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ASSESSING ENERGY SECURITY AND SYSTEM RESILIENCE: EVIDENCE FROM THE GEORGIAN ENERGY SECTOR

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Abstract. In modern energy systems, energy security has become one of the key priorities, as it directly affects the stability of energy supply, economic sustainability and national security. This study aims to evaluate the level of energy security within the Georgian energy system, considering technological transformation and emerging systemic risks. This research takes a mixed-methods approach, combining systems analysis, multi-criteria decision analysis (MCDA), resilience-based assessment and scenario analysis. A composite Energy Security Evaluation (ESEC) index has been developed to assess the performance of the national energy system. This index incorporates three key aspects: technological and operational resilience, energy dependency and supply diversification, and systemic resilience. The indicators were normalised on a 0–100 scale and aggregated using a weighted composite model. The empirical results show that Georgia's overall energy security level reaches ESEC ≈ 67, indicating a moderately high level of energy security. However, the analysis reveals several structural vulnerabilities, particularly with regard to external energy dependency and supply diversification. A scenario-based assessment shows that digitalising the energy sector and implementing smart energy management technologies could significantly strengthen system resilience. The findings suggest that improving energy security in Georgia requires a focus on energy diversification, smart grid development and modernising digital infrastructure. The proposed analytical framework can also be used to evaluate the energy security of other emerging energy systems.

Keywords: energy security, systemic resilience, smart grid, energy diversification, Georgia.

JEL Classification: Q40, Q48, O13

1. Introduction

In the contemporary world, energy security has emerged as one of the most important determinants of national security, economic stability and social welfare. In modern academic and policy discussions, the concept of energy security encompasses more than just the physical availability of energy resources; it also includes dimensions such as supply reliability, price stability, infrastructure resilience, geopolitical risks, environmental sustainability and technological vulnerabilities. This multidimensional understanding of energy security is widely reflected in academic literature and policy frameworks (Winzer, 2012).

In recent years, the global energy sector has undergone a rapid technological transformation, driven by digitalisation. The integration of operational technologies (OT) and information technologies (IT), increased automation and data-driven decision-making processes have all served to significantly improve the efficiency and flexibility of energy systems. However, these developments have also introduced new systemic vulnerabilities, particularly with regard to cybersecurity risks and the complexity of technological infrastructures. Previous studies indicate that the resilience of modern energy infrastructure increasingly depends on cybersecurity architecture, data governance and institutional management mechanisms (Sovacool, 2011; Cherp & Jewell, 2015).

Energy systems often depend on outdated technological platforms and diverse digital ecosystems, which increases operational and technological risks (Kruyt et al., 2009). Supervisory Control and Data Acquisition (SCADA) systems play a crucial role in the management of critical energy infrastructure by enabling real-time monitoring, data collection and operational control of energy networks. Disruptions or failures

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within these systems can result in significant electricity supply interruptions and technological incidents in the energy system (Seturidze et al., 2023).

The issue of energy security is particularly important for Georgia due to its geopolitical location, its role in regional energy transit corridors and the ongoing modernisation of its national energy infrastructure. Given these circumstances, energy security has become a strategic national priority, necessitating scientifically sound analysis and innovative management strategies. An integrated research framework combining technological transformation, systemic resilience and energy governance is therefore necessary to support the evidence-based planning and development of the national energy system.

2. Literature Review

Energy security is increasingly being conceptualised as a multidimensional construct that goes beyond the mere physical availability of energy resources. It encompasses supply reliability, price stability, technological robustness, infrastructure resilience and vulnerability to geopolitical and climatic risks (Cherp & Jewell, 2015). Contemporary energy systems therefore require integrated assessment frameworks that synthesise technological, economic and systemic perspectives to provide a comprehensive understanding of the complex issues impacting national and regional energy security.

Recent advancements in digitalisation and smart grid technologies have fundamentally transformed the operational management of energy systems. The convergence of operational technologies (OT) and information technologies (IT) enables greater automation and continuous system monitoring, as well as data-driven decision-making. This substantially improves operational efficiency, flexibility and reliability (Zhang, Shahidehpour & Alabdulwahab, 2018; IEA, 2019). Nevertheless, these technological developments introduce new systemic vulnerabilities, particularly with regard to cybersecurity threats, complex interdependencies and potential operational failures (ENISA, 2021; NIST, 2018; NIST, 2020). Resilience-oriented frameworks emphasise the importance of having the capacity to adapt, redundancy and rapid recovery mechanisms in order to maintain stable energy provision in the face of both anticipated and unforeseen disturbances (Linkov & Trump, 2019; OECD, 2019).

Empirical studies of the Georgian energy system reveal its strengths and vulnerabilities in detail. Although the system exhibits relatively high operational and technological resilience, structural dependencies, particularly the reliance on hydropower and electricity imports during peak demand, create pronounced seasonal and geopolitical risks (Narmania et al., 2025b). These findings highlight the dual nature of energy security in Georgia, where robust infrastructure coexists with strategic vulnerabilities, necessitating targeted interventions in policy, investment and operational management.

Integrating these theoretical and empirical insights, it is clear that enhancing energy security in Georgia requires a multidimensional strategy that addresses structural vulnerabilities, operational efficiency and systemic adaptability. It is essential to diversify the national energy portfolio by developing alternative renewable sources, such as solar and wind power, alongside conventional generation in order to reduce hydrological and supply-side risks, improve reliability and strengthen overall system resilience (Cherp & Jewell, 2015; Narmania et al., 2025a).

The digital transformation of the energy sector is equally important. The deployment of advanced monitoring, automation and data-driven management systems, particularly through Smart Grid technologies, enables real-time system oversight, predictive maintenance and a rapid response to operational disturbances. This digitalisation improves flexibility and adaptability, and helps to proactively mitigate emerging risks (ENISA, 2021; IEA, 2019; Zhang et al., 2018; Narmania et al., 2025b).

Finally, it is necessary to enhance system resilience to ensure uninterrupted operation in the event of natural and man-made disruptions. Strengthening infrastructure, developing comprehensive crisis management protocols and building institutional resilience – including network redundancy, contingency planning and mechanisms to ensure uninterrupted operation– collectively enhance the resilience, reliability and operational efficiency of the national energy system (Linkov & Trump, 2019; OECD, 2019; Seturidze et al., 2023).

Taken together, diversification, digitalisation and systemic resilience form a comprehensive and mutually reinforcing strategic framework for ensuring sustainable energy security in Georgia. By simultaneously reducing external dependence, enhancing operational response capacity and supporting adaptive capacity, this framework provides a solid foundation for policy-making, attracting investment and implementing technological innovations in Georgia's energy sector.

3. Methodology

The study of energy security requires an interdisciplinary and multidimensional methodological framework because it encompasses technological, economic, institutional and security-related aspects. Contemporary research increasingly conceptualises energy systems as complex socio-technical systems whose evaluation cannot rely on a single analytical method. This study takes a mixed-methods approach, combining theoretical analysis, comparative research, systems modelling and analytical synthesis to allow for qualitative and quantitative assessment of the Georgian energy system.

Analytical Framework

The research methodology was designed to integrate three core analytical perspectives:

1. Systems approach. The national energy system is analysed as an integrated structure consisting of interconnected technological and institutional elements. This approach enables both individual components and their systemic interactions to be assessed, which is essential for evaluating complex infrastructure networks.

2. Interdisciplinary research perspective. The evaluation draws on theoretical insights from energy economics, technological innovation and public governance to provide a comprehensive understanding of the challenges associated with energy security.

3. Resilience-based analysis. The resilience of an energy system is evaluated based on its ability to withstand disruptions, adapt to disturbances and recover quickly from failures.

Analytical Methods

The study applies a combination of analytical methods:

– Theoretical analysis. A systematic review of the academic literature on energy security, technological transformation and emerging systemic risks was conducted to establish a conceptual foundation.

– Comparative analysis. Benchmarking the Georgian energy sector against international practices in the European Union, the United States and other energy organisations to identify best practices and context-specific insights.

– Case study approach. Examining the Georgian energy sector in detail enables an assessment of global energy security trends within a national context (Yin, 2018).

– Systemic risk analysis. An evaluation of the technological, operational and institutional risks affecting the energy system, including those relating to cybersecurity, operational reliability and infrastructure performance.

– Conceptual and quantitative modelling. The development of an integrated analytical framework for the measurable and reproducible assessment of energy security.

Practical Assessment and Composite Index

The practical element of the methodology connects theoretical knowledge with actionable insights to inform strategic and operational decision-making. Energy security was assessed along three key dimensions:

– Technological and operational resilience (T/O);

– Energy dependency and supply risk (D);

– Systemic resilience and recovery capacity (R).

Indicators were normalised using Min–Max scaling:

$$S_i = 100 \cdot \frac{x_i - \min(x)}{\max(x) - \min(x)} \text{(higher is better)} \quad (1)$$

$$S_i = 100 \cdot \frac{\max(x) - x_i}{\max(x) - \min(x)} \text{(lower is better)} \quad (2)$$

A composite Energy Security Evaluation (ESEC) index was then constructed:

$$ESEC = w_T \cdot T + w_D \cdot D + w_R \cdot R \quad (3)$$

$$w_T + w_D + w_R = 1 \quad (4)$$

Weights were determined using the Analytic Hierarchy Process (AHP), which combines expert judgement with qualitative and quantitative factors. Example weights are: $w_T = 0.39$, $w_D = 0.28$, $w_R = 0.33$. The index interpretation is as follows:

– 80–100: high energy security (resilient and protected system);

– 60–79: moderately high (targeted improvements required);

– 40–59: medium/risky (multiple vulnerabilities);

– 0–39: high vulnerability (systemic risk zone).

Data Sources

The empirical analysis is based on 2017–2024 energy sector data, including:

– National energy balance statistics (generation, consumption, import–export flows, generation structure).

– Grid reliability and performance indicators (outage statistics, network losses, restoration times).

– Cybersecurity and operational technology data (OT assets, segmentation, patching/backups, access management).

– International standards and assessment frameworks (ISO 31000, NIST CSF, ENISA energy infrastructure risk assessments).

Robustness and Sensitivity Analysis

To ensure methodological reliability, the ESEC index was subjected to a sensitivity analysis, during which the stability of the results was tested when the weighting coefficients varied within a range of ±20 per cent. The analysis showed that the composite index remained stable within a range of ±3 points, confirming the reliability of the methodology and the relative independence of the final assessment from any individual indicator. Data triangulation, reproducible calculation procedures and transparency in the selection of indicators mitigate methodological limitations such as data availability, the use of proxy indicators and the subjective determination of weighting coefficients.

4. Results and Discussion

The assessment of Georgia's energy system aimed to quantify the current level of energy security and analyse temporal trends from 2017 to 2025, establishing a basis for international benchmarking in the process. Energy security was evaluated across three core dimensions: Technological and Operational Resilience (T), Energy Dependence and Supply Risk (D), and Systemic Resilience (R). The indicators were normalised on a 0–100 scale and aggregated using weighted coefficients, which allowed for the cross-comparison of heterogeneous data. Seasonal fluctuations, cross-border dependencies and infrastructural heterogeneity were also taken into account to provide a comprehensive overview of the vulnerabilities of the system.

Energy System Structure and Consumption Trends

Hydropower accounts for 70–80% of Georgia's electricity generation (see Table 1). While this ensures low carbon intensity, it makes the system more vulnerable to changes in the water cycle. During dry years, reliance on thermal generation or imports increases, amplifying operational and geopolitical risks. In recent years, the proportion of thermal power has increased in order to balance the system and meet peak load requirements.

Table 1
Electricity generation structure in Georgia (%)

Year	Hydropower	Thermal power	Solar/wind power	Other
2017	79.9	19.4	0.8	6
2018	81.9	17.4	0.7	5
2019	75.3	24.0	0.7	5
2020	73.9	25.3	0.8	4
2021	80.5	18.8	0.7	4
2022	75.6	23.8	0.6	3
2023	75.5	23.9	0.6	2
2024	79.7	19.8	0.5	1
2025	79.4	20.0	0.6	1

Note: The percentages have been calculated on the basis of data on total energy production provided by ESCO. In the 'Solar/Wind Power' category of ESCO's balance sheet classification for these years, the Kartli Wind Power Plant and Solar Power Plants are grouped together.

Electricity consumption in Georgia demonstrated a consistent upward trend, rising from 11.9 TWh in 2017 to 14.3 TWh in 2025 (Table 2).

Seasonal imbalances, particularly during the winter heating period, put extra strain on the transmission and distribution networks (see Figure 1). Although high-voltage interconnections with neighbouring countries allow for electricity imports and exports, they also increase dependence on external factors. Winter imports can account for 10–15% of total consumption, which highlights the importance of energy dependence within the national system.

Table 2
Electricity consumption in Georgia (2017-2025)

Year	Consumption (TWh)	Annual growth (%)
2017	11.9	—
2018	12.6	6.1
2019	12.8	1.4
2020	12.2	-4.8
2021	13.8	13.1
2022	14.2	3.1
2023	13.1	-7.8
2024	13.9	6.0
2025	14.3	3.5

Note: Consumption uses ESCO's 'Supplied to the Consumers' row and is converted from million kWh to TWh. Annual growth is calculated from exact ESCO values.

Energy Security Component Analysis

Quantitative evaluation of energy security revealed differences across the three dimensions:

– Technological and Operational Resilience (T) reflects the technical reliability and operational efficiency of the energy system. This is assessed through network losses, the frequency and duration of outages, substation automation and operational monitoring. The average score of T=72 indicates relatively stable system functionality, with ongoing automation and SCADA deployment contributing positively (Table 3).

– The Energy Dependence (D) index captures generation diversification, seasonal import reliance and supply flexibility. A high proportion of hydropower generation makes a country more vulnerable during the winter months. An average score of D=58 shows that energy dependence limits overall energy security (see Table 4).

– Systemic Resilience (R) is a measure of a system's ability to withstand and recover from disruptions. It is based on factors such as restoration time, network redundancy, operational continuity mechanisms and crisis management preparedness. An R value of 70 indicates good adaptive capacity (see Table 5).

The composite energy security index (ESEC) integrates these dimensions:

$$ESEC = w_T T + w_D D + w_R R$$

Using the initial weights and Georgia's indicator values (T = 72, indicating strong operational performance; D = 58, indicating a primary weakness; and R = 70, indicating good resilience), the composite index is calculated as ESEC ≈ 67. This suggests that there is above-average energy security, but that there are structural vulnerabilities primarily associated with energy dependence (D = 58).

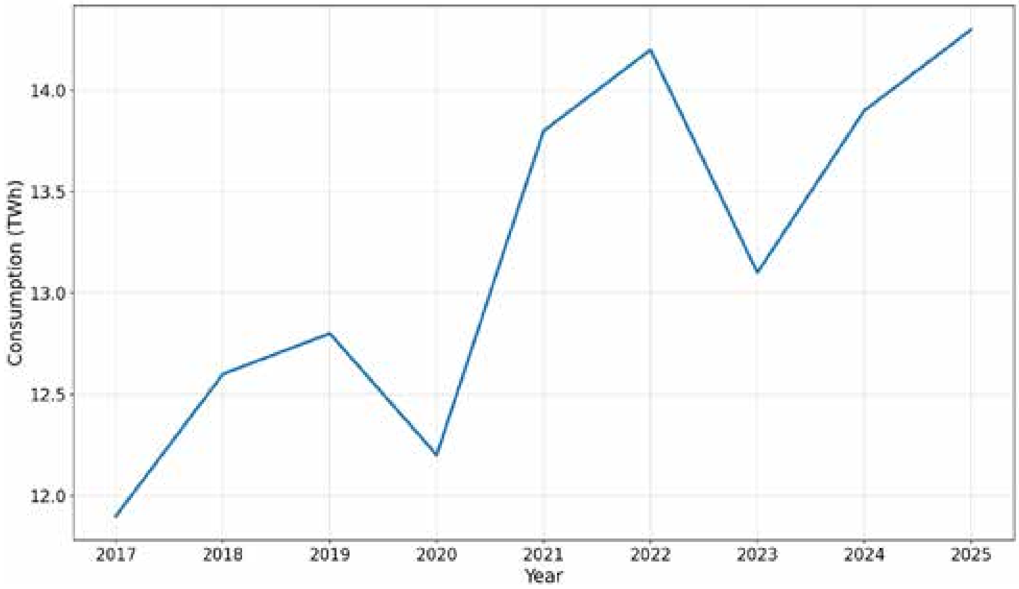

Figure 1. Electricity consumption growth trend (2017–2025)

Table 3
Evaluation of technological indicators

Indicator	Rating (0–100)
Network reliability	74
Technical losses	68
Level of automation	70
Operational monitoring	76

Source: compiled by the authors

Table 4
Energy dependence assessment

Indicator	Rating (0–100)
Generation diversification	55
Import dependence	60
Seasonal balance	58

Source: compiled by the authors

Table 5
Resilience indicators

Component	Score
Technology (T)	72
Dependence (D)	58
Resilience (R)	70

Source: compiled by the authors

International Benchmarking

A comparative analysis was conducted with selected countries that represent different energy system typologies and levels of development. While Georgia's technological component (T=72) aligns with regional averages, its systemic resilience is comparable to that of other developing energy systems. However, energy dependence remains the most significant area of difference compared to European countries with diversified and digitised energy systems (see Table 6).

Table 6
Comparison of energy security components by selected countries

Country	Selection factors	Indicators			Index
		T	D	R	
Georgia	Research Object	72	58	70	67
Norway	Hydropower-Based System	88	85	90	87
Estonia	High Digitalisation	80	72	82	80
Turkey	Regional Energy Hub	74	63	71	69
Germany	Energy Transition Leader	85	78	86	83

Source: compiled by the authors

The analysis identifies the following as Georgia's strengths: a high share of renewable energy; relatively stable operational infrastructure; and regional energy connections. Key limitations include seasonal dependence on hydropower, partial digitalisation and reliance on imports during the winter months. The results suggest that improving energy security would be most effectively achieved by strengthening the D components through diversification and risk mitigation.

Scenario-Based Analysis

Scenario-based analysis was applied to assess the system's response to hypothetical but plausible events:

– S1 – Hydrological Crisis (Dry Year). Reduced hydropower generation by 15–25%, decreasing reservoir levels and increasing electricity import requirements. ESEC decreases from 67 to 60 (≈ −7%), primarily affecting D and R components (Table 7, 8).

– S2 – Accelerated Digitalisation. Implementation of Smart Grid technologies, extensive SCADA integration, and real-time data analytics improve automation and operational efficiency. ESEC increases from 67 to 76 (≈ +9%), enhancing all three components, particularly T and R (Tables 7, 8).

Table 7
Component changes according to scenarios

Component	Baseline	S1 – Hydrological Crisis	S2 – Accelerated Digitalisation
T	72	68	82
D	58	45	62
R	70	63	82

Source: compiled by the authors

These scenarios demonstrate that Georgia's energy security is highly sensitive to natural and technological factors. Hydrological crises highlight the system's vulnerability to climate change, while technological advancement is the most effective way to enhance security. Scenario analysis emphasises the importance of developing energy diversification and digital infrastructure in parallel to achieve sustainable resilience.

Table 8
Changes in ESEC indices according to scenarios

Condition	ESEC index	Change
Baseline	67	—
S1 – Hydrological Crisis	60	-7%
S2 – Accelerated Digitalisation	76	+9%

Source: compiled by the authors

The results indicate that Georgia's energy system exhibits moderate to high energy security (ESEC ≈ 67), with structural constraints primarily relating to energy dependence. Technological and operational stability, supported by automation and SCADA systems, ensures a reliable electricity supply under normal conditions. However, reliance on hydropower introduces seasonal risk, while dependence on imports increases vulnerability in winter.

International benchmarking confirms that, in terms of resilience, Georgia's energy systems are similar to those in development, but lag behind highly digitised and diversified European systems. Scenario-based assessments show that investing strategically in smart grid technologies and energy diversification can enhance operational efficiency and systemic resilience while reducing exposure to climatic and geopolitical risks.

Overall, the findings suggest that achieving sustainable energy security in Georgia requires a dual approach of mitigating dependence on hydropower and imports, while also accelerating technological modernisation and digitalisation. The integrated methodology provides policymakers with a diagnostic framework and a decision-support tool, highlighting priority areas for investment and system optimisation.

6. Conclusions

Energy security remains a critical component of sustainable development and national stability. This study shows that Georgia's energy system has a moderately high level of energy security (ESEC ≈ 67), thanks to its strong technological performance and systemic resilience.

Nevertheless, structural vulnerabilities, particularly in terms of energy dependence and limited diversification, remain key challenges. Scenario-based analysis shows that digitalisation can substantially enhance resilience, but hydrological variability continues to pose risks.

Based on the findings, long-term energy security in Georgia requires parallel advancement in three strategic directions, which can be implemented through concrete policy and operational measures:

– Energy diversification. To mitigate seasonal and geopolitical risks, reduce dependence on hydropower and electricity imports by expanding alternative renewable sources (such as solar and wind power) and enhancing conventional generation capacity.

– Digital infrastructure and Smart Grid development. Deploy advanced monitoring, automation and data-driven energy management systems to improve operational efficiency, system responsiveness and predictive maintenance capabilities.

– Systemic resilience strengthening. Invest in robust infrastructure and comprehensive crisis management protocols to ensure rapid recovery from disruptions. This should include network redundancy, emergency response planning and operational continuity mechanisms.

Collectively, these strategic directions provide a comprehensive framework for achieving sustainable energy security in Georgia. They enable the national energy system to reduce its reliance on external sources, improve operational efficiency and maintain its ability to adapt in the face of anticipated and unforeseen challenges. The integrated methodology also provides policymakers with a decision-support tool, identifying priority areas for investment, technological modernisation and strategic planning.

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