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ENHANCING SECURITY IN SUSTAINABLE ENERGY SYSTEMS FOR CENTRAL EUROPEAN BUSINESSES: AN ADAPTIVE RESPONSE METHODOLOGY UNDER NATIONAL ECONOMY

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Abstract

The increasing complexity of energy security threats, both internal and external, poses significant challenges for businesses in Europe, necessitating a robust framework for evaluating and responding to these risks. This article introduces a comprehensive methodology designed to assess the effects of these threats on a state's energy security through two distinct approaches. The first method focuses on identifying imbalances by analysing the deviation of key indicators from established sustainability benchmarks. The second method combines expert evaluations of changes in comprehensive index components with mathematical computations to assess their overall impact through an energy security model. By employing adaptive control techniques, this methodology disaggregates integrated indices of components and security metrics, allowing a nuanced understanding of energy security dynamics. The energy security model incorporates contemporary evaluation methods that define secure thresholds within various security levels, facilitating a structured analysis of vulnerabilities. This flexible response approach formalises the impacts of threats on the holistic index, establishes new pathways for

achieving objectives after a threat and dissects emerging dynamics into actionable components and metrics. The primary research objectives include enhancing the strategic planning capabilities of businesses, improving management decision making processes and quantifying threats to energy security in a systematic manner. The findings indicate that this methodology significantly aids managerial decision making, enabling businesses to alleviate the impacts of threats on energy security strategy elements. Furthermore, the Energy Sustainability Plan formalises relevant response strategies at multiple tiers, ensuring the adaptability of energy systems to maintain a sustainable development trajectory. This study contributes to the broader discourse on energy security by providing a practical framework that can be utilised by policymakers and business leaders to navigate the complexities of energy threats in Central Europe.
Implications for Central European audience: By assessing internal and external threats to energy security, businesses in Central Europe can proactively address risks and optimise their sustainable energy strategies. Utilising adaptive control techniques and contemporary evaluation methods enhances resilience to evolving threats and ensures the stability of energy systems. This approach provides practical decision making insights and empowers businesses to customise their response strategies, thereby advancing the region's energy security and sustainability initiatives.

Keywords: Strategic planning for energy security; adaptive management methodologies; management decision; threat quantification and mitigation; Central European energy landscape; sustainable energy systems; regulatory frameworks and compliance
JEL Classification: Q40, O30

1 Introduction

To effectively manage the emergence of sustainable development, there is a pressing need for national approaches that address energy security challenges. Achieving sustainability involves meeting current needs while ensuring that future generations can meet theirs (Butlin, 1987; Daly & Townsend, 1993; UN, 2002, 2012; European Union Global Strategy, 2016). This goal is unattainable without universal access to affordable, long-lasting and modern energy sources. Consequently, ensuring energy security remains a priority for national governments committed to sustainable development.

The evolving trends in technological advancements, shifts in energy market frameworks and the strategic utilisation of energy assets for political influence necessitate a re-evaluation of methodologies for assessing energy security. Current methodologies often overlook the dynamic nature of energy security, which requires a comprehensive understanding of both static and dynamic parameters. It has been proposed that "energy security is the ability to meet society's energy resource needs in a technically reliable, cost-effective and environmentally acceptable manner, thus ensuring the sustainable functioning of the national economy under normal and crisis conditions" (Sukhodolia, 2020, p. 10). This highlights a critical research gap: the need for adaptive methodologies that can quantify the probability and cumulative consequences of threats to energy security while addressing how to protect the state from potential negative impacts.

When discussing the enhancement of security in sustainable energy systems for Central European businesses through an adaptive response methodology, several unique aspects of the Central European context emerge as particularly relevant to the research. Central Europe is situated at the crossroads of significant geopolitical tensions, particularly due to its proximity to Russia and the ongoing conflict in Ukraine. This geopolitical landscape influences energy security, as many Central European countries rely on energy imports from Russia. The need for diversification of energy sources and routes is critical to mitigate risks associated with geopolitical instability.

Many Central European countries have historically depended on fossil fuels, particularly coal and natural gas, for their energy needs. However, there is a strong push towards transitioning to renewable energy sources, such as wind, solar and biomass. This transition is essential not only for sustainability but also for reducing dependency on external energy supplies, which enhances energy security. Moreover, Central European countries are part of the European Union, which imposes specific regulations and directives aimed at promoting sustainable energy practices. The integration of EU policies into national frameworks presents both opportunities and challenges for businesses. Understanding these regulatory landscapes is crucial for developing adaptive strategies that align with both national and EU-level energy goals.

The economic landscape in Central Europe is diverse, with varying levels of development among countries. While some countries, such as Poland and Czechia, have robust industrial bases, others may still be developing their energy infrastructure. This economic diversity necessitates tailored adaptive response methodologies that consider the specific needs and capacities of each country. Public attitudes towards energy sources, particularly regarding the transition to renewables, can vary significantly across Central European countries. In some regions, there may be resistance to abandoning traditional energy sources due to economic concerns or cultural factors. Engaging with local communities and addressing their concerns is essential for the successful implementation of sustainable energy initiatives. Also, Central Europe has a growing capacity for technological innovation and research in the energy sector. Universities and research institutions are increasingly collaborating with businesses to develop new technologies and solutions for sustainable energy. Utilising this research capacity can enhance the adaptive response methodologies by integrating cutting-edge technologies and practices. The energy infrastructure in Central Europe varies widely in terms of age, efficiency and capacity. Many countries face challenges related to outdated infrastructure that requires significant investments for modernisation. Addressing these infrastructure challenges is vital for enhancing energy security and ensuring the reliability of sustainable energy systems.

Central European countries are also susceptible to the impacts of climate change, which can affect energy production and consumption patterns. For instance, changes in weather patterns can influence the availability of renewable energy sources such as hydropower and solar energy. Adaptive response methodologies must account for these climate vulnerabilities to ensure long-term sustainability and resilience.

There is a growing emphasis on regional cooperation among Central European countries to enhance energy security. Collaborative initiatives, such as joint energy projects and crossborder energy trading, can strengthen the resilience of energy systems. This regional integration is crucial for developing comprehensive adaptive strategies that benefit multiple countries.

Within the framework of sustainability, the term is increasingly mentioned alongside security, reflecting the system's ability to withstand various threats and maintain desired functioning parameters despite external changes. This distinction underscores the multifaceted nature of these concepts, encompassing both the static state of security and the dynamic preservation of sustainable development trajectories. Hence, it raises pertinent questions:

a) How to quantify the probability and cumulative consequences of threats to energy security?

b) How to protect the state from the potential negative impacts of these threats?

c) How to maintain or restore the trajectory of sustainable development if these threats cannot be fully neutralised?

Based on the outlined objectives and research questions, the following hypotheses are proposed:

- **Hypothesis 1 (H1):** There exists a measurable relationship between the quantification of threats to energy security and the effectiveness of adaptive methodologies in mitigating these threats. Specifically, as the accuracy of threat quantification improves, the effectiveness of response strategies in enhancing energy security will also increase.
- **Hypothesis 2 (H2):** The implementation of adaptive response methodologies will significantly reduce the cumulative consequences of energy security threats on the national economy. This reduction will be evident in improved energy access, cost-effectiveness and environmental sustainability metrics.
- **Hypothesis 3 (H3):** The ability to maintain or restore the trajectory of sustainable development in the face of energy security threats is positively correlated with the robustness of the adaptive response strategies employed. Specifically, states that utilise comprehensive adaptive methodologies will demonstrate greater resilience in sustaining development goals compared to those that do not.
- **Hypothesis 4 (H4):** The integration of static and dynamic parameters in assessing energy security will lead to a more holistic understanding of energy vulnerabilities, thereby enhancing the capacity of national governments to formulate effective energy policies that align with sustainable development objectives.

2 Literature Review

The exploration of energy security has become increasingly critical as countries strive to balance sustainable development with the need for reliable energy sources. Studies have investigated different facets of energy security, yet a cohesive understanding remains elusive due to methodological inconsistencies and a lack of comprehensive frameworks. This literature review critically examines existing research, contrasts diverse approaches and identifies significant gaps that this study aims to address through an adaptive response methodology tailored for Central European businesses.

Different investigations have been dedicated to facets of energy security and related topics (Hutsaliuk et al., 2023, Kwilinski et al., 2022; Kotowicz et al., 2022; Dźwigol et al., 2019; Miśkiewicz et al., 2022; Miśkiewicz, 2018, 2020; Saługa et al., 2020, 2021; Hussain et al., 2021; Szczepańska-Woszczyna & Gatnar, 2022; Polcyn et al., 2022; Coban et al., 2022; Drożdż et al., 2021). For illustration, studies have focused on sustainable energy sources (Kotowicz et al., 2022; Miśkiewicz et al., 2022), comprehensive assessment of smart grids through content analysis (Kwilinski et al., 2022), multidimensional evaluation of energy independence at the national and regional levels (Dźwigol et al., 2019) and societal, environmental and economic impacts of introducing novel technology for generating electricity from the heat of gases at industrial facilities (Hussain et al., 2021; Gonchar et al., 2022). Other works have explored the choice of discount rates in investment decision making (Saługa et al., 2020, 2021; Hutsaliuk et al., 2020a, b), modernisation and development of the electric power industry, information technology and impact of innovations on greenhouse gas emissions (Voloshyn et al., 2023; Miśkiewicz, 2018), the influence of global integration, economic development and natural aspects on environmental impacts (Hussain et al., 2021), factors influencing decarbonisation efforts in urban and rural areas (Miśkiewicz et al., 2020), the impact of electricity market regulation reforms on the competitive environment and identification of competencies of R&D project managers (Szczepańska-Woszczyna & Gatnar, 2022).

Additionally, studies have looked at the characteristics of companies in the energy sector, the connection between the growth of a nation's economy and the use of renewable energy (Polcyn et al., 2022) and the role of electric vehicles and how they integrate into the power grid in transportation networks (Coban et al., 2022). Bin Abdullah et al. (2020) carried out an evaluation of Pakistan's energy security by examining various indicators from 1991 to 2018. The study focused on analysing Pakistan's energy security and energy policy, specifically looking at factors such as availability, affordability, management, technology and environment. By utilising the Z-score technique and principal component analysis to assign weights, the researchers computed energy security index scores ranging from 7.59 to 8.29, deviating from the standard [0, 1] scale. Notably, this methodology did not categorise indicators as positive or negative influences, nor did it establish thresholds for secure sustainability.

In another set of studies (Axon & Darton, 2021; Azzuni & Breyer, 2017; Brown et al., 2014; Huang et al., 2021; Shaikh et al., 2022), the authors provided an objective review of works on the evaluation of energy security, examination of dangers, risks and methods of response. These studies highlighted challenges in defining energy security, the absence of a standardised methodology for determining its level and the lack of a comprehensive definition encompassing the impact of threats and counteraction methods. Additionally, limited analysis has been conducted on the relationships between energy security and its measurements. The structural approach, factor analysis, fuzzy technique, Z-score method, Malmquist productivity index and SWOT analysis are the primary research methods used in these investigations. Iyke et al. (2021) examined the theory that energy security includes important information that helps predict how well energy stocks will perform. The authors created ten energy security indices and examined their relationship with nine energy stock return indices in order to test this theory. The investigation showed that stock profitability may be predicted by each of the ten energy security indices. Also, a study examined the Energy Trilemma Index tool developed by the World Energy Council (WEC), which assesses countries based on their capacity to supply renewable energy across three dimensions: energy security, energy equity (affordability and availability) and environmental stability (World Energy Council, 2023). The index scores are determined by grouping countries into four categories according to standardised energy efficiency measures, which fall between 0 and 10. There is some subjectivity involved because the energy trilemma index calculator is implemented as a black box without revealing the calculation formulas. As a result, several experts are displeased with the ranking system used to obtain the energy trilemma indices.

In national security systems, a risk-based approach is typically used to evaluate threats. According to ISO 31000 (2018), risk is the result of uncertainty about the objectives of the management object or the general likelihood (probability) that a threat would materialize, interfere with the operation of a vulnerable management object and have unfavourable effects. The International Energy Security Risk Index is presented in the U.S. Chamber of Commerce Global Energy Institute (2023) materials as the first energy risk indicator of its kind. It makes use of quantifiable data, historical trends and government forecasts to evaluate the factors that either favourably or unfavourably affect global energy security. The benchmark index, which has a value of 1,000 and represents the average for Organization for Economic Cooperation and Development (OECD) members in 1980, is used to calculate the index scores for this group of countries.

The intersection of energy security and sustainable energy systems has garnered significant attention, particularly in the context of Central Europe. Early works in energy security laid the groundwork for understanding the complexities of energy supply, demand and geopolitical influences. The book "The Prize: The Epic Quest for Oil, Money, and Power" by Yergin (2011) provided a historical perspective on energy security, emphasising the importance of diversification and resilience in energy systems. Similarly, Moran and Russel (2009) in "Energy Security and Global Politics" discussed the geopolitical dimensions of energy security, highlighting the vulnerabilities faced by countries reliant on external energy sources. The concept of sustainable energy systems has evolved alongside these discussions. Sovacool et al. (2013) argued for a holistic approach to energy security that incorporates social equity and environmental sustainability. This foundational understanding is crucial for developing adaptive methodologies that address both security and sustainability in energy systems.

Recent studies have expanded on these foundational concepts, reflecting the latest developments in energy security, particularly in the context of Central Europe. Nagel et al. (2023) explored the implications of the European Union's Green Deal on energy security, arguing that transitioning to renewable energy sources can enhance resilience against geopolitical risks. Their findings suggest that a diversified energy portfolio, including renewables, can mitigate dependence on fossil fuels and improve overall security. In a similar vein, Ashari et al. (2024) examined the role of energy storage technologies in enhancing energy security. Their research highlighted how advancements in battery storage and other technologies can provide flexibility and reliability to energy systems, particularly in regions with high renewable energy penetration. This adaptability is essential for businesses in Central Europe, where fluctuating energy prices and supply disruptions pose significant challenges.

Ige et al. (2024) focused on the adaptive response methodologies that businesses can employ to enhance energy security. Their study emphasised the importance of risk assessment and scenario planning, enabling organisations to prepare for various energy supply disruptions. By integrating these methodologies into their strategic planning, businesses can better navigate the uncertainties of the energy landscape.

To underscore the critical role of policy in shaping energy security strategies, Schmidt (2023) argued that effective governance frameworks are essential for fostering collaboration between public and private sectors in Central Europe. Their research advocates for policies that incentivize investment in renewable energy and energy efficiency, thereby enhancing the resilience of energy systems. Gajdzik et al. (2024) highlighted the importance of regional cooperation in addressing energy security challenges. Their study suggested that collaborative initiatives among Central European countries can lead to shared resources, improved infrastructure and collective responses to energy crises, ultimately strengthening the region's energy security.

The studies on enhancing security in sustainable energy systems for Central European businesses reveal a dynamic interplay between foundational theories and contemporary research. As the region navigates the complexities of energy transition, adaptive response methodologies grounded in recent studies will be crucial for ensuring energy security.

According to the risk evaluation methodology for safeguarding critical infrastructure, Part II, a novel methodology approved by the European Union (EU) in 2015 (Theocharidou & Giannopoulos, 2015), national risks are evaluated by comparing the relational influence of particular dangers and the probability assessed by experts. Typically, a 5×5 grid is employed to evaluate both the ramifications and likelihood. Outcomes are assessed on a scale ranging from negligible (1) via insignificant (2), moderate (3), significant (4) to disastrous (5), representing the impact of the threat on the objectives of the control object functioning. Probability, or relative likelihood, is the plausibility of the threat occurrence, which encompasses a set of events leading to the consequences as determined by experts. As the risk increases, so does the probability of threat occurrence and the consequences. An example illustrating the application of such an approach to enhance national resilience can be seen in the UK Government's annual risk analysis, which includes risk identification, the formation of a risk register and risk assessment detailed in the publicly available National Risk Register document (UK Cabinet Office, 2015, 2020), published biennially. A similar approach is adopted in the United States, where risks are evaluated based on analysis of threats, vulnerabilities and consequences using expert assessments on a five-point scale.

It is important to bring up the creation of a threat assessment methodology during the National Risk Register setup. The UK Cabinet Office's 2020 assessment is different from its 2015 assessment in that it divides threats into eight target elements/outcomes: financial impact, human casualties, shelter and evacuation, public opinion, environmental damage or pollution, critical services, power supply and international relations. The criteria used for threat assessment in relation to these components are deduced from a retrospective examination and applied by specialists when assessing the outcomes of the impact of threats (Cybersecurity & Infrastructure Security Agency, 2020). However, it is important to acknowledge that full quantification of threats is often challenging due to the absence of a comprehensive mathematical model that incorporates dangers, vulnerabilities and outcomes, as well as the associated high costs and/or lack of system information. In cases where such conditions exist, it is crucial to recognise that the calculated levels are estimates and should not be overly emphasised or attributed with higher accuracy than the data and methods employed. Thus, the existing approaches (Kotowicz et al., 2022; Axon & Darton, 2021; Hussain et al., 2021; Kwilinski et al., 2022; Dźwigol et al., 2019; Miśkiewicz et al., 2022; Saługa et al., 2020, 2021; Drożdż et al., 2021; Miśkiewicz, 2018, 2020; Szczepańska-Woszczyna & Gatnar, 2022; Coban et al., 2022; Bin Abdullah et al., 2020; Polcyn et al., 2022; Azzuni & Breyer, 2017; Brown et al., 2014; Huang et al., 2021; Shaikh et al., 2022; Iyke et al., 2021; ISO 31000, 2018; World Energy Council, 2023; U.S. Chamber of Commerce Global Energy Institute, 2023; UK Cabinet Office, 2015, 2020; Theocharidou & Giannopoulos, 2015; Cybersecurity & Infrastructure Security Agency, 2020) reveal significant shortcomings, including the high subjectivity of expert evaluations. Moreover, the methods do not offer precise instructions for determining upper bounds on energy security indicator values. They also fail to address the following issues in a rigorous scientific manner: (i) absence of a well-defined scientific methodology to establish energy security levels, evaluate threat impacts and choose suitable defences;

(ii) absence of a scientific methodology for strategic planning to enhance energy security; (iii) inability to objectively compare the degree of energy security between countries and determine the objective state of security or danger, due to the absence of scientifically substantiated security gradations and quantitative measurements; (iv) inconsistencies in assigning weighting coefficients and the lack of shadow indicators to describe energy security; (v) insufficient understanding of the necessary actions that management entities should undertake to protect themselves from negative consequences of threats or reduce their likelihood; (vi) arbitrary gradations in the 5x5 matrix and vague scoring of relative consequences and probabilities, lacking proper justification; (vii) oversimplification of negative consequences of threats and probabilities of their occurrence, leading to inconsistencies; (viii) inadequate comprehension of which security indicators should be modified and how, in order to maintain or restore desired parameters of state functioning and sustainable developmental trajectory; (ix) inability to objectively determine the influence of dangers on security levels due to the lack of a mathematical model linking risks, vulnerabilities and consequences; (x) absence of a mechanism for adapting the research object to the consequences of threat impacts; and (xi) inability to scientifically justify changes in research object indicators to ensure consistency with the trajectory of sustainable development.

To address these limitations, Sukhodolia et al. (2022) proposed an approach to evaluating the criticality of threat impacts by comparing the actual normalised value of an integral energy security index component to its normalised target and threshold values. This aligns with the risk assessment approach adopted in European Union member states (Theocharidou & Giannopoulos, 2015). However, the presence of a mathematical model alone does not resolve the shortcomings observed in existing methodologies (Sukhodolia et al., 2022; Bin Abdullah et al., 2020; Kotowicz et al., 2022; Hussain et al., 2021; Axon & Darton, 2021; Kwilinski et al., 2022; Dźwigol et al., 2019; Miśkiewicz et al., 2022; Saługa et al., 2020, 2021; Drożdż et al., 2021; Shaikh et al., 2022; Miśkiewicz, 2018, 2020; Theocharidou & Giannopoulos, 2015; Polcyn et al., 2022; Szczepańska-Woszczyna & Gatnar, 2022; Coban et al., 2022; Azzuni & Breyer, 2017; Brown et al., 2014; Huang et al., 2021; Iyke et al., 2021; World Energy Council, 2023; UK Cabinet Office, 2015, 2020; ISO 31000, 2018; Cybersecurity & Infrastructure Security Agency, 2020; U.S. Chamber of Commerce Global Energy Institute, 2023), such as abstract point estimates and the inability to determine how each indicator or energy security component should be adjusted to maintain the desired trajectory of sustainable development. Furthermore, this mathematical model only assesses the relative consequences and probabilities of existing threats, without providing current and projected security levels. Therefore, the aim of this article is to develop a quantitative methodology to evaluate the impact of threats on energy security levels and a methodology for adapting energy systems to withstand both external and internal threats, ensuring alignment with the defined strategic trajectory of sustainable development.

2.1 Diverse approaches to energy security assessment

Research has delved into various aspects of energy security, including sustainable energy sources (Kotowicz et al., 2022; Miśkiewicz et al., 2022) and the assessment of smart grids (Kwilinski et al., 2022). While these studies provide valuable insights, they often focus on isolated components rather than integrating them into a holistic framework. For instance, Dźwigol et al. (2019) offered a multidimensional evaluation of energy independence at national and regional levels but failed to connect these dimensions to a broader understanding of energy security. This fragmentation highlights a critical need for a unified approach that encompasses the various dimensions of energy security, rather than treating them as separate entities.

In contrast, some researchers adopt a more systematic perspective, examining the interplay between energy security and broader economic and environmental factors (Hussain et al., 2021; Miśkiewicz, 2020). However, these studies often lack standardised methodologies for measuring energy security levels, leading to inconsistencies in findings and interpretations. The critiques of the Energy Trilemma Index (World Energy Council, 2023) exemplify this issue, as its subjective ranking system raises questions about the reliability of comparative assessments across different contexts. This inconsistency in measurement frameworks complicates the ability to draw meaningful conclusions about energy security across different regions.

2.2 Methodological limitations and subjectivity

A significant body of literature employs quantitative methods, such as the Z-score technique and principal component analysis (Bin Abdullah et al., 2020). While these methods offer structured approaches to evaluating energy security, they often lack transparency in their calculations and fail to categorise indicators effectively as positive or negative influences. This limitation is echoed in the studies by Axon and Darton (2021) and Azzuni and Breyer

(2017), which emphasised the need for a standardised methodology to define energy security comprehensively. The absence of clear guidelines for categorising indicators not only complicates the assessment process but also undermines the validity of the results. Moreover, the reliance on expert evaluations in risk assessment methodologies, such as those outlined by ISO 31000 (2018) and the U.S. Chamber of Commerce Global Energy Institute (2023), introduces a degree of subjectivity that can skew results. The 5x5 matrix approach used in these assessments, while systematic, often lacks rigorous justification for its scoring, leading to arbitrary gradations that may not accurately reflect the complexities of energy security threats. This subjectivity is problematic, as it can lead to inconsistent evaluations and hinder effective decision making in energy policy.

2.3 Addressing shortcomings in previous research

This study aims to address the identified shortcomings in the existing literature by proposing a novel adaptive response methodology that integrates both quantitative and qualitative assessments of energy security. Specifically, it seeks to: (i) establish a comprehensive framework; (ii) enhance methodological rigour; (iii) reduce subjectivity; and (iv) facilitate comparative analysis.

Thus, by synthesising insights from previous studies, we will develop a cohesive framework that encompasses the diverse dimensions of energy security, allowing a more holistic assessment. This framework will facilitate a better understanding of how different factors interact and influence overall energy security. Next, the proposed methodology will incorporate a transparent mathematical model that not only evaluates the impact of threats on energy security levels but also provides clear guidelines for adjusting indicators to maintain alignment with sustainable development trajectories. This approach aims to reduce the ambiguity associated with existing methodologies and provide actionable insights for policymakers. In addition, by minimising reliance on expert evaluations and employing data-driven approaches, this study aims to enhance the objectivity of energy security assessments, addressing the criticisms of existing methodologies. This shift towards a more empirical basis for evaluation will improve the reliability of the findings. Finally, the research will establish standardised metrics for energy security, enabling more effective comparisons across different countries and contexts, thereby contributing to a more nuanced understanding of global energy security dynamics. By providing a common framework for assessment, this study will help bridge the gaps identified in previous research and facilitate more informed discussions on energy security.

To underscore, while the existing studies have contributed to different aspects of energy security, significant gaps remain in terms of methodological rigour, standardisation and comprehensive assessment. This article seeks to fill these gaps by proposing an adaptive response methodology that enhances the resilience of energy systems in Central Europe, ensuring their alignment with sustainable development goals. By addressing the limitations of previous research, this work aims to contribute to a more robust understanding of energy security and its implications for national and regional economies.

3 Materials and Methods

The methodology integrates expert evaluations with quantitative computations, allowing a comprehensive understanding of energy security. The following steps summarize the approach, with technical details provided in the appendices for readers seeking deeper insights.

3.1 Methodology overview

Defining energy security metrics. The first step involves formalising a set of indicators that measure energy security. These indicators are categorised into seven strategic objectives: resource adequacy, economic sustainability, economic feasibility, energy efficiency, environmental health, resilience of the energy sector and protection of national interests. This categorisation helps in organising the assessment process and ensuring that all critical aspects of energy security are considered.

Evaluating indicators. Each indicator is evaluated to determine whether it promotes (S) or impedes (D) energy security. This evaluation is crucial for understanding the overall impact of each metric on the energy security landscape.

Constructing the energy security index. The components and structure of the energy security index are identified. This index serves as a composite measure that reflects the overall energy security level based on the selected indicators.

Normalisation of data. A suitable normalisation method is chosen to ensure that all indicators are comparable. Normalisation adjusts the values of the indicators to a common scale, facilitating meaningful comparisons.

Dynamic weighting of indicators. The methodology incorporates dynamic weighting variables to account for the changing importance of different indicators over time. This approach recognises that the relevance of specific metrics may fluctuate due to external factors, such as political or economic changes.

Setting threshold values. Threshold values for each indicator are established to define acceptable levels of energy security. These thresholds help identify when an indicator is performing adequately or when intervention is necessary.

Calculating the energy security index. The comprehensive energy security index is calculated using the normalised indicators and their respective weights. This index provides a quantitative measure of energy security, allowing easy tracking of changes over time.

Integrating metrics and thresholds. Finally, the metrics and their threshold values are integrated to create a holistic view of energy security. This integration enables decision makers to assess the current state of energy security and identify areas for improvement.

3.2 Methodology justification

The proposed methodology is designed to provide a comprehensive and dynamic assessment of energy security, addressing several limitations found in alternative approaches:

- Integration of expert evaluations and quantitative data: Unlike many existing methodologies that rely solely on expert assessments or quantitative models, this approach combines both. This integration enhances the robustness of the analysis by making use of the strengths of both qualitative and quantitative data.

- Dynamic weighting: The use of dynamic weighting allows the methodology to adapt to changing circumstances, making it more responsive to real-world conditions. Many traditional models use static weights, which can lead to outdated assessments that do not reflect current realities.
- Comprehensive indicator set: By utilising a broad range of indicators categorised into strategic objectives, the methodology ensures that all relevant aspects of energy security are considered. This comprehensive approach contrasts with narrower models that may overlook critical factors.
- Clear thresholds and gradations: Establishing clear threshold values for indicators provides a structured framework for evaluating energy security. This clarity is often lacking in other methodologies, which may present results without actionable benchmarks.
- Focus on sustainability: The methodology emphasises the importance of aligning energy security assessments with sustainability goals. This focus is increasingly relevant in today's context, where environmental considerations are paramount.

3.3 Technical details

At the strategic planning level for the development of specific aspects of national security, we propose a methodology that integrates expert evaluations with quantitative computations to define the level of security at different standards of granularity. This methodology makes it possible to assess the influence of risks and the trajectory of sustainable development. Determining the degree of energy security and developing plans to raise it within the framework of sustainability—a comprehensive management system that includes a systematic approach to moving from the current state of the control objective to the desired state—are the tasks at hand (Kharazishvili et al., 2021). There are multiple steps involved in determining the energy security level: (i) formalising and establishing a range of energy security measures; (ii) evaluating whether these metrics promote (S) or impede (D) energy security; (iii) identifying the components and structure of the energy security index; (iv) choosing a suitable normalisation method; (v) justifying dynamic weighting variables; (vi) determining the parameters necessary for secure operation, such as defining the metric threshold values; (vii) integrating the metrics and their threshold values simultaneously; and (viii) calculating the threshold values for the components of the comprehensive energy security index utilising security gradations over the extended homeostatic plateau and comparing them with target metrics.

Using 48 indicators, we determine the energy security level in our methodology, providing a comprehensive picture of the system (while balancing completeness with complexity). According to the Energy Security Strategy of Ukraine (Cabinet of Ministers of Ukraine, 2021), these indicators are categorised into seven strategic objectives: (I) resource adequacy, (II) economic sustainability, (III) economic feasibility, (IV) energy efficiency, (V) environmental health, (VI) energy sector resilience and (VII) protection of national interests (Table 1). To illuminate the technical aspects of the methodology, we provide detailed explanations of the models, normalization techniques, dynamic weighting calculations and threshold value determinations in Appendix 1. The data sources are thoroughly discussed in the work of Kharazishvili et al. (2024, pp. 1802-1804), providing a clear framework for understanding how the methodology can be effectively implemented.

Table 1 | Comprehensive metrics for assessing Ukraine's energy security across key dimensions

No.	(I) Indicator	Type	Dimension
	I–Resource adequacy		
(1)	Supplying energy demands with primary resources sourced domestically	S	Consumption in (%)
(2)	Cost of importing energy resources	D	GDP in (%)
(3)	Share of oil and petroleum products in the energy mix	D	Balance in (%)
(4)	Use of natural gas	D	Balance in (%)
(5)	Use of thermal coal	D	Balance in (%)
(6)	Sources of energy that fuse and use nuclear power	S	Balance in (%)
(7)	Generation of hydropower	S	Balance in (%)
(8)	Wind and solar energy	S	Balance in (%)
(9)	Use of biomass energy	S	Balance in (%)
	II–Economic sustainability		
(10)	State expenses related to energy resource consumption	D	GDP in (%)
(11)	Per capita annual electricity use	S	(MWh)
(12)	Annual per capita energy consumption	S	(toe)
(13)	Percentage of household income spent on housing and utilities	D	in (%)
(14)	Dependability of fuel, energy supply and basic resources	S	Expert evaluation in (%)
	III–Economic feasibility		
(15)	Country GPD per capita	S	1,000 (USD)
(16)	Level of investment by fuel and energy sector enterprises	S	Production of fuel and energy complex in (%)
(17)	Fuel and energy complex fixed asset renewal rate	S	Fuel and energy complex fixed assets in (%)
(18)	Fuel and energy complex informal economy	D	Fuel and energy complex gross value added in (%)
(19)	Pay rates in energy and fuel industry	S	Production of complex fuels and energy in (%)
(20)	Energy market concentration measured by Herfindahl-Hirschman Index	D	Supplier index
	IV–Energy efficiency		
(21)	GDP energy intensity	D	toe / 1,000 (USD)
(22)	Contribution of energy to GDP	D	Fuel and energy complex gross value added to GDP in (%)
(23)	Unreported energy resource usage	D	GDP in (%)
(24)	Total energy resource losses (balanced)	D	Entire stock in (%)
(25)	Percentage of energy used to meet energy needs	D	Entire stock in (%)
(26)	Network losses in heat supply	D	Volume of transmission in (%)

No.	(I) Indicator	Type	Dimension
(27)	Losses in power grid	D	Volume of transmission in (%)
	V–Environmental health		
(28)	Emission levels of carbon dioxide (CO_2) per entire primary energy supply	D	t CO_2 / toe
(29)	Emissions of carbon dioxide (CO_2) per GDP unit	D	kg / USD
(30)	Ultimate energy carbon intensity	D	g CO_2 / MJ
(31)	Proportion of CO_2 emissions from power and heat production facilities	D	Overall emissions in (%)
(32)	Percentage of renewable energy used (final consumption)	S	Ultimate usage in (%)
	VI–Energy sector resilience		
(33)	Share of leading supplier in terms of energy imports (by type of primary resource)	D	In (%)
(34)	Degree of reliance on single source for imports and exports of technology (based on energy technology types)	D	Expert evaluation in (%)
(35)	Quantity of reserves and stockpiles by main categories of energy resources	S	Monthly usage in (%)
(36)	SAIDI (System Average Interruption Duration Index)	D	Minutes / year
(37)	Effectiveness and efficiency in handling crisis situations	S	Expert evaluation in (%)
	VII–Protection of national interests		
	Institutional and organisational support:		
(38)	Infrastructure and procedures for production	S	Expert evaluation in (%)
(39)	Infrastructure and processes for management	S	Expert evaluation in (%)
(40)	Infrastructure and processes for support and service	S	Expert evaluation in (%)
(41)	Infrastructure and maintenance procedures during a facility's lifecycle	S	Expert evaluation in (%)
(42)	Infrastructure and procedures for information and communication	S	Expert evaluation in (%)
	Quality of policy implementation:		
(43)	Degree of participation in EU energy markets	S	Expert evaluation in (%)
(44)	Utilisation of informal economies in energy and fuel sector (generation of water, gas, electricity and extractive industries)	D	Officially in (%)
(45)	Government policy integrity	S	Expert evaluation in (%)
(46)	Standard of technical and management human resources	S	Expert evaluation in (%)
(47)	Political leaders' relevance to systematic issues	S	Expert evaluation in (%)

Source: Model and professional projections combined with data from Ukrainian State Statistics Service (compiled by Kharazishvili et al., 2024)

We select the multiplicative (nonlinear) structure for the integral index since the energy security system processes are nonlinear. It means that a logarithmic function can be used to connect to the additive form (Kharazishvili et al., 2021):

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

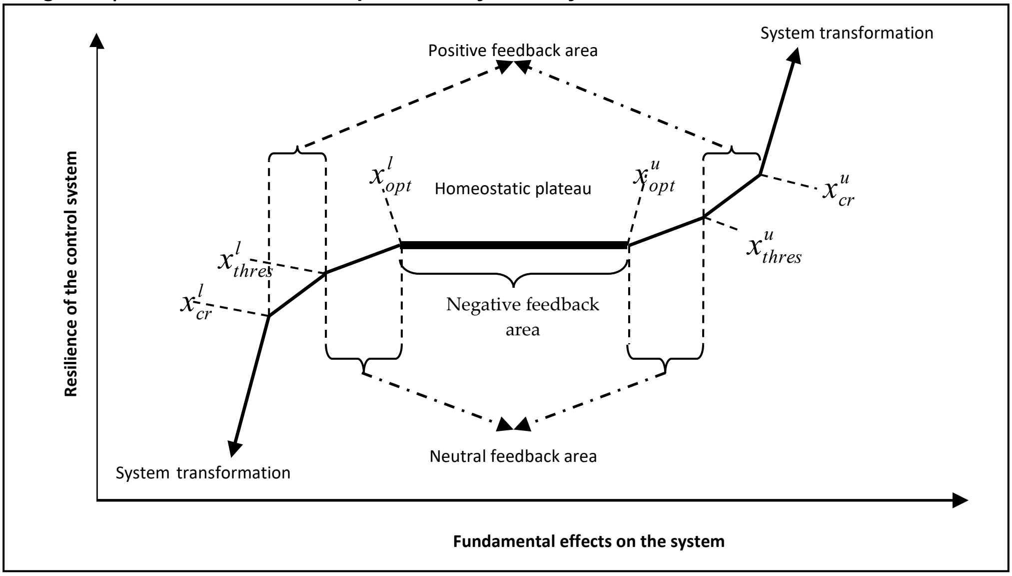
where $z_{i,t}$ are the indicator values that have been adjusted using the combination technique; in the case of stimulators $z_{i,t} = x_i / k_{n,t}$, in the case of destimulators $z_{i,t} = \left(k_{n,t} - x_i\right) / k_{n,t}$; $k_{n,t} \geq x_{\max,t}$; x_i are the values of the current indicator; $k_{n,t}$ denotes a normalisation coefficient (the maximum value for stimulators is $x_{\max,t}$ of the set of indicators and each one's limit value; in the case of destimulators $1.1x_{\max,t}$); a_i are coefficients for dynamic weighting; *t* is a time period; *i* is an ordinal index number. The constantly shifting external environment, which is particularly affected by political and foreign economic issues influencing the empirical evaluations of econometric linkages, is the cause of the varying weighting coefficients.

In accordance with Kharazishvili et al. (2024), we use the following methods to introduce dynamism. (i) We construct a minimum necessary matrix based on the condition of having an equal number of principal components (indicators) positively determined by the eigenvalue of this matrix. Typically, the row count (time periods) is one greater than the number of principal components (indicators). (ii) We calculate the constant weighting coefficients for the phase of acceleration utilising the method of principal components, followed by shifting the grid by one time period. (iii) We compute the weighting coefficients for the subsequent time period using the matrix derived from the previous step:

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

where C_i showcases the dispersion vector matrix and D_i is the matrix of absolute factor loading magnitudes. These methods improve the robustness of the strategy for determining the stability of the sustainable development trajectory and assessing degrees of energy security by enabling a more dynamic and accurate representation of the weighting coefficients (Kharazishvili et al., 2024). Next, we justify the limit value vector for the indicators in order to determine the boundaries of safe existence (Van Gigch, 1978). We relate the number of safety gradations (critical, threshold and ideal) to regions of positive, neutral and negative feedback as well as the idea of an extended homeostatic plateau (Figure 1).

Figure 1 | Extended homeostatic plateau of dynamic system



Source: Kharazishvili et al. (2024)

Technical systems could be destroyed and economic and social systems could change when the current indicator levels exceed critical values to different extents. Both the controlled object and the control system may be qualitatively affected by these modifications in a positive or negative way. As an example, it is reasonable to believe that the emergence of a critical mass of indicators (more than half of all security indicators) that exceed upper critical values may portend an impending transition of the economy to the advanced technology mode. Conversely, surpassing the lower bound of significance may lead to disruptions in operation and the loss of essential features within the current technological paradigm. By building the probability distribution function and determining the distribution type by examining the statistical properties of the sample, such as a mean (*μ*), the standard deviation (*σ*) and asymmetry coefficient (k_{as}) the *t*-criterion method is expanded to determine the numerical values of safety levels. Table 2 officially establishes the locations of bifurcation for the three characteristic distribution types (lognormal, exponential and normal).

Table 2 | Formalised threshold vector values for various probability indicator types

Probability indicator type	Lower limit	Upper limit	Lower opt. value	Upper opt. value
1. Typical/normal	$\mu - t\sigma$	$\mu + t\sigma$	$\mu - \sigma$	$\mu + \sigma$
2. Lognormal with a left tail	$\mu - t\sigma$	$\mu + t\sigma/k_{as}$	$\mu - \sigma$	$\mu + \sigma/k_{as}$
3. Lognormal with a right tail	$\mu - t\sigma/k_{as}$	$\mu + t\sigma$	$\mu - \sigma/k_{as}$	$\mu + \sigma$
4. Exponential with a left tail	$\mu - t\sigma$	$\mu + t\sigma/k_{as}$	$\mu - \sigma$	μ
5. Exponential with a right tail	$\mu - t\sigma/k_{as}$	$\mu + t\sigma$	μ	$\mu + \sigma$

Source: Kharazishvili et al. (2024)

A distinctive feature of this study is its thorough examination of the complete range of limit values, which includes both lower and upper boundaries—critical, threshold and optimal values—rather than a limited vector that only considers threshold and optimal values. This approach accounts for the potential adjustments of these boundaries in response to the military aggression from Russia. To calculate the reduced vector of limit values (threshold and optimal), a confidence level of 0.98 or 0.99 can be used from the Student's *t*-distribution tables to obtain *t* values. Additionally, the critical values of indicators (lower and upper critical limits) can be established with a confidence level of 0.998 or 0.999.

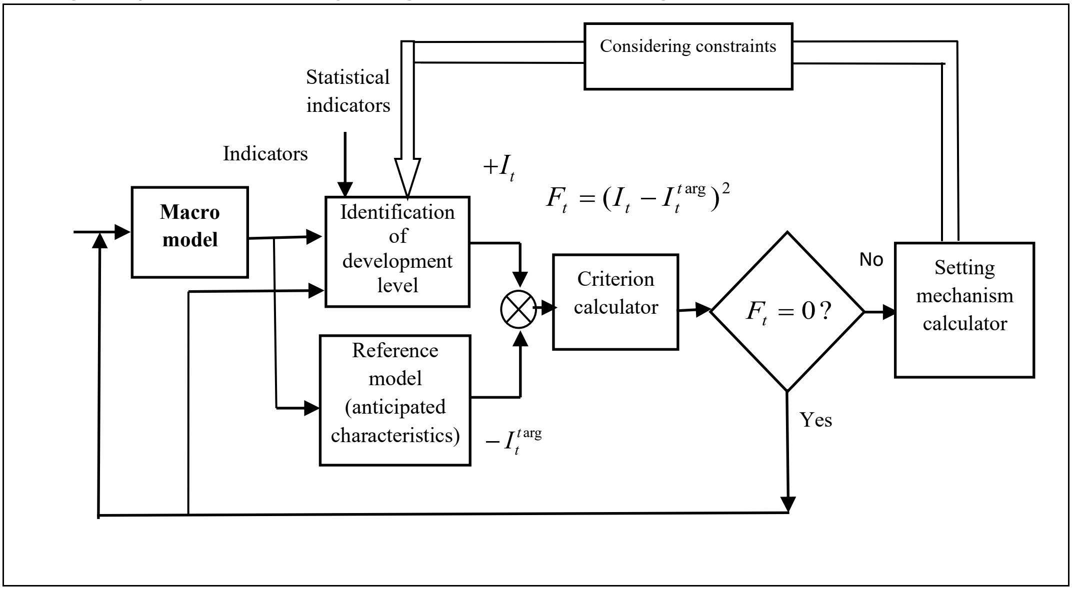
By convoluting the indicators (I) with their corresponding limit values (P), we can formulate a hierarchical multifactor mathematical model that depicts energy security:

$$I_{I-VII} = \prod_{k=1}^{7} I_{k,t}; \quad P_{i,j} = \prod_{j=1}^{6} P_{i,j}^{b_{i,j}}; \quad P_{i,j} = \left[P_{kr,ij}^{low}; P_{th,i,j}^{low}; P_{opt,i,j}^{low}; P_{opt,i,j}^{app}; P_{th,i,j}^{app}; P_{kr,i,j}^{app}\right];$$
$$I_{I,t} = \prod_{i=1}^{9} z_{i,t}^{a_i}; \quad I_{II,t} = \prod_{i=1}^{5} z_{i,t}^{a_i}; \quad I_{III,t} = \prod_{i=1}^{6} z_{i,t}^{a_i}; \quad I_{IV,t} = \prod_{i=1}^{7} z_{i,t}^{a_i}; \qquad (3)$$
$$I_{V,t} = \prod_{i=1}^{5} z_{i,t}^{a_i}; \quad I_{VI,t} = \prod_{i=1}^{5} z_{i,t}^{a_i}; \quad I_{VII,t} = \prod_{i=1}^{11} z_{i,t}^{a_i};$$

in this case, *j* stands for the number of security levels and *k* for the number of elements.

The integral index of energy security (I_t) and the limit values (*P*) of components *I–VII* can be calculated using Model (3) for each security level of the extended homeostatic plateau. These values can then be compared to the target indicators in order to make inferences about the current state of energy security (Kharazishvili et al., 2021). We use the strategic planning principle—which states that the future is determined by the path projected into the future—to decide the development strategy. To do this, strategic goals must be set, the expected future development trajectory must be built and the inverse problem must be solved by combining the necessary values of the components and indicators using the stepwise decomposition of integral indices. In this process, the adjustable regulatory techniques of management theory (Leondes & Aoki, 1965; Kharazishvili et al., 2021) are essential (Figure 2).

Figure 2 | Adaptive control system generalised scheme using a reference model



Source: Kharazishvili et al. (2021)

As a result, the goal of strategising should include both identifying the intended destination and outlining the route to get there. Not only must the future be envisioned, but the appropriate actions must also be planned and swiftly carried out in order to achieve the intended outcome (Kusumano & Joffy, 2018).

Using this method, one has to be familiar with the integral indices beforehand, namely (I_t) for each year, allowing their use as reference values ($I_t^{t\arg}$) within the model of adaptive regulation. Equations for the integral blending of the elements from Equation (3) using each of their unique weighting coefficients (a_i) are developed sequentially in the "Identification of development level" block. The role of the control device is to figure out how to change the normalised indicators ($z_{i,t}$) so that the squared error, or adjustment parameter (F_t), goes to zero. The changes in the indicators are computed using gradient methods, while considering the imposed constraints. This formulation aligns with the class of nonlinear parametric optimisation challenges. For the real-world implementation of the strategizing methodology, we utilise the strategizing procedure implemented in the C++ coding language. This procedure was authored by the developer of the proposed strategic guideline justification method, Yurii Kharazishvili. The strategizing procedure utilises an adaptive regulation technique with a brief feedback loop, omitting the usage of a macromodel. For more in-depth studies, the long feedback cycle mode is employed.

In the context of the classical model of aggregate supply within Keynesian theory, where the price level influences economic activities, the model calculations determine the following indicators (16 in Table 1): 16-19, 22, 23, 45.

Apart from model-based computations, the expert technique is applied to ascertain indicators that cannot be obtained from official data. Table 1 lists these indicators as follows: 14, 34, 37–44, 46–48.

These indicators are established through expert assessment and are of significant importance in evaluating the comprehensive energy security system.

4 Theory

There are numerous internal and external threats to energy security that require an impact assessment. However, defining these threats as indicators with relative values is often challenging or not always possible. Therefore, expert assessments are justified in determining the influence of such threats on energy security levels when other objective assessments are unavailable or impractical. Consequently, expert assessments should be employed as a last resort when other scientific approaches are not feasible.

It should be noted that any classification of threats is conditional to some extent, since, firstly, depending on the purpose and methods of scientific research, it can be carried out on different grounds and pursue different goals; secondly, it is subjective in nature, since it depends on the subject carrying it out. Therefore, we will divide threats into two categories below.

4.1 Internal threats

Threats that are internal elements of the security object and reflect its state are indicators. Every indicator is defined by a vector containing threshold values (Table 2) and may assume different values in the process of development. Furthermore, the homeostatic plateau is defined by a set of ideal values that provide the best, or most suitable, conditions for the system operation and negative feedback. Therefore, the midpoint of the "homeostatic plateau", or the mean between the two optimal values (upper and lower optimal), can be used as a criterion to determine when indicators, as well as composite and comprehensive indices, have reached the level of sustainable development. During the process of gauging the sustainable development level in the security aspect, certain indicators emerge as critical risks that impede the accomplishments of sustainable development. In this regard, there is an urgent need for an empirical rationale for identifying threats and challenges to sustainable development in the security realm to determine their impact and further justify the primary focus areas of institutional measures to address them. In other words, the list and significance of threats are defined by the method of imbalances – the standard of distance in terms of sustainable development for each element and indicator (Table 1). This approach is used after the identification phase, which involves the integrated blending of indicators and threshold values to determine the degree of sustainable growth in the security domain.

4.2 External threats

Threats that cannot be described by indicators of the state of the security object are external to the security object and require other approaches to take into account their influence regarding the energy security level. To this end, an expert and mathematical method for evaluating the influence of threats on the energy security level of the state has been developed, which combines expert assessments of changes in the components of the integral index and formalised mathematical calculations of their impact on the integral index and indicators by decomposing the integral indices into the components by the method of adaptive regulation (Sukhodolia et al., 2023).

To assess the impact of threats, experts should estimate how much the values of the elements of the integral index of energy security will change during a certain period under the influence of each specific threat. In this case, the current and limit values of the integral index components are known as of a certain date, as determined by Model (3). The most optimal are expert assessments of changes in components (7 in total) instead of indicators (47) and the integral index for 20 threats (as indicated in Table 3), which are created by specialists following normalisation and integral convolution of components (Kharazishvili et al., 2024).

Table 3 | Standardised values of Ukraine's comprehensive energy security index components for 2021–2022

Group of (I)	Normalised values of vector of limit values and components of integral index of energy security							
	X^{lower}_{crit}	X^{upper}_{crit}	X^{lower}_{thres}	X^{upper}_{thres}	X^{lower}_{opt}	X^{upper}_{opt}	I_t	
							2021	2022
Energy security integral index, broken down by component	0.1678	0.9187	0.3316	0.8011	0.4917	0.6664	0.3798	0.3066
I–Resource adequacy	0.1067	0.8585	0.2248	0.6459	0.3588	0.5141	0.3184	0.3195
II–Economic sustainability	0.1280	0.9252	0.2877	0.8299	0.4422	0.6649	0.4681	0.3338
III–Economic feasibility	0.2512	0.9695	0.3593	0.8667	0.4868	0.6693	0.2692	0.2097
IV–Energy efficiency	0.1427	0.8748	0.3375	0.8099	0.5109	0.6877	0.3510	0.2057
V–Environmental health	0.1016	0.8767	0.2719	0.7497	0.4416	0.6188	0.3145	0.2668
VI–Energy sector resilience	0.2295	0.9571	0.4437	0.8988	0.6720	0.8207	0.5493	0.3927
VII–Protection of national interests	0.3622	0.9871	0.5245	0.8721	0.6666	0.7913	0.4503	0.4216

Source: Model calculations by the authors (Kharazishvili et al., 2024)

At the same time, the expert evaluation of the influence of threats is conducted by analysing their impact on the change in normalised values of energy security components relative to current values, rather than based on abstract point estimates (Sukhodolia et al., 2023). Equation (3) in the mathematical model of integral convolution is used to evaluate the overall effect on the integral index of energy security following expert assessments of the impact of threats on the integral index constituents.

This procedure is carried out by gradually combining each component to create the integral index in Equation (4), after which the trajectory of sustainable development is planned utilising flexible regulatory techniques (Figure 2). This method solves the previously described issue of translating threats into indicators by making it possible to determine how associated indicators should change when integral index components change. Thus, the previously unresolved problem of assessing the impact of threats on indicators is proposed to be resolved via the decomposition of comprehensive indices of components utilising the adaptive controlling method (Figure 2).

We propose an adaptive response methodology to address threats by constructing a new trajectory that aligns with predefined strategic goals. This involves assessing the impact of threats, decomposing the new dynamics of the integral index into components and analysing the impact of these components on specific energy security indicators using adaptive regulation methods. By doing so, we obtain scientifically based changes in components and indicators that contribute to achieving the defined goals.

5 Calculation

5.1 Threat identification and impact assessment using imbalance methodology

Risks to sustainable development can be identified scientifically by making a direct connection between the need to operate dynamic systems within safe bounds and the identification of potential risks. This method creates a link between sustainable development and security issues by combining the identification stage with a comprehensive assessment of the degree of sustainable development in security coordinates. Therefore, we obtain a list of sustainable development components and indicators that deviate most from the defined criteria and are located either at or below the lower critical value as well as between the lower threshold and lower critical values by applying a scientific approach to defining threats based on the deviation from the point of sustainable development for each component or indicator. Elasticity coefficients are used to estimate the importance of the impact of various indicators (Tables 4 and 5).

Table 4 | Identification of problematic components affecting Ukraine's energy security in 2022

Components below or at lower critical value	Components between lower threshold and lower critical values
I–Resource adequacy II–Economic sustainability III–Economic feasibility VII–Protection of national interests	IV–Energy efficiency V–Environmental health VI–Energy sector resilience

Source: Model calculations by the authors (Kharazishvili et al., 2024)

Table 5 | Critical threats to Ukraine's energy security indicators in 2022: Coefficients of elasticity

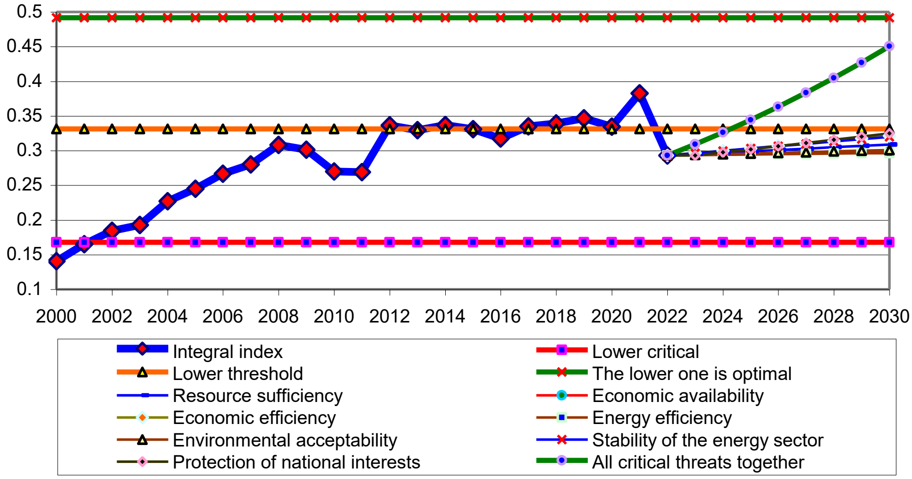
Components and indicators	Coefficient of elasticity
I–Resource adequacy - Wind and solar energy	0.135265
II–Economic sustainability - Annual per capita energy consumption	0.075179
III–Economic feasibility - Country GPD per capita - Level of investment by fuel and energy sector enterprises - Fuel and energy complex fixed asset renewal rate - Fuel and energy complex informal economy - Pay rates in energy and fuel industry	0.072209
IV–Energy efficiency - Network losses in heat supply	0.029966
V–Environmental health - Emissions of carbon dioxide (CO_2) per GDP unit - Ultimate energy carbon intensity	0.074160
VI–Energy sector resilience - SAIDI (System Average Interruption Duration Index) - Effectiveness and efficiency in handling crisis situations	0.147037
VII–Protection of national interests **VII(1) Institutional and organisational support:** - Infrastructure and processes for support and service - Infrastructure and maintenance procedures during a facility's lifecycle - Infrastructure and procedures for information and communication **VII(2) Quality of policy implementation:** - Utilisation of informal economies in energy and fuel sector (generation of water, gas, electricity and extractive industries) - Government policy integrity - Standard of technical and management human resources - Political leaders' relevance to systematic issues	0.123595

Source: Model calculations by the authors (Kharazishvili et al., 2024)

These are the components and indicators that require the most attention to improve. Elasticity coefficients determine how much the output value (value of the integral index) will change if the input value (value of the indicator) changes by 1%. Based on the calculation outcomes, the most influential components of Ukraine's energy security are the following: energy sector sustainability, resource sufficiency and protection of national interests.

Let us assume that all critical indicators will reach their lower optimal values by 2030 as a result of institutional measures and use Model (3) to evaluate the impact of the changed indicators on the energy security level. The next step is to build exponential trajectories towards the desired goals (Figure 3).

Figure 3 | Impact of critical indicators on energy security level at end of 2030



Source: Compiled by the authors (Kharazishvili et al., 2024)

Next, using the computer program "Strategising", which implements the adaptive regulation method from management theory (Figure 2), we will obtain the required dynamics of elements and indicators through the decay of the integral index (2023-2030), which ensures attainment of the established objectives. The resulting dynamics are, in fact, a strategy for rehabilitation of the energy sector for public authorities.

5.2 Identification of scope and consequences of threats

Using the provided integrated assessment technique, we have ascertained the energy security level for Ukraine as of 31 December 2022, prior to evaluating the impact of threats not detected by indicators (Figure 3).

In order to establish the impact of the 20 identified risks to energy security, a poll of 20 Ukrainian specialists was undertaken to find out how they felt about possible changes to the existing values of the integral index component parts throughout the year. Sukhodolia et al. (2023) provided a detailed explanation of them. As shown in Table 6, internal and external risks were categorised according to their possible relative impacts on each of the seven integral index factors.

Table 6 | Mean expert ratings of adverse effects of energy security threats in Ukraine

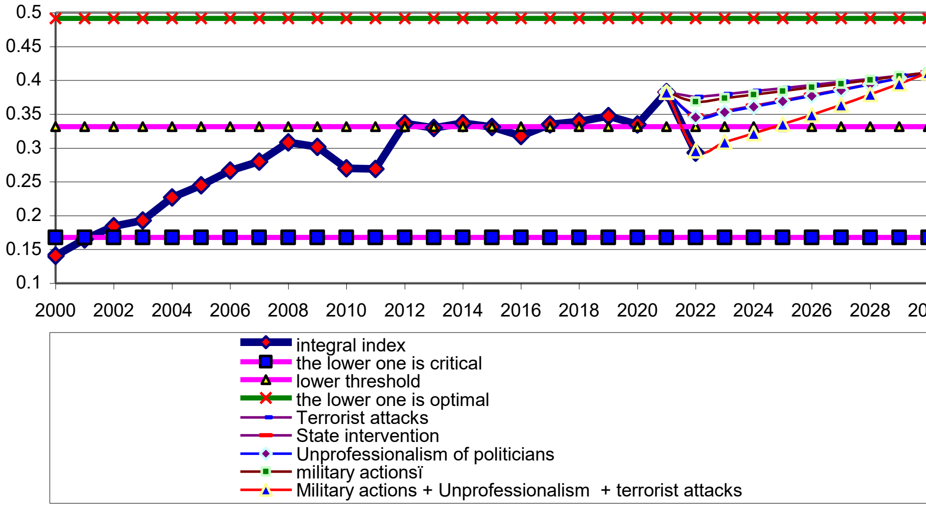
Threat to energy security	Average evaluation of integral index of energy security component parts						
	I	II	III	IV	V	VI	VII
Energy security risks (internal)							
Policymaking incompetence	0.2966	0.3286	0.2410	0.3363	0.3194	0.4985	0.4286
Energy system and network deterioration	0.2895	0.4337	0.2592	0.3334	0.2890	0.5134	0.3857
State intervention in market operations	0.3090	0.3445	0.2654	0.3246	0.3075	0.5129	0.4260
Reliance on resources and technology	0.3030	0.4184	0.2611	0.3485	0.3107	0.5213	0.4028
Energy poverty	0.3097	0.4149	0.2602	0.3295	0.3051	0.5417	0.4132
Economy's high energy intensity	0.2838	0.4490	0.2508	0.3367	0.3125	0.5418	0.4071
Detrimental environmental impacts of energy sector	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
Changing composition of energy resource supply and consumption	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
Energy security risks (external)							
Military actions	0.3092	0.4452	0.2602	0.3435	0.3092	0.5275	0.4366
Acts of terrorism	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
Pandemics and epidemics	0.3084	0.4284	0.2561	0.3448	0.3070	0.5248	0.4420
Loss of qualified personnel	0.2754	0.4439	0.2574	0.3310	0.3049	0.5261	0.4314
Integration process obstruction	0.3071	0.4647	0.2574	0.3370	0.3057	0.5306	0.4423
Influence from outside on policy making	0.3058	0.4511	0.2692	0.3482	0.3121	0.5224	0.4229
Supply blockage	0.3040	0.4441	0.2458	0.3438	0.3106	0.5213	0.4267
Financial crisis	0.3064	0.4341	0.2592	0.3392	0.3082	0.5375	0.4353
Shadow economy	0.3180	0.4653	0.2686	0.3445	0.2986	0.5427	0.4302

Source: Assembled in accordance with opinions of experts (Sukhodolia et al., 2023)

To demonstrate the evaluation of the impact of threats on the energy security level, we selected the most significant and current internal and external threats facing Ukraine: government intervention in market operations, policymaking incompetence, armed conflicts and terrorist activities. In order to reduce subjectivity during expert assessments, they were advised to provide a clear description of these threats, including their impact factor, vulnerability and consequences (Sukhodolia et al., 2023).

By the end of 2021, we assume that these concerns had begun to affect energy security. We obtain changes in the integral index by the end of 2022 by performing the integral convolution of components affected by these threats. After these threats have established sustainable development trajectories, we will evaluate their effect on the energy security level in relation to a realistic development scenario (Figure 4).

Figure 4 | Impacts of risks on energy security and countermeasures to maintain stability along sustainable development trajectory



Source: Based on Sukhodolia et al. (2023) and compiled by Kharazishvili et al. (2024)

First, we can use the mathematical identification model in Equation (3) to compute the integral index if we know the integral index values of the energy security constituents for a certain perspective. After that, by entering the component values for each year into the adaptive adjustment model (Figure 2) in Equation (4) and decomposing the points of the new integral index trajectory, we can obtain the desired dynamics of indicators that neutralise the impact of threats. This allows us to observe the function of adapting the energy system to the influence of threats in order to achieve strategic goals and return to a sustainable development trajectory. Policy decisions aimed at altering specific component indices can be determined based on the assessment of the adequacy of the response to threats affecting energy sustainability.

For this study, prioritising responses to threats is crucial in terms of achieving goals within the specified timeframe outlined in the strategic plan. The modelling process entails: (i) Prioritising measures to prevent, avoid, mitigate or eliminate the impact of each threat, with a focus on components of energy security such as the economic efficiency of its functioning, financial affordability for consumers and sustainability of the energy sector. These components are the most affected by the selected threats and deviate the most from the desired trajectory of achieving strategic goals. (ii) Giving priority to actions that ensure the elimination of the threat impact on the energy sector sustainability, aiming to restore the desired trajectory of achieving strategic goals by no later than 2026. (iii) Determining the weighting of response measures and required resources for each component, aiming to restore the desired trajectory of strategic goals.

By taking these steps, we can develop informed measures to respond to threats and adapt the sustainable development trajectory to achieve our strategic goals. It is worth noting that individual constituents of the integral index may lag behind or exceed the initial sustainable development trajectory, as there are interrelationships between components through dynamic weight coefficients that affect the overall integral index. According to expert assessments and the outcomes of mathematical modelling, the following threats—in order of significance—will have the biggest effects on the level of energy security in 2022: terrorist acts, military operations, policymaking incompetence and state intervention in the market. The combined impact of state interference in the functioning of markets, incompetence in policymaking and terrorist acts is equivalent to the actual situation in 2022. However, it is essential to gather information on the individual impact of each identified threat on Ukraine's energy security level to develop an appropriate policy for countering threats (Table 7).

Table 7 | Impact of internal and external threats on energy security integral index in Ukraine (2022)

Internal threats to energy security	2022	External threats to energy security	2022
Incompetence in policymaking	0.3453	Military operations	0.3685
State interference in functioning of markets	0.3474	Terrorist acts	0.3750
Degradation of energy systems and networks	0.3509	Cyber attacks	0.3766
Resource and technology dependence	0.3635	Epidemics and pandemics	0.3675
High energy intensity of economy	0.3637	Loss of professional staff	0.3593
Energy poverty	0.3653	Blockage of integration processes	0.3692
Negative environmental impact of energy sector	0.3730	External impact on policymaking	0.3703
Negative climate changes	0.3642	Blockage of supplies	0.3657
Changing structure of consumption and supply of energy resources	0.3777	Debt crisis	0.3687
Imperfect competition	0.3675	Shadow economy	0.3767

Source: Computational modelling by the authors (Kharazishvili et al., 2024)

These five major dangers are both causes and consequences, intertwining together. Incompetence in policymaking hinders the achievement of desired outcomes, while state interference in market functioning exacerbates the situation due to the incompetence. These factors ultimately lead to the demission of the energy system and deaths of staff, resulting in a high energy intensity of the economy. As a result, the modified indicators that promote sustainability in development serve as a strategic framework for achieving established objectives in the face of emerging threats. This allows the development of plans to respond to threats from a technical perspective, specifically in the structuring of operations of energy supply systems. The resulting dynamics of components (see Figure 4) and indicators fulfil the strategy for adapting the trajectory to sustainability in response to threats. It is the responsibility of policymakers to ensure the realisation of these dynamics of components and indicators through various means of influencing macroindicators.

Businesses in Central Europe stand to gain by being aware of and responsive to domestic challenges to energy security, such as those posed by the situation in Ukraine. To ensure effective and informed decision making, companies should prioritise investing in policymaking expertise, thereby reducing the risk of policy incompetence affecting their energy security. Companies can promote transparency and minimise state interference in market operations to foster a more conducive business environment for sustainable energy initiatives. Proactive measures such as infrastructure upgrades and maintenance can help mitigate potential risks to energy supply reliability. To contribute to long-term sustainability and growth, Central European businesses should implement strategies to retain and attract skilled professionals that can bolster workforce resilience and expertise within the energy sector.

6 Discussion

The dynamics of social, political and technological developments in the energy sector, as well as the changing models of national, regional and global market functioning, necessitate the establishment of an early detection and prevention system for energy security threats. Given the complexity of developing a unified approach to formalizing energy security and the need to consider various factors and components in the analysis of the energy sector, two approaches were employed to evaluate the influence of energy security threats:

(1) Quantitative mathematical methods for threats that are internal elements of the security object and reflect its state, i.e., indicators. The integral convolution of all components and their indicators in the security dimension clearly identifies indicators and components that exceed critical values and become threats to the attainment of sustainable development objectives. This leads to complications in the operation and potential loss of key functions within the current technological framework. The significance of recognising these indicators and their impact on the integrated energy security index cannot be overstated. Understanding the required dynamics of their change is a necessary objective component of the security development strategy, since every dynamic system has its own stable state of dynamic equilibrium and the means of achieving this state can be seen as the system trying to stay within the "homeostatic plateau". Therefore, the priority improvement of the “critical” indicators strengthens the system resilience to all other threats.

(2) Qualitative methods and expert assessments for threats that cannot be described by indicators of the state of the security object. In addition to the study of objective threats (indicators that exceed critical values), it is necessary to assess the impact of numerous additional dangers on the security situation that are not captured by the security object indicators. In this regard, an expert mathematical method for evaluating the influence of such threats on the energy security level was proposed, which combines expert assessments of changes in the components of the integral index and formalised mathematical calculations of their impact on the integral index and indicators by decomposing the integral indices into the components using the adaptive control method. This approach is a significant improvement over the existing expert scoring of impacts of threats on the security level. All forecast expert assessments, even if they are drawn from thin air, are undoubtedly highly speculative and subjective, but they are necessary for estimating the approximate size of the decline and for supporting indicators and macroeconomic indicators of the future economic strategies of restoring various aspects of

Ukraine's national security in the post-war era. Notwithstanding the involvement of proficient specialists in evaluating the impact of energy security risks, obstacles endure because of the intricacy, scope and subjective nature of assessments.

The ongoing war in Ukraine has significantly transformed the country's socio-economic and political landscape, creating a complex environment that profoundly influences energy security and sustainable development. As Ukraine confronts the immediate repercussions of war, it faces a multifaceted crisis that affects its energy systems, economic stability and social cohesion. This conflict has resulted in extensive destruction of critical energy infrastructure, including power plants, transmission lines and distribution networks. This devastation disrupts energy supply and impedes efforts to transition to sustainable energy sources. The loss of infrastructure has led to energy shortages, increased reliance on imports and heightened vulnerability to fluctuations in external energy markets.

The current situation in Ukraine has precipitated a severe economic downturn characterised by diminished industrial output, rising unemployment and inflation. This economic instability has strained public finances, thereby limiting the government's capacity to invest in energy security initiatives and sustainable development projects. As businesses struggle to operate within a wartime economy, the prospects for long-term economic recovery become increasingly uncertain. The war has also triggered a significant humanitarian crisis, displacing millions of Ukrainians both internally and externally. This displacement exacerbates social tensions and burdens local economies and public services. The urgent need for humanitarian assistance diverts resources away from critical energy security initiatives, further complicating the pursuit of sustainable development.

National security priorities have been reevaluated, with energy security emerging as a pivotal component of Ukraine's defence strategy. The government has prioritised diversifying energy sources and suppliers to reduce dependence on foreign energy, particularly from adversarial countries. This strategic shift is essential for national security and fostering resilience in the face of ongoing threats.

The conflict has galvanised international support for Ukraine, resulting in increased cooperation with Western countries and organisations. This support encompasses financial aid, technical assistance and investments in energy infrastructure. However, the effectiveness of this assistance is contingent upon establishing transparent governance structures and implementing reforms aimed at enhancing energy security and sustainability.

The prolonged nature of the conflict may lead to fatigue and disillusionment, potentially destabilising the political landscape. The government must navigate these sentiments with care, ensuring that energy policies align with public expectations and contribute to long-term stability.

The analysis of Ukraine's energy security offers critical insights relevant to the Central European business environment, especially considering the region's ongoing energy transition and geopolitical challenges. As Central European countries grapple with their own energy security issues, the lessons drawn from Ukraine's experiences can serve as a valuable guide for strategic decision making and policy development. One of the critical implications for businesses in Central Europe is the need to understand energy security risks. Identifying internal and external threats to Ukraine's energy security—such as policymaking incompetence, state intervention in market operations, military actions and terrorist activities—highlights the importance of recognising similar risks in Central Europe. Companies must remain vigilant in assessing how these threats could affect their operations, supply chains and overall energy security. By comprehensively understanding these risks, businesses can develop more robust risk management strategies that enhance their resilience.

Our findings underscore the detrimental effects of poor policymaking on energy security, making it imperative for Central European businesses to invest in policymaking expertise. Engaging with policymakers to advocate for transparent and effective energy policies is crucial for promoting market stability and sustainability. By fostering collaborative relationships with government entities, businesses can help mitigate the risks associated with policy incompetence, thereby ensuring a more favourable regulatory environment for energy initiatives. Our analysis also emphasises the negative impact of state interference in market operations, suggesting that Central European businesses should advocate for market transparency and fair competition. By minimising state intervention, companies can create a more conducive environment for innovation and investment in sustainable energy solutions. This approach enhances energy security and fosters a competitive marketplace that can drive economic growth. In addition, the findings indicate that proactive measures, such as infrastructure upgrades and maintenance, are essential for mitigating risks to energy supply reliability. Central European businesses should prioritise investments in resilient energy infrastructure to ensure consistent energy availability. This includes adopting advanced technologies and practices that enhance the efficiency and reliability of energy systems, thereby reducing vulnerability to disruptions.

Another critical aspect emphasised by our analysis is workforce development. Central European businesses must implement strategies that promote workforce resilience and expertise in the energy sector. This can be achieved through targeted training programmes, partnerships with educational institutions and initiatives that enhance the attractiveness of careers in the energy field. A skilled workforce is vital for navigating the complexities of energy security and driving innovation in sustainable energy practices.

The wide range of indicators and threats can often make expert assessments of the impact of threats on Central European enterprises difficult or impractical. Incorporating expert opinions into determining the overall index of energy security may dilute the essence of the multidimensional concept and undermine the credibility of economic and mathematical models. Given the need to strengthen a country's capability to address a widening spectrum of threats and their complex impact on energy security, there is a need to reevaluate the methods used for analysing matters in this domain and adapt approaches for assessing energy security levels and threats within the Central European business context.

The suggested methodology for adaptive response to threats in the energy sector encompasses several distinctive features: (i) *Availability of a mathematical model*: The methodology relies on a mathematical model of the research object, enabling modelling and quantitative assessment of the influence of threats on energy security levels. (ii) *Systematic approach*: The methodology employs a systematic approach to describe energy security, which leads to an expanded collection of indicators adaptable to various aspects of energy security analysis, specifically the components of the integral index. (iii) *Modern assessment* *methodology*: The methodology employs modern integral assessment methods, including a multiplicative structure of the integral index, a modified normalisation method and the use of the sliding matrix method to determine dynamic weighting coefficients. (iv) *Scientific basis for safety gradations*: Safety gradations, including critical, threshold and optimal standards of safety indicators, are defined and derived from scientific reasoning. The idea of an extended homeostatic plateau and regions of positive, neutral and negative feedback are related to the quantity of safety gradations. Using the extended *t*-criterion method, formalised definitions of bifurcation points and probability density functions for normal, lognormal and exponential distributions are developed and quantitative criteria of the safety spectrum are created. (v) *Threat assessment:* First, threats are identified using the criterion of deviation from the sustainable development point; then, threats are evaluated using the normalised values of integral index components [0, 1] to determine their relevance. This approach allows a continuous scale of threat assessment, avoiding the coarsening of expert judgments commonly encountered in existing risk analysis approaches. (vi) *Calculation of threat impacts*: The methodology includes the mathematical calculation of the impact critical indicators and of expert-defined threats on components and, through the mathematical model of integral convolution, on the integral index of energy security. (vii) *Adaptation mechanism*: The methodology provides a mechanism for adapting the research object to the consequences of threat impacts. It uses modern strategy techniques, such as scientific and strategic foresighting, based on the idea that the course of events in the future will determine the course of events in the future. This makes it possible to create a trajectory for sustainable development for the integral index components of the research object. (viii) *Formalised breakdown of threats:* Using the mathematical model and adaptive regulatory techniques, threats are formally converted into indicators by means of decomposition of altered components and the integral index. By combining indicator values that guarantee the altered dynamics of components under the influence of both internal and external dangers, the technique resolves the inverse problem.

The methodologies employed to enhance security in sustainable energy systems in Central Europe must be adaptable, participatory and data-driven. The unique challenges of geopolitical instability, energy dependency, regulatory frameworks and public sentiment necessitate a multifaceted approach that incorporates stakeholder engagement, adaptive management, scenario planning, integrated resource planning, technology assessment, policy analysis and data-driven decision making. By justifying these methodologies in relation to the Central European context, businesses can develop effective strategies that not only enhance energy security but also contribute to sustainable development and resilience in the region.

It should be noted that, while the proposed methodology for enhancing energy security offers a comprehensive and adaptive framework, several potential limitations and assumptions could affect the findings. One significant limitation is the reliance on expert assessments, which, despite being informed by specialists, may still introduce subjectivity and bias into the evaluation process. The accuracy of the threat assessments and the subsequent calculations of their impacts on energy security levels depend heavily on the quality and reliability of the expert opinions gathered. Additionally, the mathematical model assumptions regarding the relationships between indicators and their weights may not fully capture the complexities of real-world dynamics, particularly in a rapidly evolving energy landscape influenced by geopolitical factors and technological advancements.

If alternative methodologies were employed, such as purely quantitative approaches that rely on historical data and statistical analyses without expert input, the outcomes might differ significantly. For instance, a data-driven approach could yield more objective results but may overlook nuanced insights that experts provide regarding emerging threats or contextual factors. Conversely, a purely qualitative approach might emphasise expert judgment but could lack the rigour and precision of quantitative assessments, leading to less reliable conclusions. Ultimately, the choice of methodology can shape the findings and recommendations, showing the importance of carefully considering the strengths and weaknesses of each approach in the context of energy security strategy development.

Conclusion

This study contributes to the existing body of knowledge by addressing the critical intersection of energy security and sustainable development within the context of Central European businesses. It highlights the need for adaptive methodologies that account for the dynamic nature of energy security, filling a research gap in the literature.

The use of an advanced methodology in developing energy security strategies, assessing current and future security levels and evaluating threat impacts is crucial for steering businesses towards sustainable development. This approach emphasises adaptability, enabling businesses to adjust key indices, components and indicators to effectively address threats and promote sustainable growth. The methodology prioritises the use of tools to determine the necessary changes to security components and indicators to align with evolving threats, rather than solely relying on expert assessments for accuracy. Through a continuous process of surveys and evaluations, the methodology offers an increasingly precise assessment of energy security measures over time.

By aligning the mathematical model with the strategic goals of state policies, this methodology can be effectively employed within the public administration system to support evidence-based decision making and assess the effectiveness of managerial choices. This enables a thorough assessment of the influence of threats and managerial decisions on the attainment of precise strategic objectives. Ultimately, by using this methodology, Central European businesses can formulate a comprehensive set of managerial decisions to mitigate threats and reinforce various components of their energy security strategy. This forms the foundation for establishing a structured threat response plan, culminating in the creation of a unified document known as the country's Energy Sustainability Plan, which can be implemented at local, regional and national levels.

Still, several areas warrant further exploration and testing to validate its effectiveness across different contexts. Future research could focus on cross-regional testing, where the methodology is implemented in diverse geographical regions, particularly in Eastern Europe, the Balkans or even in Western European countries. Each region has unique energy dynamics, regulatory environments and socio-economic conditions that may influence the applicability of the methodology. Comparative studies could reveal best practices and highlight regional variations in energy security threats, thereby refining the methodology for broader applicability. Also, sector-specific applications of the methodology could uncover vulnerabilities and resilience strategies unique to various industries, such as manufacturing, transportation and agriculture. Each sector has distinct energy consumption patterns and risk profiles, necessitating tailored approaches within the overarching framework. Longitudinal studies would also be beneficial, as they could evaluate the effectiveness of the methodology over time, providing insights into its robustness and adaptability in the face of evolving threat. By tracking energy security indicators and the impacts of implemented strategies, researchers could evaluate the long-term sustainability of the proposed solutions and identify areas for continuous improvement. Moreover, future research could explore how emerging technologies—such as smart grids, blockchain and artificial intelligence—can be integrated into the methodology. These technologies have the potential to enhance data collection, improve real-time monitoring of energy security indicators and facilitate more dynamic responses to threats. Investigating the interplay between technological advancements and the adaptive response methodology could yield innovative solutions for enhancing energy security.

Understanding the social dimensions of energy security is also crucial for developing comprehensive strategies. Future research could focus on stakeholder engagement processes, examining how different groups—such as local communities, businesses and policymakers—perceive energy security threats and their willingness to adopt proposed measures. This research could inform more inclusive policy frameworks that consider the perspectives and needs of all stakeholders involved.

To effectively implement our findings and influence policy changes, businesses and policymakers can take several actionable steps. First, businesses should consider integrating the adaptive response methodology into their strategic planning processes. This involves conducting regular assessments of energy security threats and utilising both quantitative and qualitative data to inform decision making. By establishing a systematic approach to monitoring and responding to energy security risks, businesses can enhance their resilience and sustainability.

Policymakers should foster collaboration between businesses, government agencies and research institutions to create a unified approach to energy security. Establishing public-private partnerships can facilitate knowledge sharing, resource allocation and joint initiatives aimed at enhancing energy security across sectors. Investing in capacity building through training programmes and workshops can equip businesses with the skills and knowledge necessary to implement the adaptive response methodology effectively. This effort should focus on data analysis, risk assessment and strategic planning, enabling businesses to navigate the complexities of energy security more adeptly. Furthermore, policymakers can introduce incentives for businesses that adopt sustainable energy practices and demonstrate resilience to energy security threats. This could include tax breaks, grants or subsidies for investments in renewable energy technologies, energy efficiency improvements and innovative solutions that align with the adaptive response methodology. Establishing regulatory frameworks that support the implementation of the methodology is also essential. Governments can create standards for energy security assessments, mandate regular reporting on energy security indicators and establish guidelines for businesses to follow in their strategic planning processes.

Finally, promoting research and innovation in energy security is crucial for continuous improvement. Policymakers can allocate funding for research initiatives that explore new technologies, methodologies and best practices in energy security, fostering a culture of innovation that benefits both businesses and society as a whole. Thus, by focusing on these areas for future research and implementing the findings through targeted actions and policy changes, businesses and policymakers can significantly enhance energy security in Central Europe. This proactive approach will strengthen the resilience of individual businesses and contribute to the overall sustainability and stability of the region's energy systems.

The practical recommendations derived from this study serve as a guide for businesses seeking to enhance their energy resilience and sustainability. By emphasising the importance of collaboration, investment in renewable energy and the adoption of data-driven strategies, the present study encourages a proactive approach to energy management that aligns with broader national and global sustainability goals.

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Appendix 1: Methodological overview of energy security assessment techniques

A thorough description of the calculations (1) – (36) and their corresponding interpretations is provided by Kharazishvili et al. (2024, pp. 1802-1804). The values for the energy security indicators presented in Table 1 were derived from a combination of official information sources (28), model calculations (7) and expert assessments (13). The expert method was employed to derive indicators 14, 34, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46 and 47, which could not be computed using official data (Kharazishvili et al., 2024, pp. 1802-1804).

This article outlines the comprehensive methodology used to assess energy security indicators for Ukraine, detailing the data sources, models and calculations employed in the study. Below is a summary of the key components.

Data collection and sources. The data for the study were gathered from a variety of official sources, expert assessments and model calculations. The indicators were categorised into different components of energy security, each with specific data sources:

a) Official sources: These include government statistics and reports from the State Statistics Service of Ukraine (Ukrstat) and the International Energy Agency (IEA). Data on energy consumption, emissions and energy resource shares were sourced from specific URLs provided in the work by Kharazishvili et al. (2024, pp. 1802-1804).

b) Model calculations: Certain indicators were derived from mathematical models, such as the aggregate supply model, which is part of the Alpha general economic equilibrium model. This approach allows a more nuanced understanding of the relationships between various economic factors and energy security.

c) Expert assessments: Some indicators that could not be calculated using official data were assessed through expert opinions, ensuring a comprehensive view of the energy security landscape.

Indicators and their definitions. The appendix lists various indicators used in the analysis, categorised into internal and external threats to energy security. Each indicator is defined with a specific focus, such as:

a) Internal threats: These include factors such as policymaking incompetence, energy poverty and the degradation of energy systems. Each indicator is linked to a specific data source, ensuring transparency and traceability.

b) External threats: These encompass risks such as military operations, cyberattacks and external influences on policymaking. The average evaluations of these threats are calculated to assess their impact on the overall energy security index.

Model calculations. The methodology incorporates model calculations to derive certain indicators, such as:

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a) Investment levels: The level of investment in the fuel and energy complex is calculated based on capital investments relative to output, considering factors such as gross domestic product (GDP) and intermediate consumption.

b) Shadow economy indicators: The study assesses the shadowing of the fuel and energy complex, which reflects the impact of the informal economy on energy security.

Normalisation techniques are applied to ensure that the data are comparable across different indicators. This process involves adjusting the values of indicators to a common scale, allowing meaningful comparisons and aggregations. For instance, energy consumption per capita may be normalised against GDP to assess efficiency.

Dynamic weighting calculations are employed to assign appropriate weights to different indicators based on their relative importance to energy security. This approach allows a more flexible and responsive assessment, reflecting changes in the energy landscape over time.

Threshold value determinations. Threshold values are established for various indicators to identify critical levels of energy security. These thresholds help in determining when an indicator falls below a critical value, signalling potential risks to energy security. For example, a certain level of energy poverty may be deemed unacceptable, prompting policy interventions.

Practical application of methodology. The methodology outlined in Appendix 1 can be applied in practice by:

a) Conducting regular assessments: By utilising the defined indicators and data sources, policymakers can regularly assess the state of energy security in Ukraine and identify emerging threats.

b) Informed decision making: The insights gained from the analysis can guide strategic decisions regarding investments, policy reforms and crisis management in the energy sector.

Engaging stakeholders: The expert assessments and model calculations can facilitate discussions among stakeholders, including government agencies, industry representatives and civil society, fostering a collaborative approach to enhancing energy security.

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