MODELING THE INTERCONNECTED OPERATION OF ENERGY SYSTEMS FOR ENERGY SECURITY STUDY IN TODAY'S CONTEXT

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Abstract

The paper shows the need for comprehensive research into energy security problems to assess the possibilities of interconnected operation of all energy industries with the view to identifying the implications for consumers of energy resources in the event of emergencies in one or several industries at the same time. The paper presents a methodological framework and features of modeling the interrelated operation of the industries in current context and a model developed for these studies. The results of experimental studies using the developed methodology are shown through the analysis of several critical situations (threats to energy security) of various nature.

Keywords: energy security; critical situations; economic and mathematical model.

I. Introduction

Ensuring energy security and maintaining reliability of fuel and energy supply are crucial in today's social and economic landscape. Energy security (ES) is of utmost importance for protecting the citizens, society, the state, and the economy from the threat of a shortage when meeting their energy needs with economically affordable energy resources of high quality and from the threats of potential disruption of constant energy supply [1, 2]. Essentially, we are discussing the importance of maintaining the balance between the supply and demand of different kinds of fuel and energy when various kinds of threats that affect the energy sector and lead to a decrease in the supply of consumers with energy resources come into being [3].

Energy systems form the energy sector of a country or individual regions. The fuel and energy sector of the country is one of the largest intersectoral complexes, including formally independent industries, such as electric power, thermal power, coal, oil, oil refining and gas industries, which are united technologically and territorially [4,5, 6]. At the present level of consideration, it is crucial to highlight and incorporate renewable energy, cooling energy, water management system, and water supply system into the structure of the energy sector.

The primary objectives of the energy security research are to predict the conditions for the operation and expansion of fuel and energy systems and the development of the energy sector as a whole in the context of possible critical situations and emergencies; to provide state estimation under these conditions and to identify "bottlenecks" in fuel and energy systems, and in the energy supply to the consumer; to choose possible alternatives and specific measures to prevent critical situations and emergencies in these systems and at energy facilities, or reduce their negative impact to an acceptable level [7, 8]. In the current context, it is imperative to enhance the existing methodological, modeling, and software tools and develop new ones for conducting such studies, since the concept of risk of critical and emergency situations and their consequences is becoming increasingly prominent. Of particular importance is analysis of potential threats, the development of disturbance scenarios (critical situations and emergencies) based on the analysis results, and the related modeling problems [8].

Assessment of the energy security level normally rests on two methods: an indicator-based method, which is the primary and simplest way of assessing the level of energy security, and a method based on mathematical modeling of the interconnected operation of energy systems. The second method is used to investigate and assess the impact of energy security threats on the reliability of energy supply to consumers with adequate mathematical models of energy components and systems.

The indicator-based method has found wide application in the analysis of the energy security level in many countries, since the indicators obtained are the most understandable and minimal effort is required to determine them. Despite its simplicity, this method is quite effective for energy security assessment.

In Russia, since the 1990s, the indicator-based method of analysis has been widely developed in the works performed by the research team of L.A. Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, which focused on the energy security studies for the country and its regions [9-14]. These works offered a wide set of parameters (indicators) to characterize the state and conditions for the expansion and operation of individual energy systems and the levels of threats to energy security [10]. The developed system of indicators was applied to assess the state of energy security of Russia's regions [11, 12]. A methodology developed for the indicator-based analysis determines:

a) a set of energy security indicators at the federal level;
b) a procedure for obtaining the numerical value of each indicator from this set;
c) a procedure for determining threshold values for each indicator at issue [13].

The impact of energy security threats on the reliability of fuel and energy supply to consumers was also assessed using the method of indicator-based analysis [14].

Researchers in other countries use the method of indicator-based analysis to assess the level of energy security based on the indicators established for their country. Eighteen indicators are used for China [15]. They are categorized into three areas: energy supply, economic-technical, and environmental. The studies carried out for six countries of the Caspian Sea basin (Azerbaijan, Iran, Kazakhstan, Uzbekistan, Turkmenistan, Russia) aim to analyze the level of energy security [16] for each country individually and collectively based on three dimensions: resources and dependency, intensity and sustainability, cost and poverty.

At the same time, the indicator-based analysis is static and yields an assessment of the indicators for a specific time span, neglecting the influence of the dynamics of processes in the energy sector and the influence of the system-wide effect from the mutually coordinated operation of energy systems. Therefore, studies of the interrelated operation of energy industries and their modeling to assess the impact of energy security threats on reliability of energy supply are of greatest interest.

Modeling the interconnected operation of industry systems can be divided into two categories: modeling of concentrated nodes, this modeling concept is also called the concept of an energy hub, and detailed modeling of energy systems, which either partially or fully considers the transmission links between individual nodes.

Studies based on the concept of energy hubs [17-19] normally present an energy hub model involving interaction of three types of energy resources (heat, electricity, and gas). These studies also take into account renewable generation and the possibility of using energy storage systems (ESS). Particular interactions of energy flows are considered, for example, modeling the interdependence of the gas and electric power industries [20]. The main difference between the models lies in the description of the production capacities of the region for the processing and storage of energy resources in the form of energy nodes or hubs. For example, regional condensing power plants (CPPs), combined heat and power plants (CHPPs) and boiler houses are combined into an energy hub to generate heat and electricity. This method of description offers a convenient scheme for presenting the initial data and simplifies the architecture of the corresponding software, which provides a gain in time during distributed computing. In this case, the focus is on simplification of calculations but without sufficient consideration of the links between industries as an interconnected system.

The second approach to modeling the interrelated operation of various sectoral systems is more preferable for investigating energy security problems and analyzing threats to the normal functioning and expansion of sectoral energy systems. The analysis of the current state of research in this area helped identify the following areas: 1) research on the conceptual area of the energy security problem in terms of reliable energy supply and 2) research on modeling energy systems and energy sector.

The papers [21-26] present the results of studies that involve assessing the possibilities of network flow modeling of resource supply processes with a sharp deterioration in the properties of the energy infrastructure. These works examine power supply options in geographically distributed systems after destructive impacts. The studies focus on the conditions of regulatory restrictions on accidents, in contrast to the research presented in this paper, which considers all possible emergency situations, analyzes threats and their manifestations, evaluates the operating conditions of sectoral systems in this context, assesses the reliability of supplying the consumer with energy resources (in the form of undersupplied amounts).

The studies presented in [27] are also close in their formulation of the problem. They are aimed at solving the security problem for a group of target objects that receive energy resources from the network infrastructure in case of a negative impact on the network components. The problem solved however belongs to the industry level of the hierarchy. At the same time, a comprehensive assessment of energy facilities with their mutually coordinated operation within a single system is not carried out.

Of some interest are studies related to the energy independence of countries importing energy resources, and the related issues of creating reserves of these energy resources and diversifying them in the event of supply disruptions. In these studies [28], a quantitative model of the energy security of the country (China) is proposed to calculate the optimal scale of strategic reserves of oil and alternative fuels (for example, coal-fired methanol). The developed model mainly focuses on cost-benefit analysis, including the economic costs of creating such reserves and reserves of alternative fuels, and thereby increasing the energy security of the country. The results of experimental calculations for China show that the creation of strategic oil reserves and alternative fuels have a positive effect on energy security, and alternative fuel is an additional way to reduce the negative consequences of rising oil prices and related economic losses. This approach can be used when creating structural redundancy in case of emergencies affecting the energy supply of consumers.

There are important developments in modeling energy systems and energy sector, with two classes of models to be distinguished: 1) simulation ones that optimize the technological structure of the energy industry; 2) economic or macroeconomic ones, in which energy is presented as a sector of the economy as a whole.

The main representatives of simulation class models are MARKAL (MARKet ALlocation), EFOM (Energy Flow Optimization Model), MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts), and others [29-32].

The MESSAGE model is the most widespread. It was developed by the International Institute for Applied Systems Analysis (IIASA) with the view to planning and projecting the expansion of energy systems. This modeling system is intended for medium- and long-term expansion planning of energy systems, energy policy analysis, and design of development scenarios. This tool allows comparing alternative energy technologies and build the most appropriate scenario for the development of the energy system. It also enables comparison of alternative scenarios for the development of the energy system in terms of environmental impact. The linear programming method is used to find the optimal solution in MESSAGE. The selection criterion is the minimum of the reduced system costs. According to the objectives to be accomplished, this model tool is focused on a time interval under average statistical conditions of development. Therefore, it cannot be used to study the response of sectoral systems to disturbing influences when threats to the normal functioning of industry systems and consumer systems materialize, which is proposed to be used in this article.

The main representative of the second class is the National Energy Modeling System (NEMS) developed by the US Department of Energy [33].

This system models the US economy with the allocation of energy as a separate sector. This model makes projections for energy production, import, processing, consumption and prices, given the macroeconomic and financial indices of the world market for energy resources; supports the choice of certain technologies, their quantitative and qualitative characteristics. Adaptation of this modeling system to assessing the behavior of the energy industries and the consumer sector in critical situations is not possible for the following reasons:

- The considered time intervals do not coincide;
- The insufficiently detailed representation of the energy industries in the complex;
- The impossibility of determining the shortage of energy resources in the event of emergencies in the energy industries.

The most representative domestic development in the field of energy system modeling is the SCANER model-information system developed at the Energy Research Institute of the Russian Academy of Sciences [34]. This is a unique tool for systems research into the development of Russia's energy sector as an important part of the national economy, and global energy markets in the medium and long term (until 2030-2050). SCANER combines powerful analytical tools, about twenty mathematical models for comprehensive projection and optimization of the national and global energy development for the main stages of energy conversion - from production (about 20 types of primary energy resources) to consumer use (10 main energy carriers). The analyzed tool is aimed at studying the prospects for the development of the country's energy economy under normal operating conditions, considering the influence of global factors. At the same time, the reliability of power supply is taken into account according to average statistical standards, leaving extreme situations out of consideration. It is problematic to use it to investigate the mutually coordinated operation of energy industries in critical situations, since this tool does not determine the impact of energy shortages on the reliability of fuel and energy supply to the consumer.

The presented developments and models focus on solving the problems of long-term planning of the power industry under normal operating conditions with a horizon of up to 15-20 years. The studies conducted and described in this paper stand out by their emphasis on assessing the behavior of energy systems in the face of energy security threats and optimizing the interrelated operation of energy systems in the event of emergencies to provide reliable energy supply to consumers.

Modern conditions for the advancement of information technologies, the emergence of high-performance computing tools, as well as the intelligentization of energy systems and the need for their functioning in a digital economy, on the one hand, impose special requirements on the modeling and computing tools to be used. On the other hand, they provide opportunities to enhance the adequacy and correctness of modeling the real-world systems by considering the inertia of processes, the dynamics of unfolding critical situations in the models designed to optimize energy systems within the energy sector; by taking into consideration non-linearity in terms of the adequacy of the representation of processes in energy systems to improve the accuracy of decisions made.

This paper aims to present a methodological tool for modeling the interlinked operation of energy systems within the energy sector for examining energy security problems and illustrating the outcomes achieved by applying the developed models.

II. Methodology for integrated modeling of energy systems to solve the energy security problems.

To investigate the problems of energy security in today's context, it is proposed to develop new and improve (adapt) existing mathematical models and methods of the interrelated operation of large energy systems within energy sector under various operating conditions. The use of an enhanced modeling system will make it possible to assess the possibilities of providing consumers with energy resources when various threats to energy security materialize.

The general scheme of tasks to be accomplished when assessing the effect of threats on the state of energy security is shown in Figure1.

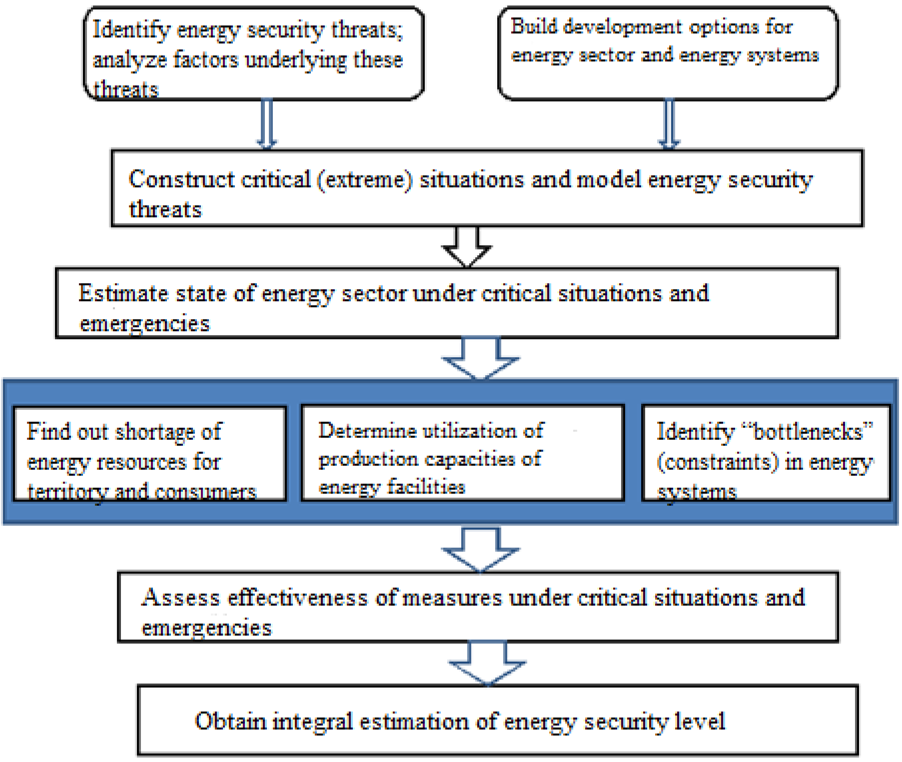


Figure 1. *General scheme of energy security research*

The initial basis for the research is the technical and economic characteristics of energy facilities and reporting data on the state of energy systems, the findings of the energy development research providing the rationale for the choice of a long-term strategy and the formulation of an energy policy. Based on the adopted socio-economic program for the future development of the national economy, which determines the demand for fuel and energy resources, an analysis and assessment of energy consumption levels is made considering energy conservation.

Following the above characteristics and analysis of energy security threats, the design conditions are established for a computational experiment, which is carried out using models of energy systems.

Models of energy systems represent ***a system of economic and mathematical models for assessing the territorial and production structure of the energy sector, in terms of energy security requirements*** [35]. These models can be used in two modes:

- in the mode of determining the optimal development of energy technologies (given structural redundancy in the form of capacity reserves, fuel reserves, interchangeability of energy resources) and the optimal distribution of consumed energy resources,

- in the mode of identifying undersupply of energy resources (shortage in fuel and energy resources) in the country as a whole and in individual regions.

The structure of the energy sector is shown in Figure 2. Technologically, it consists of the modules of industry-specific subsystems of the energy sector (gas, coal, oil refining (in terms of fuel oil supply), electricity, and thermal power industries), and a module of consumers (consumption of energy resources at various types of power plants and boiler houses for generating electricity and heat, and other consumers, with separately allocated export consumers). This version does not include energy storage systems, water management and water supply systems.

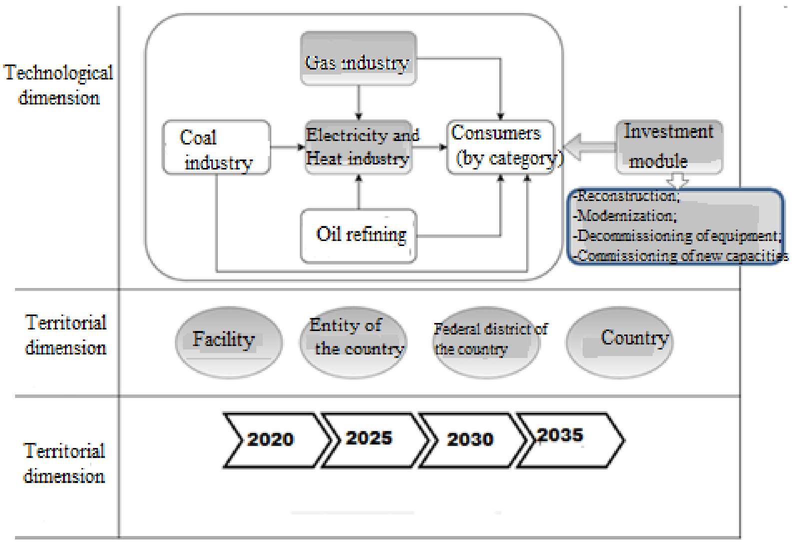


Figure 2. *Territorial, temporal and technological structure of models*

The mathematical description of the model is represented by balance equations and constraints on variables and the corresponding objective function.

$$AX - \sum_{t=1}^{T} y^t = 0, \tag{1}$$

$$0 \leq X \leq D, \tag{2}$$

$$0 \leq Y^t \leq R^t, \tag{3}$$

where t is consumer category; X is the desired vector, with the components characterizing the intensity of using technological methods for operation of energy facilities (extraction, processing, conversion and transportation of energy resources); Y^t is the desired vector with the components characterizing the volumes of individual types of fuel and energy consumed by certain categories of consumers (t); A is matrix of input-output ratios of production (extraction, processing, conversion) and transportation of individual types of fuel and energy (inputs - output); D is a vector that determines the technically possible intensity of using individual technological and production methods; R^t is a vector with components equal to the volumes of specified consumption of individual types of fuel and energy by individual categories of consumers.

The objective function has the following form:

$$(C, X)+\sum_{t=1}^{T}(r^t, g^t) \rightarrow \min. \tag{4}$$

The first component of such an objective function reflects the costs associated with the operation of the industries within the energy sector, its constituent energy systems and subsystems, and capital investments for their development. Here *C* is the vector of unit costs for individual technological methods of operation of existing, reconstructed or modernized, as well as newly constructed energy facilities.

The second component is the damage from shortages for each type of fuel and energy for each of the selected consumer categories. The magnitude of the energy resource shortage (g^t) for consumers of category t corresponds to the difference (R^t – $У^t$). Vector r^t consists of components conventionally called "specific damages." The cost assessment of the real (full) amount of damage caused by a shortage poses certain difficulties due to the various manifestations of the consequences of a shortage of energy resources, which cannot always be identified and quantified. In this case, this difficulty is (rather conventionally) overcome by introducing a scale of priorities in meeting the demand of the consumer of the categories at issue for certain fuel and energy types.

The final implementation of the models includes a financial module that describes the investment costs for reconstruction, modernization of existing facilities, decommissioning of obsolete equipment, and commissioning of new facilities at energy facilities. With these models, it is also possible to take account of the development dynamics, which allows tracking such features of the multi-stage development process of the energy sector as:

- commissioning of new production facilities;
- dismantling and conservation of old facilities,
- reconstruction of facilities with a change in the flow diagram.

Consideration of dynamics is implemented in the form of *T* independent static modules, each of which describes all the territorial and technological links of the energy sector for stage *t* of the considered period. Dynamic connections between modules are built using equations that formulate for all x_i facilities of the energy sector the condition for the continuity of their productive capacities at various stages of the considered period. This condition for the first stage is written as

$$x_{i1}^o + x_{i1}^c + x_{i1}^d = P_{i0}, \tag{5}$$

and for subsequent stages, it is written in the form of equations

$$x_{it-1}^o + x_{it-1}^c + x_{it-1}^n = x_{it}^o + x_{it}^c + x_{it}^d, \tag{6}$$

where P_{i0} is productive capacity of technology (facility *i*) by the beginning of the considered period,

x_{it-1}^n is productive capacity of a new part of technology (facility *i)* in stage *t-1,*

x_{it}^o is productive capacity of the operating part of the technology (facility *i*) in stage *t*,

x_{it}^c is conservation of part of facility *i* in stage *t*,

x_{it}^d is liquidation of part of facility *i* in stage *t*.

For the convenience of building the connections, equation (6) is divided into two parts

$$-x_{it-1}^o - x_{it-1}^c - x_{it-1}^n + Z_{it-1} = 0,$$

$$-Z_{it-1} + x_{it}^o + x_{it}^c + x_{it}^d = 0,$$

where Z_{it-1} is an intermediate variable characterizing the overall performance of facility *i* at the beginning of stage *t*. It takes into account the retirement of capacities in stage *t* and the introduction of new capacities in the stage *t+1.*

In general, these models are used to determine the following characteristics (indices):

- the size of undersupply (shortage) in certain types of energy resources for the categories of consumers at issue, selected territorial entities and the entire country, as the value of discrepancy between set demand and feasibility of producing this type of energy resource (considering such factors as the reserves, the possibilities of replacing this type of energy resource in other consumers, etc.);
- changes in the capacity of transportation links, which are determined by comparing the relevant indicators of the considered option with the original one;
- rational use of production capacities of energy facilities, and the distribution of certain types of energy resources according to selected categories of consumers.

The backbone module in the energy sector model is the one of electricity and heat industry, therefore, correct modeling of the facilities that constitute the system boosts the adequacy of the model.

The developed modeling system consists of industry models connected by information flows and an integrating model of the energy sector as a whole. This system makes it possible to enhance the existing practice of assessing the materialization of energy security threats through:

- identifying the mutual influence of energy systems on each other and comprehensively assessing the impact of energy security threats;
- considering the dynamics of the development of critical situations in the models of optimization of energy systems within the energy sector;
- taking into account the load curve, which imposes requirements of the consumer on industry systems;
- taking into consideration nonlinearity in terms of the adequacy of the representation of processes in energy systems to improve the accuracy of decisions made (in models of industry systems);
- allowing for natural factors in terms of their impact on the operation of renewable energy sources (periods of low water for hydropower plants, cloudy days for solar power plants, low-wind periods for wind turbines);
- considering the influence of inertia in the gas, coal, and oil refining industries on the development of emergencies in them and relate them with their unfolding in the electricity industry, which is a backbone for the energy sector.
- taking into account the specific features of the mutual influence of the gas and electricity industries when meeting the conditions for the reliability of gas and electricity supply to the production facilities of these industries;
- taking into consideration the specific features of the mutual influence of the oil/oil refining and electricity industries when meeting the conditions for the reliability of electricity and oil products supply to the production facilities of these industries.

III. Case study. Assessment of a shortage caused by critical situations in energy systems.

There are many energy security threats of which the natural and technology-driven are the most common ones. We will analyze the materialization of several of them in a real energy sector.

For countries with harsh climatic conditions, a particularly urgent threat is the threat of a sharp cooling. Critical situations in the fuel and energy supply arise from the rapid and widespread cooling that can envelop vast areas of the country. At the same time, depending on the climatic conditions of a particular region and the type of consumers, the maximum seasonal heating loads can deviate from the average annual values by a significant amount, up to 20-30%. The threat of a cold snap is extremely relevant for Russia. Modeling and analysis of the threat of a sharp cooling and its implications will be made on the example of the Russian energy sector. The calculations assumed a decrease in the average outdoor air temperature during one quarter of the heating season in the European part of Russia by 2°C versus the long-term average, which will lead to an increase in the demand for boiler and furnace fuel by about 8% (Critical situation (CS)1).

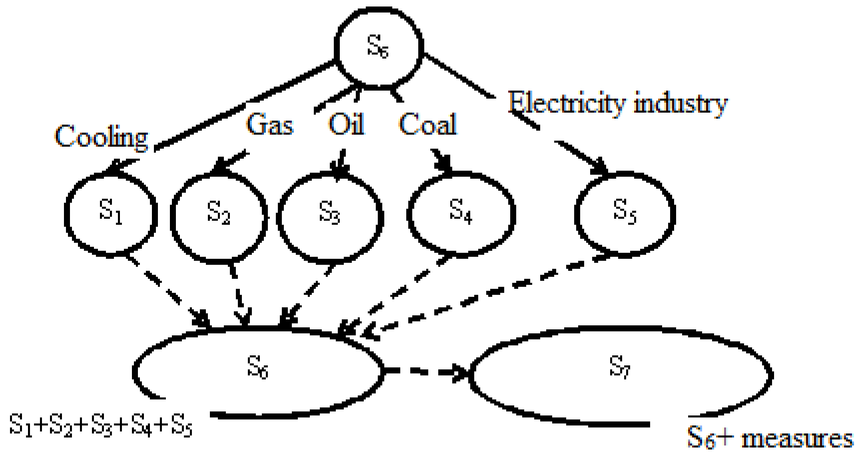
One of the most dangerous (in terms of consequences) situations in the gas supply system is the possibility of damage to transcontinental gas pipelines. This threat is especially acute with a large share of gas in the production of electricity and heat, which is typical of some regions of Russia. The possibility of failure of one of the main gas pipeline sections was considered as the design conditions for a critical situation in the gas supply system. This situation, given the restoration work leads to a decline in gas supply to some regions of Russia by 5% per quarter (CS 2).

In the oil system, it is important to analyze the impact of a decrease in the fuel oil supply from regions where large oil refining capacities are concentrated and possible complications of a various nature, including socio-political ones. At the same time, disturbances were introduced into the model in the form of a decrease in the fuel oil supply by 8% of its total production during the analyzed period (CS 3).

In coal supply, a potentially dangerous situation is when a high proportion of coal comes from one source. In this case, the design conditions provide for a 30% reduction in coal supplies to power plants in one of Russia's regions and a similar reduction in coal supplies from another region (CS 4).

Currently, one of the dangerous factors for reliable fuel and energy supply is the imbalance of some regional electric power systems. Therefore, consideration was given to the consequences of the rupture of backbone ties in the electric power industry. In addition to this, a possible reduction of 30% in the capacity of nuclear power plants in one of the energy systems was introduced (CS 5).

Furthermore, the issue of potential overlap between the aforementioned disruptions (CS 6) and the potential utilization of additional reserves of fuel oil and coal equivalent to a 10-day demand (CS 7) was considered. While it is highly improbable for all critical situations to overlap, this circumstance provides a valuable opportunity to evaluate the limitations of the energy sector in meeting the fuel and energy demands of consumers. In addition, it emphasizes the importance of mutual reservation of energy systems and regions in the face of a global deterioration in energy conditions. The diagram for the formation of emergency situations is shown in Fig. 3.



S_1 - Cooling	S_2 - CS in gas system
S_3 - CS in oil system	S_4 - CS in coal system
S_5 - CS in electricity system	S_6 - CS (a combination of S_1,S_2,S_3,S_4,S_5)
S_7 - CS with potential use of additional fuel reserves (preventive measures)	

Figure 3. *Scheme of formation of critical situations.*

An analysis of calculations based on the generated scenarios of critical situations indicates that the most significant situations in terms of their consequences for consumers of energy resources proved to be those with cooling (CS 1) and mutual overlap of critical situations (CS 6). A good example is the shortage observed in the case of a decrease in fuel supplies and other disturbances (CS 1-CS7) (Fig. 4).

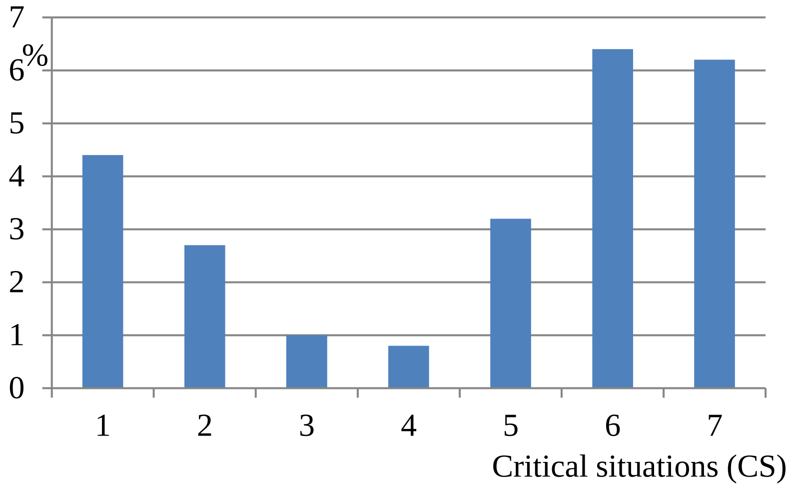


Figure 4. *Electricity shortage in critical situations №№ 1-7, % of the needs.*

Disturbing impacts caused by a combination of critical situations (CS6) had a greater impact on the systems of coal, electricity, and heat supply. The overall shortage of coal in the country amounted to about 11% of its total consumption, electricity and heat shortage was about 6% (Fig.5).

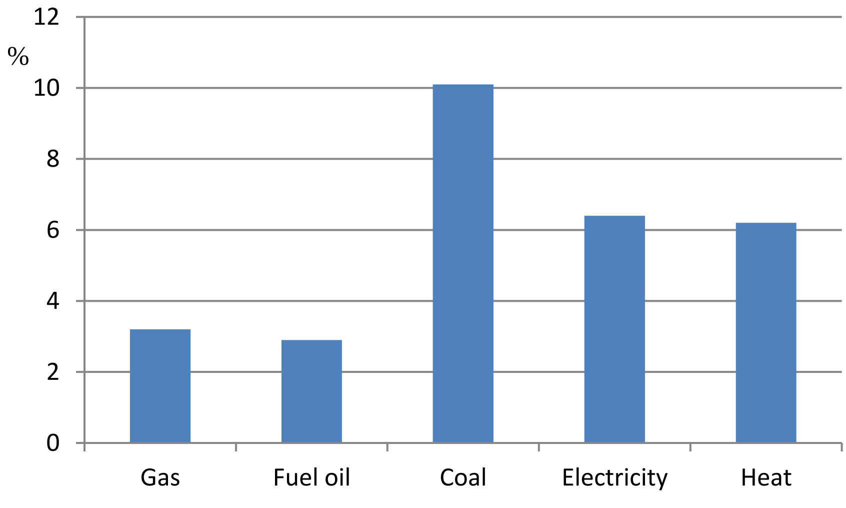


Figure 5. *Shortage of energy resources in CS, % of the needs.*

There is no shortage of resources in gas and fuel oil systems, but there has been a decrease in gas and fuel oil consumption at power plants and boiler houses. This led to a greater consumption of coal for the production of heat and electricity, resulting in a significant shortage of this fuel. This is explained by the fact that the closing type of fuel in this implementation of the model is coal.

The cooling and rupture of links in the electric power system and the reduction in the power of nuclear power plants, assumed in the calculations (CS 5), resulted in a shortage of electricity throughout country by about 7% (with the full use of the available backup generating capacities of thermal power plants).

The introduction of additional fuel reserves (coal and fuel oil) into the model in the amount of a 10-day demand (CS 7) reduced the shortage of coal to 10%. This was achieved by redistributing electricity generation between gas-oil and coal-fired thermal power plants, i.e., additional fuel oil resources were used at thermal power plants, which freed up coal to partially compensate for the coal shortage of consumers in non-energy industries.

The involvement of additional fuel reserves in the supply of electricity and heat did not cause changes and the shortage amounted to the same value. This is explained by the fact that all the reserves of thermal power plants were used to compensate for the growth in demand for energy resources and the decrease in the power of nuclear power plants. In this case, the increase in fuel resources without additional commissioning of generating capacities of power plants did not lead to additional generation of electrical and thermal energy.

In the context of Critical Situation 6 (CS 6), coal shortage was observed in almost all regions. However, after the creation of 10-day fuel reserves, this shortage has decreased in many regions.

The performed experimental calculations have demonstrated the effectiveness of energy security research based on modeling of the energy security threats. A preliminary assessment of the fuel and energy supply to consumers under various critical situations showed a rather high degree of sensitivity of the model to changes in parameters and the possibility of its effective use for this kind of research.

IV. Conclusion

Assessing the energy security and reliability of fuel and energy supply in the context of current social and economic development in different countries is crucial and highly relevant. This is because the functioning of all life-sustaining systems and structures relies heavily on a reliable energy supply.

The energy security research requires an adequate dedicated modeling system for analyzing the interrelated operation of energy systems in the event of materialization of energy security threats. The paper presents a methodological framework of such a system and the methodological features of modeling the interlinked work of industries in today’s context. The developed system is designed to conduct experimental research to find ways to provide consumers with energy resources without a shortage when functioning under normal conditions and in critical situations.

The experimental part illustrates the results of case studies on the application of the presented methodological tool to real energy systems with the view to analyzing several different critical situations (energy security threats). These are a severe drop in temperature, damage to transcontinental gas pipelines, a decrease in the supply of fuel oil, the termination of coal supply from the dominant source, rupture of backbone connections in the electric power system, overlap of all the listed situations and overlap with one compensatory measure. The findings of all cases show the high performance and efficiency of the proposed methodological tool for the energy security research.

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