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Review of methods for researching energy security. Modeling

Dmitry S. Krupenev[1], Viktoria M. Shchukina[2]✉

[1]*Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia*
[1,2]*Irkutsk National Research Technical University, Irkutsk, Russia*

Abstract. The paper aims to review literature sources that provide an assessment of energy security and energy supply reliability. Various methods for modeling energy systems presented in the sources are compared and evaluated. About 50 scientific articles and reviews selected from scientific indexes (including IEEE, Web of Science, and Scopus) were studied using the keywords "energy security", "energy supply reliability", "large-scale systems", and "bottleneck analysis". A systematic review method for reviewing specialized sources according to article categories was applied to provide a well-defined structure for the given research area. A comprehensive review of literature sources and analysis of the methods of modeling power systems presented in the papers was carried out. Emphasis was placed on the sources in which analysis of energy security and reliability of energy supply was selected as the primary function of the presented model. Works having other target functions (cost minimization, profit maximization, etc.) were also considered to provide a comparison of the applied modeling methods for different target functions. Most studies were found to focus on modeling energy systems of different scales, from individual buildings to national or regional power grids, and to be mainly aimed at minimizing energy costs or maximizing profits. Conversely, less research has focused on energy scarcity minimization and reliability assessment, indicating a significant research gap and highlighting the need for further research in this critical area. The results of the presented literature review clarify the application of various methods of modeling energy systems in the analysis of energy security and reliability of fuel and energy supply, as well as in other target functions. It is concluded that similar modeling methods are used for diverse target functions. Static nonlinear models, representing the most widely used approach, will be used as a basis for further research.
Keywords: energy security, energy supply reliability, energy sector, multi-energy systems, modeling
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ЭНЕРГЕТИКА

Обзорная статья
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Обзор методов исследования энергетической безопасности. Моделирование

Д.С. Крупенёв[1], В.М. Щукина[2]✉

[1]*Институт систем энергетики им. Л.А. Мелентьева СО РАН, Иркутск, Россия*
[1,2]*Иркутский национальный исследовательский технический университет, Иркутск, Россия*

Резюме. Цель – провести обзор литературных источников, посвященных оценке энергетической безопасности и надежности топливо- и энергоснабжения. В работе анализируются источники, в которых применяются различные методы моделирования оцениваемых энергетических систем. Изучено около 50 научных статей и обзоров, подобранных в различных научных источниках (в том числе IEEE, Web of Science и Scopus) по следующим ключевым словам: «энергетическая безопасность», «надежность энергоснабжения», «крупномасштабные системы», «анализ узких мест». Применен метод систематизированного обзора специализированных источников, который дает возможность обеспечить четко определенную структуру для данной области исследований путем категоризации статей. Проведен комплексный обзор литературных источников и проанализированы представленные в работах методы моделирования энергетических систем. Акцент поставлен на источники, в которых в качестве целевой функции модели выбран анализ энергетической безопасности и надежности топливо- и энергоснабжения. Были также рассмотрены работы и с иными целевыми функциями (минимизация затрат, максимизация прибыли и др.) для сравнения применяемых методов моделирования при различных целевых функциях. Анализ показал, что большинство исследований сосредоточено на моделировании энергетических систем различного масштаба, от отдельных зданий до национальных или региональных сетей, и направлено в основном на минимизацию затрат на энергоносители или максимизацию прибыли. И, наоборот, меньше исследований посвящено минимизации дефицита энергоресурсов и оценке надежности, что свидетельствует о значительном пробеле в исследованиях, подчеркивающем необходимость дальнейших исследований в этой важнейшей области. В статье выполнен обзор литературных источников, результаты исследований в которых направлены на применение различных методов моделирования энергетических систем при анализе энергетической безопасности и надежности топливо- и энергоснабжения, а также при иных целевых функциях. Сделан вывод о том, что при различных целевых функциях используются аналогичные методы моделирования. Наиболее часто встречаются статические нелинейные модели, именно такой тип моделей будет использован для дальнейших исследований.

Ключевые слова: энергетическая безопасность, надежность энергоснабжения, энергетический сектор, мультиэнергетические системы, моделирование

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INTRODUCTION

Energy security (ES) covers a wide range of issues related to the sustainability and independence of the energy system from external and internal threats. It includes protection against terrorist acts, sabotage, cyber-attacks, as well as ensuring sufficient energy resources to meet the needs of the population and the economy.

Ensuring a reliable supply of fuel and energy, as well as achieving an acceptable level of energy security is the main objective of the energy policy of any state. This is necessary for sustainable economic growth, improving the quality of life of the population and strengthening the national security of the country. To achieve these goals, it is important to systematically assess the level of energy security and reliability of fuel and energy supplies, monitor the technical condition of energy facilities, carry out timely technical re-equipment and modernization, ensure import substitution in the energy sector, support the reproduction of the mineral resource base, improve environmental safety of the region and develop international cooperation with other countries, borrowing best practices.

The study considers the task of assessing the level of energy security and reliability of fuel and energy supply. Various approaches can be used to assess the level of ES, among which two main approaches were identified: the indicative method and modeling of energy systems in order to determine the volume of under-delivery of energy resources. In order to select the approach and evaluation methods, it is necessary to evaluate the degree of research on the topic. This article analyzes the studies in which the modeling of energy systems to determine the amount of under-delivery of energy resources to consumers is performed to assess the level of ES.

REVIEW OF ENERGY SYSTEM MODELING METHODS TO ANALYZE FUEL AND ENERGY SUPPLY RELIABILITY AND ENERGY SECURITY

The most profound analysis of the level of energy security, as well as the reliability of fuel and energy supply can be made using the apparatus of simulation modeling. This apparatus is based on correct mathematical models of power system elements, power systems themselves and the energy sector as a whole. In this connection, the existing methods of modeling the energy sector and mathematical models of elements and power systems in assessing the level of energy security, as well as mathematical models of elements and power systems used in solving not only the problems of determining the deficit of energy resources, but also the problems of other criteria will be considered and analyzed.

[3]Rudenko Yu.N. Handbook of general models for energy system reliability analysis and synthesis. Reliability of energy systems and their equipment: in 4 volumes, V. 1. Moscow: Energoatomizdat; 1994. 472 p. / Руденко Ю.Н. Справочник по общим моделям анализа и синтеза надежности систем энергетики. Надежность систем энергетики и их оборудования: в 4 т., т. 1. М.: Энергоатомиздат, 1994. 472 с.

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The works[3] [1–55] present studies aimed at analyzing the reliability of energy supply and assessing the level of energy security. They are based on modeling of power systems of different territorial extent, the calculation scheme of which is presented from a single node (zone, cluster) to a multi-node model. All works consider from three energy resources, and the following regularity is traced: the more territorial clusters are represented in the model, the less energy resources are considered. The exception in this case is the study presented in [22, 23].

In [2–11, 12–16, 29–33], studies are presented in which energy systems are modeled with objective functions other than energy supply reliability analysis and energy security level assessment. Most often these are economic or environmental objective functions. These works are interesting from the point of view of mathematical description of power systems and consideration of its various features. Further in the article all the considered works will be divided into groups depending on the scale and volume of the modeled power system, as well as the number of considered power flows.

1. Representation of power systems by a single-zone model

In single-area models of power systems, no consideration is given to energy interconnections, only the possibility of meeting consumer demand with specific energy sources is analyzed. One of the concepts of such analysis is the concept of energy hub.

In [2–11], a single-area energy system described by the energy hub concept is considered (Fig. 1). The energy hub acts as an intermediate link between energy producers, transportation infrastructure and consumers. The main functions of the hub include transmission, transformation and storage of energy resources. The energy carrier can be transferred from input to output either in an unchanged form (e.g., electricity) or converted into another form (e.g., gas is converted into heat energy) [7].

The hub consists of elements - converters, each of which is characterized by a value of efficiency. According to this concept, the balance equations can be written in the vector form A*B = C, where B is a vector of incoming energy flows, C is a vector of outgoing energy flows, A is a matrix of conversion coefficients (efficiency). To form the matrix, all values of energy flows are converted to unified units of measurement: ue, MW, Gcal/h, etc. The possibility of converting one type of energy into another is modeled by the presence or absence of efficiency in the coefficient matrix. Fuel systems are mainly represented by gas [3–5, 9, 10], less frequently by biofuels [7, 8]; coal and petroleum products are usually absent. Gas boilers [8, 9], GTUs [2, 3, 7–9] and utilization boilers [10] are most often modeled as fuel converters into electric and thermal energy.

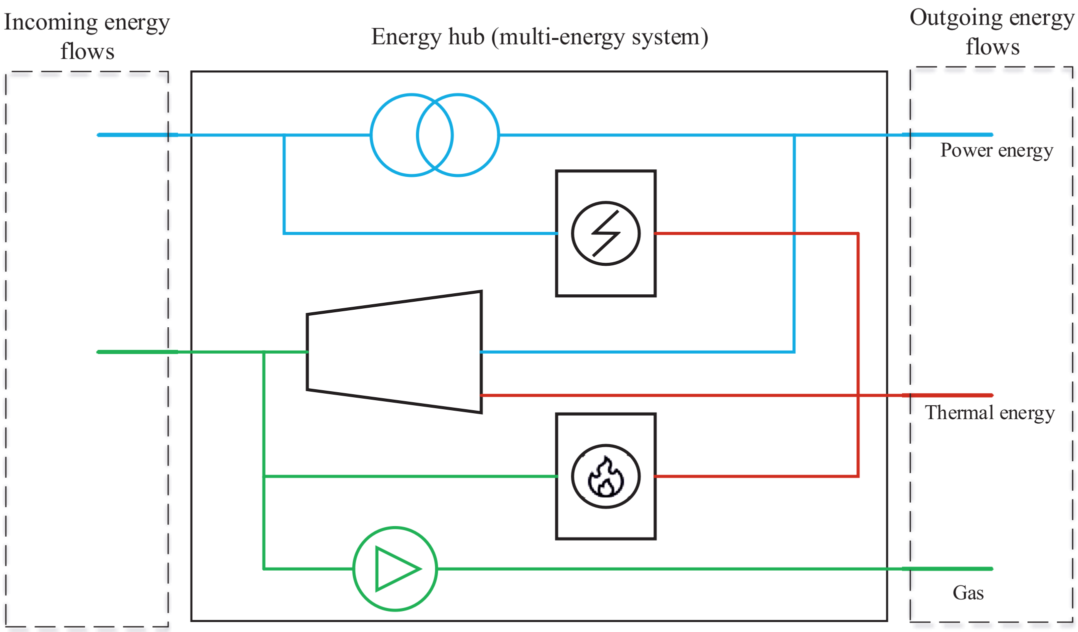

Fig. 1. *Energy hub concept-based representation of a single-area energy system*
Рис. 1. *Представление энергосистемы одной зоны с использованием концепции энергетического узла*

In this concept there is no territorial reference. This means that the model of such a system does not take into account the territorial location of both the source of the primary energy resource (mainly fossil fuels: coal, gas, etc.) and final consumers, aggregating their load. The main emphasis is on the system of equations describing the transformation of one energy resource into another. Accordingly, the optimization objective function is mainly either reliable energy supply to consumers or the most economical energy consumption, by using available energy resources.

The paper [1] presents such a concept, named by the authors as "energy hub security area (SA)", which evaluates the power generation and transmission capability of a district multi-energy system (MES). For the study, the MES is modeled based on the energy hub concept for three energy carriers: electricity, thermal energy and cold energy. The carrying capacity of the hub is described by a vector of input energy flows, a vector of hub state variables and a set of operational (energy conversion equations, energy flow capacity limits) and safety (operational limits of hub elements) constraints. To account for contingencies, the safety domain is narrowed by including appropriate constraints. The authors also specify a set of values at which the above constraints are satisfied under the contingency. The region of safety in this case is expressed as the intersection of a number of such sets.

To define the safety region, a polyhedron in the hyperspace formed on the basis of input and output flow vectors is formed. The authors develop a vertex-based algorithm to compute the OB. The key point is to construct an initial polyhedron, which is a subset of the security domain, and its iterative expansion, to approximate the OB. The first step is to obtain the set of vertices lying on the axes of the hyper-space and construct the original polyhedron. Then the new vertices of the OB are searched along with the normal directions of the IM surfaces. After the search iteration, the IM is updated using the newly obtained vertices. With the search and update process, the IM grows closer to the OB.

To express the ability of an energy hub to withstand multiple energy loads, the concept of Volume of the security region (VSR) is introduced. It is defined as the volume of the corresponding protected area.

To assess the ratio of scenarios in which the demand for all types of energy resources can be covered, the authors introduce the Load-Weighted Volume (LWV), which differs from the VSR by taking into account the load distribution. A higher LWV indicates a higher probability of non-deficiency in all load types.

To identify critical elements of the energy hub and to determine their level of influence on the reliability of the entire hub, the authors define two indices. The first index is the Important degree of volume, which reflects what percentage of the VSR of the element in question is from the VSR of the hub. The second index is the Important degree of load, which measures the impact of the element on the ability of the hub to cover the load:

$$IDV_i = \left(1 - \frac{VSR_i}{VSR_0}\right) \cdot 100\%\,; \qquad (1)$$

$$IDL_i = \left(1 - \frac{LWV_i}{LWV_0}\right) \cdot 100\%\,. \qquad (2)$$

The presented approach allows defining the security area and identifying critical elements for an energy hub involving two or three energy carriers. This concept allows visualizing the level of energy security and reliability of fuel and energy supply. In addition, the vertex-based algorithm proposed by the authors can be applied not only to assess the security area, but also to describe the operating modes of power plants (mainly interesting for thermal power plants) and other elements of energy systems. This concept with some adaptation can be applied to assess the reliability and ES of large-scale systems including many converters and having a greater variety of power flows than presented in the paper.

Modeling of single-zone energy systems at the neighborhood and building scale

Papers [12–16] present studies on district and building scale optimization of energy systems.

In [12], an energy system consisting of an internal combustion engine, waste heat recovery equipment, a gas boiler, air and absorption heat pumps, and a heat exchanger is modeled. The paper describes in some detail the models of each of the above elements, all of which are nonlinear. Of the energy supply system models, only thermal energy transfer is presented. Balance equations are not presented explicitly, but by analyzing all the presented equations and the scheme of the modeled power system it can be assumed that the authors used the concept of an energy hub with some modifications for modeling. The objective function is to minimize the annual total cost of the IES, which includes annual operating costs, natural gas and electricity costs. An exhaustive search method is applied to optimize the model.

In [13], a power system consisting of solar panels, wind turbine, heat exchanger, micro gas turbine, air conditioner, absorption chiller, storage, pipelines and transmission lines is modeled. Although the paper does not mention it, when analyzing the equations and the scheme, it is obvious that the concept of energy hub has been used to describe the integrated power system. The paper describes in great detail a two-level optimization model based on the principles of the master-slave game.

In [14] a system of interconnected energy hubs is modeled. They are described by standard balance equations and constraint systems. Minimization of operating costs is considered as the objective function. The alternating direction multiplier method is applied for optimization. Also in this paper, robust optimization is used to model the uncertainty associated with wholesale market prices.

In [15], the power system is modeled in GAMS software by a traditional method based on a system of balance equations and constraints. In the model, some elements (fuel-to-electricity conversion formulas and power plant production constraints) are described using nonlinear equations, so a mixed nonlinear programming method was applied for optimization using the solver built into GAMS. In this paper, two objective functions are presented: the first one is to minimize the total system cost and the second one is to maximize the total system efficiency.

In [16], energy transformations are modeled using the energy hub concept described earlier. Balance equations and constraints are presented for the remaining subsystems of the modeled system. Such subsystems as electric power, energy storage and consumers are modeled in a standard way and are not of great interest in contrast to gas and heat supply models. The gas supply model takes into account a large number of constants describing the modeled object and technological process (pipe length and diameter, temperature, gas density, compression ratio, etc.), the general type of balance equations and constraints is standard. The heat supply model also presents a large number of constants (specific heat capacity of water, heat resistance per unit of pipe cross-section, etc.), almost all the equations presented are nonlinear. The aim of the paper under consideration is to develop a decentralized multi-energy resource aggregation method based on two-level interactive transactions in a virtual power plant under integrated energy market conditions. The objective function of the model is the maximization of revenues from two-level interactive transactions. The authors used two methods to solve the nonlinear programming problem: The Gomori Algorithm and the method of internal points.

According to the results of the analysis of the above mentioned papers, it can be concluded that all models of single-area energy systems described by the energy hub concept are similar. The models of power systems in the reviewed papers are not of special interest due to the absence of fundamentally new concepts. It makes sense to analyze these papers rather from the point of view of optimization problem formulation and applied methods. In [13], a two-level optimization is described in a rather interesting and detailed way, which can be adapted to solve the problems of improving energy security and reliability of power supply. And in [16] the gas and heat supply subsystems are modeled in an original way, but, for example, this model is too detailed for scaling up to the energy system of a country.

The very concept of an energy hub can be fully transferred to larger systems up to the energy sector of the country. If we consider it more generally, we can see that the matrix used to describe the relationship between energy resources is a set of balance equations of the system, each variable has constraints, and the conversion factor is a combination of efficiency and conversion factor of one unit of measurement into another. Thus, by decomposing the hub into its components, a system of absolutely any magnitude can be modeled, as long as it is aggregated across energy districts.

MODELING OF MULTI-NODE TWO-PRODUCT POWER SYSTEMS

Often several energy systems, for example, electric power and gas supply systems, dominate in the structure of the energy sector. In practice, the tasks of considering the interconnected operation of such energy systems become interesting.

The paper [17] presents a systematic framework for analyzing the reliability of power supply of integrated energy systems (IES), for which a model of bidirectional energy conversion system is developed to consider the impact of "Power to Gas" on the reliability of IES. The structure of the mathematical model developed by the authors is presented in Fig. 2.

The output data of the mathematical model calculated by means of systems of nonlinear equations are used to describe the state of the IES. All dependencies in the work reflect the technological process of the described object in quite detail. It can be emphasized that unlike similar works, this work describes in detail the method of methane production from carbon dioxide and water in the "Power to gas" block. For this block the equations of chemical reactions are presented, the amount of heat released (or required) during the reaction is taken into account. The model of the gas turbine in the paper is as follows. The gas flow rate in the turbine is directly proportional to the generation of electrical energy and inversely proportional to the efficiency of the turbine and the calorific value of gas. The efficiency of the turbine, in turn, has an inversely proportional dependence on the square of the electrical energy produced by the plant. This dependence does not seem quite usual, as most often the efficiency of the unit has a direct dependence on the generation. In the paper, when describing this dependence, reference is given to the article [18], which, however, does not contain data on the formation of this dependence.

The gas supply pressure is used as a failure criterion of the system to account for compressibility. The minimum value of the system pressure at which the system is able to function is set as constraints. The probability of failure in the system is analyzed on the basis of a tree of dynamic events. It can describe the evolution of the state of a physical system governed by discrete random events and continuous system behavior [19]. System failure is defined as an event in which the power supply cannot meet the demand.

Based on the analysis of this paper, it can be concluded that the model presented in the paper is of interest for further analysis and experience in modeling gas-fired power plants. There are also critical points, so in the block "Power to gas" and in the modeling of wind turbines cubic dependencies and a large number of conditions significantly complicate the application of the above models in large-scale systems. Despite the fact that the authors have modeled the IES of a rather large area, further scaling of the models is questionable due to a rather high level of detail and complexity of dependencies of some elements of the mathematical model. This remark applies

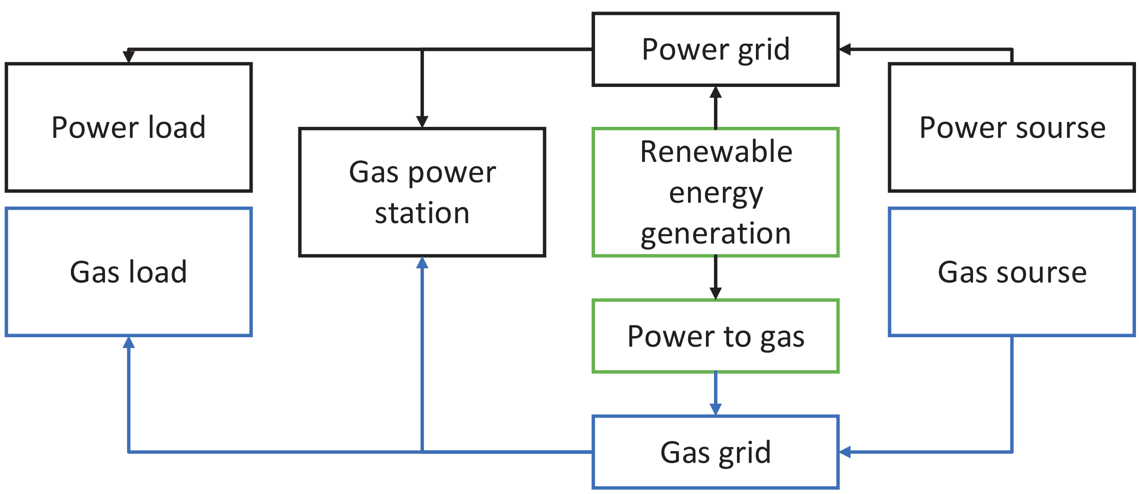

Fig. 2. *Mathematical model structure*
Рис. 2. *Структура математической модели*

to the model of the pipeline, gas compressor and electrical networks. Within the framework of the work presented by the authors, the level of detail is more than sufficient and competently developed.

The paper [20] analyzes the safety of interconnected operation of gas and electric systems. The authors determine the predicted values of electricity generation by gas power plants based on the values of variables describing the current state of the gas pipeline. Gas pipelines are described using Renoir's formula [21], which shows the dependence of the absolute pressure at the pipe outlet on the inlet flow rate at constant pressure. To simplify the calculations, the authors perform a stepwise linear approximation for each section of the gas pipeline. Depending on the length and diameter of the pipe, certain restrictions are imposed on the gas flow velocity. The calculations are then performed using the Shirmohammadi method, which is similar to that for electrical networks: pressure is treated as voltage, and flow is treated as electricity. This approach allows gas and electricity networks to be considered as a single system. Energy security is defined as the ability of the system to meet the demand for electricity and gas in the event of an outage of one of the network elements without external redundancy. The authors calculate two scenarios for the Serbian energy system, which represent the worst cases of operation. Based on these calculations, a predictive control model is created.

It is also worth noting that within the framework of this work the authors have considered the possibility of realizing the Smart Grid concept at gas-fired power plants. For specific emergency situations, the necessary alarm signals were determined, for example, "the minimum allowable pressure at the gas turbine inlet has been reached" or "the shutoff valve on the gas pipeline installation at the plant is closed". The aggregate of input parameters and these signals allowed the authors to develop a model of predictive control, on the basis of the data of monitoring of the state of the gas pipeline equipment and indicators of the gas process possible situations are modeled in order to determine the scenarios important for predicting the operation of CCPP, as well as measures to prevent negative and unplanned impact on the EES.

The paper presents a non-standard approach to modeling the interconnected operation of the electric power and gas subsystems. The gas pipeline model in the paper is piecewise linear, which greatly facilitates further calculations and does not significantly reduce their computational accuracy. According to preliminary estimates, the model presented in the paper scales very well and could serve as a basis for modeling larger integrated power systems.

Summarizing the works on modeling multinode two-product power systems we can conclude that gas supply and electric power systems are mainly considered. Mathematical models of the elements of these systems are presented in sufficient detail, these models with some modification can be used in modeling of the fuel and energy sector.

MODELING OF MULTI-NODE MULTIPRODUCT POWER SYSTEMS

This type of model is the most complex in terms of the number of variables considered and their coupling equations. These systems are analyzed to a much lesser extent than the first two types, since a comprehensive analysis of the interaction of all power flows has a number of serious difficulties and is a very complex task. The obtained models can be used to estimate the deficits in critical and emergency situations and to determine the "bottlenecks" of the power system both in the tasks of development planning and for evaluating the operation modes of the power system.

In [22], a multi-parameter transmission model (MEP-model) is presented that depicts the operation of a unified fuel and energy system in different modes of operation. The model includes four types of elements connected by transportation highways: consumers, energy and fuel sources, reserves, and processing points. The operation of each element is described by the corresponding micro-model.

The MEP model studies dynamic processes. Dynamics is accounted for by fictitious arcs (marked in red in Fig. 3), which connect the nodes-stocks of several stationary models (each of which refers to a certain time interval). For their mathematical description, standard balance equations are used: the energy resource stock in the next time period is equal to the sum of the current stock and the energy resource inflow to the considered node-stock minus the part of the stock withdrawn from the node. In addition, a system of constraints is introduced, according to which all variables are non-negative and the amount of reserves does not exceed a given maximum permissible value.

This study analyzes the delivery of energy resources such as electricity, gas, oil and coal. Two types of elements performing transportation functions are considered: interchange nodes and trunk arches. The latter are indicated in Figure 3 by black lines (arrows) and are divided into the following types: transmission line arches, gas arches, oil arches and railroad arches.

Since the authors emphasize the supply of energy resources to all consumers as the main function of the MEP model, the paper under consideration also takes into account the damage from under-supply of resources. The damage is expressed through the penalty function, which has a piecewise linear form. The authors define the objective function of the model as the problem of minimizing the cost of energy resource flows. In addition, in the article [23] the authors propose mathematical formulations of the problems of optimization of energy flows under various damages in the network on the basis of the considered model.

The considered model allows to simulate the operation of the energy sector under various disturbing influences, as well as to conduct forecasting studies. The dynamic component of the system is realized quite simply, but at the same time fully reflects the essence of changes in the system state over time. Taking into account the level of failure of converters and power sources increases the accuracy of the MEP model.

It should be noted that the electric power component is not sufficiently developed in the article. Representation of electric power flow in conventional units does not fully convey all electric power processes. In addition, the article lacks a description of how the dependence of fuel consumption on the final load of the consumer is taken into account (through the efficiency of turbine units).

REVIEW OF ENERGY SECTOR MODELS FOR ANALYZING THE RELIABILITY OF ENERGY SUPPLY AND ENERGY SECURITY DEVELOPED AT ESI SB RAS

ESI SB RAS has long been engaged in research in the field of energy security and development of mathematical models of energy systems and energy sector [24–27]. The models created since 1980 are divided into three main modifications: “Energy sector Reliability”, “Reserve” and “REKS”. All of them are based on the system of linear balance equations with a given matrix of constraints and are aimed at analyzing large energy facilities.

Model “Reliability of Energy sector”. The main purpose of the “Reliability of Energy sector” model is to analyze the consequences of major disturbances in the energy sector of the country. The model calculates optimal ways to compensate for disturbances through the use of interchangeable fuels and redistribution of

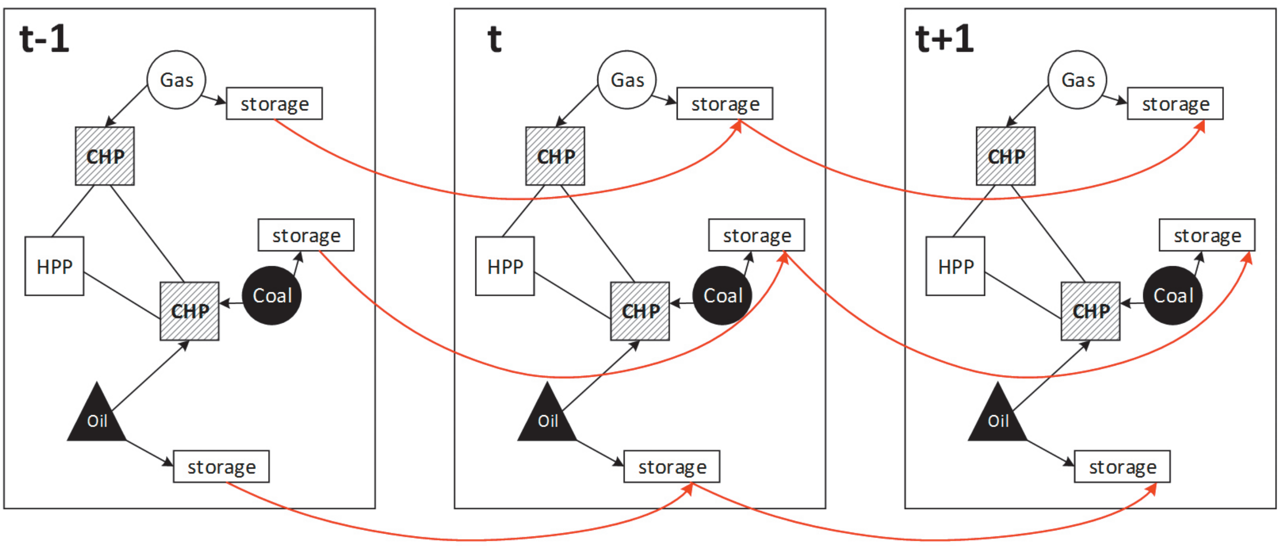

Fig. 3. *MEP model dynamic component*
Рис. 3. *Динамическая составляющая модели МЕР*

energy flows. To simplify the calculations, the model takes into account two key factors: interchangeability and transportation links. All elements of the system are divided into four subsystems: gas, oil, coal and electricity, and consumers are classified into three categories.

The "Reserve" model. The Reserve model is an improved version of the model "Reliability of Energy sector". It includes a new thermal energy subsystem and a two-component approach to modeling thermal plants. The model also takes into account the end-of-period energy reserve, which affects current decisions.

The "Reserve 2" model. In the "Reserve 2" model the structure is changed, autonomous regions are selected and the modeling period is shortened.

The REX model. In parallel with the "Reserve 2" model, the REX model, which takes into account energy security, was developed. The model includes eight economic regions and a modified CHP modeling method reflecting the relationship between heat and electricity. It also includes a financial block describing investment costs for modernization and reconstruction of energy facilities, which allows tracking the dynamics of the sector's development [28].

Models of multi-node multiproduct power systems with economic objective functions. In a number of papers [29–33], integrated energy systems are modeled to minimize total cost or maximize profit.

For example, in [29], Sh. Yang et al. introduce the concepts of time-of-use (TOU) price [34–44] and Shepley's benefit sharing method [45–50] to consider the rational energy utilization in IES. The paper consists of three phases: the first phase involves modeling an IES and creating an energy pricing model using TOU tariffs; the second phase involves developing an operation optimization model for revenue maximization; and the third phase involves creating a benefit sharing optimization model based on the Shapley method. The mathematical model of IES is represented by the classical system of equations and constraints, all energy converters are described as in the concept of energy hub - through conversion ratio, in some cases efficiency. The main emphasis in the work is on modeling of pricing and other economic aspects.

In [30], a matrix modeling method based on graph theory is proposed, in which all elements of the IES are represented as nodes and branches. It is difficult to say that this idea is relevant; as a result, systems of equations similar to the concept of an energy hub are formed. However, this method is very illustrative and quite convenient for building calculation programs in object-oriented programming languages.

In [31], a two-level robust IES optimization model is presented, which aims at minimizing the annual total system cost, protecting the environment and satisfying consumer needs. Topsis method and genetic algorithm for non-dominated sorting were used for optimization, which was applied to find the Pareto front. The mathematical model of IES is similar to [24], more emphasis is placed on the experimental part.

In [32], a hierarchical mathematical model of the IES and a local marginal price model, which aims to analyze the energy market dynamics in the implementation of carbon emission constraints and carbon dioxide trading. The presented models are nonlinear and describe the energy system in sufficient detail. The proposed optimization model is a two-level model: the upper level is minimization of operating costs on the power supply side, and the lower level is maximization of regional consumer surplus. The extended particle swarm method, a combination of the particle swarm method and the interior point method, is used as the optimization algorithm.

In [33], a three-level model of planning-catastrophe-prevention-replanning, oriented to the evaluation of IES sustainability for the purpose of investment planning, is proposed. The task of the first level is to plan the composition of IES equipment and make an investment plan, the optimization objective is to minimize the operating and investment costs. The task of the second level is to maximize the possible total deficit in case of various catastrophic events. The task of the third level is the re-planning of the investment plan taking into account the data obtained from the second task, the objective function of the level is the minimization of total deficits under various catastrophic events. This paper describes the elements of the IES in quite detail, the model of the electric power subsystem includes active and reactive power, voltages and power coefficients, the gas model takes into account pressure, volume and a large number of coefficients.

The works considered in this section mostly have similar mathematical models and economic objective functions. The works [30] due to the application of graph theory and visualization and [32] due to a very detailed mathematical model of the power system stand out. To simplify the mathematical modeling of large-scale systems and to solve energy security problems, the most interesting work is [30], whose methodology can greatly simplify the visualization of a large power system and its software adaptation. In addition, we can highlight the work of [28], since despite the stated economic objective function, the work presents the analysis of system bottlenecks by modeling various emergency situations. It would be interesting to consider this approach within the framework of energy security analysis.

COMBINED ENERGY SECURITY ASSESSMENT

In [51] the authors consider the issues of energy security and propose a methodology for its assessment. The main objective of this approach is to quantify the level of energy security for different energy development scenarios. The proposed framework is based on indicative and modeling studies, including differential equations and Bayesian methods to estimate this level.

Earlier in [52], the authors presented a methodology for assessing energy security based on historical statistical data using empirical calculation of an integral indicator. Two methodologies are described in [53–55]: one uses a dynamic indicator model and a Bayesian method to predict the level of energy security, and the other is based on modeling, which are then combined and complemented in [51]. Thus, the methodology developed by the authors allows combining modeling and indicative approaches to forecast the level of energy security in the future in the context of different directions of energy system development.

The algorithm of the energy security assessment methodology is realized step by step. It is presented further in the form of a scheme (Fig. 4).

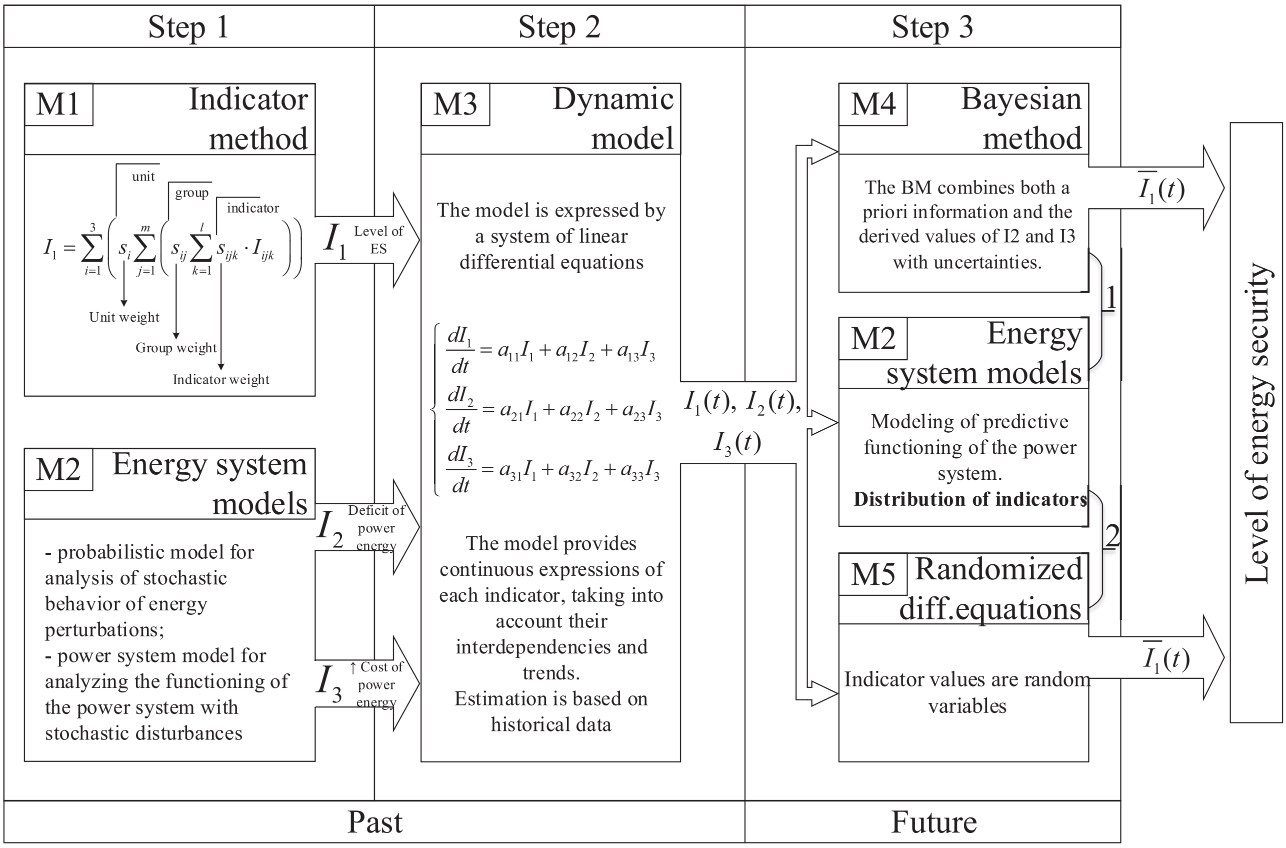

Fig. 4. *Energy security level detection algorithm*
Рис. 4. *Алгоритм определения уровня энергетической безопасности*

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Summary table of the research review results
Сводная таблица результатов обзора исследований

No. of references	Objective function	Equation type	Type of model	Method of optimization / standardization	Territorial cluster
[1]	Determining the load-bearing capacity of the hub	Linear	Static	Vertex-based algorithm	MES, district MES
[2–11]	Optimizing equipment performance / maximizing profits	Linear	Static	–	MES, district MES
[12]	Minimizing the annual total cost of the IES	Non-linear	Static	Exhaustive search method	District IES
[13]	Optimization of equipment operation	Non-linear	Static	The master-slave game	District IES
[14]	Minimization of operating costs	Non-linear	Static, probabilistic	Method of alternating direction multipliers, robust optimization	A system of interconnected energy hubs
[15]	Minimize total system cost and maximize total system operational efficiency	Non-linear	Static	Mixed-valued nonlinear programming method	Decentralized IES
[16]	Maximizing revenue from two-tier interactive transactions	Non-linear	Static	Gomori algorithm and primal-dual interior point method	Decentralized IES
[17]	Determination of the reliability level of the energy system	Non-linear	Probabilistic	DET, probabilistic safety margin method	IES of the district
[20]	Level of energy security	Linear, Non-linear, Renoir's formula.	Static, probabilistic	Piecewise linear approximation, Shirmohammadi method	Energy system of the country, an example for Serbia
[22–23]	Minimization of damages from under-energy supply	Linear	Dynamic	Simplex	Russia
[24]	Minimizing deficits and operating costs	Linear	Statistical	Simplex	19 economic regions of the USSR
[25]	Minimizing shortages, operating costs and inventory holding costs	Linear	Statistical	Simplex	27 economic regions of Russia
[26]	Minimizing shortages, operating costs and inventory holding costs	Linear	Statistical	Simplex	35 E.D. and autonomous subjects of the Russian Federation
[27]	Minimizing deficits, costs of operation and the cost of new and retired capacities	Linear	Statistical	Simplex	8 federal districts
[29]	Income maximization, benefit sharing	Non-linear	Static	The Shapley method	Park IES
[30]	–	Non-linear	Graphs	Graph theory	District IES
[31]	Minimize annual total system cost, protect the environment and meet customer needs	Non-linear	Static	Topsis method and genetic algorithm for non-dominated sorting	District IES
[32]	Minimize operating costs on the electricity supply side, maximize regional consumer surplus	Non-linear	Static	Particle swarm method and interior point method	District IES
[33]	Minimizing operating and investment costs in a risk-adjusted manner	Non-linear	Probabilistic	–	District IES
[51–55]	Level of energy security	Linear differential	Dynamic, probabilistic	Weight setting	Energy system of the country, an example for Lithuania

Step 1 consists of two parts: the indicative method M1, developed on the basis of a system of 68 security indicators; and two mathematical models M2 - a probabilistic model and a power system model. The probabilistic model is based on the analysis of different external and internal disturbances, which are characterized by different parameters (e.g. initial moment and duration of the disturbance, type of energy source, technology availability constraint, etc.). The perturbation parameters are described by probability distributions (uniform, normal, lognormal, and others). This feature allows generating a complete set of disturbance scenarios, which is used for modeling the prospective development of the power system.

The power system model in the proposed approach is based on the linear optimization method and implemented in the Open Source Energy Modeling System tool, whose objective function is minimization of the total discounted cost.

Step 2 is a dynamic M3 model that utilizes energy security indicator data from the indicator system (part M1) and under-recovered energy and cost growth indicators from the energy system model (part M2). The M3 model allows for continuous expressions for each indicator (taking into account their interdependencies and trends), expressed as a homogeneous system of linear differential equations.

Step 3 has two possible calculation methods: alternative 1 - Bayesian method (blocks M2, M4) and alternative 2 - system of random differential equations (block M5). Both alternatives require the output of step 2, the general solution of the differential equation system, as input. This dynamic model allows for the inclusion of interdependencies among indicators and provides expressions of the indicators as continuous time-dependent functions.

The advantages of alternative 1 are the disadvantages of alternative 2 (and vice versa), so we can summarize 2 main differences:

1. For the Bayesian method, information on only one indicator is sufficient: the probable value (for different scenarios) and the known probability distribution of I_2 and / or I_3. Alternative 2 requires information on all indicators.

2. Alternative 2 does not require new methods (only M3 block output and input data), and the calculation does not depend on the probability distributions of the indicators. In alternative 1, the complexity of the calculation depends on the probability distributions of the indicators.

This study is interesting in terms of the methodological framework presented. The streamlined interaction of different models and methods allows for a more comprehensive analysis and comparison of the values of all indicators to further combine them into a common energy security index (Table).

CONCLUSION

Ensuring deficit-free energy supply to consumers is the most important task of the energy sector. In this regard, determining the level of energy security and calculating reliability indicators plays a determining role in planning the functioning and development of the energy system as a whole.

In this paper, an analysis of scientific studies aimed at analyzing the reliability of energy supply and energy security using modeling of energy systems was carried out.

When analyzing the works, it was found that most of the studies are aimed at forming models of energy systems of different territorial extent (from a single building to a country or interstate associations), having as an objective function minimization of costs for primary energy carrier or maximization of profit. The works aimed at minimizing the deficit of energy resources and assessing reliability were presented much less, in this regard, we can conclude that research in this direction is relevant. This method allows modeling the most severe modes of power system operation and identifying “bottlenecks” that need to be strengthened to increase the level of energy security.

A combined method, which combines elements of modeling and indicative assessment, was also considered. In this group, only one paper was presented, combining indicative assessment and probabilistic models to account for the stochastic nature of external disturbances. This direction is the most promising for further research, as it allows to analyze both the current and forecasted state of the energy sector in the most complete and accurate way, to assess the level of energy security and to outline further ways of development of the energy sector.

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INFORMATION ABOUT THE AUTHORS

Dmitry S. Krupenev,
Cand. Sci. (Eng.), Associate Professor,
Head of the Laboratory of Fuel and Energy Supply Reliability,
Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences,
130 Lermontov St., Irkutsk 664033, Russia;
Associate Professor of the Department of Power Supply and Electrical Engineering,
Irkutsk National Research Technical University,
83, Lermontov St., Irkutsk 664074, Russia
krupenev@isem.irk.ru
orcid.org/0000-0002-3093-4483

Viktoria M. Shchukina,
Postgraduate Student,
Assistant Professor of the Thermal Power Engineering Department,
Irkutsk National Research Technical University,
83, Lermontov St., Irkutsk 664074, Russia;
✉ vitapiskunova98@gmail.com
orcid.org/0000-0003-4019-8472

ИНФОРМАЦИЯ ОБ АВТОРАХ

Крупенёв Дмитрий Сергеевич,
к.т.н., доцент,
заведующий лабораторией надежности топливо- и энергоснабжения,
Институт систем энергетики им. Л.А. Мелентьева СО РАН,
664033, г. Иркутск, ул. Лермонтова, 130, Россия;
доцент кафедры «Электроснабжение и электротехника»,
Иркутский национальный исследовательский технический университет,
664074, г. Иркутск, ул. Лермонтова, 83, Россия
krupenev@isem.irk.ru
orcid.org/0000-0002-3093-4483

Щукина Виктория Михайловна,
аспирант,
ассистент кафедры теплоэнергетики,
Иркутский национальный исследовательский технический университет,
664074, г. Иркутск, ул. Лермонтова, 83, Россия
✉ vitapiskunova98@gmail.com
orcid.org/0000-0003-4019-8472

Authors' contribution

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