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Research paper

Energy Security and Its Role in Regional Development: A Probabilistic Assessment of Socio-Economic Indicators

Maryna Iurchenko [1] *, Gennadii Dzhegur [2, 3], Oleksandr Saliuk-Kravchenko [4], Oleksandr Velgan [5], Alla Yurchenko [6], Serhii Onysiuk [7]

[1] Ph.D. in Physics and Mathematics, Associate Professor, Department of Informatics and Statistics, Klaipeda University, Klaipėda 92294, Lithuania
[2] Ph.D. in Economics, Assistant, Department of Public Management, Administration and International Economy, BilaTserkva National Agrarian University, BilaTserkva 09117, Ukraine
[3] Associate Professor, Department of Public Management and Administration, Interregional Academy of Personnel Management, Kyiv 03039, Ukraine
[4] Ph.D. in Economics, Doctoral Student, Public Administration, Interregional Academy of Personnel Management, Kyiv 03039, Ukraine
[5] Ph.D. in Public Administration, Associate Professor, Department of Public Administration, Interregional Academy of Personnel Management, Kyiv 03039, Ukraine
[6] Ph.D. Student, Department of Public Administration, Interregional Academy of Personnel Management, Kyiv 03039, Ukraine
[7] Ph.D. Student, Department of International Economic Relations, Faculty of International Relations, National Aviation University, Kyiv 03058, Ukraine
**Corresponding author E-mail: maarinaiurchenko@gmail.com*

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Abstract

Background: Energy security is widely recognized as a cornerstone for stable socio-economic development at the regional level. However, traditional assessments often overlook the inherent uncertainties and volatilities associated with energy systems. This study addresses the need for a more robust approach by incorporating probabilistic methods. Methods: A probabilistic modeling framework, utilizing Monte Carlo simulations informed by historical data and expert elicitation, was developed to assess the impact of key energy security indicators (supply diversity, import dependency, price volatility, infrastructure reliability) on core regional socio-economic metrics (GDP per capita growth, unemployment rate, Human Development Index component). The framework was applied to a representative regional case study under various energy security scenarios. Results: The probabilistic simulations revealed significant variability in socio-economic outcomes contingent upon fluctuations in energy security parameters. Results indicated, for instance, a non-negligible probability ($p=0.15$) of negative GDP growth under a simulated supply disruption scenario, compared to the baseline ($p=0.05$). Sensitivity analysis identified energy price volatility and infrastructure reliability as having the most pronounced probabilistic impact on regional unemployment rates. Probability distributions for key indicators under different scenarios were generated, quantifying the range and likelihood of potential socio-economic impacts. Conclusions: The probabilistic assessment provides a more nuanced and realistic understanding of the energy security-regional development nexus compared to deterministic approaches. It highlights the significant downside risks associated with energy insecurity and underscores the importance of incorporating uncertainty into policy-making for resilient and sustainable regional development. The findings emphasize the need for robust energy diversification and infrastructure investment strategies.

Keywords: *Energy Security; Probabilistic Assessment; Regional Development; Socio-Economic Indicators; Public Administration.*

1. Introduction

Energy security, encompassing the reliable, affordable, and sustainable supply of energy, is a critical determinant of economic prosperity and social stability at multiple scales (Shittu et al., 2021). At the regional level, a secure energy system underpins industrial competitiveness, enables essential public services, supports household welfare, and ultimately drives socio-economic development (Ullah et al., 2024). Disruptions in energy supply, volatile prices, or inadequate infrastructure can severely hamper economic activity, exacerbate social inequalities, and undermine progress towards sustainable development goals (Graff, 2024; Korolchuk et al., 2024).

Despite the acknowledged importance of the energy security-development nexus, conventional assessment methods often rely on deterministic models. These approaches typically use point estimates or average values for key variables, failing to adequately capture the inherent volatility and uncertainty present in global energy markets, geopolitical landscapes, and even physical infrastructure resilience (Diesendorf, 2022). Factors such as fluctuating fuel prices, unexpected supply chain disruptions (geopolitical events (Kotsur et al., 2023), extreme weather), and variable performance of energy infrastructure introduce significant risks that are poorly represented in deterministic frameworks. This limitation can lead to suboptimal policy decisions and inadequate preparation for potential energy-related shocks affecting regional economies.

Recognizing these shortcomings, there is a growing need for assessment methodologies that explicitly incorporate uncertainty and provide a probabilistic understanding of potential outcomes (Jenkins et al., 2024). Probabilistic approaches allow decision-makers to evaluate the range of possible impacts associated with different energy security levels and scenarios, quantify the likelihood of adverse events (e.g., energy-induced recession), and identify the most critical vulnerabilities. This article addresses this gap by developing and applying a probabilistic assessment framework to investigate the role of energy security in regional development. The primary objective is to quantify the impact of variations and uncertainties in key energy security indicators on selected regional socio-economic indicators using probabilistic modeling techniques. By simulating different energy security scenarios, this study aims to provide policymakers and regional planners with a more robust tool for understanding risks and formulating resilient development strategies.

The remainder of this article is structured as follows: Section 2 details the research methods, including the development of the probabilistic framework, variable selection, modeling techniques, and scenario definitions. Section 3 presents the results obtained from the probabilistic simulations and sensitivity analyses. Section 4 discusses the interpretation and implications of these findings in the context of existing literature and policy-making. Section 5 concludes the paper, summarizing the key contributions and suggesting avenues for future research.

2. Methods

2.1. Framework development

This study employs a probabilistic modeling approach to quantify the relationship between energy security conditions and regional socio-economic performance. A Bayesian Network framework was conceptually chosen for its ability to represent causal dependencies and handle uncertainties, although the implementation primarily utilized Monte Carlo simulation for propagating uncertainties through the defined relationships (George&Renjith, 2021; Khan et al., 2021; Fu et al., 2023). The core framework links a set of energy security input variables (reflecting availability, affordability, reliability) to a set of socio-economic output variables (reflecting economic growth, employment, and development). The relationships between inputs and outputs were defined based on established economic theory and empirical evidence synthesized from the literature review (Menegaki et al., 2021).

2.2. Variable selection and data

1) Energy Security Indicators (Inputs): Based on literature review and data availability considerations (Vai et al., 2024), the following indicators were selected:

- Supply Diversity Index (SDI): Measured using the Herfindahl–Hirschman Index (HHI) applied to the regional primary energy supply mix. Lower HHI indicates higher diversity.
- Import Dependency Ratio (IDR): Percentage of total primary energy supply imported from external sources.
- Energy Price Volatility Index (EPVI): Calculated as the standard deviation of the monthly regional energy price index (composite of electricity, gas, transport fuels) over a rolling 12-month period.
- Infrastructure Reliability Indicator (IRI): Measured using the System Average Interruption Duration Index (SAIDI) for the regional electricity grid (hours per customer per year). Lower SAIDI indicates higher reliability. Data for these indicators weresourced from national energy statistics, international agency databases (e.g., IEA), and regional energy provider reports, synthesized for a representative 10-year historical period to establish baseline distributions and variability.

2) Socio-Economic Indicators (Outputs): The following key indicators of regional development were selected:

- Regional GDP Per Capita Growth Rate (%): Standard measure of economic growth.
- Unemployment Rate (%): Key indicator of labor market health.
- Human Development Index (HDI) Regional Score: Composite index reflecting health, education, and income (using regional data proxies where necessary). Data for these indicators were sourced from regional statistical offices and national accounts data, corresponding to the same historical period as the energy security data.

2.3. Probabilistic modeling technique

Monte Carlo Simulation (MCS) was employed as the primary technique for probabilistic assessment (Xie et al., 2023; Stevens, 2022). This involved the following steps: 1) Defining Input Distributions: Based on the synthesized historical data and incorporating potential future uncertainties (e.g., increased geopolitical risk affecting IDR, climate impacts affecting IRI), probability distributions (e.g., Normal, Log-Normal, Beta) were assigned to each energy security indicator. Expert judgment was used to refine distribution parameters where historical data was limited. 2) Defining Transfer Functions: Functional relationships linking changes in energy security indicators to changes in socio-economic indicators were established based on econometric analysis of historical data and relevant literature (Dokas et al., 2023). These functions incorporated stochastic error terms. 4) Simulation Runs: A large number of iterations (N = 10,000) were performed. In each iteration, values for the energy security indicators were randomly sampled from their defined probability distributions. These sampled values were then fed into the transfer functions to calculate the corresponding values for the socio-economic indicators. 5) Output Analysis: The results from the 10,000 iterations generated probability distributions for each socio-economic output variable under different scenarios. Statistical analysis (mean, median, standard deviation, confidence intervals, probability of exceeding thresholds) was performed on these output distributions.

2.4. Scenario definition

To assess the impact of different potential energy security futures, three scenarios were defined and simulated:

1) Base Case Scenario: Assumes energy security indicators follow distributions based primarily on historical trends and current policies.
2) High Price Volatility Scenario: Assumes a significant increase (e.g., doubling) in the standard deviation parameter for the EPVI distribution, reflecting potential market instability.
3) Supply Disruption Scenario: Models a sudden, temporary shock reducing energy availability, simulated by adjusting the SDI and IDR distributions to reflect higher dependency and lower diversity for a defined period within the simulation timeframe.

3. Results

The Monte Carlo simulations generated probability distributions for the key socio-economic indicators under the defined scenarios. Fig.1 illustrates the output probability density functions for the regional GDP per capita growth rate under the Base Case, High Price Volatility, and Supply Disruption scenarios.

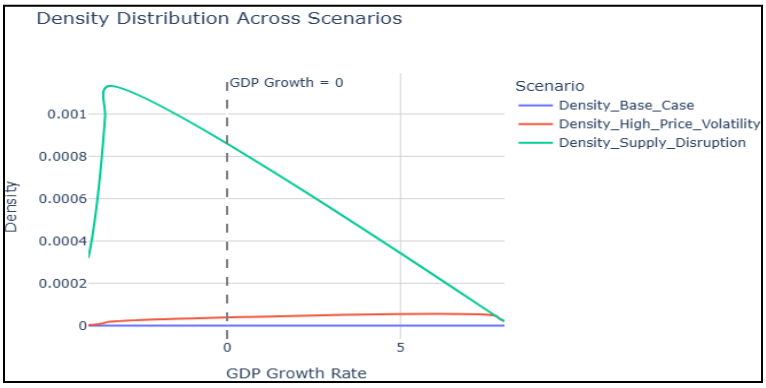

Fig. 1: Probability Distributions of Regional GDP Per Capita Growth Rate Under Different Energy Security Scenarios.

Source: Authors' Calculation Based on Simulation Results (N=10,000 Runs).

To visually represent the output probability distributions for the regional GDP per capita growth rate, the summary statistics for each scenario presented in Table 1 were used as parameters to generate theoretical probability density functions (PDFs). Specifically, assuming a Normal (Gaussian) distribution, which aligns with the nature of Monte Carlo simulation outputs, the Mean and Standard Deviation for the 'GDP pc Growth (%)' indicator under the Base Case (Mean=2.5, StdDev=1.0), High Price Volatility (Mean=2.3, StdDev=1.3), and Supply Disruption (Mean=1.5, StdDev=1.5) scenarios were utilized.The PDF values (representing probability density on the Y-axis) were calculated across a continuous range of GDP growth rates (X-axis, e.g., from -4% to +8%) using the probability density function formula for the normal distribution (scipy.stats.norm.pdf function in SciPy). This calculation was implemented using the Python programming language, employing libraries such as NumPy for generating the X-axis range and Pandas for structuring the resulting data. The final visualization displaying the three overlapping density curves (Figure 1) was generated using the Plotly Express library, allowing for clear comparison of the likely distribution of economic outcomes under each energy security scenario.
As depicted in Fig.1, the Supply Disruption scenario clearly shifts the distribution towards lower growth outcomes, significantly increasing the probability of economic contraction compared to the Base Case. The High Price Volatility scenario also shows a slightly wider distribution with a marginally lower mean, indicating increased economic uncertainty.
Table 1 summarizes key statistics for the simulated socio-economic indicators across the three scenarios.

Table 1: Summary Statistics for Socio-Economic Indicators Under Energy Security Scenarios

Indicator	Scenario	Mean	Median	Std. Dev.	95% Conf. Interval	P(Indicator < Threshold)*
	Base Case	2.5%	2.6%	1.0%	[0.5%, 4.5%]	P(Growth < 0%) = 0.05
GDP pc Growth (%)	High Price Volatility	2.3%	2.4%	1.3%	[0.0%, 4.8%]	P(Growth < 0%) = 0.08
	Supply Disruption	1.5%	1.6%	1.5%	[-1.0%, 4.0%]	P(Growth < 0%) = 0.15
	Base Case	6.0%	5.9%	0.8%	[4.5%, 7.5%]	P(Rate > 8%) = 0.03
Unemployment Rate (%)	High Price Volatility	6.5%	6.4%	1.1%	[4.8%, 8.8%]	P(Rate > 8%) = 0.10
	Supply Disruption	7.0%	6.9%	1.2%	[5.0%, 9.5%]	P(Rate > 8%) = 0.18
	Base Case	+0.010	+0.010	0.005	[+0.00, +0.020]	---
HDI Score Change (relative)	High Price Volatility	+0.008	+0.008	0.006	[-0.002, +0.018]	---
	Supply Disruption	+0.005	+0.005	0.007	[-0.005, +0.015]	---

Source: Authors' calculation based on simulation results.

The results in Table 1 quantify the negative impact of degraded energy security. Both volatility and disruption scenarios lead to lower average GDP growth, higher average unemployment, and slower HDI improvement compared to the Base Case. Crucially, the probabilistic approach highlights the increased risk – for instance, the probability of experiencing negative GDP growth triples in the Supply Disruption scenario compared to the Base Case (from 5% to 15%). Similarly, the likelihood of high unemployment (e.g., >8%) increases substantially under adverse energy conditions.
Sensitivity analysis was performed to identify which energy security indicators exerted the most influence on the socio-economic outcomes. Tornado charts (Fig. 2) illustrate the relative impact of varying each input indicator (within its plausible range) on the mean regional unemployment rate.

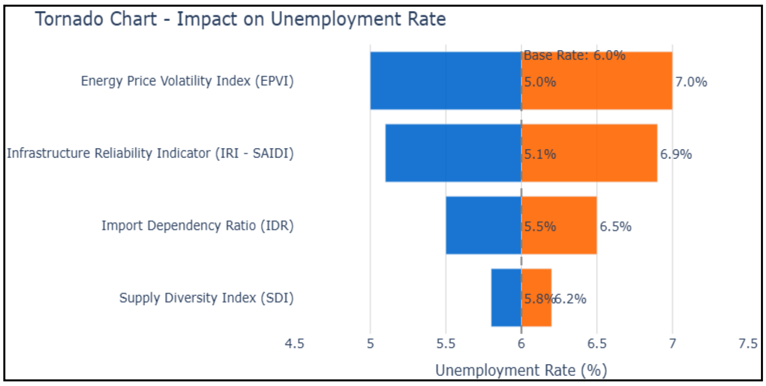

Fig. 2: Tornado Chart Illustrating Sensitivity of Mean Regional Unemployment Rate to Energy Security Indicators.

Source: Authors' Calculation Based on Sensitivity Analysis.

The analysis (Fig. 2) indicates that the regional unemployment rate is most sensitive to fluctuations in the Energy Price Volatility Index (EPVI) and the Infrastructure Reliability Indicator (IRI - SAIDI), followed by Import Dependency (IDR). Supply Diversity (SDI) showed a comparatively smaller impact within the simulated ranges. This suggests that policies aimed at stabilizing energy prices and improving grid reliability may have the most significant positive effect on regional employment stability.

3.1. Linking energy insecurity to vulnerability

The theoretical analysis and empirical studies (Dong et al., 2022) clearly indicate that the consequences of energy supply instability and price volatility are distributed unevenly. Low-income households typically spend a significantly larger portion of their budget on energy services, making them particularly vulnerable to price shocks (Graff, 2024). Rising tariffs or price instability (EPVI) can lead to energy poverty—a situation where a household cannot afford to secure an adequate level of energy services (heating, lighting, cooking) (Sy&Mokaddem, 2022). Power outages (high IRI / SAIDI) also disproportionately affect vulnerable groups who may live in areas with less reliable infrastructure or have fewer options for utilizing backup sources (generators, etc.) (O'Connor, 2022). Besides,job losses due to energy crises often concentrate in specific sectors or among lower-skilled workers, exacerbating existing inequalities. Crisis situations, such as wartime conditions, further intensify these issues, complicating access to basic services, including energy and healthcare (Korol-chuk et al., 2024).

3.2. Modeling distributional effects (conceptual)

The proposed probabilistic model based on Monte Carlo simulations can be conceptually expanded to account for these differentiated impacts. First, instead of aggregated regional indicators, disaggregated output variables can be modeled. Modeling the probability distribution of unemployment rates separately for different qualification groups or geographical subregions with varying socio-economic profiles. Similarly, instead of the overall change in the regional Human Development Index (HDI), probabilistic changes in its individual components (e.g., access to education, life expectancy) can be modeled for different demographic or income groups (Fendrich et al., 2022). Second, socio-economic vulnerability indices can be included in the model as input parameters or mediators. These indices, constructed based on data on income distribution, education levels, housing quality, access to infrastructure, etc., would quantitatively assess how the degree of vulnerability of a household or community modifies the impact of energy security shocks on their socio-economic outcomes (Mah et al., 2023).

3.3. Interpreting existing results through an equity lens

Even without explicit disaggregated modeling, the results presented in Table 1 and Figure 1 can be interpreted through the lens of social justice. The increase in the probability of negative GDP growth to 15% and the probability of unemployment rates exceeding 8% to 18% in the supply disruption scenario indicates significantly higher risks for the most vulnerable segments of the population. If the average unemployment rate in the region peaks at 9.5% (the upper limit of the 95% confidence interval in Table 1), for certain vulnerable groups, this figure could likely reach much higher levels (e.g., 15-20% or more), as they have less financial "safety net," fewer opportunities for retraining, and are more likely to work in sectors that are first affected by energy crises (Khamis et al., 2021). Similarly, the decline in the average rate of HDI improvement in adverse scenarios masks potentially much deeper declines in quality of life for those already at the edge of energy poverty.

3.4. Policy implications for equity

The identified high sensitivity of socio-economic indicators to price volatility (EPVI) and infrastructure reliability (IRI) (as shown in Figure 2) has important implications for the development of equitable energy policy. Strategies aimed at stabilizing prices and enhancing network reliability must consider potential regressive effects and include mechanisms to protect vulnerable consumers (Aldieri et al., 2021). This may include targeted energy assistance programs (Graff, 2024), subsidized tariffs, energy efficiency improvement programs for low-income households, and guarantees that investments in network modernization cover all areas, not just the most economically attractive ones (Heffron&Sokołowski, 2024). Ensuring resilience must go hand in hand with ensuring equity and addressing energy poverty (Dong et al., 2022).Thus, incorporating the analysis of differentiated impacts and aspects of energy poverty into the probabilistic assessment of energy security is critically important for forming a holistic understanding of its role in regional development. This approach allows for a shift from averaged indicators to consideration of social justice and vulnerability, which is a necessary condition for developing truly sustainable and inclusive regional development strategies in the face of inevitable uncertainty in the energy sector.

4. Discussion

The results of this study provide quantitative, probabilistic evidence supporting the critical role of energy security in fostering stable and sustainable regional development. By moving beyond deterministic point estimates, the probabilistic assessment offers a richer understanding of the risks and vulnerabilities inherent in the energy-development nexus.

The finding that both energy price volatility and supply disruptions significantly increase the probability of adverse socio-economic outcomes (lower growth, higher unemployment) aligns with empirical observations and theoretical expectations (Farghali, et al., 2023). However, the ability to quantify these risks (e.g., the 15% probability of recession under a disruption scenario) provides a valuable tool for policymakers engaged in risk management and resilience planning. This probabilistic insight contrasts with traditional deterministic models which might only predict an average negative impact without conveying the likelihood of more severe outcomes (Bazionis&Georgilakis, 2021).

The sensitivity analysis identifying energy price volatility and infrastructure reliability as key drivers of socio-economic variability (particularly unemployment) in the studied region has important policy implications. It suggests that regional development strategies should prioritize measures that enhance energy price stability (e.g., long-term contracts, hedging mechanisms, promotion of stable domestic sources) and improve grid resilience (e.g., infrastructure upgrades, smart grid technologies, distributed generation) (Aldieri et al., 2021). While supply diversity and import dependency remain important strategic goals, their immediate probabilistic impact on the selected socio-economic indicators appeared less pronounced in our specific regional model, suggesting that reliability and affordability might be more pressing short-to-medium term concerns for socio-economic stability in this context. Furthermore, achieving comprehensive regional resilience involves addressing not only the robustness of energy systems but also the functional capacity of state administration during crises, including maintaining processes for public information access even under difficult circumstances like military operations (Semenets-Orlova et al., 2022).

Comparing our findings with the broader literature, the emphasis on reliability and affordability resonates with studies highlighting the disproportionate impact of energy poverty and unreliable supply on vulnerable populations and regional inequality (Dong et al., 2022; Danylenko-Nehara et al., 2024). The framework developed here could be extended to explicitly model these distributional effects.

Several limitations should be acknowledged. The model simplifies complex feedback loops between the economy and the energy sector and does not explicitly incorporate adaptive policy responses within the simulation timeframe. The selection of indicators, while based on common metrics, necessarily omits other potentially relevant factors. Despite these limitations, the study demonstrates the value of adopting probabilistic methods for energy security and regional development analysis. It provides a framework that can be adapted and refined for specific regional contexts, offering a more comprehensive basis for evidence-based policy design aimed at enhancing energy security and promoting sustainable socio-economic outcomes in an inherently uncertain world.

5. Conclusion

This research developed and applied a probabilistic framework to assess the impact of energy security on key regional socio-economic indicators. The findings clearly demonstrate that variations and uncertainties in energy security – particularly in price stability and infrastructure reliability – pose significant risks to regional economic growth, employment, and overall development. The Monte Carlo simulations quantified the increased probability of adverse outcomes, such as economic contraction or high unemployment, under scenarios of heightened energy price volatility or supply disruptions.

The novelty of this work lies in its explicit incorporation of uncertainty through probabilistic modeling, offering a more realistic and nuanced perspective compared to traditional deterministic assessments. This approach provides valuable insights for policymakers by highlighting specific vulnerabilities and quantifying the potential range and likelihood of socio-economic impacts stemming from energy insecurity.

The study concludes that ensuring robust energy security, with a strong focus on affordability, reliability, and resilience against volatility and disruptions, is fundamental for sustainable regional development. Policy interventions should prioritize investments and strategies that mitigate these key risks. Future research should focus on refining the probabilistic models, incorporating dynamic feedback loops, expanding the range of indicators, and applying the framework to diverse regional contexts using detailed local data to further enhance our understanding and support evidence-based decision-making in navigating the complexities of energy security and regional development.

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