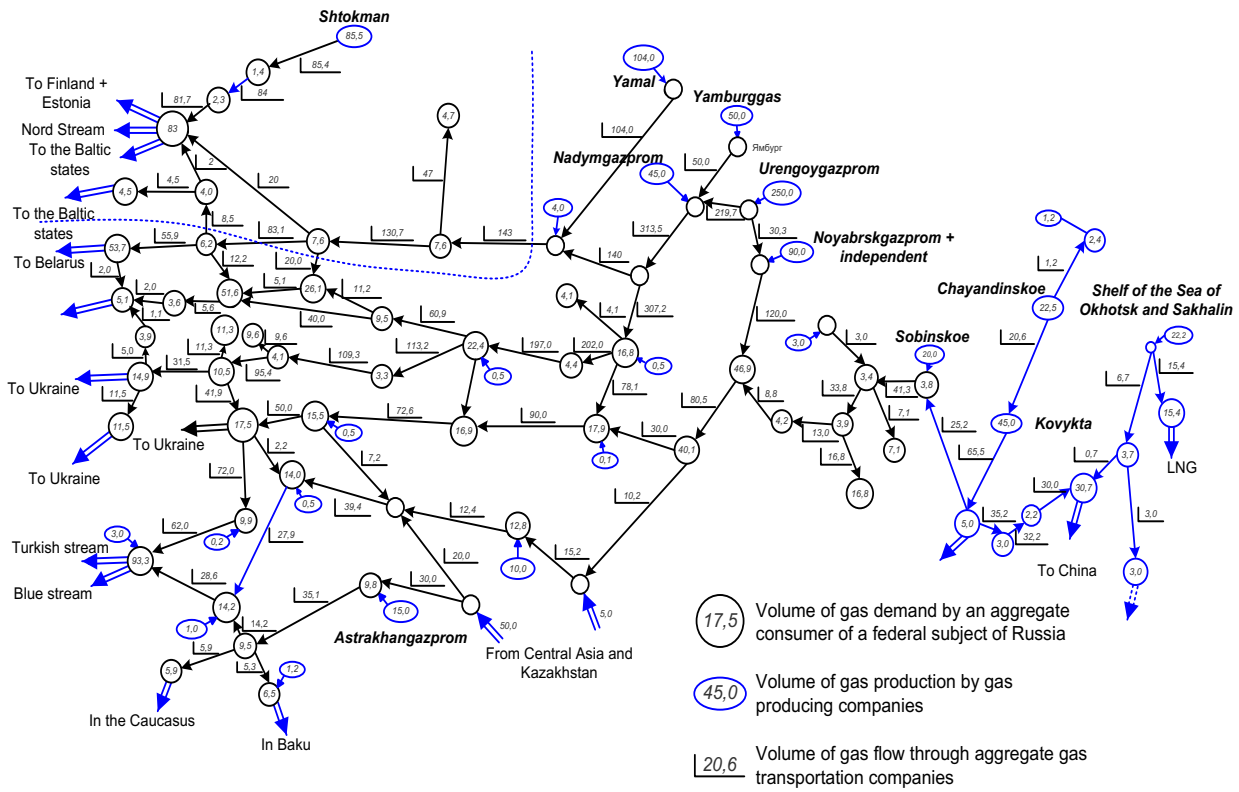

Figure 4. Optimal gas production and transportation volume for the averaged scenario of consumption in the Russian Federation and exports in 2030, bcm/year.

production, transportation, storage, and consumption by seasons of the year is as follows:

$$\sum_{i=1}^{n}\sum_{\tau=1}^{T}(c_{i\tau}^{P}x_{i\tau}^{P}+c_{i\tau}^{T}x_{i\tau}^{T}+c_{i\tau}^{x}x_{i\tau}^{x}+$$

$$\sum_{l=1}^{L}c_{i\tau l}^{U}x_{i\tau l}^{U}+c_{i\tau}^{b}x_{i\tau}^{b}+u_{i\tau}z_{i\tau})\rightarrow \min;$$

$$\sum_{\tau=1}^{T}(a_{i\tau}^{P}x_{i\tau}^{P}+a_{i\tau}^{T}x_{i\tau}^{T}+a_{i\tau}^{x}x_{i\tau}^{x}+$$

$$\sum_{l=1}^{L}a_{i\tau l}^{U}x_{i\tau l}^{U}+z_{i\tau})=\sum_{\tau=1}^{T}(x_{i\tau}^{-T}+a_{i\tau}^{b}x_{i\tau}^{b}+b_{i\tau}),$$

$$0\le a_{i\tau}^{P}x_{i\tau}^{P}\le d_{i\tau}^{P};0\le a_{i\tau}^{T}x_{i\tau}^{T}\le d_{i\tau}^{T};$$

$$0\le a_{i\tau}^{x}x_{i\tau}^{x}\le d_{i\tau}^{x};0\le a_{i\tau}^{U}x_{i\tau}^{U}\le d_{i\tau}^{U}$$

The model can take into account constraints on limited resources: fuel oil (d^f), coal (d^c), total capital in-vestment (k) and metal (M).

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}\sum_{l=1}^{L}a_{i\tau l}^{U}x_{i\tau l}^{U}\le d^{f};$$

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}(\sum_{l=1}^{L}a_{i\tau l}^{U}x_{i\tau l}^{U}+a_{i\tau l}^{b}x_{i\tau l}^{b})\le d^{c};$$

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}(k_{i\tau}^{P}x_{i\tau}^{P}+k_{i\tau}^{T}x_{i\tau}^{T}+k_{i\tau}^{x}x_{i\tau}^{x}+$$

$$\sum_{l=1}^{L}k_{i\tau l}^{U}x_{i\tau l}^{U}+k_{i\tau l}^{b}x_{i\tau l}^{b})\le k;$$

$$0\le\sum_{i=1}^{n}\sum_{\tau=1}^{T}\mu_{i\tau}x_{i\tau}^{T}\le M,$$

The criterion is the minimized function of costs of gas production, transportation, storage and use; the following expression is a condition of equality to preserve gas production, transportation, storage and consumption flow; it is followed by constraints on gas flows, capital expenditures, and metal inputs.

As a result of solving this problem, the capacity of fields, gas transportation companies, and underground gas storage facilities is determined by standard methods of linear programming as applied by seasons of the year.

The detailed scheme of gas supply to the Northwestern Federal District in 2030 was calculated based on the model of seasonal irregularity regulation (see Figure 6). It 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.

3. Models for analysis and synthesis of reliability of complex gas supply systems companies

Reliability analysis models for existing GSS facilities. The facilities include the gas main pipeline, the field, and the underground gas storage facility.

The calculation scheme of a complex multi-line MGP consists of several branches. Each branch is a chain of serially connected links, line pipes of different diameters and compressor stations with gas pumping units (GPUs) of various standard sizes.

The calculation scheme of the gas field represents a number of clusters. A cluster is understood as a parallel connected set of wells with associated equipment, as well as a separator and flow lines. A head field station is defined as a set of parallel connected elements that are, in general, heterogeneous aggregates.

Underground gas storage (UGS) facilities are typically established in depleted gas and oil field, porous aquifers, and salt deposits. Underground storage facilities in aquifers and salt layers are artificially created gas deposits.

The main process links of UGS facilities include the following: wells, connecting pipelines, and near well-bore area structures, gas treatment and drying devices, compressor stations.

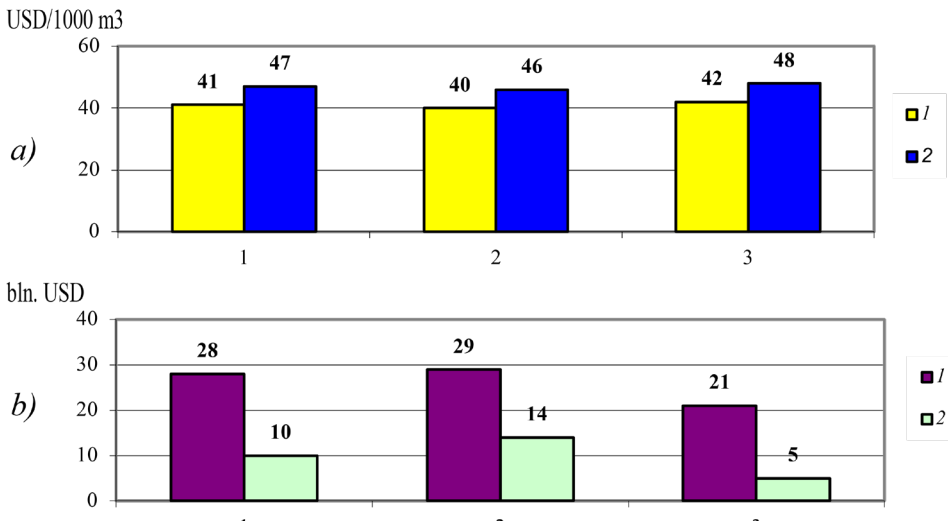

Figure 5. The problem of choosing areas of investment. ***Average costs (a) and net discounted profit (b) by options of gas supply system development in Russia. Scenario: 1 — maximum, 2 — minimum.***

The reliability analysis of the indicated facilities (MGP, field, UGS) is performed as follows:

1. Initial links (line pipe, CSs, well clusters), consisting, in general, of heterogeneous elements are replaced by a system consisting of homogeneous elements by way of 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 covering various types of deposits;
3. as per a predefined rule, taking into account a parallel and serial connection, the composition of distribution functions of the working condition of a given facility is performed;
4. as a result the following indicators of the facility are determined: a series of the probability distribution of its working condition; a function of the probability distribution of its working condition; mathematical expectation, dispersion, and standard deviation of throughput capacity of the facility within the considered time interval and a number of other indicators. The reliability factor is also determined for the MGP.

The reliability analysis model of a complex gas supply system is an estimation model. The object of the study is a multi-node gas supply 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 development.

The purpose of the problem of estimating the reliability of functioning 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 backup supplies.

In terms of its content, the model allows to determine the following based on gas demand and gas supply to the system from the fields as presented in a probabilistic form, as well as gas withdrawal to the system or injection into underground gas storage facilities and taking into account UGS reserves, as well as taking into account the throughput capacity of gas main pipelines, also stated in the probabilistic form, and taking into account losses of gas for auxiliaries at the fields, during its UGS storage and its transportation through the MGP, as well as the inter-changeability of fuels: key reliability indicators by individual gas supply system nodes, namely: reliability of gas supply as a probability of meeting the predefined demand, mathematical expectation of undersupply of gas and the coefficient of meeting the gas demand of consumers; depending on the ratio of obtained and set reliability of meeting gas demand by each calculated consumption node — various measures that facilitate its reduction or increase.

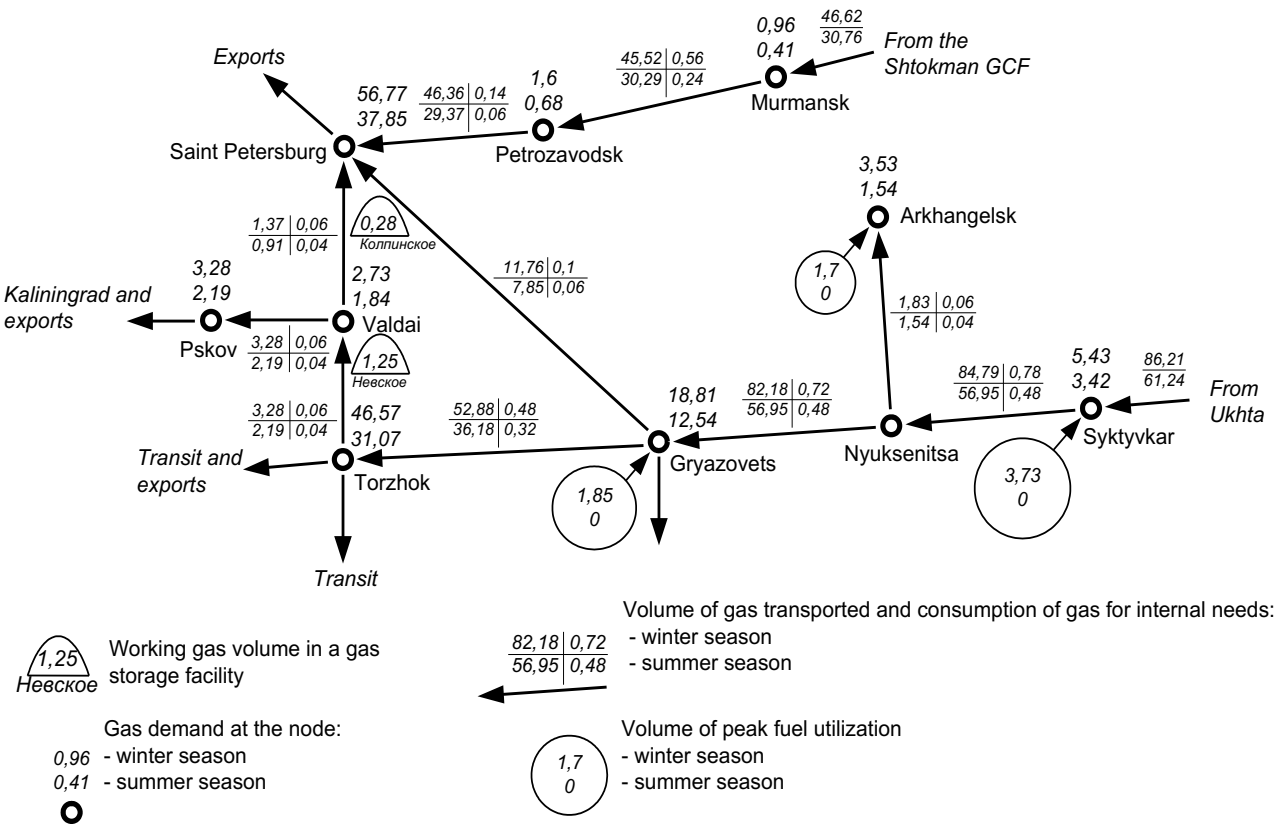

Figure 6. Regulation of seasonal irregularity of gas supply in the Northwestern Federal District in 2030 million tons of fuel equivalent.

The algorithm for the problem of evaluating the reliability of the gas supply system operation includes 3 modules used to solve the problem:

1. Probabilistic module.
2. Module for calculation of the system operation mode.
3. Reliability parameters calculation module.

The various nature of subproblems predetermines the use of various methods, namely: the method of statistical modeling for the composition of the calculated states of the system (Monte Carlo method); the method of calculating the distribution functions of random states of gas imbalances and the theorem of adding and multiplying the probabilities of various events; the method of flow distribution in networks for calculating operating modes.

In the probability module for simulating the states of the system facilities, a pseudo-random number generator (PRNG) is used to get the numbers evenly distributed within the interval from 0 to 1.

In the second module, the problem of calculating the optimal mode is stated as follows:

$$\sum_{i\in R_1} C_i^o - x_i^o + \sum_{i\in R_1} C_{0i} - x_{0i} + \sum_{i\in R_3} C_i^+ - x_i^+ \left(\sum_{i\in R_3} C_i^- - x_i^- \right) + \sum_{(i,j)\in U} C_{ij} - x_{ij} + \sum_{i\in R_2} y_{0i} - x_i^d \to min$$

subject to

$$\left.\begin{aligned} &\sum_j \lambda_{ji} - x_{ji} - \sum_j x_{ij} + \lambda_i^0 - x_i^0 = 0 \\ &0 \le x_i^0 \le X_i^0 \end{aligned}\right\} i \in R_1;$$

$$\left.\begin{aligned} &\sum_j \lambda_{ji} - x_{ji} - \sum_j x_{ij} + x_{0i} - x_i^s = 0 \\ &\text{where } x_i^s = x_i^I + X_i^{II} + X_i^{III} - x_i^d \\ &0 \le x_i^{I(\text{II},\text{III})} \le X_i^{I(II,III)} \\ &0 \le x_{0i} \le B_i \\ &0 \le x_i^d \le x_i^I + X_i^{II} + X_i^{III} \end{aligned}\right\} i \in R_2;$$

$$\left.\begin{aligned} &\sum_j \lambda_{ji} - x_{ji} - \sum_j x_{ij} - \lambda_i^+ - x_i^+ = 0 \\ &0 \le x_i^+ \le \min\{X_i^+, S_i\} \\ &0 \le x_i^- \le \min\{X_i^-, V_i - S_i\} \end{aligned}\right\} i \in R_3;$$

$$\begin{aligned} &\sum_j \lambda_{ji} \cdot x_{ji} - \sum_j x_{ij} = 0 && i \in R_4 \\ &0 \le x_{ij} \le X_{ij} && (i,j) \in U. \end{aligned}$$

The minimum discounted costs of gas delivery to consumers and the mathematical expectation of damage due to undersupply of gas for individual nodes are considered as a criterion. The constraints in the form of equations represent gas balances of the corresponding nodes, while the other constraints are set as bilateral inequalities.

In the third module, the above reliability indicators are determined for each design consumer node, and integral performance values, i.e. its utilization factor, are determined for each facility (MGP, UGS, field).

The model of synthesis 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 [22]:

Stage 1. Determination of equivalent reliability characteristics (dependences 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 using them as gas substitutes. For this purpose, we employ the models of reliability analysis of GSS facilities.

Step 2. Optimization of redundancy means of the gas supply system. In doing so we assume that the problems of the upper hierarchical level should be solved first: the network flow problem, i.e. the justified volume of gas production in gas production centers as well as the volume and directions of inter-district gas flows are determined. This solution should be detailed in the seasonal gas consumption optimization model and it must be the basic input for the two-stage approach to model optimal reliability.

We formulate the problem of determining the optimal combination of redundancy methods satisfying at each node of the calculation scheme the balance of incoming and outgoing mathematical expectations of capacity of facilities, providing the consumers with the required volume of gas and reserves of the alternative fuel with the given reliability and under the given constraints:

$$\sum_{(i,j)\in U} \left(c_{ij} x_{ij} + k_{ij} y_{ij} \right) + p_j z_j \to min$$

$$\sum_{i\in \Gamma_j^+} \left(\lambda_{ij} x_{ij} + \pi_{ij} y_{ij} \right) + \alpha_j z_j - \sum_{j\in \Gamma_j^-} x_{ji} = \begin{cases} -Q, \ j = s; \\ 0, \ j \ne s,t; \\ B, \ j = t. \end{cases}$$

$$x_{ij} \le d_{ij}; \quad 0 \le y_{ij} \le d_{ij}^r - d_{ij}; 0 \le z_j \le Z_j \quad .$$

The minimum of the objective cost function is considered as a criterion. It shows balances of incoming and outgoing capacity of facilities with existing redundancy (x) and with additional redundancy means for these facilities (y), as well as taking into account the supplies of a backup fuel (z). For each node, a balance of incoming and outgoing capacity should be maintained (as per Kirchhoff's First Law). The last line shows two-way capacity constraints of facilities.

This problem is solved by standard methods of linear programming.

Figure 7 shows the results of the optimization of system reliability for the Northwestern Federal District during the winter season of 2030, which details the solution of the problem of seasonal irregularity. In order to meet the actual gas demand of the federal subjects in the Northwestern Federal District with the production-to-demand ratio of 0.99, it is required to build up redundant capacity to

supplement the actual capacity of the elements, as well as redundant fuel reserves at a number of consumers in the district, as shown in Figure 7.

4. GSS integrated development models of the third hierarchical level

These include ***the models for the determination of optimal parameters of GSS facilities taking into account their reliability***. The overall process of deciding on the optimal parameters presupposes the following:

1. Multi-variant consideration of the ways of prospective development of the facility under consideration.
2. Analysis of its reliability.
3. The optimal choice of a reasonable option on the basis of calculation of technical and economic performance indicators and integral reliability indicators.

Thus, for example, *the problem of the determination of justified values of parameters of the MGP currently being designed, while taking into account its reliability,* in general terms is formulated as follows.

Based on the average daily MGP capacity (Q), its technical and process (T), reliability (N), and technical and economic performance indicators (E), the basic scheme of the MGP and redundant final backup methods (r) to determine the diameters of a line for line pipes, the number of CSs and installed GPUs that would maximize income Z from gas sales, provided that the specified reliability standard of P^* of gas supply is to be complied with.

$$Z = f(T, N, E, r) \to \max$$

$$P = y(Q, N, r) \geq P^*$$

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 trunkline it is 0.75.

Technical and process indicators (T) are as follows: the MGP length, the list of the number of lines and corresponding diameters, the list of standard sizes of rated GPU capacity (the number of considered options for LPs and CSs).

Reliability indicators (N) are understood as the rate of failure and recovery of LPs and GPUs. As a normative reliability indicator of gas pipeline P^*, we take reliability factor K_n. Its current value (P) is the ratio of the mathematical expectation of performance to its rated value:

$$K_n = \frac{M[Q]}{Q_n}.$$

Technical and economic performance indicators (E) are understood to be: specific annual operating costs and capital expenditures for 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 synthesis (optimization) of structural reliability of the MGP currently being designed the following parameters are determined: the number of lines; corresponding optimum diameters; the number of CSs; the number and length of LPs; the number of operating and redundant GPUs at each CS; optimum rated capacity of GCUs; metal inputs in LPs.

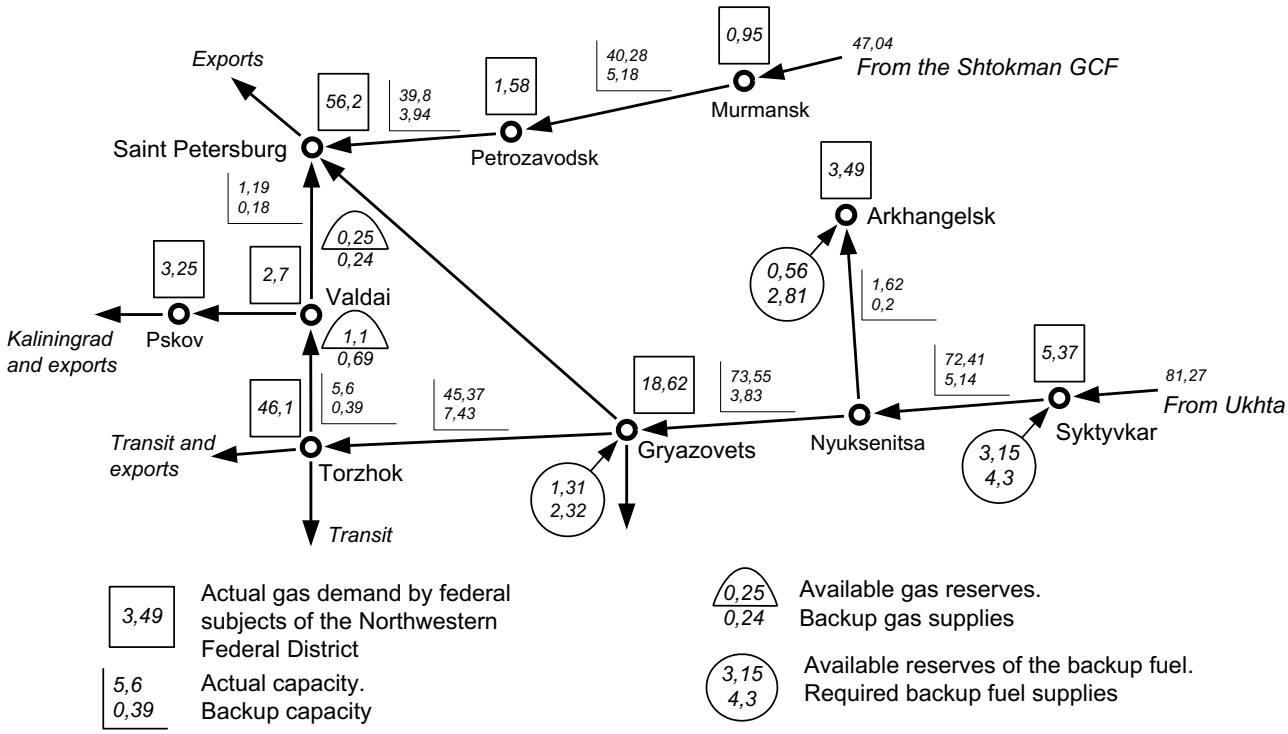

Figure 7. Optimal supply redundancy of the gas supply system of the Northwestern Federal District in the winter period of 2030.

The number of all possible considered options of the MGP currently being designed is equal to the product of the numbers of MGP LP options and GPU standard sizes for the CS and the maximum number of backup units at the CS, which should not exceed the number of operating units.

The above stated problem can be treated as a combinatorial optimization problem. The research-based engineering experience attests to the fact that the number of pipeline development options is relatively small, and all of them can be accounted for by simply cycling through the entire set.

Table 1 shows the results of parameters optimization taking into account reliability of the Kovykta GCF-Irkutsk-Beijing gas transportation system.

5. Comprehensive problems of pricing in the development of gas supply systems

We deal with the following three pricing problems:

1. Determination of retail prices and tariffs for natural gas for individual categories and groups of consumers and federal subjects of Russia.

2. Determination of the components of the wholesale gas price for federal subjects of Russia.

3. Determination of the supply and demand equilibrium between natural gas suppliers and consumers.

Determination of retail prices and tariffs for natural gas for individual categories and groups of consumers in federal subjects of Russia

Here, retail prices and tariffs for natural gas are modeled for selected categories and groups of consumers [4].

Modeling of the average tariff for gas for certain categories and groups of consumers of a federal subject is defined as an arithmetic sum of average tariffs of gas production and gas transportation companies of Gazprom PJSC, independent gas production companies, and gas marketing companies that distribute gas in the given region. That is, according to the existing scheme for gas producing and gas transportation companies, distribution systems of high, medium and low pressure gas pipelines, the path of gas supply to consumers in the region is considered. The analysis of natural gas balance (its incoming and outgoing parts) in the region for a specific period of time is provided. The cost estimates of financing for production, transportation, and gas distribution serves as a basis to determine the cost of production, contributions to investment funds, profits for auxiliaries and payments into the budget. That is, there are contingently variable and contingently fixed costs for which the average tariff (price) is calculated.

$$T_y^{\text{avg}} = T_{\text{gas-aux}}^{\text{avg}} + T_{\text{oil-gas}}^{\text{avg}} + T_{\text{gas-aux}}^{\text{avg}} + T_{\text{vat}}.$$

The two-rate tariff for gas for certain categories and groups of consumers of the federal subject is calculated as the sum of products of the rate for daily capacity and estimated gas demand and annual capacity, as well as the rate of the value added tax.

$$R_n = T_n^{day} \times q_n^{\max} + T_n^{year} \cdot Q_n + T_{vat}.$$

Methodological and practical issues of studying the impact of prices and tariffs for natural gas were used in determining the profitability levels of various aluminum production options at the Bogoslovsk Aluminum Smelter (BAS), see Figure 8 [23].

The profitability level of the Bogoslovsk Aluminum Smelter is set as a function of primary aluminum prices at London Metal Exchange, Table 2.

The data presented in the table shows that the efficiency of the plant's operation by years may decrease due to a significant increase in natural gas prices and tariffs. Even given a relatively high LME primary aluminum price of over $1,500 per ton in 2020, the production of the plant's marketable products may prove to be not profitable.

Table 1. Optimization of gas transportation system parameters Kovykta GCF – Irkutsk – Beijing, with reliability factored in.

Parameter	Kovykta GCF - Irkutsk	Irkutsk-Beijing
Diameter and number of lines	1220x2+1420	1420
Pipeline length, km	470	2170
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	2.35	2.32
per 1 km, million USD		
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	1634

Determination of wholesale gas price components for federal subjects of Russia

This problem is solved in two stages [24]. At the first stage (the direct problem) for the existing gas supply system for a given period of time on the basis of the network flow model, the optimal gas distribution and dual estimates (marginal nodal prices) are calculated.

The problem makes use of an address-based algorithm that allows determining the volume of gas entering consumption node *i* from any node *r*, it makes it possible to distribute the cost of gas transmission over the links between gas consumption nodes.

With the help of the address-based algorithm, the nodal gas price is spread over eight constituents $\overline{h}_i^M = \overline{h}_i^1 + \overline{h}_i^2 + \overline{h}_i^3 + \overline{h}_i^4 + \overline{h}_i^{M5} + \overline{h}_i^{M6} + \overline{h}_i^{M7} + \overline{h}_i^{M8}$, that are determined as based on the following: $\overline{h}_i^1$ – gas production; $\overline{h}_i^2$ - gas losses; during production $\overline{h}_i^3$ – by gas transportation; $\overline{h}_i^4$ – by losses due to transportation; $\overline{h}_i^{M5}$ – marginal gas production premium; $\overline{h}_i^{M6}$ – marginal gas production added loss; $\overline{h}_i^{M7}$ - marginal gas transportation addition; $\overline{h}_i^{M8}$ - marginal added gas transportation loss. The first four constituents represent the cost-based gas price at the node of the calculation scheme, the remaining constituents represent the marginal markups added to this price.

On the basis of the above methodological approach for the aggregate Unified Gas Supply System, direct and dual problems of linear programming were solved by calculation for year 2005. Cost-based and marginal nodal prices are determined using the address-based algorithm, see Figure 9. The prices for federal subjects of Russia set by the RF Federal Energy Commission (FEC) are also shown here.

Such a methodological approach to determining the components of the wholesale price of natural gas makes it possible to evaluate in an unbiased way the wholesale prices set by the RF FEC and shows the bottlenecks in the gas supply system where the price increase takes place.

Determining the balance of supply and demand between suppliers and consumers of natural gas.

Gas consumption and supplies are considered in terms of market competition in the single-product wholesale market [4]. The natural gas market in the Russian Federation is scattered across various federal subjects, therefore, wholesale prices of gas supply and consumption will also vary. The gas supplier is Gazprom PJSC, a monopolist company, therefore it is impossible to determine the equilibrium price of gas purchase and sale, as the monopolist maximizes their profit by simultaneously setting the values of gas price and sales volume. It would be advisable to suggest a regulator that would suit both the monopolist and consumers. Such a regulator can be based on the concept of the two-person zero-sum game.

Gas consumers and gas producers place their bids into wholesale markets of federal subjects of Russia. Consumers want to buy gas at the lowest possible price, while producers are willing to sell it as expensive as possible. There is a conflict of interest between the supplier and the consumer.

This conflict can be resolved by solving the problems of the flow of the cost of extreme capacity of gas production and transportation:

$$\sum_{(i,j)\in U} \delta_{ij} z_{ij} \to ext$$

$$\text{(i.e. } \sum_{(i,j)\in U} \delta_{ij} z_{ij} \to min \text{ or } \sum_{(i,j)\in U} \delta_{ij} z_{ij} \to max\text{);}$$

$$\xi_{ij} z_{ij} - \sum_{i\in \Gamma_j^-} z_{ji} = \begin{cases} -\left(\overline{Z}_u + \overline{Z_T^T}\right), \ j = s; \\ 0, \ j \neq s,t; \\ 3, \ j = t. \end{cases}$$

$$0 \le z_{ij} \le \overline{z}_{ij}, \left(i,j\right) \in \overline{U}.$$

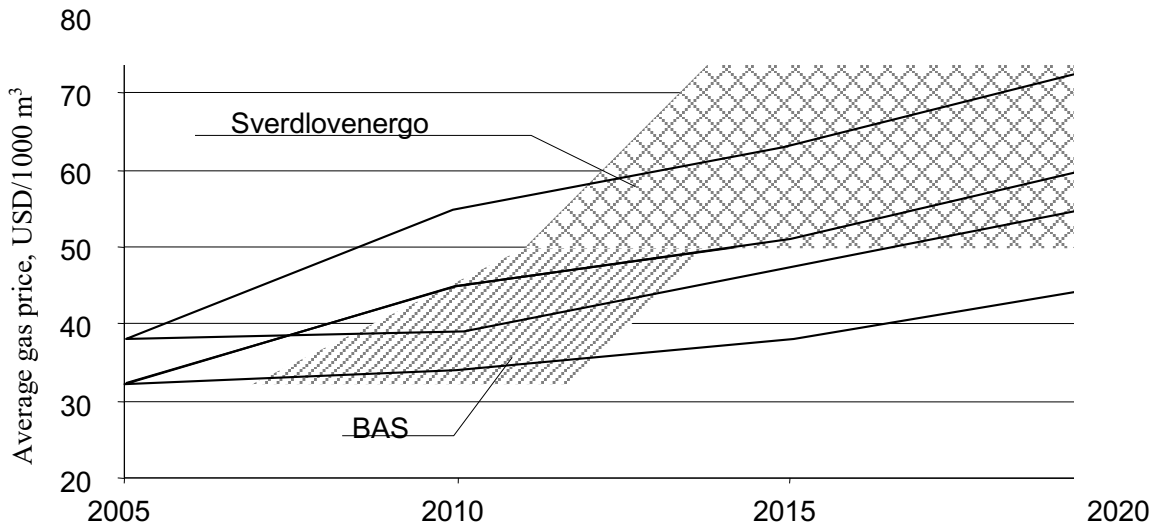

Fig. 8. Dynamics of natural gas prices for Sverdlovskenergo and BAS.

Table 2. Dynamics of profitability of the bogoslovsk aluminium smelter.

Indicators		Profitability, %			
		2005	2010	2015	2020
1. LME primary aluminium price, USD/t	1200	- 3.1	- 7.8	- 12.5	- 17.9
	1300	2.5	- 2.4	- 7.3	- 13.0
	1400	8.1	2.9	- 2.2	- 8.2
	1500	13.5	8.1	2.7	- 3.5
	1600	18.8	13.1	7.6	1.2
	1700	23.9	18.1	12.4	5.7
	1800	29.0	22.9	17.1	10.2
2. Dynamics of increase in average prices of energy resources, %	Natural gas	100	123	139	165

The objective function minimizes or maximizes the capacity of gas production and gas transportation flows. Balances of gas cost inflow and outflow at the nodes of the calculation network and constraints on cost flows and links of the calculation graph are shown.

If the problem is stated as that of searching for the minimum performance and transport, then we arrive at the problem of the most favorable distribution of cost flows from the point of view of gas suppliers (the most expensive production and transport companies will be selected first as part of the optimal plan, while the cheapest ones will be the last to make it to the plan). In this case, the declared cost is satisfied by the minimum volume of production and transportation at the maximum selling price.

If the problems is stated as that of searching for the maximum performance of gas production and transportation, then we arrive at the problem of the most favorable distribution of cost flows from the point of view of gas consumers (here, the cheapest production and transportation companies will be selected first as part of the optimal plan, while the most expensive ones will be the last to make it to the plan).

The declared value is satisfied by the maximum volume of production and transportation given the minimum sales prices.

A rational solution can be found in an iterative process that results in optimal cost flow allocation plans from the point of view of consumers and gas suppliers. The natural gas producing and transportation companies most efficient from the view of consumers and suppliers are selected. The capacity of these sources decreases by some Δ-value, i.e. new constraints are defined. The iterative calculation process continues until the minimum and maximum objective functions coincide with some specified error.

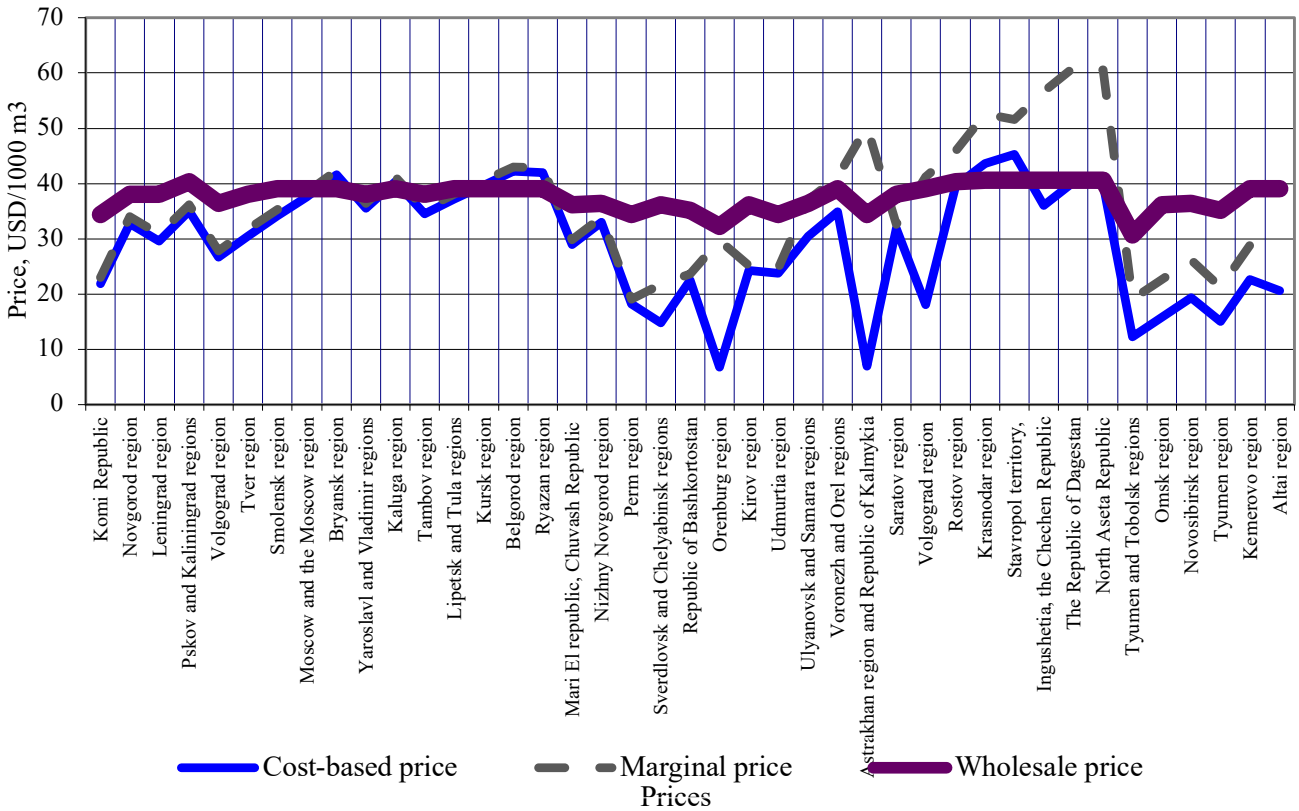

Figure 9. Wholesale gas prices calculated or set by the RF Federal Tariff Service for federal subjects of Russia.

Solving the problem may result in three options.

1. Gas purchase prices at wholesale markets are equal to sales prices of gas sources and routes of gas supplies to consumers.
2. The desired gas purchase prices will be higher than gas supply prices. In this case, more gas will be purchased at the same cost given a lower price.
3. The gas purchase prices will be lower than the gas supply prices. Given this relationship, consumers will buy less gas at the same cost.

In the first option, finding the balance of supply and demand is considered complete. The second and third ones require further research, which should determine at what prices of gas consumers and suppliers their objective functions will prove equal.

The testing and identification of the model's possibilities in studying the optimal cost flows from the point of view of gas suppliers and consumers was carried out on the basis of the calculation scheme of gas supply of the Ural Federal District.

Eight iterative calculations were performed. The eighth iteration resulted in the convergence of the values of the objective functions given the specified error. Gas consumption volume declared and received as a result of optimization in the scattered markets is shown in Table 3. In the gas markets of nodes 3 – 8, the declared prices of gas purchase are less than the prices offered by the gas supplier. Therefore, 20.2 billion m^3 less gas will be purchased at the Igrim node market for the same cost of gas purchase and sales; accordingly, a smaller volume of gas will be purchased in the markets of the following nodes: Nizhnyaya Tura – by 37.7 billion m^3, Polyanskaya – by 12.4 billion m^3, and Surgut – by 1.6 billion m^3. On the other hand, in the markets of nodes 6 and 7 the desired gas purchase prices are higher than the gas supply prices, therefore, at the Dolgoderevyanskaya node it is possible to buy 0.5 billion m^3 more gas than it was declared, and at the Tyumen node it is possible to buy 0.9 billion m^3 more gas.

V. Conclusion

1. Taking into account the general issues of aggregation of companies of gas supply systems, the hierarchical modeling of optimal development was considered, which is: 1) structure optimization and investment processes; 2) optimization of seasonal gas consumption, reliability analysis and synthesis; 3) optimization of parameters of a facility with its reliability factored in, as illustrated by the main gas pipeline.
2. The principles of gas pricing and methods of gas price calculation are given, namely the determination of the following: retail prices and tariffs, wholesale gas price, and its components for federal subjects of Russia, balance of supply and demand between gas suppliers and consumers.
3. Optimization calculations were carried out on the basis of the proposed multi-level modeling methodology for the gas supply system development: the volume of gas production and transportation for the averaged scenario of consumption in the Russian Federation, the choice of investment area, justified seasonal irregularity of gas consumption in the Northwestern Federal District, backing up the gas supply system of the Northwestern Federal District during winter periods, parameters of the Kovykta GCF-Beijing MGP.
4. On the basis of the developed methods of gas prices calculation, the following was determined: natural gas tariffs for Sverdlovskenergo, which made it possible to establish a justified level of the rate of return of the Bogoslovsk Aluminum Smelter depending on the London Metal Exchange primary aluminium prices;

Table 3. Gas consumption volumes as declared and resulted from optimization in scattered gas markets.

Node code	Node name	Inflow		Outflow		Entered the markets, billion m3.	Declared consumption, bcm	Gas shortage, bcm
		Link name	bcm	Link name	bcm			
3	Igrim	Nadym - Igrim	408.8	Igrim – Nizhnyaya Tura	348.5	60.3	80.5	20.2
4	Nizhnyaya Tura	Igrim – Nizhnyaya Tura	348.5	Nizhnyaya Tura - Polyanskaya	137	211.5	249.2	37.7
5	Polyanskaya	Nizhnyaya Tura – Polyanskaya	137			145	157.4	12.4
		Dolgoderevenskayaя – Polyanskaya	8					
		Total	145					
6	Dolgoderevenskaya	Tyumen – Dolgoderevenskaya	27.5	Dolgoderevenskaya - Polyanskaya	8	19.5	20	-0.5
7	Tyumen	Surgut – Tyumen	60.4	Tyumen – Dolgoderevenskaya	27.5	32.9	32	-0.9
8	Surgut	Urengoy – Surgut	11.3	Surgut – Tyumen	60.4	0.9	2.5	1.6
		Surgutgazprom	50					
		Total	61.3					
Total						470.1	541.6	71.5

components of the wholesale natural gas price for federal subjects of Russia that are instrumental in making unbiased evaluation of the price level set by the the RF Federal Energy Commission.

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