UDC 332.1:338.2
DOI: 10.15587/1729-4061.2024.308056

DEVISING AN INTEGRATED METHODOLOGY FOR ENERGY SAFETY ASSESSMENT AT AN INDUSTRIAL POWER-GENERATING ENTERPRISE

Viktoriia Prokhorova
Corresponding author
Doctor of Economic Sciences, Professor
Department of Economics and Management*
E-mail: vkprohkorova@gmail.com
Mykola Budanov
PhD Student
Department of Economics and Management*
Pavlo Budanov
PhD, Associate Professor
Department of Physics, Electrical Engineering and Power Engineering*
*Ukrainian Engineering Pedagogics Academy
Universytets'ka str., 16, Kharkiv, Ukraine, 61003

This paper's research object is a process of estimating the level of energy safety at an industrial enterprise within an electricity-power system at a microeconomic level. The task to estimate the energy safety of an industrial enterprise was solved on the basis of a combined method for the continuous monitoring of threats under an automated mode to the hour, in order to make management decisions related to reducing the influence of threats to energy safety.

Analysis of known methods for investigating the state of energy safety was performed, which revealed the lack of continuous control over the dynamic state of research objects, as well as the complexity in objectivity when giving exact and reliable primary information to calculate indicators-indexes.

It has been shown that the use of the combined approach could underlie the development of methodology for estimating the energy safety of industrial power-generating enterprise.

Such approach involves comprehensive combination of logical methods when implementing continuous monitoring of technological parameters at generation, transmission, distribution, and energy consumption facilities.

The process of choosing the objects of research and criteria for describing their properties and functions has been substantiated, in order to build the system of indicators-indexes when estimating the level of enterprise energy safety.

It has been shown that a computation algorithm makes it possible to monitor the dynamics of changes in indicators and take a management decision to eliminate energy safety threats, which leads to a reduction in economic losses in the amount exceeding USD 150,000.

Practical significance of the current research relates to the fact that the results could be used by enterprises (public authorities) for determining obstacles on a way to reducing the consumption of power resources and devising a set of organizational-economic measures

Keywords: energy safety of enterprise, threats to energy safety, estimation of energy safety level, risk, management decisions

Received date 15.03.2024
Accepted date 21.05.2024
Published date 23.08.2024

***How to Cite:** Prokhorova, V., Budanov, M., Budanov, P. (2024). Devising an integrated methodology for energy safety assessment at an industrial power-generating enterprise. Eastern-European Journal of Enterprise Technologies, 4 (13 (130)), 118–131. https://doi.org/10.15587/1729-4061.2024.308056*

1. Introduction

Energy safety (ES) is an important component of economic and national security as it is a necessary condition for the existence and development of the economy in Ukraine [1, 2]. It is known [3] that the practice of ES assessment shows the versatility and multifactorial nature of methodological approaches, criteria, and assessment indicators depending on the tasks and the object of analysis. This practice does not allow for the construction of a single methodical approach to determining the state of ES at the macro-, meso-, and micro-levels of the economy.

Research and analysis of the state of ES at electric power system (EPS) facilities was conducted mainly at the state and regional level of the economy, using statistical data on short-term and long-term periods. There are also well-known methodical approaches to determining the level of ES at the macroeconomic level, which do not take into account the ES status of objects such as industrial energy enterprises (IEEs) as criteria. It follows that it allows quantitative and qualitative assessment of the impact of negative factors in the form of external and internal threats at the microeconomic level.

This introduces significant errors in the assessment of the real state of ES in the future, leads to significant material losses and economic losses. In existing procedures of research and analysis of the state of ES at industrial objects, it is recommended to use various methods: indicative analysis, the method of hierarchies and expert assessments, the scenario method, and others [4].

These procedures could be used as a basis for devising a comprehensive methodology for assessing the state and level of an energy company's ES. Hence, it follows that the application of such procedures makes it possible to assess the level of ES only in the domain of economic activity and only at the level of regions or the economy of the state in general. At the same time, there is a problem of assessing the level of ES for energy enterprises in EPS, which function in the economic system at the meso- and microeconomic level. In this case, the approaches to ES assessment are significantly different from existing ones since it is necessary to select indicators that characterize such continuous processes at energy enterprises as the generation, transmission, distribution, and consumption of energy.

The relevance of this subject relates to the fact that current procedures for assessing the level of energy safety at EPS facilities at the macro- and meso-economic levels do not take into account the state of the level of ES at industrial energy enterprises at the micro-economic level.

To determine the state of ES at an industrial energy enterprise, it is necessary to devise a comprehensive methodology for assessing the level of ES at an energy enterprise, taking into account the objects of generation, transmission, distribution, and consumption of electric and thermal energy included in it. That is why research topics aimed at improving the comprehensive methodology for assessing the level of ES at an industrial energy enterprise at the microeconomic level are relevant.

2. Literature review and problem statement

For an adequate estimation of ES, works [5, 6] suggest using a system of ES indicators, on the basis of which it is possible to form an ES strategy of an energy company in the future. A number of aspects were comprehensively considered, such as organizational and production, technical and technological, environmental, stability of energy supply, etc. A methodical approach was proposed for determining the integral indicator of ES based on the application of the indicative and qualitative method, which does not make it possible to solve the problem of comprehensive estimation of ES of the enterprise in real time.

In works [7, 8], the problem of assessment and management of ES at an enterprise was considered, as well as existing approaches to the definition, classification, and assessment of the level of ES at an enterprise were researched and analyzed. A method for assessing the level of enterprise ES based on the comparison of actual data with normative data was proposed; however, it does not make it possible to solve the problem of automated monitoring of the level of enterprise ES.

Thus, in work [9], it was established that determining ES has a contextual and dynamic nature, while an important aspect is the energy efficiency of the enterprise. A huge number of significant differences between studies and observations of ES of enterprises were noted. However, the problem of choosing the main criteria for assessing the state of energy safety at enterprises has not been solved, especially when building a system of indicators.

In [10], ES is defined as the safety of availability and reliability of energy supply. The ES assessment was carried out taking into account energy and economic efficiency, sustainability, and safety of power supply of energy consumption facilities. At the same time, the problem of accounting for the state of ES at energy generation sites was not solved.

In [11], the growth of the use of ES indicators is shown; approaches based on indicators are particularly suitable for modeling a set of measurements and comparisons. However, this does not make it possible to solve the problem of determining the quantitative and qualitative indicators of the ES level.

The authors of work [12] showed that the assessment of the level of ES is carried out using a system of indicator indexes, while taking into account their dependence on:

– different types of fuel and general economic situation;
– heat and electricity price policies.

This approach does not solve the problem of assessing the level of ES at the micro-level of the economy of electric power system facilities.

In work [13] it is shown that ES is not limited only to nuclear power plant generation facilities but involves the construction of a new basis for research and analysis of ES in a cause-and-effect context. The results obtained showed that the problem of making a management decision to reduce the impact or eliminate threats to the enterprise's ES has not been solved.

In [14], the authors showed that ES, as a variable, can be used as a dependent or independent variable. In most studies, ES is still implied and defined by variables. Studies have shown that the problem of the connection between renewable energy sources and ES in the short term is not resolved, as well as the problem of the impact of energy production from renewable sources on the risks that threaten ES.

Work [15] shows that since ES is becoming an increasingly relevant topic, a reliable methodical basis for raising the level of ES is needed. Methodological recommendations based on quantitative approaches for measuring and increasing ES at all levels of the economy are proposed. The results obtained demonstrated that the problem of comprehensive assessment of the level of energy safety of generation, transmission, distribution, and energy consumption facilities has not been solved.

In [16] it was noted that the stages of economic development of an industrial enterprise depend on transport and telecommunication structure; energy supply; consequences of climate change; renewable energy sources; production technologies; health care; education and ecosystem diversity. Studies have shown that the problem of managing material flows has not been solved due to the lack of operational dynamic information about the state of energy safety at the enterprise.

In [17], a system of economic estimation of the results of scientific and technical works under the conditions of economic development of an industrial enterprise is proposed, which makes it possible to aggregate current estimation approaches. The results obtained demonstrated that the problem of comprehensive assessment of the level of energy safety of the energy enterprise, taking into account external threats emanating from EPS at the macro- and meso-economic levels, has not been solved.

In work [18], a set of structural and logical subsystems of development, which are interconnected and functioning, considering the specificity of their impact on the strategic and analytical support of industrial enterprises, was substantiated and researched. The results obtained showed that the problem of comprehensive assessment of the level of energy safety of industrial enterprises by using various methods of analysis and assessment of the state of ES at the energy enterprise has not been solved.

In [19, 20], the problem of making management decisions, based on the assessment of the state and level of ES at industrial enterprises, is shown and revealed. The results obtained demonstrated that the problem of making management decisions to eliminate threats under an automated real-time mode has not been solved.

In work [21], methods for assessing the level of these obstacles are proposed for the totality of studied industrial enterprises and for certain types of financial and economic barriers on the way to reducing the consumption of energy resources. Models of substantiation of the parameters of preferential lending for energy-saving projects aimed at the implementation of measures to reduce natural gas consumption at industrial enterprises have been built. Studies have shown that the problem of the impact of reducing energy consumption on the ES of energy enterprises has not been resolved.

Work [22, 23] considered the construction of theoretical and methodological approaches to the structuring of information support and the assessment of its significance for achieving energy-saving economic development of industrial enterprises. The results obtained showed that the problem of developing formalized conditions under which energy-saving economic development takes place at industrial enterprises and the justified importance of information management of this development has not been solved.

In [24], models of cost estimation of scientific and technical developments of industrial enterprises are considered. It is shown that the application of a complex approach makes it possible to achieve a higher level of accuracy of economic profit since a set of heterogeneous features of factors affecting the price of scientific and technical development is taken into account based on the algorithm of the theory of fuzzy large quantities. Studies have shown that the problem of taking into account a set of heterogeneous signs of influencing factors on the threat of ES of an energy company in real time has not been solved.

Thus, our review of the literature [5–24] revealed that there is a partly unsolved problem of assessing the level of ES at an industrial enterprise, namely:

– there is no single methodology for choosing the criteria for evaluating ES and the system for forming indicators of ES of objects at an industrial enterprise;

– there is no continuous monitoring of external and internal threats to the power company's ES under an automated real-time mode;

– no account is taken of the state of ES at the objects of generation, transmission, distribution, and consumption of energy for the calculation of the integrated comprehensive assessment of ES at the industrial energy enterprise;

– there is no mechanism for producing a management decision to reduce the impact or eliminate external and internal threats to ES of an energy company.

This necessitates a deeper study into the main areas that provide a solution to the problem of assessing the level of ES at an industrial enterprise at the microeconomic level.

The study of this topic relates to the fact that in current procedures for assessing the level of energy safety at an industrial energy enterprise, there is a problem of continuous control over criteria and indicators of energy safety at facilities of generation, transmission, and consumption of energy. To this end, it is necessary to continuously monitor indicators and their threshold values for the development of management decisions to reduce the impact of external and internal threats to the energy safety at an industrial enterprise.

Based on the specificity of these processes, it is necessary to continuously monitor the state of objects in real time using software and computing systems (SCSs) within automated technological process control systems (ATPCSs).

In practice, the would-be research results could be implemented to assess the level of energy safety at the Zaporizhia Nuclear Power Plant (ZNPP) under martial law conditions by implementing a computational algorithm of an integrated methodology in ATPCS SCS. This would make it possible in real time to detect internal threats in the form of emergency signs caused by deviation in technological parameters from the norm and to produce a management decision to reduce the impact of threats to the energy safety at ZNPP.

3. The aim and objectives of the study

The purpose of our study is to devise a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise based on the organization of continuous monitoring and control of changes in indicator indices, taking into account the influence of external and internal threats to ES. This makes it possible, based on the calculation of general integral indicators, to determine:

– the degree of criticality and assess the level of ES at IEEs, in order to produce a management decision to reduce the impact or eliminate external and internal threats to ES;

– to reduce material damages and economic losses at IEEs.

To achieve the goal, the following tasks were set:

– to design stages in the construction of a comprehensive methodology for assessing the level of ES at an industrial energy enterprise at the microeconomic level;

– to select the criteria of ES research object to build a system of indicators and their indices;

– to develop a computing algorithm as part of the software-computing package for the automated system for managing the technological processes at an energy enterprise for the implementation of an integrated methodology for assessing the level of ES at an industrial energy enterprise;

– to study the results of practical application of the comprehensive methodology for assessing the level of energy safety at the Zaporizhzhia nuclear power plant.

4. The study materials and methods

The object of our study is the process of assessing the level of energy safety at the industrial enterprise in the electric power system (EPS) at the microeconomic level. The hypothesis of the study assumes that once the selection and calculation of criteria-indicators for assessing the energy safety of the enterprise are carried out on the basis of the method of automated monitoring, this then could make it possible to quickly identify threats, reduce material damage and economic losses to the energy enterprise.

The complexity of ES description of an energy enterprise relates to the fact that its representation as a management object requires taking into account a certain set of parameters that characterize its main properties and functions.

In existing approaches for the assessment of the ES level of research and analysis of industrial enterprises, such sets of parameters are grouped on the basis of various criteria and characteristics of parameters related exclusively to energy consumption processes. From the point of view of ES assessment, in such approaches it is proposed to consider only the process of ensuring the stability of energy supply, thus narrowing the interpretation of ES to «continuity of energy supply in accordance with the needs of the enterprise».

However, this approach does not take into account the impact of external and internal threats on the quantitative and qualitative indicators of electrical and thermal energy during its generation, transmission, and distribution to consumption facilities. In addition, this leads to a limitation of the set of parameters that must be taken into account during the analysis and assessment of the impact on ES of external threats from negative factors on the meso-level economy. At the same time, indicators and parameters should be determined based on current values that change dynamically in real time. The analysis of methodological approaches revealed that there should not be a relative simplification of the analysis of the ES level in the way of assessing threats and ensuring the security of only «important» energy systems. These systems are connected by one process of «energy flow» (energy resources, technologies, and consumers) and provide critical functions at different levels of the economy. From here it should be noted that such a contradiction is one of the reasons why scientists and specialists do not have a single methodical approach to the selection and description of the state of ES at EPS objects. This dictates the need to improve methodical approaches to the study and analysis of ES, which can be used as a basis for the construction of a comprehensive methodology for assessing the level of ES at an energy company. At the same time, it is necessary to take into account external threats that can come from objects at the macro- and meso- levels, as well as the control of internal threats in the process of energy production, transmission, distribution, and consumption.

For the qualitative and quantitative assessment of the state of ES at EPS objects at the macro-, meso-, and micro-levels of the economy, in energy safety assessment procedures, various effective methods of research and analysis of ES have practical application.

The following methods were used to study the process of assessing the level of energy safety at an industrial enterprise:

1. Method of indicative analysis is for the construction of a system of indicators and their threshold values, which make it possible to assess the degree of criticality of the state of energy safety at an energy enterprise and to devise a set of measures for the elimination and prevention of threats.

2. Hierarchy analysis method is to represent the decision-making process in the form of a hierarchical structure: the top of the structure is the decision, below are groups of criteria that combine the criteria by which alternatives are evaluated. At the bottom level of the hierarchy there are objects that are compared according to the values of the criteria of the higher control levels. This will make it possible to choose priority scenarios for managing the development at an industrial energy enterprise from the standpoint of increasing the level of energy safety in the long term.

3. The method of expert estimations is for determining quantitative (qualitative) criteria and weighting factors when assessing the level of energy safety at an industrial energy enterprise and making the optimal decision in the case of possible unreliability or insufficiency of primary data.

4. The method of placing priorities makes it possible to determine the influence of individual management influences on the factors of energy safety of objects at an industrial energy enterprise.

5. The method of automated continuous monitoring is for operational control over the dynamics of changes in indicators-indices for the development of management decisions to reduce the impact of ES threats, which can significantly reduce material losses and economic losses. This makes it possible to describe the degree of change in the indicator criteria in real time, as well as to expand and increase the range of detection of threats, which will quickly make it possible to initiate measures to eliminate them at early stages.

Each of these methods has advantages and disadvantages, unique features that apply to EPS objects at different economic levels.

The analysis of the methods of researching the state of ES from the point of view of their application in the comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise and the development of criteria for assessing the degree of ES of an energy enterprise at the micro-level of the economy showed the following:

– they are templated;

– the application of formalized methods under similar conditions is limited and implies the involvement of professional analysts in the field of ES assessment;

– application of primary information for calculating indicators and their threshold values in the form of statistical data;

– use of specialized energy-metric tools.

It should also be noted that the components (objects) of ES estimation at an energy enterprise are highly dependent on the technical equipment and technological production of energy. Therefore, technological parameters in the form of primary information change in real time. This also contributes to the addition and removal of indicators, which is why it becomes impossible to achieve a high level of ES of an energy company using the methods discussed above. In addition, the application of ES research methods based on the selected indicators and criteria should prevent many emergencies, as well as contribute to increasing the quality of energy and its continuity. Thus, from the point of view of applying the above-mentioned methods for assessing the level of ES of an energy company, it is advisable to simplify their partial application. The completeness of these methods does not justify the result of the ES analysis, due to the incompatibility of the entire range of standard criteria.

Analysis of the considered methods also showed that decision-making based on these methods, due to assumptions, often does not give the desired effect due to significant errors and risks. The main reasons for these assumptions are:

– firstly, the impossibility of taking into account all sources: external, and especially internal threats;

– secondly, the lack of complete enough primary non-contradictory information;

– thirdly, the influence on the processes of formation of various kinds of uncontrolled external influences, mostly of a negative nature.

The set task can be solved by taking into account the fact and the assumption that the primary information, which is the basis of the construction of the system of indicators and their threshold and generalized indicators, is incomplete and unclear. It can be unreliable, which usually leads to material damage and economic losses.

The application of the combined method of studying the ES of an energy enterprise in the form of a set of known methods for continuous monitoring of threats in real time is a completely logical and natural solution to this problem. Moreover, in comparison with other methods, the prediction error in this case is minimal. Hence, it follows that the practical application of the proposed combined method for the continuous monitoring of ES indicators will allow industrial energy enterprises to timely prevent or minimize the loss of production resources and thereby affect the amount of profit.

5. Results of devising a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise

5. 1. Development of stages in the construction of an integrated methodology for assessing the level of energy safety at an industrial enterprise

To study the state of ES of an energy enterprise, it should be understood that this is the state of complete satisfaction of the energy needs of the enterprise, provided that its energy resources are used most efficiently. At the same time, the main goal of achieving the ES level of the energy enterprise is to ensure effective functioning under real conditions and in the predicted future.

It is proposed to determine the state of ES at an energy enterprise based on the use of a comprehensive methodology for assessing the level of ES of an energy enterprise with objects of the generation, transmission, distribution, and consumption of energy. On the basis of the considered methodical approaches to the study of the state of energy enterprise ES, it is proposed to devise and research the process of forming a comprehensive methodology for assessing the level of energy enterprise ES at the microeconomic level.

The purpose and task of a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise is that it should provide justification for the effectiveness of management decisions. This will make it possible to significantly reduce the impact or completely eliminate external and internal threats, and thereby minimize material damage and economic losses.

For this purpose, it is proposed to devise and research the main stages in building a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise and its facilities for the generation, transmission, distribution, and consumption pf power (Fig. 1):

– the stage of selecting the objects to study ES of the energy enterprise;

– the stage of selecting the criteria for the construction of a system of indicators and their threshold criteria, with the help of which the structure and functions of each object of research and analysis of ES could be investigated and displayed;

– the stage of selecting the information sources, as well as collection and analytical processing of primary information for calculation of indicators and their threshold values;

– the stage of performing calculations of indicator values and their threshold criteria;

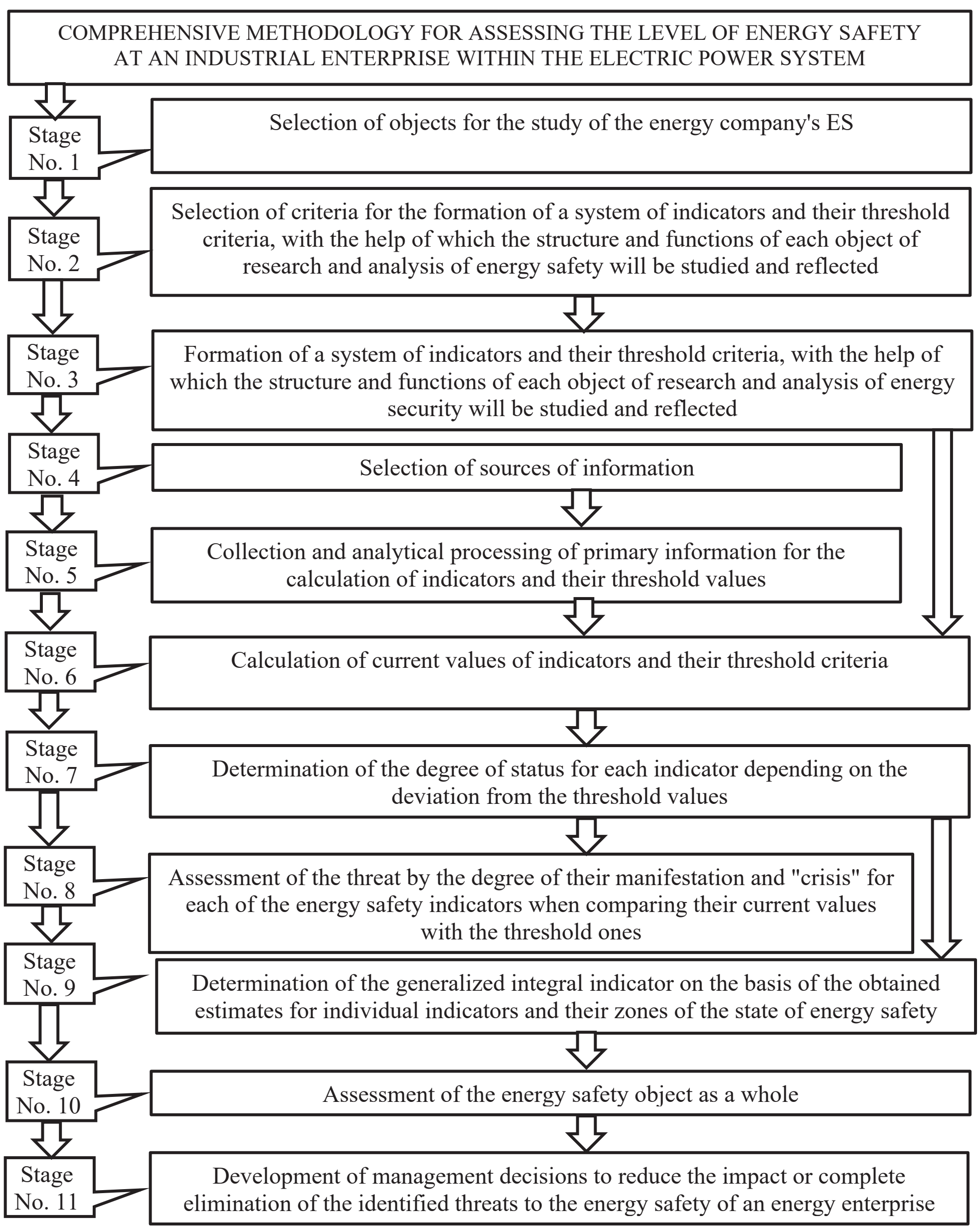

Fig. 1. Comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise

– the stage of threat assessment according to the degree of their manifestation and «crisis» for each of the ES indicators when comparing their current values with the threshold values;

– the stage of determining the degree of condition for each indicator depending on the deviation from the threshold values;

– the stage of defining a generalized integral indicator on the basis of the obtained estimates for individual indicators and their zones of the ES state;

– the stage of estimating the object of energy safety in general;

– the stage of producing management decisions to reduce the impact or completely eliminate identified threats to the ES of the energy enterprise. We shall consider and investigate the results of the construction of a comprehensive methodology for assessing the level of ES at an industrial enterprise on the basis of the proposed stages.

There is no clear separation of these enterprises by functional purpose in the procedures for assessing the level of ES at an industrial energy enterprise. This introduces significant assumptions or limitations regarding the application of various indicators, indices, and their threshold values for determining the state of the energy company's ES.

Therefore, this paper proposes to consider the following energy enterprises as objects of ES research at the microlevel of the economy:

– electricity generation facilities (nuclear and thermal power plants);

– heat generation facilities (thermal stations; boiler houses);

– electricity transmission and distribution objects (electrical networks, power transmission lines, distribution devices, electrical substations);

– objects of heat transmission and distribution (heat networks, main heat pipes, heating points, gas pipelines, gas regulation points);

– objects of electricity and thermal energy consumption (construction, industry, agriculture, transport, and others);

– separate technological processes, sub-processes, and functions that can generate internal threats to the ES of an energy company.

This division will make it possible to determine specific objects of ES research, in which there may be negative factors in the form of threats affecting the change in the state of ES of the energy company. In addition, such an approach will make it possible to more reliably and qualitatively determine a generalized comprehensive indicator for assessing the level of ES of the entire energy enterprise at the microeconomic level.

To this end, it is necessary to conduct a study of each object at energy enterprise, so that it is characterized by specific criteria and state parameters that describe the current state of ES.

5. 2. Selection of the criteria for an ES research object to construct a system of indicators and their values

An important element of the methodology is the selection of ES criteria for the construction of a system of indicators and the justification of their threshold values when analyzing the state of ES.

The assessment of the state and level of ES of the energy enterprise is an indicator of the reliability of its economic development and is carried out by selecting criteria that characterize the properties of the objects of analysis of ES of the energy enterprise in their performance of the main functions and prevention of energy threats.

It follows from this that the main element in the study of ES of the analyzed energy enterprises is the choice of its criterion. Such a criterion should not only state the existence of the ES at an industrial energy enterprise but also clearly assess the level of its energy safety.

To this end, indicators are used, which are usually considered as the limit values of indicators characterizing the activity and development of enterprises in various functional areas, which correspond to a certain level of both energy and economic security. Threshold values are limit values, non-compliance with which values prevents the normal course of development of various elements of reproduction, leads to the construction of negative, destructive trends, both in terms of ES and financial and economic security. The system of indicators, which have acquired a quantitative expression, makes it possible to signal in advance about the threat and take measures to prevent the emerging threat to the enterprise's ES. In order to study the state of the company's ES, it is necessary to predict the occurrence of various threats, and therefore, to determine indicators, which, when comparing their calculated values with the threshold values, will characterize the degree of influence of the emerging threats. Therefore, in order to ensure the ES of energy enterprises, it is proposed to form such a system of indicators that comprehensively takes into account possible forecasted external threats that may form in the region. At the same time, internal threats must be taken into account at the facilities of energy generation, transmission, distribution, and consumption.

As part of the integrated system of indicators, it is proposed to introduce the following indicators given in Table 1. At the stage of calculating the indicators according to the formulas below, the obtained values are compared with the threshold values to determine the transition limit of the indicators from normal to pre-crisis and then to crisis.

In accordance with the requirements for the devised comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise, the following methodical approach is proposed. It makes it possible to determine the zones of the ES state, which can include the current values of the indicators after their determination (calculation) for comparison with the threshold values (Table 2). Table 2 demonstrates that the state of ES is conditionally divided into the following zones and subzones:

– normal state;

– pre-crisis (initial; developing; critical);

– crisis (unstable; threatening; critical; extraordinary).

For all zones and subzones of the ES state, indices of the criticality of the situation are defined, which correspond to certain values of the indicators and their threshold criteria. The ratio of current indicator values to threshold criteria varies by zone (subzone) and depends on which zone (subzone) the indicator falls into and is compared with the threshold value for this zone (subzone). Then, depending on the selected zone (subzone), the weighting factor is determined, which varies from $0 \div 1$.

Thus, our approach makes it possible to determine the ES status zone of the entire system of formed indicators. However, it should be noted that when calculating indicators and their threshold values, the time criterion is an important factor, therefore, for each such time segment, it is necessary to enter a sliding limit value of the indicator.

We have considered stages in the procedure regarding the determination of the general integral indicator of the degree of crisis of ES at an energy enterprise.

Table 1

Selection of criteria for the construction of a system of energy safety indicators

No.	Criterion	Indicator	Parameter
1	Energy consumption per capita of the region, kWh/person	$I_{n1}=\frac{E_{pkb}\cdot 10^6}{N_n}$	E_{pkb} – energy consumption, kWh; N_n – population of the region, thousand persons
2	The share of own sources in the balance sheet of the EE region, %	$I_{n2}=\frac{E_{vee}}{E_{pee}}\cdot 100\,\%$	E_{vee} – EE production during the analysis period, kWh; E_{pee} – EE consumption, kWh
3	The share of own sources in the balance of fuel and energy resources (FER), %	$I_{n3}=\frac{R_{sr}}{P_{pee}}\cdot 100\,\%$	R_{sr} – own energy resources (ER) in the balance sheet of the energy resources, t.o.p.; P_{pee} – ER consumption in the FER balance, t.o.p.
4	The share of the dominant ES of own sources in the balance of FER, %	$I_{n4}=\frac{\max\left(P_y,P_g\right)}{P_{pter}}\cdot 100\,\%$	P_y – the share of coal in the balance of the region's energy resources t.o.p.; P_g – the share of gas in the balance of the region's energy resources, i.e.; P_{pter} – FER in the balance of the region, t.o.p.
5	The share of the installed capacity of the largest ES in the region, %	$I_{n5}=\frac{P_{kr}}{P_{yst}}\cdot 100\,\%$	P_{kr} – capacity of a large power plant in the region, MW; P_{yst} – installed capacity of the region's power plants, MW
6	The share of the available ES power to the maximum electrical load of consumers in the region, %	$I_{n6}=\frac{\max\left(P_{ps}\right)}{P_{\max}}\cdot 100\,\%$	P_{ps} – capacity of a powerful power transmission line in the region with neighboring regions, MW; $P_{\max}$ – maximum electric load of consumers in the region, MW
7	Investment level of regional facilities, %	$I_{n7}=\frac{W_{kv}}{W_{gop}}\cdot 100\,\%$	W_{kv} – volume of investments in objects, UAH; W_{gop} – annual production of EE, USD
8	The amounts of emissions into the atmosphere from facilities per unit area, t/km^2	$I_{n8}=\frac{V_{vv}}{S_{ter}}$	V_{vv} – volume of emissions of harmful substances from EE facilities near the region, tons; S_{ter} – Territory area, km^2
9	Specific volume of emissions of harmful substances from TPP facilities near the region per unit area, t/kW·h	$I_{n9}=\frac{V_{tes}\cdot 10^3}{E_{ee}+Q_{tes}\cdot a_{tes}}$	V_{tes} – volume of emissions of harmful substances, tons; E_{ee} – volume of EE generation at TPPs, kWh; Q_{tes} – volume of thermal energy production (TE) at TPPs, Gcal; a_{tes} – TE conversion factor, MWh/Gcal
10	The share of net profit to the volume of EE production, %	$I_{n11}=\frac{P_{spee}}{V_{eer}}\cdot 100\,\%$	P_{spee} – net profit of the UES, UAH; V_{eer} – annual EE production, kWh
11	Energy intensity of the gross product in comparable prices for the production of EE, t.u.p./USD	$I_{n12}=\frac{Q_{ven}\cdot 10^6}{V_{vrp}}$	Q_{ven} – the amount of energy consumed, t.o.s.p.; V_{vrp} – volume of gross regional product in comparable prices, USD
12	The degree of wear of the OFP of the EE industry, %	$I_{n13}=\frac{\beta_{\max}-\beta_{\min}}{n-1}$	$\beta_{\max}$ – the maximum degree of depreciation of the OPF produced by EE for the accounting period, %; $\beta_{\min}$ – minimum degree of depreciation of the OPF produced by EE for the accounting period, %; n – number of years, year
13	The share of overdue payables of objects to the annual volume of EE, %	$I_{n10}=\frac{S_{kz}}{V_{eer}}\cdot 100\,\%$	S_{kz} – overdue accounts payable of the EE object for the period, USD; V_{eer} – annual EE production, kWh

Table 2

Determining the status zone of the level of energy safety at an industrial enterprise

No.	Energy safety state zone	Correlation of the current values of the indicator with the threshold criterion
1	Normal	$X_{ij}<X_{nk,i}$
2	Pre-crisis	$X_{nk,i}\leq X_{ij}<X_{k,i}$
3	Crisis	$X_{ij}\geq X_{k,i}$

The following expression (1) is proposed to determine the general integrated indicator of the state of ES at an energy enterprise:

$$I_{\Sigma}=\frac{\sum_{i=1}^{n} I_i}{N}, \quad (1)$$

where I_{Σ} is the general integrated indicator of the degree of crisis of ES; I_i – quantitative assessment of the degree of crisis of the situation based on significant indicators; n is the number of indicators used to determine the crisis degree of ES; N is the number of objects of the ES state analysis.

After determining the general integrated indicator of the degree of crisis degree of ES at an energy company, the value of the indicator is compared with the value ranges of quantitative estimates of the degree of crisis, which correspond to one or another situation with ES. After determining whether the general integrated indicator I_{Σ} belongs to one or another range of point estimates, a conclusion is made about the level of crisis of the situation, and, therefore, an assessment of the level of ES is performed.

Thus, the built system of indicators, as well as their calculation and comparison with the threshold criteria for determining the overall integrated indicator, allows taking into account the hierarchical structure of the IEE ES at the macro- and meso- levels. This makes it possible to enable the integration of these indicators as primary information for the selection and calculation of indicators in the comprehensive methodology for assessing the level of the energy company's ES at the macro- and meso- levels of the economy.

We have considered approaches to the implementation of the management decision-making stage for a comprehensive methodology for assessing the level of ES at an industrial energy enterprise.

According to the generalized results and a comprehensive assessment of the level of ES, the stage of making a management decision is being implemented, which is necessary for a timely response to the emerging threats to ES.

To this end, it is necessary to take the following measures:

– to build and implement a system of operational and long-term measures to prevent and neutralize internal and external threats;

– to devise a set of measures to block and eliminate threats;

– to use energy safety indicators;

– to design a system of continuous monitoring and control of the dynamics of indicator indices, under an automated real-time mode.

Here, the coordination of the state variables of ES at an energy enterprise can take place. If the variables are outside the acceptable threshold values, control actions are required to return the variables to a safe state. From which it follows that under the mode of normal functioning of an energy enterprise, the norm of acceptable risk must be ensured, and in the event of an abnormal situation (threats), the task of minimizing risk values arises.

Hence, it follows that for an objective and comprehensive study and analysis of ES, it is necessary to carry out continuous monitoring and control, which makes it possible to constantly monitor the state of crisis of the situation and identify threats. This makes it possible to determine directions and devise measures to counter these threats, to prevent material damage and economic losses.

Such an operational information and analytical system for monitoring the dynamics of ES indicators is of particular importance for such generation facilities as power units at power plants. In addition, at these generation facilities, for research and analysis of the state of ES, it is necessary to obtain primary information and monitor its changes in real time.

5. 3. Development of a computational algorithm for the practical implementation of a comprehensive methodology for assessing the level of energy safety of an energy enterprise

An important element in a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise is the selection of primary information for the calculation of indicators and their threshold criteria based on the organization of a continuous monitoring system. Collection and provision of reliable information of the required quantity and quality, necessary for solving the task of analysis and research of ES of energy enterprise objects, which reflects the actual state of the object under investigation, must be carried out using continuous monitoring. Monitoring, as a system of regular long-term observations in space and time, allows for operational control over the current parameters of the technological processes of generation, transmission, distribution, and consumption of electric and thermal energy. This makes it possible to provide information about the past and present state of the object of observation, which allows predicting all extraordinary changes in its parameters. Since a distinctive feature of energy enterprises is that the processes of generation, transmission, distribution, and consumption of electric and thermal energy occur simultaneously, continuous monitoring must be carried out under an automated real-time mode. At the same time, it is necessary to use such information and measurement systems as ATPCS of the power unit of power plants and ACS for control and accounting of electric energy. It is proposed to carry out constant monitoring of the dynamics of changes in the primary information on the technological parameters of the processes of generation, transmission, distribution, and consumption of thermal and electric energy for the quantitative determination of the values of the indicators-indices for ES. Carrying out continuous monitoring of factors that cause ES threats when using indicators and threshold values makes it possible to detect the probability of crisis situations at the facilities of energy enterprises and to prevent possible material damages and economic losses. Also, our analysis showed that these indicators and their threshold values have a dynamic state, therefore, for their operational calculation, it is necessary to obtain initial primary data under an automated real-time mode.

A computational algorithm was developed and proposed for the implementation of the stages in the construction of an integrated methodology for assessing the level of ES at an industrial energy enterprise and the collection and processing of primary information about indicators for their calculation (Fig. 2).

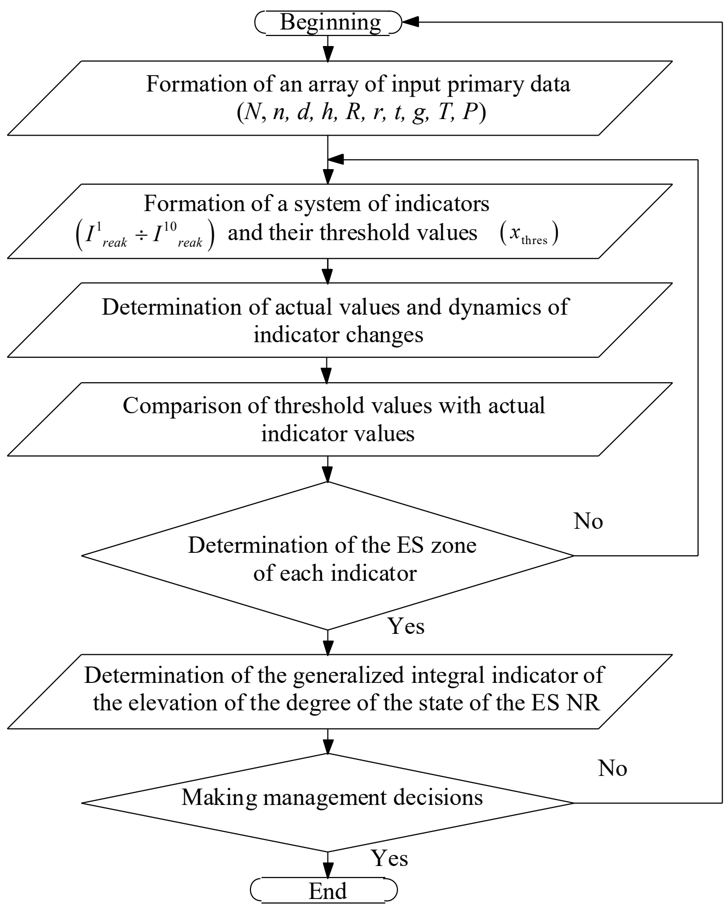

Fig. 2. Algorithm of an integrated methodology for assessing the level of energy safety at an industrial energy enterprise

The algorithm, based on the definition of a generalized integrated indicator, makes it possible to select the state zone of ES, and in the case of a pre-crisis or crisis state, produce a management decision on the operational influence and regulation of the selected indicators. This helps reduce the influence or eliminate the identified threats to ES in real time. For the practical implementation of the computing algorithm, in relation to defining the stages in the construction of an integrated methodology for assessing the level of the industrial energy enterprise under an automated mode, a structural and functional scheme of the computing complex was built and proposed (Fig. 3).

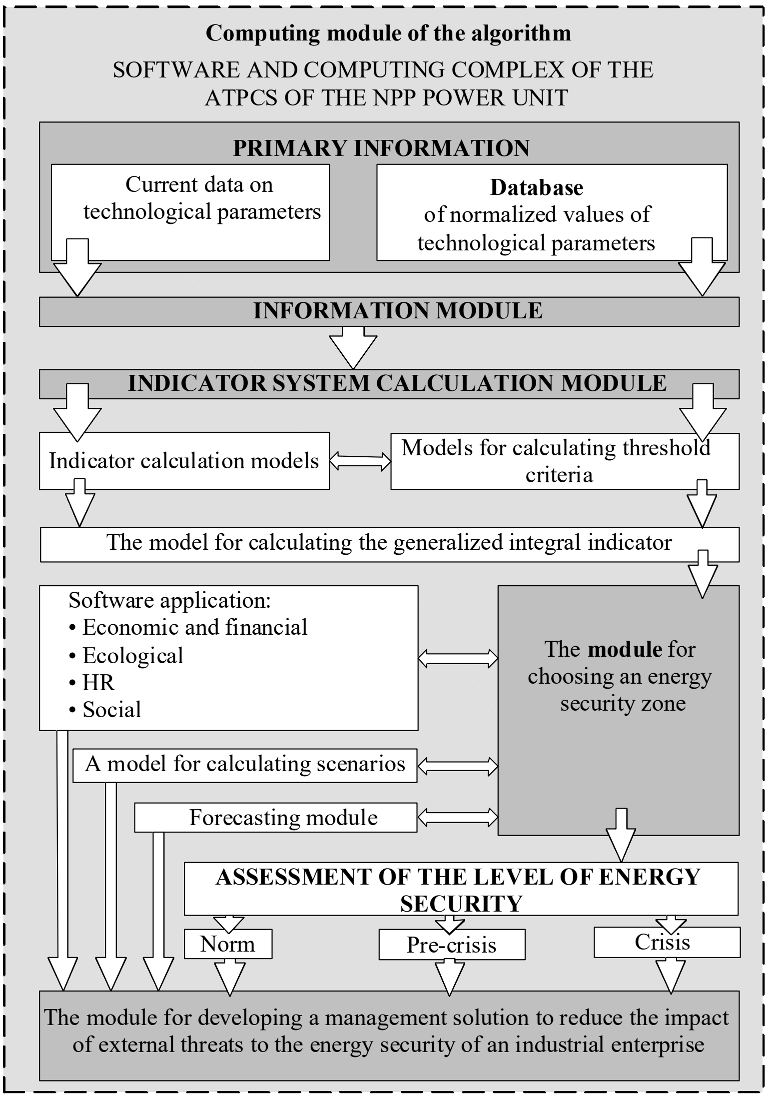

Fig. 3. Structural-functional scheme of the software-computing system in the automated technological process control system at the industrial enterprise's generation facility

As can be seen from the diagram (Fig. 3), the computing module of the algorithm for assessing the level of energy safety of an energy enterprise is included in the software and computing system within ATPCS of the power plant power unit. Data on the current values of technological parameters (more than 50,000 technological parameters at NPP), as well as from the database of the ATPCS of the power plant [25] are used as primary information for calculating the selected indicators.

This allows for continuous monitoring and control of indicators and their threshold values under an automated real-time mode and thus to calculate a generalized integrated indicator for determining the state of ES.

In order to implement a computational algorithm for continuous monitoring and control of indicators and their threshold values for the study of energy safety, it is proposed to include the following elements in the software-computing system (SCS) in ATPCS:

– an information module that performs operations for collection, processing, and storage of current values of technological parameters, which will be used as primary information to calculate indicators in real time;

– a database containing statistical normalized values of technological parameters for the technological process of energy production under various modes of operation of generation facilities;

– calculation module, in which the values of indicators and their threshold criteria are calculated based on computational models, taking into account their current dynamic state;

– a module for calculating a generalized indicator for the purpose of assessing the level of ES;

– the module for selecting the ES state zone and determining the assessment of the ES level;

– a module for forecasting changes in the dynamics of indicators and their threshold criteria for the analysis of the generalized indicator of the assessment of the ES state;

– a module for building scenarios for modeling controlling influences or possible threats, taking into account changes in the influence of threats, to assess the real state of the ES of generation facilities;

– software applications that contain components of economic, financial, environmental, personnel, and social security, and significantly affect the state of ES.

Thus, the proposed computational algorithm allows for the following:

– to implement the stages in forming a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise;

– to enable continuous monitoring and control of indicators and their threshold values in real time;

– on the basis of the received assessment of the level of the state of ES, produce a management decision to reduce the impact or completely eliminate the threats.

5. 4. Investigating the results of practical application of the comprehensive methodology for assessing the level of energy safety at the Zaporizhzhia nuclear power plant

It was proposed to consider the practical application of the integrated methodology for assessing the level of energy safety at an industrial energy enterprise using the example of a generation facility – the Zaporizhzhia Nuclear Power Plant (ZNPP).

Taking into account the specificity of the study, which is directly related to generating sources of electric power generation, the reliability of the operation of the technological equipment of the power plant becomes the dominant component of ES.

For the practical application of the comprehensive methodology for assessing the level of ES at an industrial energy enterprise at the microeconomic level, it was proposed to choose the generation object – the power unit at ZNPP as a separate object of research and analysis of the state of ES of IEE.

Since each of the power units, as an object of ES analysis, can be considered a complex multi-parameter object, separate technological processes, functions, and individual quantitative parameters can be considered the objects of ES assessment.

Thus, in accordance with the requirements established by the IAEA, during the operation of the nuclear reactor at ZNPP, it is necessary to fulfill safety criteria that depend on the number of damaged or destroyed heat-emitting elements (TVEL) at the nuclear reactor of ZNPP [26].

At the nuclear power plant, as a safe operation, in the assessment of damage to the element of the nuclear reactor, the values of the technological parameters that affect the processes of ES, both of the nuclear reactor and of the entire nuclear power plant in general, are taken.

In this regard, according to the devised comprehensive methodology for assessing the level of ES of the energy company for researching the ES state of the ZNPP reactor, a selection of the main indicators and their threshold criteria was carried out (Table 3). They can also be used to calculate the generalized integrated indicator for evaluating the level of ES at the nuclear reactor of ZNPP.

It should be noted that the results of the selection and definition of the system of indicators for the study of the state of ES at the ZNPP nuclear reactor showed that they have the same weighting factor from 0 to 1. At the same time, any of them can significantly influence the generalized integrated indicator, on the basis of which the assessment is made of ES of the entire nuclear reactor at ZNPP.

In accordance with the requirements for the devised comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise, zones of the ES state were selected to determine the state of the ES level at a nuclear reactor.

They may include the current values of the indicators after the determination (calculation) of the comparison with the threshold values, as shown in Table 4.

Table 4 demonstrates that the determination of the ES state zone is carried out according to the selected indicator, which is determined by the specified number of depressurized elements of the nuclear reactor (N3÷N10).

At the same time, their complete depressurization is determined by the threshold criteria for each zone of the state of energy safety from Table 3.

Thus, a comprehensive methodology for assessing the level of ES at an industrial energy enterprise has been devised, which allows one particularly important indicator (the number of depressurized TVELs) to determine the zone of energy safety.

This makes it possible to assess the level of energy safety of the nuclear reactor at ZNPP in real time.

In the process of research, based on the implementation of the computing module as part of ATPCS SCS of the power unit, a number of results were obtained, some of which are given in Table 5. The primary information was used on the basis of the database of ATPCS power units at ZNPP, as well as the report of IAEA experts for 2022–2023, in the assessment of ES of nuclear reactors at ZNPP.

Table 3

Selection of the main indicators and their threshold criteria for assessing the state of energy safety of the nuclear reactor at a nuclear power plant

No.	Indicator	State			Threshold value x
		Norm	Pre-crisis	Crisis	
1	I^1_{reak} – Number of fuel rods with cladding defects (direct contact), %	$0<x<0.05$	$0.05<x<0.1$	$0.1\leq x$	n=10 units
2	I^2_{reak} – number of fuel rods with cladding defects (no contact), %	$0<x<0.5$	$0.5<x<1.0$	$1.0<x$	n=100 units
3	Fuel rod cladding defect size, %	$0<x<20$	$20<x<100$	$100<x$	d=50 µm
4	Increase in the geometric length of the fuel cladding structure, %	$0<x<0.2$	$0.2<x<0.4$	$0.4<x$	h=16.0 mm
5	Local deformation of fuel rod cladding shape, %	$0<x<10.0$	$10.0<x<20.0$	$20.0<x$	R=1.83 mm
6	Radius of curvature of fuel rod cladding, %	$0<x<0.25$	$0.25<x<0.5$	$0.5<x$	r=0.39 mm
7	Maximum T of fuel rod shell, %	$100.0=x$	$100.0<x<200.0$	$200.0<x$	T=1,200 °C
8	Maximum local depth of fuel rod oxidation, %	$0<x<5.0$	$5.0<x<18.0$	$18.0<x$	g=0.124 µm
9	Heat-carrier temperature, %	$100.0=x$	$100.0<x<200.0$	$200.0<x$	T=640 °C
10	Heat-carrier pressure, %	$100.0=x$	$100.0<x<200.0$	$200.0<x$	P=160 bar

Table 4

Determining the status zone of energy safety level at a nuclear reactor

No.	ES state zone	Criticality index	Correlation of the current values of the indicator with the boundary criteria	X_{POR}
1	Normal	N at N_{POR}=3 Fuel Element	$0\leq N_3<X_{PK1}$	0.0
2	Pre-crisis (initial)	PK-1 at N_{POR}=4 Fuel Element	$X_{PK1}\leq N_4<X_{PK2}$	0.14
3	Pre-crisis (developing)	PK-2 at N_{POR}=5 Fuel Element	$X_{PK2}\leq N_5<X_{PK3}$	0.28
4	Pre-crisis (critical)	PK-3 at N_{POR}=6 Fuel Element	$X_{PK3}\leq N_6<X_{KR1}$	0.44
5	Crisis (unstable)	KR-1 at N_{POR}=7 Fuel Element	$X_{KR1}\leq N_7<X_{KR2}$	0.58
6	Crisis (threatening)	KR-2 at N_{POR}=8 Fuel Element	$X_{KR2}\leq N_8<X_{KR3}$	0.72
7	Crisis (critical)	KR-3 at N_{POR}=9 Fuel Element	$X_{KR3}\leq N_9<X_{KR4}$	0.86
8	Crisis (emergency)	KR-4 at $N_{POR}\geq$10 Fuel Element	$N_{10}\geq X_{KR4}$	1.0

Table 5

Results of a computational experiment on energy safety assessment at the Zaporizhzhia NPP

Facility No. NPP NR	Energy safety state zone									
	N	PK-1	PK-2	PK-3	KR-1	KR-2	KR-3	KR-4	∑NR	∑NPP
Criterion	<0.25	0.25	0.375	0.5	0.625	0.75	0.825	1.0	–	–
NR 1	×	×	×	×	×	×	×	0.91	0.81	Crisis threat state
NR 2	×	×	×	×	×	×	×	0.96		
NR 3	×	×	×	×	×	×	×	0.87		
NR 4	×	×	×	×	×	×	×	0.94		
NR 5	×	×	×	×	×	×	0.76	×		
NR 6	×	×	×	×	×	0.68	×	×		

The results of the computational experiment showed that the six nuclear reactors at the Zaporizhzhia NPP are in the following zones of the ES state:

– nuclear reactors No. 1–4 in the critical emergency zone;

– nuclear reactor No. 5 in the critical crisis zone;

– nuclear reactor No. 6 in the critical threat zone.

In general, the generalized integrated indicator of the level of ES of all reactors, and therefore of the entire ZNPP, was determined from formula (18) and was 0.81, which corresponds to the crisis-threatening state of ES at ZNPP.

On the basis of the obtained assessment of the state of the ZNPP ES, when making management decisions, special attention should be paid to the following facts:

– the emergence of threats in the form of emergencies, the consequence of which may be damage to equipment, disruption of energy supply to consumers or further development of the accident, it is necessary to carry out urgent management (mostly discrete) operations;

– ensuring the safety of equipment, localization of the accident, minimization of material damage and economic losses.

Depending on the specific reasons that caused the emergency, it may be necessary to completely stop the power unit (economic losses amount to USD 150,000), turn off units, reduce the load of the power unit, which prevent the development of the accident [27]. It is necessary to develop ES management algorithms under emergency modes, which will reduce the impact of threats on technological equipment under non-staff modes of the power unit, including threats typical of terrorist acts and military conflicts. All these tasks, from the implementation of management decisions, are entrusted to the operator of the automated workplace (AMP) of the ATPCS at the power plant unit [28].

On the basis of detected threats in the form of indicator deviations, the operator of the power plant sends control commands to the executive mechanisms and thus the process of reducing the impact of the threat on the state of energy safety of the power plant is carried out. Thus, for nuclear reactors No. 5 and No. 6 at ZNPP, in order to prevent them from entering the emergency crisis zone, it is recommended to carry out continuous monitoring of fuel elements with the use of the shell tightness control system.

This algorithm makes it possible to shorten the fuel element restart period and free up the maintenance staff at ZNPP, which leads to a reduction in economic losses in the amount of USD 300,000 and, in general, increases the ES of ZNPP by 15 %.

In general, due to the presence of nuclear reactors No. 1–4 in the crisis emergency zone, the ES at ZNPP decreased by 80÷85 %, which led to the shutdown of 4 power units.

According to the experts from the international organization IAEA, economic losses due to the cessation of electricity generation amounted in 2022 to 1.7 billion US dollars; in 2023 – more than 3.1 billion US dollars. At the same time, material losses due to damage to technological equipment amounted to at least USD 3.0 billion.

6. Discussion of results related to devising a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise

A feature of the proposed comprehensive methodology for assessing the level of ES at an industrial energy enterprise is that the objects of generation, transmission, distribution, and consumption of energy were considered as objects of research at the micro level. They are characterized by dynamic processes of a production and technological nature, in which negative factors of threats can form. This significantly affects the ES of the energy company and can also lead to material damages and economic losses. It should be noted that the objects of estimation of the ES of the energy company are very dependent on the technical equipment and technological production of energy, and therefore the technological parameters in the form of primary information change in real time. This also contributes to the addition and removal of indicators, which is why it becomes impossible to achieve a high level of ES of an energy enterprise, using existing ES research methods.

In contrast to [4], in which the level of energy safety at an industrial enterprise is not taken into account, the devised comprehensive methodology for assessing the level of ES at an industrial energy enterprise makes it possible to flexibly respond to changes in the state of the objects of the energy enterprise due to threats. It also allows for real-time simulation of new indicators that require changes in threshold values.

The system of indicators, formed taking into account the selected criteria, makes it possible to examine the state of ES of the energy company's objects under a dynamic real-time mode, taking into account the combined method of continuous monitoring.

Control over primary information on the processes of energy generation, transmission, distribution, for the calculation of indicators and indices, and the determination of generalized integrated indicators for assessing the level of ES, taking into account external and internal threats, was carried out.

This approach to the construction of a integrated methodology for assessing the level of ES at an industrial energy enterprise allows solving the problem of ensuring the complexity and determining the influence of factor indicators on the result, which allows determining the safety of individual objects of energy enterprises. An important feature of the proposed system of indicators is that the results of calculating the indicators according to the formulas in Table 1 could be used as primary information in the comprehensive methodology for assessing the level of ES at an industrial energy enterprise.

The result of the practical application of the computational algorithm (Fig. 2) as part of SCS (Fig. 3) within ATPCS of generation facilities and in the ACS of control and accounting of electricity is the implementation of an integrated methodology for assessing the level of ES. It is also provided for the development and construction of a management decision to reduce the impact or eliminate external and internal threats to the ES. On the basis of the proposed comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise, an assessment of the state of ES at ZNPP was carried out and analyzed, where nuclear reactors No. 1÷6 were chosen as research objects. A study of the state of their ES was conducted on them based on monitoring and control of the number of depressurized fuel elements at a threshold value of $N \leq 10$ fuel elements. On the basis of the implementation of the algorithm of the comprehensive methodology for assessing the level of energy safety of the industrial energy enterprise, the results of the state of ES of each nuclear power plant were obtained separately, as shown in Table 5:

– NR No. 1–4 – emergency crisis zone;

– NR No. 5 – critical crisis zone;

– NR No. 6 and ZNPP in general are in a dangerous crisis zone.

Our results were used to produce a management solution, which should be implemented using the influence of technical means (as executive mechanisms) to reduce the impact of identified threats.

The result of the application of the computational algorithm for the estimation of the ES at ZNPP showed that it makes it possible to determine the number of fuel elements even on one integrated indicator. This shows that an internal threat affects the ES of NPP and puts the NPP power unit into shutdown mode, resulting in economic losses in the amount of more than USD 150,000.

The practical application of the proposed comprehensive methodology for assessing the level of ES at an industrial energy enterprise will make it possible to solve the problem of prevention and minimization of losses of production resources in a timely manner and thereby reduce material losses and increase the amount of economic profit. As a prospect for conducting research, it is also expedient to further advance the methodical provision for information support to decision-making, regarding directions for strengthening the ES of industrial energy enterprises based on the proposed methodical approach.

The limitations inherent in this study are the definition of threats through the application of the concept of «risk» – a threat to approaching a «safe state». The identification of threats by comparing the actual parameters of the indicators with the target parameters should not be considered as a reasonable condition for the identification of critical threats to the energy safety of energy enterprises. This research method allows the researcher to be oriented to a more detailed analysis of this parameter and the determination of all the factors causing the corresponding deviation from the target values (the target state of the energy safety system of energy enterprises).

As a shortcoming of this study, the lack of a single software-computing system for connecting automation systems when assessing the level of ES of objects of generation, transmission, distribution, and consumption of electric and thermal energy can be noted. In the future, to eliminate this shortcoming, it is necessary to design an integrated automated system for monitoring external and internal threats to the energy safety of energy enterprises at the macro-, meso-, and micro-levels, for evaluating ES in real time.

The development of this research implies that the classification of threats can also be carried out in view of the «detailing» of the analysis of the energy safety system of the energy enterprise. In some cases, it is advisable to take a closer look at individual components of an energy company's energy safety system and identify threats to these components (elements, connections, functions, processes). In particular, there is a theoretical and practical need to analyze risks to vital energy systems that provide the process of providing the objective function/service. In the course of the research, difficulties of an experimental nature may arise, which require a simultaneous assessment of threats in the power supply sector, which reveals the need to distinguish between internal and external threats to the energy company at the macro-, meso-, and micro-levels.

7. Conclusions

1. The main stages in the construction of a comprehensive methodology for assessing the level of energy safety at an industrial energy enterprise have been devised and researched. The main principle of building stages in the construction of an integrated methodology for assessing the level of ES at an industrial energy enterprise was the accounting of such objects of energy safety research as objects of generation, transmission, distribution, and consumption of electric and thermal energy. The designed stages allowed for the following:

– to determine specific objects of energy safety research, in which there may be negative factors in the form of external and internal threats, affecting the change in the state of ES of the energy enterprise and its objects;

– to solve the problem of forming a system of indicator indices taking into account the primary information of both static and dynamic state, which made it possible to assess the level of the crisis state of ES at the energy enterprise in real time;

– to implement a mechanism for producing a management solution to reduce the impact or eliminate external and internal threats to the energy company's ES, based on continuous monitoring of ES indicators under an automated real-time mode.

2. It has been shown that the basis for the construction of a system of indicators and their threshold indicators is the selection of ES research objects and ES criteria, which characterize the properties and functions of the selected research objects. It is shown that the indicators have a dynamic nature, which requires their continuous monitoring and control under an automated real-time mode. It is proposed to use the results of the calculation of the indicator indices in the ES estimation procedures as primary information at the macro- and meso-levels of the economy.

3. A computing algorithm was developed as part of the software-computing system within an energy enterprise's ACS, which allowed us to implement under an automated

mode the stages of forming the integrated methodology for assessing the level of ES at an industrial energy enterprise. The peculiarity of this computational algorithm is that it made it possible to quickly, in real time, compare the actual current values of indicators with their threshold values for determining the criticality zone of ES at an energy company. A distinctive feature of the computational algorithm is its implementation on the basis of a computational module as part of the software-computational complex in the ACS of generation facilities, which made it possible to quickly develop a controlling influence on the reduction of ES threats. The computing module of the algorithm made it possible to collect, process, and store the current values of 5,000 technological parameters, which are used as primary information to calculate indicators in real time. This made it possible to monitor the dynamics of changes in the values of the main and auxiliary indicators and their threshold values for the calculation of the generalized integrated indicator, in order to assess the level of ES of the energy enterprise at the microeconomic level.

The developed algorithm, based on the definition of a generalized integrated indicator, made it possible to select the state zone of ES, and in the case of a pre-crisis or crisis state, produce a management decision on the operational impact and regulation of the selected indicators. This contributed, in real time, to the reduction of the influence or elimination of the identified threats to the ES of the industrial energy enterprise.

4. The practical implementation of the integrated methodology for assessing the level of energy safety at an industrial energy enterprise was carried out using the example of ZNPP. It was found that the ES level at ZNPP depends on the ES state of each nuclear reactor and is equal to 0.81 based on the generalized integrated index. Thus, the level of ES at ZNPP is assessed as a critical threatening state.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Pro natsionalnu bezpeku Ukrainy. No. 2469-VIII. Available at: https://zakon.rada.gov.ua/laws/show/2469-19#n355
2. Proekt Zakonu pro zasady derzhavnoi polityky u sferi enerhetychnoi bezpeky Ukrainy. No. 8609. Available at: http://w1.c1.rada.gov.ua/pls/zweb2/webproc4_1?pf3511=64445
3. Pro skhvalennia Enerhetychnoi stratehiyi Ukrainy na period do 2035 roku «Bezpeka, enerhoefektyvnist, konkurentospromozhnist». No. 605-r. Available at: https://zakon.rada.gov.ua/laws/show/605-2017-%D1%80#Text
4. Shylo, Zh. S., Krechko, M. Yu. (2022). Methods of assessing the level of economic security of the enterprise: approaches to assessing and ensuring economic security. Bulletin National University of Water and Environmental Engineering, 2 (98), 278. https://doi.org/10.31713/ve2202224
5. Sukhodolia, O. M., Kharazishvili, Yu. M., Bobro, D. H., Smenkovskyi, A. Yu., Riabtsev, H. L., Zavhorodnia, S. P. (2020). Enerhetychna bezpeka Ukrainy: metodolohiia systemnoho analizu ta stratehichnoho planuvannia. Kyiv: NISD, 178. https://niss.gov.ua/sites/default/files/2020-12/sukhodolia_energy_security_sayt-1.pdf
6. Azzuni, A., Breyer, C. (2017). Definitions and dimensions of energy security: a literature review. WIREs Energy and Environment, 7 (1). https://doi.org/10.1002/wene.268
7. Payne, J. E., Truong, H. H. D., Chu, L. K., Doğan, B., Ghosh, S. (2023). The effect of economic complexity and energy security on measures of energy efficiency: Evidence from panel quantile analysis. Energy Policy, 177, 113547. https://doi.org/10.1016/j.enpol.2023.113547
8. Yang, Z., Hao, C., Shao, S., Chen, Z., Yang, L. (2022). Appropriate technology and energy security: From the perspective of biased technological change. Technological Forecasting and Social Change, 177, 121530. https://doi.org/10.1016/j.techfore.2022.121530
9. Ang, B. W., Choong, W. L., Ng, T. S. (2015). Energy security: Definitions, dimensions and indexes. Renewable and Sustainable Energy Reviews, 42, 1077–1093. https://doi.org/10.1016/j.rser.2014.10.064
10. Ren, J., Dong, L. (2018). Evaluation of electricity supply sustainability and security: Multi-criteria decision analysis approach. Journal of Cleaner Production, 172, 438–453. https://doi.org/10.1016/j.jclepro.2017.10.167
11. Gasser, P. (2020). A review on energy security indices to compare country performances. Energy Policy, 139, 111339. https://doi.org/10.1016/j.enpol.2020.111339
12. Axon, C. J., Darton, R. C. (2021). Sustainability and risk – a review of energy security. Sustainable Production and Consumption, 27, 1195–1204. https://doi.org/10.1016/j.spc.2021.01.018
13. Dobrowolski, Z. (2021). Energy and Local Safety: How the Administration Limits Energy Security. Energies, 14 (16), 4841. https://doi.org/10.3390/en14164841

14. Tansel Tugcu, C., Menegaki, A. N. (2024). The impact of renewable energy generation on energy security: Evidence from the G7 countries. Gondwana Research, 125, 253–265. https://doi.org/10.1016/j.gr.2023.08.018
15. Zhang, L., Bai, W., Xiao, H., Ren, J. (2021). Measuring and improving regional energy security: A methodological framework based on both quantitative and qualitative analysis. Energy, 227, 120534. https://doi.org/10.1016/j.energy.2021.120534
16. Prokhorova, V., Mushnykova, S., Zaitseva, A., Gavrysh, O. (2024). Convergence of dominant forms of investment capital in the development of socio-economic systems. Eastern-European Journal of Enterprise Technologies, 1 (13 (127)), 122–130. https://doi.org/10.15587/1729-4061.2024.299127
17. Prokhorova, V., Mrykhina, O., Koleshchuk, O., Slastianykova, K., Harmatiy, M. (2023). The holistic evaluation system of R&D results under the circular economy conditions. Eastern-European Journal of Enterprise Technologies, 6 (13 (126)), 15–23. https://doi.org/10.15587/1729-4061.2023.291380
18. Prokhorova, V., Bezuhla, Y., Koleshchuk, O., Zaitseva, A. (2023). Formation of economic freedom and entrepreneurial culture as strategic dominants of enterprise development transparency. Eastern-European Journal of Enterprise Technologies, 6 (13 (126)), 24–32. https://doi.org/10.15587/1729-4061.2023.292324
19. Prokhorova, V., Chobitok, V., Pershyna, K., Miahkykh, I., Shelest, O., Yukhman, Y. (2023). Patterns of the state-legal support to the dynamic information development of the socio-economic environment. Eastern-European Journal of Enterprise Technologies, 4 (13 (124)), 6–15. https://doi.org/10.15587/1729-4061.2023.285936
20. Prokhorova, V., Mushnykova, S., Kovalenko, D., Koleshchuk, O., Babichev, A. (2023). Convergence of educational technologies as an imperative for the development of innovation cooperation in the context of circular transformation. Eastern-European Journal of Enterprise Technologies, 4 (13 (124)), 26–35. https://doi.org/10.15587/1729-4061.2023.286183
21. Prokhorova, V. V., Yemelyanov, O. Y., Koleshchuk, O. Y., Petrushka, K. I. (2023). Tools for assessing obstacles in implementation of energy saving measures by enterprises. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 1, 160–168. https://doi.org/10.33271/nvngu/2023-1/160
22. Prokhorova, V. V., Yemelyanov, O. Y., Koleshchuk, O. Y., Antonenko, N. S., Zaitseva, A. S. (2023). Information support for management of energy-saving economic development of enterprises. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 6, 175–183. https://doi.org/10.33271/nvngu/2023-6/175
23. Prokhorova, V., Zalutska, K., Fedorova, Y., Obydiennova, T., Prykhodchenko, O. (2023). Ensuring sustainable development of a region in the strategic period. Eastern-European Journal of Enterprise Technologies, 4 (13 (124)), 36–45. https://doi.org/10.15587/1729-4061.2023.285418
24. Pylypenko, H. M., Prokhorova, V. V., Mrykhina, O. B., Koleshchuk, O. Y., Mushnykova, S. A. (2020). Cost evaluation models of R&D products of industrial enterprises. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5, 163–170. https://doi.org/10.33271/nvngu/2020-5/163
25. Budanov, P., Oliinyk, Y., Cherniuk, A., Brovko, K. (2024). Fractal approach for the researching of information emergency features of technological parameters. AIP Conference Proceedings. https://doi.org/10.1063/5.0191648
26. Budanov, P., Khomiak, E., Kyrysov, I., Brovko, K., Kalnoy, S., Karpenko, O. (2022). Building a model of damage to the fractal structure of the shell of the fuel element of a nuclear reactor. Eastern-European Journal of Enterprise Technologies, 4 (8 (118)), 60–70. https://doi.org/10.15587/1729-4061.2022.263374
27. Popov, O., Shmatko, N., Budanov, P., Pantielieieva, I., Brovko, K. (2019). Cost-effectiveness in mathematical modelling of the power unit control. Eastern-European Journal of Enterprise Technologies, 6 (3 (102)), 39–48. https://doi.org/10.15587/1729-4061.2019.183422
28. Budanov, P., Brovko, K., Cherniuk, A., Vasyuchenko, P., Khomenko, V. (2018). Improving the reliability of information-control systems at power generation facilities based on the fractal-cluster theory. Eastern-European Journal of Enterprise Technologies, 2 (9 (92)), 4–12. https://doi.org/10.15587/1729-4061.2018.126427