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Adaptive Response Methodology For Sustainable Energy Systems Of The National Economy In The Security Dimension

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Abstract

This article presents a methodology that combines expert assessments and mathematical calculations to quantify the impact of both external and internal threats on the energy security level of a state. The approach utilizes an energy security model to assess the overall impact of changes in integrated index components. Adaptive control methods are employed to decompose integrated indices and security indicators. The methodology incorporates indicators that determine safe existence limits within security gradations and uses normalization techniques and dynamic weighting coefficients. It also formalizes the impact of threats on the integral index, constructs a new trajectory for goal achievement, and decomposes the dynamics into components and energy security indicators. The developed methodology aids in formulating management decisions to mitigate and eliminate threats to energy security, ensuring adaptability within the energy system and maintaining a trajectory of sustainable development. This can be applied at various levels, from local to national, through the Energy Sustainability Plan of the Country.

Keywords: *Energy security, Adaptive response, Sustainable energy systems, Economic security, Digitalization, Energy investments, Energy sustainability plan.*

Introduction

Sustainable development stresses the importance of national approaches to its management. It aims to meet present needs without compromising future generations' ability to meet their own. Access to affordable, reliable, and modern energy sources is critical to achieving sustainable development. Thus, ensuring energy security is a top priority for governments committed to sustainable development (Butlin, 1987; UN, 2002, 2012; European Union Global Strategy[1], 2016).

Energy security requires a new approach due to technological advancements (Gonchar et al., 2022; Voloshyn et al., 2023), energy market changes, and geopolitical factors. It means providing reliable, cost-effective, and environmentally-friendly energy to meet society's needs and protect national interests in normal and emergency situations (Sukhodolia, 2020, p.10).

Sustainability and energy security are interlinked. It refers to a system's ability to withstand threats while maintaining its desired functioning and development trajectory. Continuous adaptation to the security environment is essential to ensure sustainability (European Union Global Strategy, 2016).

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Ensuring energy security and promoting sustainable development in the face of threats are key challenges. Numerous research studies have explored various aspects of energy security (Kotowicz et al., 2022; Hutsaliuk et al., 2023; Dźwigol et al., 2019; Miskiewicz, 2020; Saługa et al., 2021; Kostyrko et al., 2021; Polcyn et al., 2022; Coban et al., 2022). These studies have covered topics such as renewable energy sources, smart grids, energy independence, and the environmental impacts of new technologies. Other works have focused on discount rates, electricity market regulation, R&D project management, and the integration of electric vehicles into power systems.

Bin Abdullah et al. (2020) evaluated Pakistan's energy security index using the Z-score method and principal component analysis. Their assessment considered dimensions such as availability, affordability, technology, management, and environment, resulting in an energy security index ranging from 7.59 to 8.29. However, this approach did not differentiate between stimulants and destimulants or establish safe existence limits. Several studies have examined energy security assessment, analysis of threats, risks, and response methods (Axon & Darton, 2021; Brown et al., 2014; Shaikh et al., 2022).

Defining energy security is challenging due to the lack of a standardized methodology for its determination and limited research. Various research methods have been used, including the structural approach, Z-score method, factor analysis, fuzzy method, Malmquist Productivity Index, and SWOT analysis. The study by Iyke et al. (2021) explored the relationship between energy security and the profitability of energy stocks. It found that energy security indices were capable of predicting stock profitability. Another publication examined the World Energy Council's Energy Trilemma Index, which ranks countries based on their sustainable energy provision. However, the index calculation formulas are not disclosed, leading to some subjectivity and dissatisfaction with the ranking approach (2023).

In terms of assessing threats, a risk-based approach is commonly applied in national security systems. Risk is understood as the impact of uncertainties on management objectives or the probability of a threat materializing and causing negative consequences (ISO 31000, 2018).

The U.S. Chamber of Commerce Global Energy Institute introduced the International Energy Security Risk Index, which utilizes quantifiable data, historical trends, and government projections to assess factors contributing to international energy security. The index scores are measured relative to a benchmark index representing the average for OECD members in 1980.

The EU approved a new approach in 2015 for evaluating national risks in critical infrastructure protection. This approach involves comparing the relative impact of specific threats and the likelihood determined by experts. A 5x5 matrix is commonly used to assess consequences and probability. Consequences are evaluated on a scale from negligible (1) to disastrous (5). Probability represents the plausibility of threat occurrence and increases as the risk increases. The UK Government's annual risk analysis and the US evaluation of risks follow a similar approach, utilizing expert assessments on a five-point scale (Theocharidou & Giannopoulos, 2015; UK Cabinet Office, 2015, 2020).

It is worth noting the evolution of risk assessment methodology in the preparation of the National Risk Register. The UK Cabinet Office's assessment in 2020 categorizes threats into eight target components/consequences, including economic impacts, fatalities, evacuation and shelter, public perception, environmental damage or contamination, essential services, electricity supply, and international relations. These categories are derived from retrospective analysis and assessed by experts when evaluating threat consequences (UK Cabinet Office, 2020; Cybersecurity & Infrastructure Security Agency, 2020). Quantifying threats accurately is challenging without an all-encompassing mathematical model that integrates risks, vulnerabilities, and consequences. Calculated threat levels should be treated as estimates when there is no comprehensive information to avoid overemphasizing higher accuracy (Kwilinski et al., 2022; Miśkiewicz et al., 2022;

Polcyn et al., 2022; Brown et al., 2014; World Energy Council, 2023; ISO 31000, 2018; U.S. Chamber of Commerce Global Energy Institute, 2023; Cybersecurity & Infrastructure Security Agency, 2020).

Existing approaches to assessing energy security have flaws such as a lack of scientific methodology, inconsistencies in assigning weighting coefficients, and no objective way to compare energy security levels. Sukhodolia et al. (2022) proposed a new quantitative methodology that aims to help energy systems withstand threats and align with sustainable development goals.

Materials and Methods

We propose a strategic planning approach that combines expert assessments and mathematical calculations to determine national security levels. This approach evaluates the impact of threats and stability of sustainable development trajectory. The problem involves defining energy security levels and devising strategies to improve it in alignment with sustainable development. This framework provides a systemic view of transitioning from the current state to the desired state (Sukhodolia et al., 2020; Kharazishvili et al., 2021a,b; Kharazishvili et al., 2023).

The identification of the energy security level involves the following steps:

1. Defining and formalizing a set of energy security indicators.

2. Determining whether these indicators stimulate (S) or hinder (D) energy security.

3. Selecting the form of the integral energy security index and its components.

4. Choosing a suitable normalization method.

5. Justifying dynamic weighting coefficients.

6. Establishing the boundaries of safe existence, i.e., defining the range of limit values for the indicators.

7. Simultaneously integrating the indicators and their limit values.

8. Calculating the limit values for the components of the integral energy security index using security gradations on the extended homeostatic plateau and comparing them with target indicators.

In our approach, we define the level of energy security using 48 indicators, which provide a comprehensive description of the system (while considering the trade-off between completeness and complexity). These indicators are categorized into seven strategic goals outlined in the Energy Security Strategy of Ukraine (Cabinet of Ministers of Ukraine, 2021): resource sufficiency (I), economic affordability (II), economic acceptability (III), energy efficiency (IV), environmental acceptability (V), sustainability of the energy sector (VI), and protection of national interests (VII) (Table 1).

Table 1. Indicators of energy security in Ukraine*

No.	Indicator (I)	Type	Dimension
I. Resource sufficiency			
1	Meeting needs with own primary energy resources	S	% of consumption
2	Cost of import of energy resources	D	% of GDP
3	Share of the resource in the energy balance: oil and petroleum products	D	% in balance
4	natural gas	D	% in balance
5	thermal coal	D	% in balance

No.	Indicator (I)	Type	Dimension
6	nuclear and thermonuclear energy	S	% in balance
7	hydropower	S	% in balance
8	solar and wind energy	S	% in balance
9	biomass energy	S	% in balance
II. Economic affordability			
10	Cost of consumed energy resources for the state	D	% of GDP
11	Annual electricity consumption per person	S	Mwh
12	Annual energy consumption per person	S	toe
13	Share of household income used for housing and related services	D	%
14	Quality of supply of primary resources, fuel and energy	S	% (expert assessment)
III. Economic efficiency			
15	Gross domestic product per person	S	thousand US dollars.
16	Level of investment by enterprises of the fuel and energy complex	S	% of fuel and energy complex production
17	Level of renewal of fixed assets of the fuel and energy complex	S	% of the fixed assets of the fuel and energy complex
18	Shadowing of the fuel and energy complex	D	% of Gross value added of the fuel and energy complex
19	Labor remuneration in the fuel and energy complex	S	% of fuel and energy complex production
20	Concentration of energy markets according to the Herfindahl-Hirschman index	D	Index (by suppliers)
IV. Energy efficiency			
21	Energy intensity of gross domestic product	D	toe/1000 US dollars
22	Energy share in gross domestic product	D	% of Gross value added of the fuel and energy complex in GDP
23	Shadow consumption of primary energy resources	D	% of GDP
24	Total losses of energy resources (balance)	D	%, total supply
25	Share of consumption for energy needs	D	%, total supply

No.	Indicator (I)	Type	Dimension
26	Losses in heat supply networks	D	%, transmission volume
27	Losses in power grids	D	%, transmission volume
V. Environmental acceptability			
28	Level of CO_2 emissions per TPES	D	t CO_2/toe
29	Level of CO_2 emissions per unit of GDP	D	kg/US dollars
30	Final carbon intensity of energy	D	g CO_2/MJ
31	Share of CO_2 emissions from electricity and heat generation plants	D	%, total emissions
32	Share of renewable energy in final consumption	S	%, final consumption
VI. Sustainability of functioning			
33	Share of the largest supplier in imports (by type of primary energy resources)	D	%
34	Level of technological dependence of imports/exports from a single source (by types of energy technology)	D	% (expert assessment)
35	Volume of stocks/reserves by types of primary energy resources	S	monthly consumption
36	System Average Interruption Duration Index (SAIDI)	D	minutes/year
37	Efficiency and effectiveness of response to crisis situations	S	% (expert assessment)
VII. Protection of national interests			
38	Predictability and consistency of policy	S	% (expert assessment)
39	Process assurance: production processes and infrastructure	S	% (expert assessment)
40	management processes and infrastructure	S	% (expert assessment)
41	support and service processes and infrastructure	S	% (expert assessment)
42	processes and infrastructure for maintaining facilities at all stages of the life cycle	S	% (expert assessment)
43	information and communication processes and infrastructure	S	% (expert assessment)
44	Level of involvement in EU energy markets	S	% (expert assessment)
45	Level of shadow capital utilization in the fuel and energy complex (extractive industry, electricity, gas and water production)	D	% of official

No.	Indicator (I)	Type	Dimension
46	Quality of government policy	S	% (expert assessment)
47	Quality of human resources (technical and managerial)	S	% (expert assessment)
48	Relevance of political leaders to the challenges faced by the system	S	% (expert assessment)

*Source: official data of the State Statistics Service of Ukraine, model and expert estimates.

As the processes occurring within the energy security system exhibit nonlinear behavior, we opt for the multiplicative (nonlinear) form of the integral index I_t, which can be related to the additive form through a logarithmic function (Kharazishvili et al., 2023, p.8):

$$I_t = \prod_{i=1}^{n} z_{i,t}^{a_i}; \quad \sum a_i = 1; \quad a_i \geq 0, \ (1)$$

where $z_{i,t}$ are indicator values normalized by the combined method; for stimulators $z_{i,t} = x_i / k_{n,t}$, for destimulators $z_{i,t} = (k_{n,t} - x_i)/k_{n,t}$; $k_{n,t} \geq x_{\max,t}$; x_i are current indicator values; $k_{n,t}$ is a normalization coefficient (for stimulators – the maximum value $x_{\max,t}$ of the sample of indicators and their limit values; for destimulators $1.1x_{\max,t}$); a_i are dynamic weighting coefficients; i is an ordinal indicator number; t is a time period. The dynamic nature of the weighting coefficients arises due to the constantly changing external environment, particularly the political and foreign economic factors that influence the empirical estimates of econometric relationships. To add dynamism, we use techniques explained by Kharazishvili et al. in their works of 2021b and 2023.

We construct a minimum necessary matrix with an equal number of principal components and positive eigenvalues. The number of rows is typically one more than the number of indicators. We determine constant weighting coefficients for the acceleration period using principal components method and then shift the matrix by one period.

Finally, we calculate the weighting coefficients for the next period based on the matrix:

$$|C_i| \times D_i = \begin{pmatrix} d_1c_{11} + d_2c_{12} + ... + d_jc_{1j} \\ d_1c_{21} + d_2c_{22} + ... + d_jc_{2j} \\ .... \\ d_1c_{j1} + d_2c_{j2} + ... + d_jc_{jj} \end{pmatrix} = \begin{pmatrix} w_1 \\ w_2 \\ ... \\ w_j \end{pmatrix}; \quad a_i = \frac{w_i}{\sum w_i}, \ (2)$$

where C_i is the matrix of absolute values of factor loadings; D_i is the vector matrix of dispersions.

We need dynamic representation of weighting coefficients to improve the methodology for evaluating energy security levels and sustainable development trajectory (Kharazishvili et al., 2021b, 2023). We define safe existence limits and associate safety gradations with the concept of an extended homeostatic plateau and feedback areas (Figure 1).

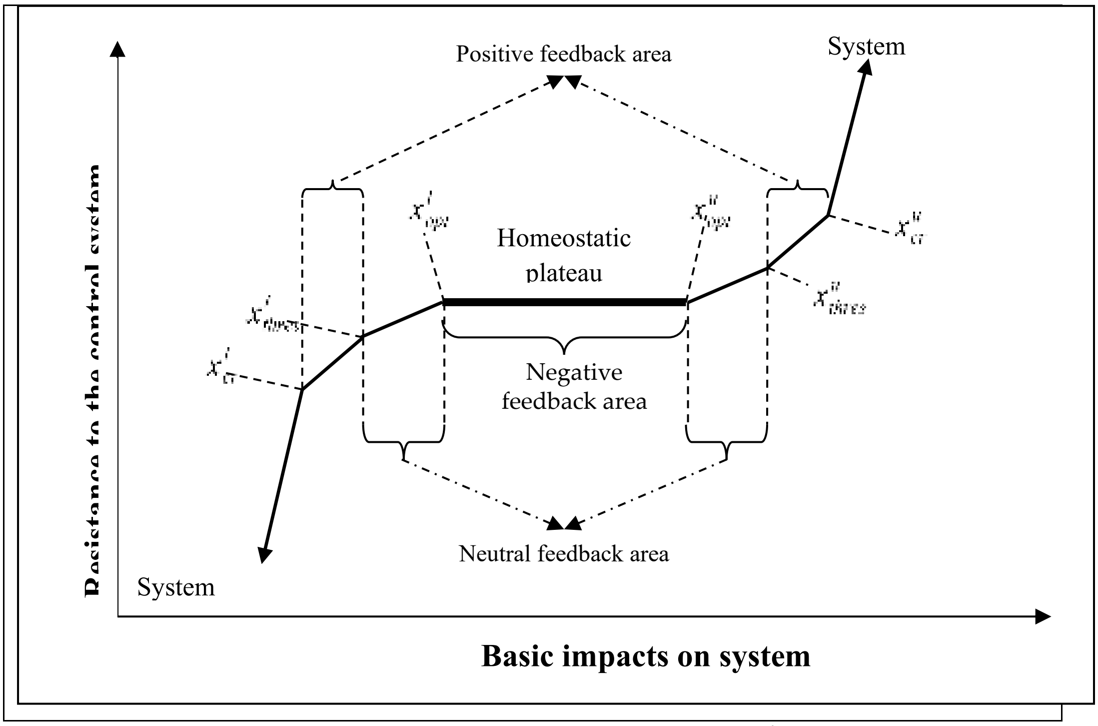

Figure 1. Extended homeostatic plateau of the dynamical system*

*Based on Kharazishvili et al. (2021b)

Indicators exceeding critical values can risk destruction of technical systems. Economic and social systems may transform, with positive or negative impacts on both control and controlling systems. When over 50% of security indicators exceed upper critical values, it may indicate an imminent shift towards a higher technological mode.

Conversely, exceeding lower critical values can lead to complications and loss of essential functions within the existing technological mode. The quantitative values of safety gradations are determined by extending the t-criterion method through the construction of the probability density function and determining the distribution type with the calculation of statistical characteristics of the sample, such as the mean (μ), standard deviation (σ), and asymmetry coefficient (k_{as}). The bifurcation points of characteristic distribution types (normal, lognormal, and exponential) are formally defined, as shown in Table 2.

Table 2. Formalized threshold vector values*

Type of Indicator Probability Density Function	**Lower Threshold**	**Lower Optimal Value**	**Upper Optimal Value**	**Upper Threshold**
Normal	$\mu - t\sigma$	$\mu - \sigma$	$\mu + \sigma$	$\mu + t\sigma$
Lognormal (tail right)	$\mu - t\sigma/k_{as}$	$\mu - \sigma/k_{as}$	$\mu + \sigma$	$\mu + t\sigma$
Lognormal (tail left)	$\mu - t\sigma$	$\mu - \sigma$	$\mu + \sigma/k_{as}$	$\mu + t\sigma/k_{as}$
Exponential (tail right)	$\mu - t\sigma/k_{as}$	μ	$\mu + \sigma$	$\mu + t\sigma$
Exponential (tail left)	$\mu - t\sigma$	$\mu - \sigma$	μ	$\mu + t\sigma/k_{as}$

*Based on Kharazishvili et al. (2021b)

This study considers the full vector of limit values, including critical, threshold, and optimal values, rather than just a reduced vector. This accounts for the potential revision of limits due to Russia's military aggression.

For calculating the reduced vector of limit values (threshold, optimal), we can use a confidence level of 0.98 or 0.99 derived from the Student's t-distribution tables for 't' values.

Moreover, the critical values of indicators (lower critical, upper critical) can be calculated with a confidence level of 0.998 or 0.999.

By convolving the indicators (I) with their respective limit values (P), we can establish a hierarchical multifactor mathematical model that represents energy security:

$$\begin{cases} I_{I-VII} = \prod_{k=1}^{7} I_{k,t}; \quad P_{ij} = \prod_{j=1}^{6} P_{ij}^{b_{ij}}; \quad P_{ij} = \left[P^{l}_{cr,ij}; P^{l}_{th,ij}; P^{l}_{opt,ij}; P^{u}_{opt,ij}; P^{u}_{th,ij}; P^{u}_{cr,ij}\right]; \\ I_{I,t} = \prod_{i=1}^{9} z_{i,t}^{a_i}; I_{II,t} = \prod_{i=1}^{5} z_{i,t}^{a_i}; I_{III,t} = \prod_{i=1}^{6} z_{i,t}^{a_i}; I_{IV,t} = \prod_{i=1}^{7} z_{i,t}^{a_i}; I_{V,t} = \prod_{i=1}^{5} z_{i,t}^{a_i}; I_{VI,t} = \prod_{i=1}^{5} z_{i,t}^{a_i}; I_{VII,t} = \prod_{i=1}^{11} z_{i,t}^{a_i}; \end{cases} \tag{3}$$

where k is the number of components; j is the number of security gradations.

The model (3) can be employed to calculate the limit values (P) of components I-VII of the integral index of energy security (I_t) in security gradations of the extended homeostatic plateau. These values can then be compared with the target indicators, and based on this comparison, conclusions can be drawn regarding the current level of energy security (Kharazishvili et al., 2021b).

To develop a strategic plan, we use strategizing. We set goals, create a plan, and break down indices to determine necessary values. Adaptive regulation methods from management theory (Kharazishvili et al., 2021a,b; Kharazishvili et al., 2022) are utilized in this process (Figure 2).

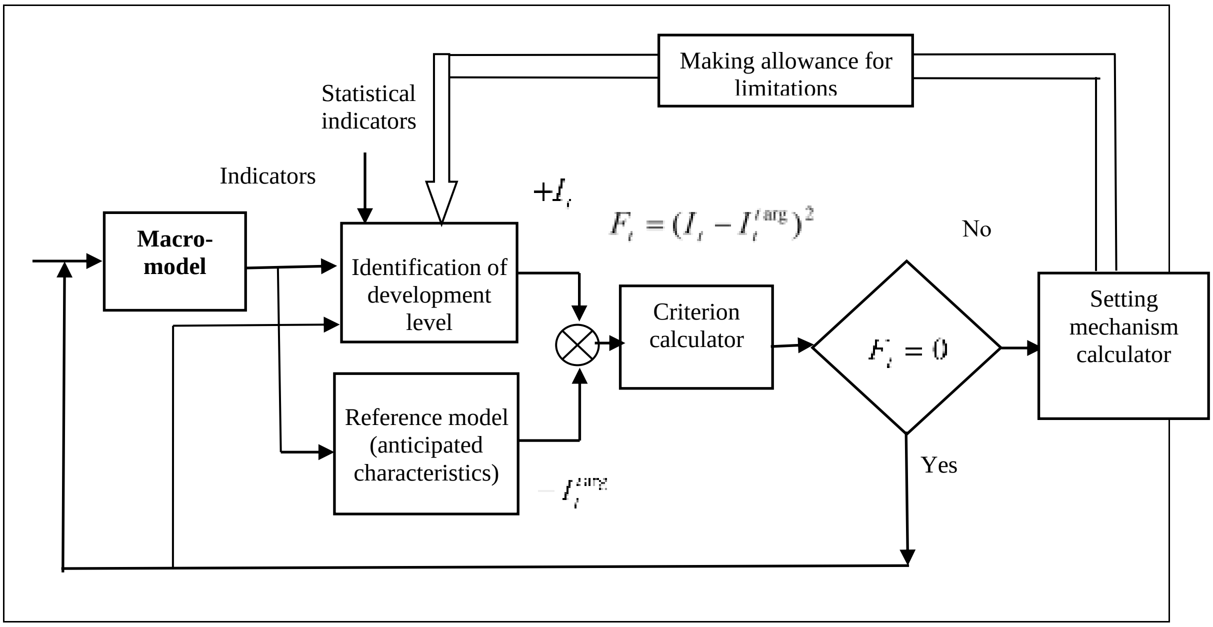

Figure 2. Generalized scheme of adaptive control system with a reference model*

*Based on Kharazishvili et al., 2021a,b; Kharazishvili et al., 2022

Accordingly, the objective of strategizing should encompass not only determining the desired destination but also establishing the course to be taken. It is crucial to not only envision the future but also calculate the necessary steps and promptly implement required changes along the path to the desired goal (Kusumano & Joffy, 2018). This approach necessitates a priori knowledge of the integral indices (I_t) for each year, enabling their utilization as reference values (I_t^{targ}) within the adaptive regulation model. In the "Identification of development level" block, equations for the integral convolution of components from equation (3) with their respective weighting coefficients (a_i) are sequentially formulated.

The role of the control device is to ascertain the changes in the normalized indicators ($z_{i,t}$) that minimize the adjustment criterion F_t (squared error) to zero. We use gradient methods with constraints to compute indicator changes, aligned with nonlinear parametric optimization problems. For practical application, we use the C++ Strategy procedure, developed by Yurii Kharazishvili. It employs an adaptive regulation method with short feedback cycle and omits the use of macro-models. Long feedback cycle mode is used for in-depth studies.

Refer to the standard Strategy procedure as follows:

$$F_{\min} = strategy(P, f, n_1, n_2, x, f_{zad}, p_{\max}, p_{\min}, eps, func), \quad (4)$$

where:

$F_{\min}$ –	resulting solution error;
P –	vector of normalized indicators of the integral index, which starts the strategizing – initial vector of sought values of indicators corresponding to the given value of the integral index;
f –	initial value of the integral index;
n_1 –	initial number of the indicator;
n_2 –	final number of the indicator;
f_{zad} –	given value of the integral index;
$p_{\max}$ –	vector of normalized maximum values of adjustable indicators;
$p_{\min}$ –	vector of normalized minimum values of adjustable indicators;
eps –	specified solution error;
$func$ –	pointer to the function to be called to calculate the optimization criterion.

The calculations in the proposed model (Kharazishvili et al., 2021a, p.7-8) determine several key indicators related to the fuel and energy complex:

1. Investment level (16) = capital investments to output correlation.

2. Level of fixed asset renewal (17) = capital investments to fixed assets transferred annually correlation.

3. Shadowing (18) of fuel and energy complex is calculated using social justice method.

4. Labor remuneration (19) = share of labor remuneration in output allocated to taxpayers.

5. Energy share in GDP (22) = correlation of fuel and energy complex's gross value added to GDP.

6. Shadow consumption of primary energy resources (23) = difference between total and actual consumption based on official data.

7. Level of shadow capital utilization (45) = calculated considering capital utilization coefficient in presence and absence of shadow economy.

In addition to model-based calculations, the expert method is utilized for determining indicators not obtainable from official data:

- The quality of supply of primary resources, fuel, and energy (14 in Table 1).
- The level of technological dependence of imports/exports from a single source (by types of energy technology) (34).

- The efficiency and effectiveness of response to crisis situations (37).
- The predictability and consistency of policy (38).
- The production processes and infrastructure (39).
- The management processes and infrastructure (40).
- The support and service processes and infrastructure (41).
- The processes and infrastructure for maintaining facilities at all stages of the life cycle (42).
- The information and communication processes and infrastructure (43).
- The level of involvement in EU energy markets (44).
- The quality of government policy (46).
- The quality of human resources (technical and managerial) (47).
- The relevance of political leaders to the challenges faced by the system (48).

These indicators are determined through expert evaluation and play a crucial role in assessing the overall energy security system.

Theory

Expert assessments are crucial to determine the impact of threats on energy security. Normalizing and integrating indicators can help compare changes on a standardized scale. Analyzing integral index components under the influence of threats can help determine their impact (3). This approach differs from abstract point estimates used in existing methods (Sukhodolia et al., 2022). There are three potential scenarios for expert assessment based on the provided indicators (Table 1):

1) Assessing changes in all indicators (48 in total) for a specific threat would require an excessive number of estimates (960 for 20 threats), making it practically impossible.

2) Assessing the change of only one integral index for a specific threat using mathematical forecasting can undermine credibility and dilute the essence of the analysis.

3) Assessing changes in energy security components (7 in total) for a specific threat seems the most feasible approach, allowing for manageable assessments (7x20) and determining the consequences on the integral index.

Experts should assess the change in integral index components based on their knowledge of current values (I_t) and the corresponding limit value gradations (critical, threshold, optimal) (Figure 1). These assessments should be conducted after normalizing the values (Table 3) for each threat (Kharazishvili et al., 2023).

Table 3. The normalized values of the vector of limit values and components of the integral index of energy security for Ukraine in the years 2021-2022*

Group of indicators	Normalized values of the vector of limit values and components of the integral index of energy security							
	X_{crit}^{lower}	X_{thres}^{lower}	X_{opt}^{lower}	X_{opt}^{upper}	X_{thres}^{upper}	X_{crit}^{upper}	**I_t**	
							2021	**2022**
Integral index of energy security, including by components	0.1678	0.3316	0.4917	0.6664	0.8011	0,9187	0.3798	0.3066
I. Resource sufficiency	0.1067	0.2248	0.3588	0.5141	0.6459	0,8585	0.3184	0.3195

Group of indicators	Normalized values of the vector of limit values and components of the integral index of energy security							
	X^{lower}_{crit}	X^{lower}_{thres}	X^{lower}_{opt}	X^{upper}_{opt}	X^{upper}_{thres}	X^{upper}_{crit}	**I_t** **2021**	**2022**
II. Economic affordability	0.1280	0.2877	0.4422	0.6649	0.8299	0,9252	0.4681	0.3338
III. Economic efficiency	0.2512	0.3593	0.4868	0.6693	0.8667	0,9695	0.2692	0.2097
IV. Energy efficiency	0.1427	0.3375	0.5109	0.6877	0.8099	0,8748	0.3510	0.2057
V. Environmental acceptability	0.1016	0.2719	0.4416	0.6188	0.7497	0,8767	0.3145	0.2668
VI. Sustainability of the energy sector	0.2295	0.4437	0.6720	0.8207	0.8988	0,9571	0.5493	0.3927
VII. Protection of national interests	0.3622	0.5245	0.6666	0.7913	0.8721	0,9871	0.4503	0.4216

*Model calculations were conducted by the authors

Expert assessments determine threats' impact on energy security. Integral convolution model (equation 3) calculates overall effect. Formalizing impact function and using reliable database is crucial for identifying threat-energy security indicator relationship. Primary objective is to transfer threats into indicators for better assessment. The process involves step-by-step convolution of components into the integral index (equation 4) and strategizing sustainable development using adaptive regulation methods (Figure 2).

This approach resolves the problem of transferring threats into indicators and minimizes potential errors in expert estimates. Overall, the methodology combines expert assessments, mathematical calculations, and adaptive regulation to quantitatively determine the impact of threats on energy security (Sukhodolia et al., 2022, p.14; Kharazishvili et al., 2023).

Threats can disrupt sustainable development goals, requiring a new trajectory. Steps:

1. Determine deviation of integral index of energy security components from limit values for each threat.

2. Use dynamic weighting coefficients (equation 2) and a model (equation 3) to get forecasted integral index values (equation 1).

3. Construct new trajectory aligned with sustainable development goals.

4. Identify trajectories for changes in specific energy security indicators.

5. Determine state regulation measures to restore desired trajectory.

Our adaptive response method evaluates threat impact, breaks down the index into components, and uses adaptive regulation to achieve defined goals.

Calculation

To assess the impact of threats on energy security, it is important to identify the baseline level and develop a comprehensive strategy. This involves defining and formalizing energy security indicators, incorporating them into the integral index, and comparing them with target indicators.

We have calculated the level of energy security for Ukraine as of December 31, 2022, using the presented methodology. Strategic scenarios of sustainable development (realistic, optimistic, balanced sustainable development) have been depicted based on the latest strategizing methodology (Figure 3).

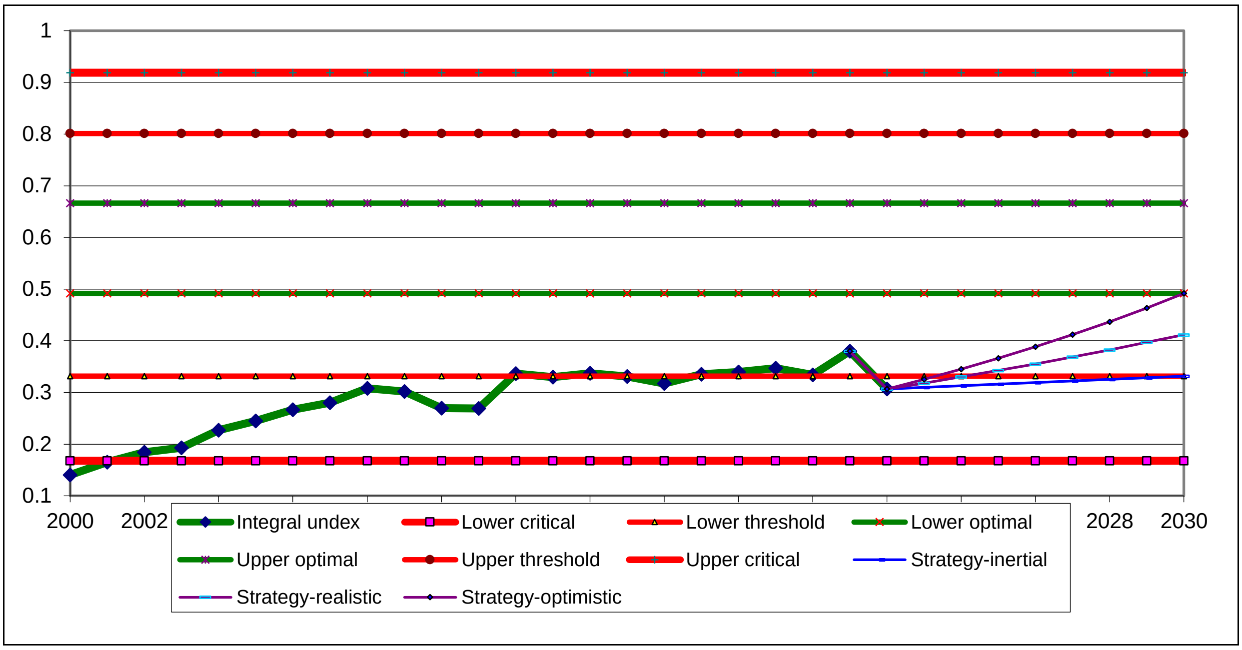

Figure 3. The level of sustainable development of energy security with strategic goals until 2030*

*Compiled by the authors

According to the predetermined strategic goals for 2030, considering the correlation between the current value of the integral index and the vector of limit values, the following scenarios have been determined:

1. Inertial scenario: Achieving the lower threshold value of the integral index between the lower threshold and lower optimal values.

2. Realistic scenario: Achieving the average value between the lower threshold and lower optimal values.

3. Optimistic scenario: Achieving the lower optimal value.

We create a trajectory using different curve functions for each scenario and synthesize necessary values using an automatic adaptive regulation procedure. The obtained dynamics of components and indicators serve as a strategic plan to achieve goals. Next, we proceed to determine the impact of threats on the level of energy security and develop adaptive strategies to achieve the defined goals.

A survey was conducted among 20 Ukrainian experts to determine how they perceive the potential changes in the current values (I_t) of the components of the integral index during the year under the influence of 20 identified threats to energy security. These threats were prioritized based on an assessment conducted in February 2022, and their detailed description can be found in the referenced paper (Sukhodolia et al., 2022).

The results of the survey were summarized by calculating the arithmetic mean, excluding the maximum and minimum expert assessments. Internal and external threats were ranked according to their potential relative consequences for the seven components of the integral index, as presented in Table 4.

Table 4. Average expert assessments of the cumulative negative consequences of energy security threats implementation*

Threat to energy security	Averaged assessment for components of the integral index of energy security						
	I	II	III	IV	V	VI	VII
Internal threats to energy security							
Incompetence in policymaking	0.2966	0.3286	0.2410	0.3363	0.3194	0.4985	0.4286
State interference in the functioning of markets	0.3090	0.3445	0.2654	0.3246	0.3075	0.5129	0.4260
Degradation of energy systems and networks	0.2895	0.4337	0.2592	0.3334	0.2890	0.5134	0.3857
Resource and technology dependence	0.3030	0.4184	0.2611	0.3485	0.3107	0.5213	0.4028
High energy intensity of the economy	0.2838	0.4490	0.2508	0.3367	0.3125	0.5418	0.4071
Energy poverty	0.3097	0.4149	0.2602	0.3295	0.3051	0.5417	0.4132
Negative impact of the energy sector on the environment	0.3167	0.4553	0.2560	0.3409	0.2997	0.5383	0.4353
Negative climate changes	0.3037	0.4427	0.2549	0.3351	0.3128	0.5159	0.4286
Changes in the structure of consumption and supply of energy resources	0.3185	0.4671	0.2631	0.3413	0.3310	0.5327	0.4394
Imperfect competition	0.3099	0.4498	0.2520	0.3375	0.3201	0.5099	0.4287
External threats to energy security							
Military operations	0.3092	0.4452	0.2602	0.3435	0.3092	0.5275	0.4366
Terrorist acts	0.3120	0.4591	0.2637	0.3460	0.3030	0.5395	0.4424
Cyberattacks	0.3126	0.4662	0.2672	0.3462	0.3073	0.5411	0.4409
Epidemics and pandemics	0.3084	0.4284	0.2561	0.3448	0.3070	0.5248	0.4420
Loss of professional staff	0.2754	0.4439	0.2574	0.3310	0.3049	0.5261	0.4314
Blockage of integration processes	0.3071	0.4647	0.2574	0.3370	0.3057	0.5306	0.4423
External impact on policymaking	0.3058	0.4511	0.2692	0.3482	0.3121	0.5224	0.4229
Blockage of supplies	0.3040	0.4441	0.2458	0.3438	0.3106	0.5213	0.4267
Debt crisis	0.3064	0.4341	0.2592	0.3392	0.3082	0.5375	0.4353

Threat to energy security	Averaged assessment for components of the integral index of energy security						
	I	II	III	IV	V	VI	VII
Shadowing of the economy	0.3180	0.4653	0.2686	0.3445	0.2986	0.5427	0.4302

*Compiled according to the expert assessments (Appendix 1)

To evaluate energy security threats in Ukraine, we identified the most significant internal and external issues: state interference in markets, policy-making incompetence, military operations, and terrorism. To ensure objective assessments, we propose providing detailed descriptions of each threat's impact factor, vulnerability, and consequences (refer to Table 5) (Sukhodolia et al., 2022, p. 5-7).

Table 5. Description of selected internal and external threats to energy security for modeling*

Threat	**Impact factors**	**Vulnerability**	**Consequences**
Internal threats to energy security of Ukraine			
Incompetence in policymaking	Inefficient decision-making; poor crisis response; uncoordinated public institutions; lack of action continuity.	No political accountability; professionalism not aligned with position; no control over decision-makers' competency compliance.	National insecurity, policy unpredictability, decision-making delays, individual/faction interests, populism, corruption, budget revenue decrease, and lack of trust in authorities.
State interference in the functioning of markets	Administrative regulation of prices, rates, supplies and services; state support of industries.	Incomplete shift to market regulation in energy sector; unformed markets; non-transparent decision-making; uncertain energy security policy.	Energy sector inefficiency leads to economic damage, tax evasion, and bankruptcies due to non-market pricing.
External threats to energy security of Ukraine			
Military operations	Physical impact on power facilities and personnel.	Inadequate physical protection and war threat neglect in energy infrastructure design.	Insecure national interests, unsustainable energy, health risks, tech disruption, energy interruption, and economic damage.
Terrorist acts	Use of weapons, committing explosion, arson or other actions, destruction of personnel and/or destruction of energy facilities	Poor physical protection of critical energy infrastructure	Unsustainable energy sector functioning can cause loss of life, economic damage, and energy supply disruptions.

*Compiled by the authors

We assume that these threats began affecting energy security at the end of 2021. By performing the integral convolution of components affected by these threats, we obtain changes in the integral index by the end of 2022. We will then compare the impact of these threats on the energy security level in relation to a realistic development scenario, after establishing sustainable development trajectories as a result of these threats (see Figure 4).

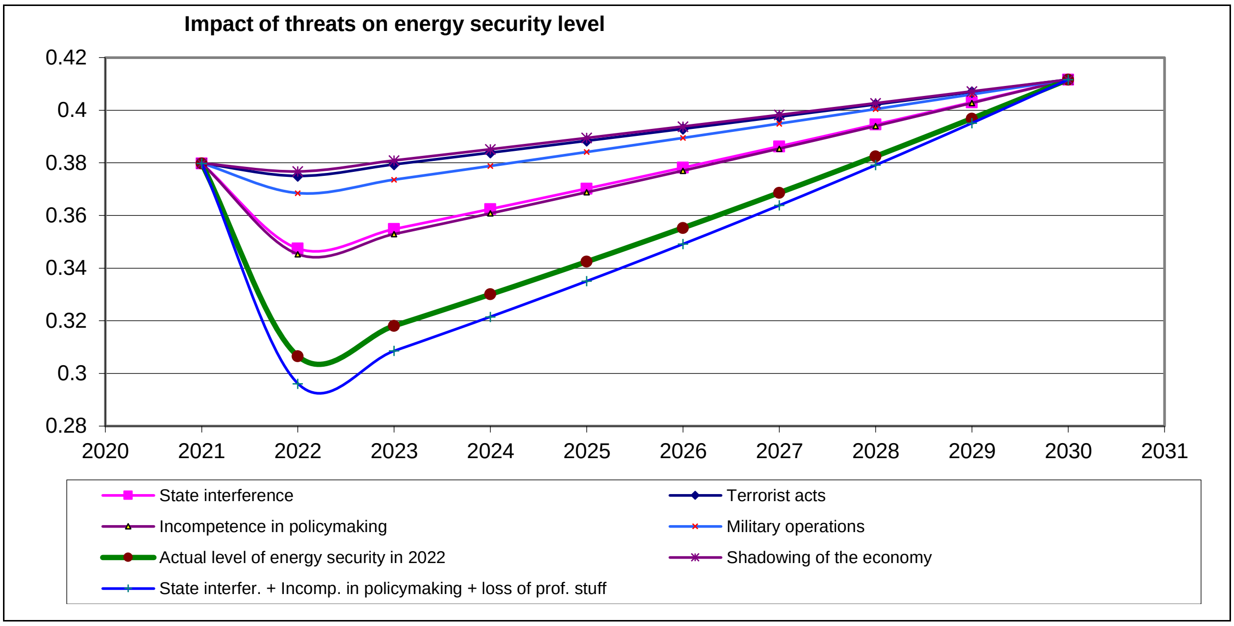

Figure 4. Impact of threats on the energy security level and adaptive response for maintaining stability in sustainable development trajectory*

*Compiled by the authors

It's vital to know the integral index values of energy security components. We can calculate the integral index using the mathematical identification model and adaptive adjustment model. To ensure energy security in 2022, we need to prioritize responses to threats. The significant threats to energy security in 2022 are incompetence in policymaking, state interference in market functioning, military operations, and terrorist acts. Gather information on each threat's impact and develop appropriate policies for countering them (Figure 5).

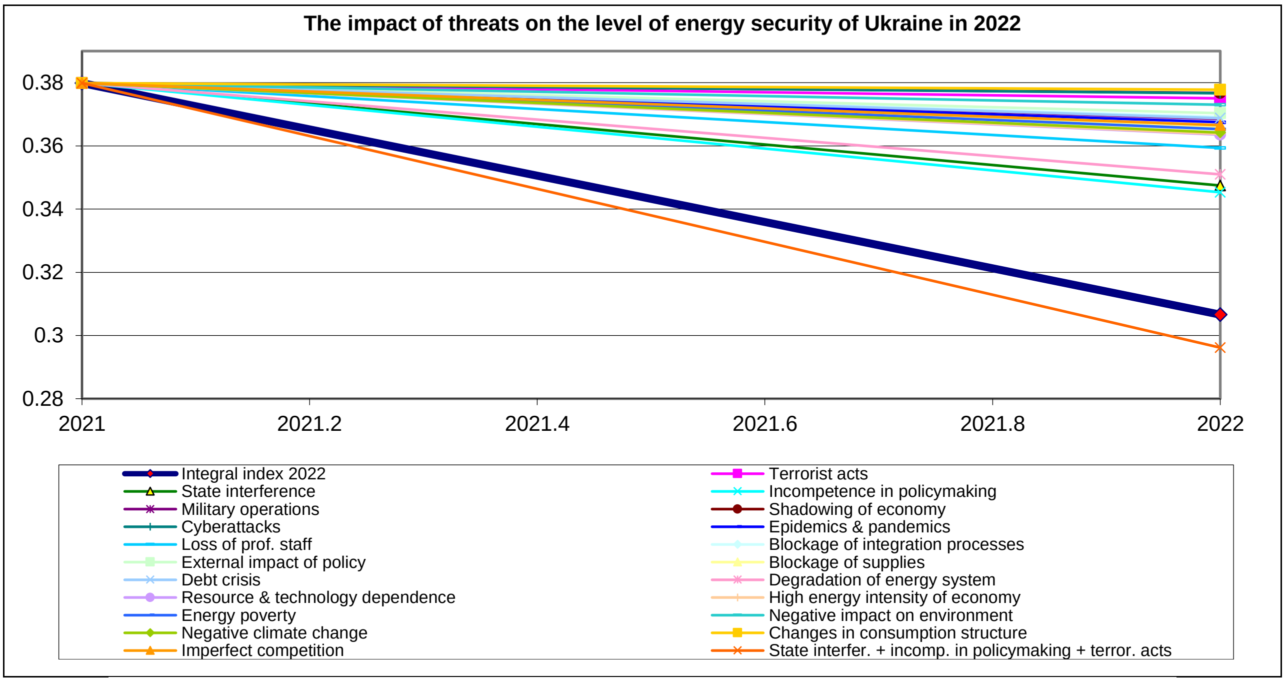

Figure 5. Impact of threats on the energy security level and the adaptive response for maintaining the stability of the sustainable development trajectory*

*Compiled by the authors

For example, the five most influential internal threats to energy security in Ukraine in 2022 are as follows, ranked in order of significance:

1. Incompetence in policymaking.

2. State interference in the functioning of markets.

3. Degradation of the energy system.

4. Loss of professional staff.

5. High energy intensity of the economy.

Ukraine needs to support scientific research, compensate scientists fairly, and allocate 3% of GDP for technological transformation, 2% for innovation, and 8% for education. Poor policymaking and state interference lead to a degraded energy system, lost staff, and high energy intensity. Necessary changes to indicators and a strategic plan are needed to achieve goals and respond to threats. Indicators serve as the plan for sustainable development, and policymakers must ensure their realization.

Conclusion

The energy sector needs an early warning system to identify and prevent energy security threats. A new approach combines math modeling, expert analysis, and adaptive regulation. This provides a more accurate assessment of energy security levels and helps to develop effective strategies.

The methodology uses a mathematical model, modern assessment methods, and a formalized process to cope with threat impacts at various levels. It allows for the evaluation of the impact of threats on the achievement of specific strategic goals, and for the formulation of managerial decisions to mitigate and eliminate the impact of threats.

The developed methodology enables the achievement of a sustainable development trajectory, forming the basis for formalizing a threat response plan. The methodology can be linked to the strategic objectives of state policy implementation, enabling its practical application in the public administration system.

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Appendix 1 – Data Availability

The data for the study was collected from various sources of information and summarized according to the research requirements. The values of the energy security indicators (for Table 1) were determined based on official sources of information (28), model calculations (7), and expert assessments (13).

According to the official data, the following calculations were made:

(1) – Meeting energy needs with own primary energy resources. Source: http://www.ukrstat.gov.ua/operativ/operativ2020/energ/z_post_pe/zp_pen_ue.xls

(2) – Cost of energy resource imports. Source: http://www.ukrstat.gov.ua/operativ/operativ2020/zd/tsztt/tsztt_u/arh_tsztt2020_u.html

(3) – Share of oil and petroleum products in the energy balance. Source: http://www.ukrstat.gov.ua/operativ/operativ2019/energ/drpeb/dr_u.

(4) – Share of natural gas in the energy balance. Source: http://www.ukrstat.gov.ua/operativ/operativ2019/energ/drpeb/dr_u.

(5) – Share of thermal coal in the energy balance. Source: http://www.ukrstat.gov.ua/operativ/operativ2019/energ/drpeb/dr_u.

(6) – Share of nuclear and thermonuclear energy in the energy balance. Source: http://www.ukrstat.gov.ua/operativ/operativ2019/energ/drpeb/dr_u.

(7) – Share of hydropower in the energy balance. Source: http://www.ukrstat.gov.ua/operativ/operativ2019/energ/drpeb/dr_u.

(8) – Share of solar and wind energy in the energy balance. Source: http://www.ukrstat.gov.ua/operativ/operativ2019/energ/drpeb/dr_u.

(9) – Share of biomass energy in the energy balance. Source: http://www.ukrstat.gov.ua/operativ/operativ2019/energ/drpeb/dr_u.

(10) – Cost of consumed energy resources for the state. Reporting: Production and sales of industrial products by types (annual data). Source: http://www.ukrstat.gov.ua/

(11) – Annual electricity consumption per person. Source: https://www.iea.org/countries/ukraine

(12) – Annual energy consumption per person. Source: https://www.iea.org/countries/ukraine

(13) – Share of total household income allocated to pay for housing and communal services. Source: http://www.ukrstat.gov.ua/operativ/menu/menu_u/energ.htm

(15) – Gross domestic product per person. Source: http://www.ukrstat.gov.ua/operativ/menu/menu_u/nac_r.htm

(20) – Concentration of energy markets according to the Herfindahl-Hirschman index. Source: http://www.bp.com/statisticalreview

(21) – Energy intensity of gross domestic product. Source: http://www.ukrstat.gov.ua/operativ/operativ2020/energ/drpeb/EBTS_2020_ua.xls

(24) – Total losses of energy resources (balance). Source: http://www.ukrstat.gov.ua/operativ/operativ2020/energ/drpeb/EBTS_2020_ua.xls

(25) Share of consumption for energy needs. Source: http://www.ukrstat.gov.ua/operativ/operativ2020/energ/drpeb/EBTS_2020_ua.xls

(26) – Losses in heat supply networks. Source: https://www.nerc.gov.ua/

(27) – Power grid losses. Source: http://mpe.kmu.gov.ua/minugol/control/uk/publish/article?art_id=245533545&cat_id=35081

(28) – Level of CO2 emissions per TPES. Source: https://www.iea.org/countries/ukraine

(29) – Level of CO2 emissions per unit of GDP. Source: https://www.iea.org/countries/ukraine

(30) – Final carbon intensity of energy. Source: https://www.iea.org/countries/ukraine

(31) – Share of CO2 emissions from electricity and heat generation plants. Source: https://www.iea.org/countries/ukraine

(32) – Share of renewable energy in final consumption. Source: https://www.iea.org/countries/ukraine

(33) – Share of the largest supplier in imports (by type of primary energy resources). Reporting: Total consumption of primary energy in 2007–2018. Source: http://www.ukrstat.gov.ua/

(35) – Volume of stocks/reserves by types of primary energy resources. Source: http://mpe.kmu.gov.ua/minugol/doccatalog/document?id=245533564

(36) – System Average Interruption Duration Index (SAIDI). Source: https://www.nerc.gov.ua/?id=51822

Based on model calculations using the aggregate supply model as a component of the Alpha general economic equilibrium model, the following indicators can be defined:

(16) – Level of investment by enterprises in the fuel and energy complext.

(17) – Level of renewal of fixed assets in the fuel and energy complex.

(18) – Shadowing of the fuel and energy complex.

(19) Labor remuneration in the fuel and energy complex.

(22) – Energy share in gross domestic product.

(23) – Shadow consumption of primary energy resources.

(45) – Level of shadow capital utilization in the fuel and energy complex.

Additionally, the expert method determines indicators that cannot be calculated based on official data:

(14) – Quality of supply of primary resources, fuel, and energy.

(34) – Level of technological dependence of imports/exports from a single source (by types of energy technology).

(37) – Efficiency and effectiveness of response to crisis situations.

(38) – Predictability and consistency of policy.

(39) – Production processes and infrastructure.

(40) – Management processes and infrastructure.

(41) – Support and service processes and infrastructure.

(42) – Processes and infrastructure for maintaining facilities at all stages of the life cycle.

(43) – Information and communication processes and infrastructure.

(44) – Level of involvement in EU energy markets.

(46) – Quality of government policy.

(47) – Quality of human resources (technical and managerial).

(48) – Relevance of political leaders to the challenges faced by the system.