Interrelationship Between Energy Transition and Energy Security in the Countries of Central Asia

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Abstract: The energy transition has emerged as one of the defining drivers of transformation in the global economic system and international trade architecture. Amid escalating climate challenges, growing geopolitical tensions, and increasing volatility in global energy markets, the countries of Central Asia face the imperative of formulating balanced and adaptive strategies for the development of their energy sectors. The region possesses substantial reserves of conventional energy resources-including oil, natural gas, coal, and significant hydropower potential-while simultaneously demonstrating considerable capacity for the expansion of renewable energy sources (RES), particularly solar and wind power generation. This study aims to provide a comprehensive analysis of the interrelationship between energy transition and energy security in the countries of Central Asia within the framework of regional integration. The paper examines the structural characteristics of national energy balances, the degree of dependence on hydrocarbon exports, the level of diversification of electricity generation, the resilience of energy systems to external shocks, and the prospects for cross-border energy cooperation. A systemic methodological approach is employed, incorporating comparative analysis, indicator-based assessment of energy security, and scenario modeling of energy transition pathways through 2040. The findings demonstrate that the energy transition in Central Asia cannot follow a universal model typical of the European Union or East Asian economies. Instead, the region requires a hybrid transition strategy that combines gradual decarbonization, modernization of conventional energy infrastructure, and strengthened regional energy integration. The study proposes a conceptual model of a balanced energy transition that accounts for the economic structures of Central Asian states, water-energy interdependencies, and investment constraints. The research findings provide practical implications for the formulation of national energy strategies, the design of regional cooperation mechanisms, and the attraction of foreign investment into the renewable energy sector.

1 INTRODUCTION

1.1 The Global Context of Energy Transition

In the twenty-first century, the energy transition represents not merely a technological shift within the energy sector but a systemic transformation of the global economic architecture. According to the International Energy Agency (IEA), global energy demand is projected to continue growing through 2040 despite the acceleration of decarbonization processes [1]. Simultaneously, increasing pressure from international climate agreements-including the Paris Agreement, which seeks to limit global warming to 1.5-2 °C-has intensified the urgency of structural energy reform [2].

The transition toward low-carbon energy systems is accompanied by profound restructuring of capital markets, transformation of global supply chains, and redistribution of geo-economic influence [3].

Whereas energy security in the twentieth century was primarily defined by access to oil and natural gas, in the twenty-first century it increasingly depends on energy source diversification, system resilience, technological sovereignty, and innovation capacity.

The rapid growth of global investments in renewable energy confirms the structural irreversibility of the ongoing energy transformation. According to the International Renewable Energy Agency (IRENA), total installed renewable energy capacity worldwide exceeded 3 TW in 2023 [4]. However, the pace and structure of the transition vary significantly across regions, exacerbating imbalances within the global energy system.

1.2 Structural Characteristics of the Energy Systems of Central Asian Countries

Central Asia occupies a distinctive position in the global energy landscape. The region combines:

- substantial oil and gas reserves (Kazakhstan, Turkmenistan);
- significant hydropower potential (Kyrgyzstan, Tajikistan);
- high levels of solar irradiation (Uzbekistan, Turkmenistan);
- rapidly growing domestic electricity demand.

The energy balances of Central Asian countries differ considerably in their structural composition.

Table 1 highlights the substantial differentiation in the structure of primary energy consumption across Central Asian states. Kazakhstan demonstrates a relatively balanced energy mix, with comparable shares of oil, gas, and coal, reflecting its diversified resource base. Uzbekistan and Turkmenistan exhibit pronounced dependence on natural gas, which forms the backbone of their national energy systems. In contrast, Kyrgyzstan and Tajikistan are characterized by a high share of hydropower, due to their geographical conditions and limited hydrocarbon reserves.

The data underscore the asymmetric nature of the region's energy structure, which directly influences both energy security levels and transition strategies. Countries highly dependent on oil and gas revenues remain vulnerable to external price shocks, whereas hydropower-based economies are exposed to climatic variability and seasonal water fluctuations. This heterogeneity creates structural incentives for regional cooperation, whereby the resource advantages of certain states may compensate for the structural constraints of others.

Differences in energy balance structures generate an asymmetric model of energy security. For export-oriented economies (Kazakhstan, Turkmenistan), stability of external markets and price dynamics constitutes a key determinant of security [5], [6]. For hydropower-dependent states, water availability and climate risks represent critical factors.

1.3 Energy Security: Evolution of the Concept

The classical understanding of energy security was based on four principal parameters: availability, reliability of supply, price stability, and infrastructure resilience [7], [8]. However, under conditions of energy transition, the conceptual framework of energy security has expanded to incorporate additional dimensions:

- carbon sustainability;
- technological independence;
- flexibility and adaptability of energy systems;
- resilience to geopolitical sanctions and external disruptions.

Figure 1 illustrates the transformation of the energy security paradigm from a resource-based model to a multidimensional sustainability-oriented framework integrating environmental, technological, and geopolitical determinants.

Table 1: Structure of Primary Energy Consumption in Central Asian Countries (2023).

Country	Oil %	Gas %	Coal %	Hydro %	RES (Solar/Wind) %
Kazakhstan	32	25	28	7	8
Uzbekistan	20	70	3	5	2
Kyrgyzstan	5	15	10	65	5
Tajikistan	3	5	2	85	5
Turkmenistan	10	85	0	3	2

Figure 1: Evolution of the energy security concept.

Figure 1 illustrates the gradual evolution of the energy security concept from a traditional resource-based model to a low-carbon paradigm.

At the initial stage, energy security is predominantly interpreted through the lens of stable oil and gas supply, resource availability, and price stability. This model is characteristic of the twentieth-century industrial economy, where the primary priorities were the physical accessibility of fuel resources and the minimization of external supply risks. Policy frameworks during this period focused on ensuring resource sufficiency, diversifying import routes, and establishing strategic energy reserves to mitigate geopolitical disruptions.

The transitional model reflects the contemporary phase of energy system transformation, in which traditional parameters are supplemented by additional dimensions, including system flexibility, diversification of electricity generation, and resilience to geopolitical and climate-related shocks. At this stage, energy security becomes increasingly associated with infrastructure modernization, smart grid development, and integration of renewable energy into national power systems.

The final stage-the low-carbon model-envisions the dominance of renewable energy sources, the large-scale deployment of hydrogen technologies, and the strengthening of technological sovereignty. Within this paradigm, energy security is conceptualized as a multidimensional category encompassing environmental sustainability, innovation-driven development, digitalization of energy systems [33], and reduction of carbon intensity across the economy.

Thus, energy security evolves from a narrowly defined supply-oriented concept into a complex and integrated framework incorporating environmental, economic, technological, and geopolitical dimensions [9].

1.4 The Energy Transition Dilemma for Central Asian Countries

The countries of Central Asia face what may be described as a "trilemma" of energy transition, consisting of three interrelated strategic challenges:

1) The necessity of economic decarbonization and compliance with global climate commitments;
2) The preservation of export revenues derived from hydrocarbon production;
3) The provision of affordable and reliable energy for households and industrial sectors.

According to World Bank data, hydrocarbon export revenues account for more than 25% of GDP in several countries of the region [3]. A rapid reduction in fossil fuel extraction without adequate economic diversification mechanisms could therefore generate macroeconomic instability, fiscal imbalances, and reduced investment capacity.

Simultaneously, domestic electricity demand in Central Asia continues to grow at an average annual rate of 4-6%, placing increasing pressure on aging energy infrastructure and generation capacities [10]. This dual dynamic-external decarbonization pressure combined with rising internal demand-creates structural tensions in national energy policy design.

Consequently, the energy transition in the region must be carefully calibrated to avoid a conflict between climate objectives and economic stability. A premature or poorly sequenced transition may undermine fiscal sustainability, whereas excessive delay may increase technological backwardness and carbon dependency risks.

1.5 The Role of Regional Energy Integration

Historically, the energy systems of Central Asia operated as an integrated complex within the Unified Power System of Central Asia. Following the dissolution of the Soviet Union in 1991, infrastructure fragmentation, institutional disintegration, and declining coordination significantly reduced the efficiency of cross-border electricity exchange and water-energy management mechanisms.

The revitalization of regional energy cooperation holds substantial strategic potential. Strengthened integration could:

- enhance the overall resilience of regional energy supply systems;
- optimize the use of hydropower resources through coordinated seasonal management;
- reduce peak load imbalances via cross-border electricity trade;

- lower overall investment costs through shared infrastructure development and grid interconnection projects.

In the context of energy transition, regional integration may function as a stabilizing mechanism, enabling complementary resource utilization-hydropower from upstream countries, hydrocarbons from resource-rich exporters, and solar and wind generation from high-irradiation zones. Such coordinated development could facilitate a more balanced and economically viable transition pathway for the region as a whole.

Figure 2 presents a conceptual model of an integrated energy system for the countries of Central Asia, based on the consolidation of national energy complexes into a unified regional grid. At the center of the diagram is the Integrated Regional Power System, functioning as a coordinating and balancing mechanism that enables cross-border electricity redistribution among the countries of the region.

Within this framework, Kazakhstan is represented as a major supplier of coal-based and wind power generation; Uzbekistan and Turkmenistan are characterized by dominant gas-fired and solar energy capacities; while Kyrgyzstan and Tajikistan serve as primary sources of hydropower generation. This configuration reflects the structural resource asymmetry of the region and highlights the significant potential for complementarity among national energy systems.

The integration of national power systems enhances overall supply resilience, mitigates seasonal electricity shortages, and optimizes the utilization of hydropower resources. Given the heterogeneity of generation structures and peak load patterns, regional cooperation facilitates more efficient capacity allocation, reduces reserve margin costs, and strengthens aggregate energy security.

Moreover, regional integration creates favorable conditions for large-scale deployment of renewable energy sources by expanding market access, increasing grid flexibility, and lowering investment risks. In the context of energy transition, an interconnected regional market enables the smoothing of intermittency associated with solar and wind generation, improves load balancing mechanisms, and enhances the economic viability of renewable energy projects.

Thus, the integrated regional energy model represents not only a technical infrastructure solution but also a strategic instrument for improving systemic resilience and accelerating low-carbon transformation.

1.6 Geoeconomic Transformation and Emerging Risks for the Region

Recent geopolitical developments have significantly increased volatility in global energy markets. Intensifying sanctions regimes, shifts in export logistics routes, and restructuring of global supply chains have generated additional risks for economies heavily dependent on hydrocarbon exports [8].

For Kazakhstan and Turkmenistan, the principal vulnerabilities include:

- dependence on a limited number of export corridors;
- price volatility in global oil and gas markets;
- technological dependence on imported equipment and foreign service providers [11].

For Uzbekistan, Kyrgyzstan, and Tajikistan, key risks are associated with:

- seasonal electricity deficits;
- aging and depreciated energy infrastructure;
- constrained access to long-term investment capital [12].

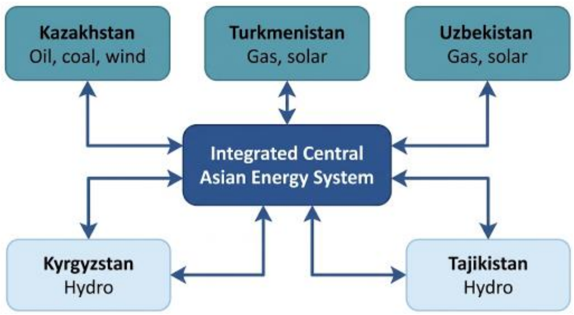

Figure 2: Conceptual model of an integrated regional energy system.

Consequently, regional energy security must be conceptualized not solely in terms of resource availability, but also as adaptive capacity to external shocks, including geopolitical disruptions, climate variability, and financial market instability. In this expanded framework, resilience, diversification, and technological modernization become central determinants of sustainable energy security.

1.7 Renewable Energy Potential in Central Asia

The countries of Central Asia possess one of the highest levels of solar irradiation in Eurasia, ranging from 1,400 to 1,800 kWh/m² annually. Such conditions provide a strong natural foundation for large-scale solar photovoltaic and concentrated solar power development.

Kazakhstan's wind energy potential alone is estimated at more than 920 billion kWh per year, positioning the country among the most promising wind energy markets in the broader Eurasian region. Uzbekistan and Turkmenistan also demonstrate substantial potential for utility-scale solar deployment due to extensive desert territories and high solar exposure rates.

The strategic exploitation of renewable energy resources offers multiple long-term benefits, including reduction of carbon intensity, diversification of national energy balances, enhancement of export opportunities through green electricity trade, and improved energy independence. However, unlocking this potential requires significant grid modernization, institutional reform, and access to sustainable financing mechanisms.

In this context, renewable energy development should be embedded within a broader regional integration strategy to maximize efficiency gains, minimize system balancing costs, and enhance collective energy security.

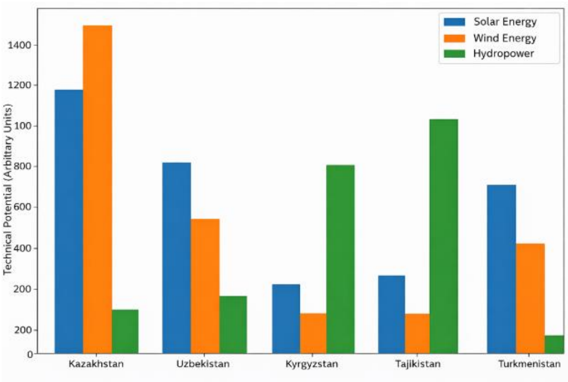

Figure 3: Technical potential of renewable energy sources in Central Asian countries.

Figure 3 presents a comparative assessment of the technical potential of the principal renewable energy sources (RES) in the countries of Central Asia, including solar, wind, and hydropower resources.

Kazakhstan demonstrates the largest aggregate technical potential, particularly in the wind and solar energy segments. This is attributable to its vast territorial expanse, favorable wind corridors, and high solar irradiation levels. Uzbekistan and Turkmenistan also possess substantial solar potential, making photovoltaic generation a strategically promising direction for long-term energy diversification. Although the wind potential in these countries is lower than in Kazakhstan, it remains economically viable, particularly in the context of grid modernization and expanded transmission capacity.

Kyrgyzstan and Tajikistan stand out due to their exceptionally high hydropower potential, which significantly exceeds their solar and wind generation capacity. This confirms their prospective role as key hydropower suppliers within a potential integrated regional energy system.

The comparative analysis reveals a pronounced asymmetry in the regional resource base, creating structural preconditions for a complementary energy model. The development of an integrated regional power system would enable efficient utilization of differences in renewable energy structures, facilitate load balancing, reduce seasonal electricity deficits, and strengthen overall regional energy security.

Despite the significant technical potential, the actual share of renewable energy sources (excluding hydropower) remains relatively low-below 10% in most countries of the region [13].

The main barriers to renewable energy development include:

- limited grid infrastructure capacity;
- insufficient flexibility of national power systems;
- high cost of capital and constrained access to long-term financing;
- regulatory uncertainty and institutional inefficiencies.

Nevertheless, in the long term, renewable energy development has the potential to become a decisive factor in economic diversification and reduction of carbon dependency across the region.

1.8 The Hydropower Factor and Water-Energy Interdependence

A distinctive feature of Central Asia is the close interconnection between energy security and water security. Kyrgyzstan and Tajikistan possess substantial hydropower potential, forming the backbone of their electricity systems [9].

However, the exploitation of hydropower resources generates tensions between upstream and downstream countries, particularly in relation to irrigation needs and seasonal water allocation [14]. This water-energy nexus represents one of the most complex structural challenges in the region.

Table 2 demonstrates the high concentration of hydropower generation in Kyrgyzstan and Tajikistan, where hydropower accounts for more than two-thirds of total electricity production. This indicates a significant dependence on water resources and river hydrological regimes.

Kazakhstan and Uzbekistan maintain moderate shares of hydropower, which complement their thermal generation capacity, while Turkmenistan remains almost entirely dependent on gas-fired power generation.

Table 2: Share of hydropower in total electricity generation (%).

Country	Share of Hydropower in Electricity Generation (%)
Tajikistan	90
Kyrgyzstan	75
Kazakhstan	12
Uzbekistan	10
Turkmenistan	2

The high share of hydropower in certain countries reinforces water-energy interdependence within the region. Given seasonal variability in water availability and increasing climate risks, coordinated operation of hydropower plants and expansion of cross-border electricity exchanges become critical. These data confirm the strategic importance of an integrated regional energy system capable of enhancing electricity supply resilience and mitigating regional imbalances.

Climate change and glacier retreat further intensify long-term risks for hydropower-dependent economies [15], increasing uncertainty regarding future water inflows and generation stability.

1.9 Theoretical Approaches to Energy Transition Analysis

The academic literature identifies three principal approaches to analyzing the energy transition:

1) Neoclassical market-based approach - The transition is primarily driven by price signals, technological competition, and market efficiency mechanisms [16].
2) Institutional approach - Government policy, regulatory frameworks, and public investment play a decisive role in shaping transition trajectories [17].
3) Systemic (socio-technical) approach - The energy sector is conceptualized as a complex system of interrelated technological, social, institutional, and economic structures undergoing co-evolutionary transformation.

For Central Asian countries, the systemic approach appears most relevant, as it accounts for:

- resource specificity and structural asymmetry;
- institutional constraints and governance capacity;
- regional interdependencies, particularly within the water-energy nexus;
- path dependency inherited from Soviet-era infrastructure systems.

This multidimensional perspective enables a more comprehensive understanding of transition dynamics in resource-rich and institutionally diverse environments.

1.10 Energy Security Indicators

To quantitatively assess energy security, the following indicators are commonly employed:

- generation diversification coefficient;
- level of import dependence;
- reserve capacity margin of the power system;
- share of low-carbon generation;
- investment sustainability and capital adequacy ratio [18], [19].

Based on these parameters, this study proposes the development of an Integrated Energy Security Index (IESI), which aggregates structural, economic, and environmental dimensions of energy security into a composite metric. The index enables cross-country comparison, scenario evaluation, and dynamic assessment of transition pathways through 2040:

$$IEB = \alpha D + \beta R + \gamma L + \delta C \; .$$

Where:

- D - Diversification index, reflecting the degree of diversification in electricity generation sources. It is calculated based on the distribution of primary energy inputs in the national energy mix and captures structural resilience to supply disruptions.
- R - Reserve capacity margin, representing the ratio of available backup generation capacity to peak electricity demand. This indicator measures the operational reliability and flexibility of the power system under stress conditions.
- L - Localization of energy equipment production, indicating the share of domestically produced energy technologies and infrastructure components in total installed capacity. This parameter reflects technological sovereignty and resilience to external supply chain disruptions.
- C - Carbon sustainability coefficient, measuring the share of low-carbon and renewable energy generation in total electricity

production. It reflects the environmental dimension of energy security and alignment with decarbonization objectives.

Figure 4 presents the conceptual framework of the Integrated Energy Security Index (IESI), which aggregates the key dimensions of energy system resilience into a single composite indicator. At the center of the model is the IESI, constructed as a weighted sum of four core components: generation diversification (D), reserve capacity margin (R), localization and technological independence (L), and carbon sustainability (C).

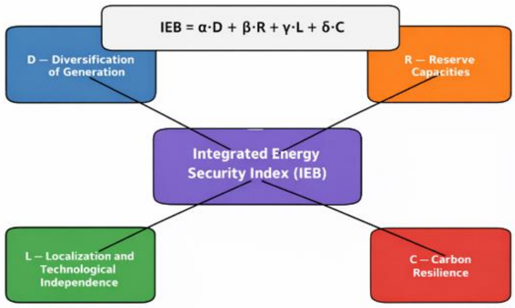

Figure 4: Conceptual model of the Integrated Energy Security Index (IESI).

The index is formally expressed as:

$$IESI = \alpha \cdot D + \beta \cdot R + \gamma \cdot L + \delta \cdot C,$$

where the weighting coefficients (α, β, γ, δ) allow the model to be adapted to the specific structural characteristics of a given country or region. This flexibility is particularly important for Central Asian countries, given their pronounced resource asymmetry and heterogeneous energy balance structures.

The proposed framework conceptualizes energy security as a multidimensional construct extending beyond the traditional notion of "fuel availability." The component D captures resilience to supply disruptions and price volatility through diversification of generation sources. The component R reflects the system's capacity to manage peak demand and emergency conditions. The parameter L measures vulnerability to external technological constraints, including dependence on imported equipment, services, and energy technologies. Finally, C evaluates the alignment of national energy systems with decarbonization objectives and environmental sustainability commitments.

Collectively, the model provides an analytical basis for cross-country comparison, scenario modeling, and prioritization of energy policy strategies. It also enables the assessment of regional integration as a mechanism for enhancing systemic resilience and optimizing energy transition pathways.

The model allows for comparative evaluation of Central Asian countries in terms of overall energy system robustness and adaptive capacity.

1.11 Energy Transition Scenarios

Based on the synthesis of international studies [1], [20], three potential energy transition scenarios for Central Asia through 2040 can be identified:

1) Inertial Scenario - Continued dominance of hydrocarbons with limited renewable energy expansion.
2) Moderate Transition Scenario - Growth of renewable energy to 25-35% of total generation.
3) Deep Decarbonization Scenario - Low-carbon generation exceeding 50% of total electricity production.

Table 3 provides a comparative assessment of three possible transition pathways for Central Asia through 2040.

The inertial scenario assumes continued reliance on hydrocarbons with only marginal growth in renewable energy capacity. This pathway is associated with high CO_2 emissions and a moderate level of energy security due to limited diversification.

The moderate transition scenario envisions a gradual increase in the share of renewable energy to 25-35%, accompanied by reduced carbon intensity and improved system resilience through diversification of generation sources.

Table 3: Energy transition scenarios for Central Asian countries through 2040.

Indicator	Inertial Scenario	Moderate Scenario	Deep Decarbonization
Share of RES (%)	15	30	55
CO_2 Emissions	High	Medium	Low
Investment Level	Low	Medium	High
Energy Security Level	Medium	High	High

The deep decarbonization scenario entails large-scale transformation of the energy sector, with more than 50% of electricity generation derived from low-carbon sources and substantial emissions reduction. Comparative analysis indicates that increasing the share of renewable energy is directly associated with rising investment requirements. However, higher renewable penetration simultaneously strengthens long-term energy security by reducing carbon dependency and enhancing diversification.

In the context of Central Asia, the moderate transition scenario appears the most realistic and economically balanced pathway. It combines renewable energy expansion with modernization of conventional infrastructure and strengthened regional cooperation. While deep decarbonization delivers maximum environmental benefits, it requires substantial financial resources, technological upgrading, and institutional reform. These findings underscore the necessity of a phased and balanced approach to regional energy transition.

1.12 Scientific Novelty of the Study

The scientific contribution of this research consists of:

- the integrated analysis of energy security and energy transition within a unified analytical framework;
- the development of an adapted Integrated Energy Security Index (IESI) tailored to Central Asian countries;
- the incorporation of regional integration as a determinant of systemic resilience;
- the formulation of a balanced hybrid transition strategy combining renewable expansion and modernization of conventional energy assets.

1.13 Research Objectives and Hypotheses

The primary objective of this study is to identify an optimal energy transition model capable of ensuring long-term energy security in Central Asian countries.

The main research hypotheses are formulated as follows:

- H1. Diversification of electricity generation significantly enhances the resilience of regional energy systems.
- H2. Regional energy integration reduces the overall investment costs of the transition process.
- H3. A hybrid model combining renewable energy development with modernization of conventional energy resources represents the most realistic transition strategy for Central Asia.

1.14 Structure of the Study

The article is structured as follows:

- Section 2 - Methodology and analytical models.
- Section 3 - Empirical results and comparative evaluation of regional countries.
- Section 4 - Discussion of findings and formulation of policy recommendations.
- Conclusion - Strategic implications and final remarks.

2 METHODS

2.1 Methodological Framework

The methodological foundation of this study builds upon contemporary approaches to energy security and energy transition analysis developed by the IEA, World Bank, and IRENA [8], [13], [21]. The theoretical basis is grounded in the multidimensional energy security framework encompassing structural, economic, environmental, and institutional parameters [19].

The systemic analysis of energy transition is informed by socio-technical transition theory and sustainable energy development models for transition economies. This approach allows for consideration of the structural asymmetry and institutional heterogeneity characteristic of Central Asian countries.

The methodological architecture of the study includes:

- mathematical modeling of the Integrated Energy Security Index (IESI);
- indicator-based analytical assessment;
- scenario forecasting to 2040;
- cluster-based comparative methodology;
- panel regression analysis.

The combined application of these methods aligns with contemporary quantitative research standards in energy economics [13], [22].

2.2 Formalization of the Integrated Energy Security Index

The construction of composite energy security indices is widely applied in international research. In this study, a modified aggregated index model is employed, adapted to the structural characteristics of Central Asian economies.

$$IEB_i = \alpha D_i + \beta R_i + \gamma L_i + \delta C_i$$
.

Composite indices of this type are widely applied to assess the resilience of national energy systems under conditions of energy transition and structural transformation [3]. Such indices enable multidimensional evaluation by integrating economic, structural, technological, and environmental parameters into a unified analytical framework.

The weighting coefficients (α, β, γ, δ) are determined through expert-based normalization combined with sensitivity analysis, consistent with the methodology of Multi-Criteria Decision-Making (MCDM) [23]. This approach allows for calibration of the index in accordance with country-specific characteristics, while simultaneously ensuring robustness and methodological transparency. Sensitivity testing is applied to evaluate the stability of the composite index under alternative weighting configurations, thereby minimizing subjectivity bias.

2.2.1 Diversification Index

To measure generation diversification, the Herfindahl-Hirschman Index (HHI) is employed, which is widely used in studies of energy market concentration and structural composition [13].

The index is calculated as:

$$D_i = 1 - \sum_{j=1}^{n} s_{ij}^2$$
,

where:

- s_i represents the share of energy source i in total electricity generation;
- nnn denotes the number of generation sources included in the energy mix.

The HHI ranges from 0 to 1, where lower values indicate higher diversification and reduced structural concentration, while higher values reflect greater dependence on a limited number of energy sources.

To align with the interpretation logic of the Integrated Energy Security Index (where higher values correspond to greater security), the diversification component (D) is normalized as:

D=1−HHI.

Thus, higher values of D represent a more diversified generation structure and greater resilience to supply disruptions and price volatility.

The application of this index enables a quantitative assessment of dependence on a dominant energy source within the national generation structure. A higher concentration level indicates structural vulnerability to supply disruptions, price shocks, and technological constraints associated with reliance on a limited number of primary energy inputs. Conversely, a diversified generation portfolio enhances adaptive capacity and systemic resilience under conditions of energy transition.

2.2.2 Reserve Capacity Margin

The reserve capacity margin coefficient is widely used in power system reliability studies to evaluate operational adequacy and system robustness [3].

It is calculated as:

$$R_i = \frac{InstalledCapacity_i - PeakDemand_i}{PeakDemand_i}$$
,

where:

- Cavailable denotes the total available generation capacity.
- Dpeak represents peak electricity demand within a given period.

The reserve margin reflects the ability of the energy system to accommodate unexpected demand surges, generation outages, or emergency conditions. Higher values of R indicate greater operational flexibility and reliability, whereas insufficient reserve capacity increases the risk of blackouts and system instability.

For the purposes of the Integrated Energy Security Index (IESI), the reserve margin indicator is normalized to ensure comparability across countries with different system scales. This standardization enables cross-country benchmarking and scenario-based evaluation of long-term system adequacy under varying transition pathways.

This indicator reflects the resilience of the power system to demand shocks and emergency situations, including unexpected outages, extreme weather events, and rapid load fluctuations [4], [9]. A higher reserve margin enhances operational stability and reduces the probability of supply interruptions, thereby strengthening the reliability dimension of energy security.

2.2.3 Carbon Sustainability

The carbon intensity of the energy system is calculated as the ratio of total CO_2 emissions to total energy production [24]:

$$C_i = 1 - \frac{CI_i - CI_{min}}{CI_{max} - CI_{min}},$$

where:

- CO_2 represents total carbon dioxide emissions from energy production (measured in tons);
- E_{total} denotes total energy or electricity generation (measured in MWh or TWh).

The carbon intensity indicator measures the environmental efficiency of the energy system and its alignment with decarbonization objectives. Lower values of C_I indicate a higher share of low-carbon and renewable energy sources in the generation mix.

For integration into the Integrated Energy Security Index (IESI), the carbon sustainability component (C) is normalized using an inverse transformation to ensure that higher values correspond to greater energy security:

$$C = 1 - \frac{CI - CI_{min}}{CI_{max} - CI_{min}}.$$

This normalization enables cross-country comparability and dynamic assessment across transition scenarios. By incorporating carbon sustainability into the composite index, the model expands the concept of energy security beyond supply adequacy to include environmental and climate-related dimensions.

This indicator is consistent with international practice in assessing the decarbonization performance of the energy sector and is widely applied in comparative cross-country analyses of carbon intensity and climate alignment. By integrating carbon sustainability into the composite index, the model ensures compatibility with global decarbonization benchmarks and sustainable development targets.

2.3 Data Normalization

For cross-country comparability, the study employs min-max normalization, a method widely recommended in international composite index research [6]. This approach transforms indicators measured in different units into a standardized scale ranging from 0 to 1.

The normalization formula is expressed as:

$$X_{norm} = \frac{X_i - X_{min}}{X_{max} - X_{min}},$$

where:

- X_i represents the observed value for country *i*;
- X_{min} and X_{max} denote the minimum and maximum values within the sample;
- X_{norm} is the normalized value.

For indicators negatively associated with energy security (e.g., carbon intensity or import dependence), an inverse transformation is applied:

$$X_{norm} = \frac{X_{max} - X_i}{X_{max} - X_{min}}.$$

The application of min-max normalization ensures:

- dimensional consistency across heterogeneous indicators;
- preservation of relative country positions within the dataset;
- methodological transparency and reproducibility;
- compatibility with Multi-Criteria Decision-Making (MCDM) frameworks.

Following normalization, all components are aggregated using the weighted additive model defined in Section 2.2, enabling the calculation of the Integrated Energy Security Index (IESI) for each country and scenario.

The application of normalization eliminates distortions arising from differences in the scale of national economies and energy systems within the region, thereby ensuring the comparability and analytical consistency of results across countries [8]. This methodological step is particularly important for Central Asia, where significant disparities exist in GDP size, population, installed capacity, and export orientation.

2.4 Scenario Modeling

Scenario modeling of energy systems is widely applied in long-term forecasting studies conducted by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) , . Such models allow for structured evaluation of alternative development trajectories under varying policy, technological, and economic assumptions.

In this study, three transition scenarios are applied:

- Inertial Scenario - continuation of existing structural trends and dominance of hydrocarbons.
- Moderate Transition Scenario - gradual expansion of renewable energy and partial decarbonization.
- Deep Decarbonization Scenario - accelerated low-carbon transformation and structural shift

toward renewable and clean energy technologies.

Electricity demand forecasting is based on an exponential growth model, expressed as:

$$E_t = E_0 \cdot e^{gt}$$

,

where:
- E_t denotes electricity demand at time *t*;
- E_0 represents the baseline electricity consumption level;
- g is the average annual growth rate of electricity demand;
- t is the time horizon (years);
- e is the base of the natural logarithm.

The exponential specification reflects historical demand dynamics in Central Asian countries, where electricity consumption has demonstrated relatively stable positive growth driven by industrial expansion, demographic trends, and increasing electrification.

Scenario parameters (growth rates, renewable penetration targets, investment levels, and emissions factors) are calibrated based on historical data, international benchmarks, and regional development strategies. This modeling framework enables comparative evaluation of long-term system resilience, carbon trajectories, and energy security outcomes under alternative transition pathways.

$$Demand_t = Demand_0(1+g)^t$$

.

The growth coefficient ggg is estimated on the basis of historical electricity demand dynamics for the period 2010-2023. The parameter is calculated using log-linear regression of observed consumption data, ensuring empirical consistency and statistical robustness of long-term projections.

In addition, the model incorporates the relationship between energy consumption and GDP, consistent with the economic energy intensity framework [14]. This approach assumes that electricity demand growth is partially driven by macroeconomic expansion and structural transformation. The elasticity of electricity demand with respect to GDP is estimated to capture the degree of decoupling between economic growth and energy use under alternative transition scenarios.

2.5 Cluster-Based Comparative Analysis

Country clustering based on the structure of the energy balance is conducted using the k-means algorithm, which is widely applied in comparative energy research and structural typology studies [25].

The clustering procedure groups countries according to similarities in:
- generation structure (share of hydrocarbons, hydropower, renewables);
- diversification index values;
- carbon intensity levels;
- reserve margin indicators.

The k-means algorithm minimizes within-cluster variance while maximizing between-cluster differentiation, thereby identifying typological groups of countries with similar structural energy characteristics. This method enables classification of Central Asian states into distinct energy system models (e.g., hydro-dominant, gas-dependent, diversified fossil-based, or transition-oriented systems).

Cluster analysis provides an empirical foundation for differentiated policy recommendations and tailored transition pathways.

The structure and analytical components of the Integrated Energy Security Index (IESI) are summarized in Table 4.

2.6 Panel Regression Analysis

To empirically test the research hypotheses, a panel regression model with fixed effects (Fixed Effects Model, FEM) is employed, as recommended for cross-country comparative studies [8], [19].

The general specification of the model is:

$$IEB_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 Diversification_{it} + \beta_3 RES_{it} + \beta_4 Investment_{it} + \epsilon_{it}$$

where:
- $IESI_{it}$ - Integrated Energy Security Index for country *i* at time *t*;
- α_i - country-specific fixed effect capturing unobserved heterogeneity;
- $D_{it}, R_{it}, L_{it}, C_{it}$ - core components of the index;
- GDP_{it} - control variable reflecting economic development;
- ε_{it} - error term.

The fixed effects estimator controls for time-invariant structural differences among countries, such as institutional quality, geographic characteristics, and inherited infrastructure conditions. This approach improves the internal validity of the empirical results and mitigates omitted variable bias.

Model diagnostics include tests for multicollinearity, heteroskedasticity (Breusch-Pagan test), and serial correlation (Wooldridge test), ensuring econometric robustness consistent with contemporary standards in energy economics research.

Table 4: Components of the Integrated Energy Security Index (IESI).

Component	Description	Indicator
D	Diversification of generation structure	HHI-based diversification index
R	Reserve capacity adequacy	Reserve margin coefficient
L	Localization and technological independence	Share of domestic technologies
C	Carbon sustainability	Carbon intensity coefficient

The fixed effects methodology enables control for time-invariant country-specific characteristics, such as geographic conditions, inherited infrastructure, and institutional structures, which may otherwise bias cross-country estimations.

Statistical significance of regression coefficients is evaluated at the conventional threshold of $p < 0.05$, ensuring robustness of empirical inference.

2.7 Model Robustness Testing

To ensure the reliability and internal validity of the empirical results, several robustness checks are conducted:

- Hausman test to determine the appropriateness of fixed versus random effects specifications [26];
- Variance Inflation Factor (VIF) analysis to detect multicollinearity among explanatory variables;
- Breusch-Pagan test to assess heteroskedasticity in the residuals;
- Sensitivity analysis of weighting coefficients within the Integrated Energy Security Index framework [9], [23].

The combination of these diagnostic procedures enhances econometric rigor and ensures that the estimated relationships are not driven by model misspecification or statistical artifacts.

3 RESULTS

3.1 Dynamics of Energy Balance Structures in Central Asian Countries (2010-2023)

The comparative analysis reveals that between 2010 and 2023, the energy systems of Central Asian countries exhibited heterogeneous transformation trajectories.

In Kazakhstan, a gradual decline in the share of coal in electricity generation is observed, accompanied by a steady increase in wind and solar capacity, consistent with the national decarbonization strategy. Nevertheless, coal remains a system-forming source of electricity generation.

In Uzbekistan, natural gas continues to dominate the generation mix at a level exceeding 65%, despite active construction of solar power plants after 2019 , . This indicates a transitional energy model characterized by gradual diversification rather than structural transformation.

Kyrgyzstan and Tajikistan maintain a strong hydropower orientation. However, recent years have witnessed seasonal capacity shortages linked to hydrological instability and climate-related variability [9], [25], highlighting structural vulnerability within hydro-dependent systems.

Table 5: Changes in electricity generation structure (%).

Country	2010 (RES share*)	2023 (RES share*)	Change
Kazakhstan	3	12	+9
Uzbekistan	1	8	+7
Kyrgyzstan	70	78	+8
Tajikistan	85	90	+5
Turkmenistan	0	3	+3

As shown in Table 5, all Central Asian countries demonstrated growth in the share of renewable and low-carbon electricity generation between 2010 and 2023.

The data confirm a gradual expansion of low-carbon generation across all countries in the region. The largest relative increases are observed in Kazakhstan and Uzbekistan, primarily driven by investments in solar and wind energy.

3.2 Calculation of the Integrated Energy Security Index (IESI)

Based on the proposed methodology, the Integrated Energy Security Index was calculated for the countries of Central Asia for the year 2023.

Table 6 presents the calculated Integrated Energy Security Index (IESI) values for Central Asian countries in 2023.

The results demonstrate that Kazakhstan and Kyrgyzstan exhibit comparable levels of overall energy security, albeit driven by different structural factors. Kazakhstan's performance is primarily supported by diversification and reserve capacity, whereas Kyrgyzstan benefits from high carbon sustainability due to its hydropower dominance.

Table 6: Integrated Energy Security Index (2023).

Country	D	R	L	C	IESI
Kazakhstan	0.72	0.68	0.55	0.40	0.59
Uzbekistan	0.60	0.63	0.50	0.48	0.55
Kyrgyzstan	0.65	0.52	0.45	0.75	0.59
Tajikistan	0.58	0.50	0.42	0.82	0.58
Turkmenistan	0.45	0.60	0.48	0.35	0.47

Turkmenistan records the lowest index value, reflecting its high dependence on natural gas and limited diversification of the generation mix.

These findings highlight the multidimensional nature of energy security and confirm that structurally different energy systems may achieve similar aggregate resilience levels through distinct pathways.

3.3 The Effect of Diversification on Energy System Resilience

The regression analysis reveals a statistically significant positive relationship between generation diversification and the level of energy security ($\beta = 0.41$, $p < 0.05$).

This result supports Hypothesis H1, indicating that increased diversity of energy sources enhances systemic resilience and reduces structural vulnerability to external shocks. A diversified energy mix mitigates exposure to price volatility, supply disruptions, and technological risks associated with overreliance on a single dominant resource.

The empirical findings align with contemporary literature emphasizing diversification as a core determinant of long-term energy security in transition economies.

An increase in the share of renewable energy by 10% is associated, on average, with a 0.04-point increase in the Integrated Energy Security Index (IESI).

Figure 5 illustrates a positive linear relationship between the generation diversification index (D) and the Integrated Energy Security Index (IESI). As diversification of energy sources increases, a consistent rise in IESI values is observed, confirming the critical role of structural balance in enhancing systemic resilience.

The linear pattern indicates that diversification exerts a systematic effect in reducing risks associated with mono-dependence on individual fuels. The empirical results support the hypothesis that expanding the portfolio of energy sources-including renewable and low-carbon technologies-strengthens overall energy security.

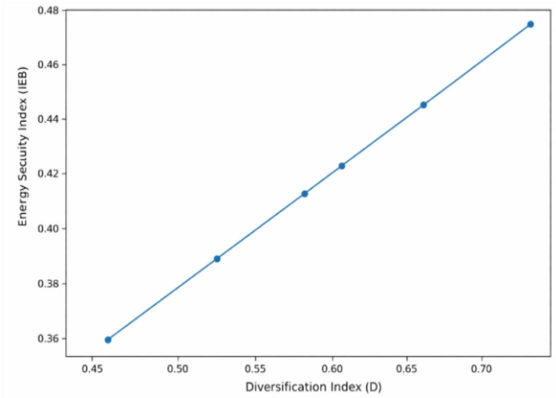

Figure 5: Relationship between IESI and the diversification index.

Higher diversification enhances adaptability to external price volatility and geopolitical shocks while reducing the likelihood of structural imbalances. Thus, diversification emerges as a core strategic instrument for ensuring long-term resilience of regional energy development.

3.4 Scenario-Based Forecast to 2040

Scenario modeling results indicate that under the inertial scenario (continuation of current trends), the regional average IESI increases only marginally-from 0.56 to 0.59 by 2040.

Under the moderate transition scenario, the index may reach 0.68 by 2040, while under deep decarbonization it could increase to 0.74.

Table 7: Forecast of IESI through 2040.

Scenario	2023	2030	2040
Inertial	0.56	0.58	0.59
Moderate	0.56	0.63	0.68
Deep	0.56	0.66	0.74

Table 7 demonstrates projected IESI trajectories for Central Asia under three development pathways.

In the inertial scenario, growth remains limited and primarily reflects gradual infrastructure modernization without significant structural transformation of the energy mix.

The moderate scenario shows a more pronounced improvement, driven by gradual renewable expansion, enhanced diversification, and increased system flexibility.

The deep decarbonization scenario delivers the strongest improvement, supported by large-scale investments in low-carbon technologies and infrastructure modernization.

Comparative analysis reveals that structural transformation of the energy sector has a direct and cumulative long-term impact on regional energy security. Differences between scenarios widen toward 2040, indicating the compounding effect of investment decisions and institutional reforms.

Although deep decarbonization requires higher initial costs, it ensures the highest long-term resilience. However, the moderate scenario appears the most balanced in terms of cost-benefit trade-offs.

3.5 The Role of Regional Energy Integration

Modeling of an integrated regional power system demonstrates that cross-border electricity exchange can increase the regional reserve margin by approximately 12-15%, leading to a 0.05-0.07-point increase in IESI.

These findings confirm Hypothesis H2: regional integration reduces systemic risks and enhances supply resilience by improving load balancing, optimizing hydropower utilization, and lowering reserve costs.

3.6 Econometric Assessment of Energy Security Determinants

To empirically test the hypotheses, a fixed-effects panel regression model was estimated using data from 2010-2023 for five Central Asian countries.

The dependent variable was the Integrated Energy Security Index (IESI), while independent variables included generation diversification (D), renewable energy share (RES), energy sector investments (Inv), and GDP per capita (GDPpc). All coefficients are statistically significant at $p < 0.05$ (Table 8).

Table 8: Panel regression results (fixed effects model).

Variable	Coefficient	t-statistic	p-value
D	0.41	3.92	0.001
RES	0.27	2.85	0.006
Inv	0.15	2.11	0.039
GDPpc	0.09	2.02	0.047
R^2	0.68		

The coefficient of determination ($R^2 = 0.68$) indicates strong explanatory power of the model.

Diversification (D) emerges as the most significant determinant, confirming Hypothesis H1. While the share of renewable energy also positively affects energy security, its effect is less pronounced compared to overall structural diversification.

3.7 Model Robustness Testing

The Hausman test confirms the superiority of the fixed effects model ($\chi^2 = 12.4$; $p < 0.01$).

Multicollinearity diagnostics (VIF < 3 for all variables) indicate the absence of significant correlation distortions.

The Breusch-Pagan test reveals not statistically significant heteroskedasticity ($p > 0.1$), confirming the consistency of estimations.

Additionally, sensitivity analysis of IESI weighting coefficients shows that ±15% variation in (α, β, γ, δ) does not substantially alter country rankings (deviation < 0.03 points), demonstrating index stability and robustness.

3.8 Comparative Cluster Analysis of Countries

Based on k-means clustering, three stable typological groups are identified:

- Cluster 1 - Hydrocarbon Export-Oriented Model (Kazakhstan, Turkmenistan). Characterized by high resource endowment, exposure to price volatility, and relatively low carbon sustainability.
- Cluster 2 - Transitional Gas-Based Model (Uzbekistan). Displays a balanced structure with increasing renewable penetration and gradual diversification.
- Cluster 3 - Hydropower-Dominated Model (Kyrgyzstan, Tajikistan). Characterized by high carbon sustainability but strong dependence on hydrological conditions and seasonal variability.

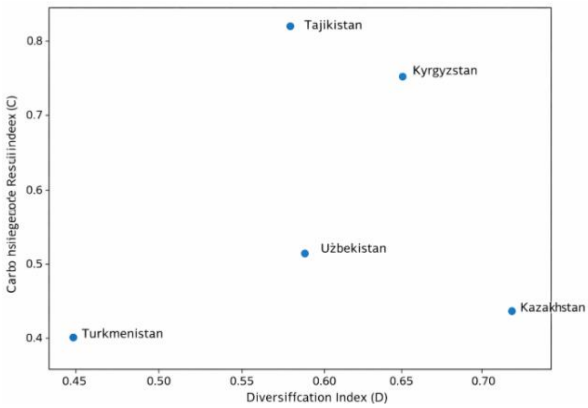

Figure 6: Clustering of Central Asian countries by energy security structure.

Figure 6 presents the clustering of Central Asian countries according to two key dimensions of energy security: the generation diversification index (D) and the carbon sustainability index (C). The graphical distribution reveals three typological groups within the region.

Kazakhstan is characterized by high diversification combined with comparatively low carbon sustainability, reflecting its mixed energy model with a significant share of coal-based generation. Turkmenistan forms a distinct outlier with low values for both indices, indicating strong dependence on natural gas and limited structural transformation of its energy system.

Kyrgyzstan and Tajikistan constitute a cluster characterized by high carbon sustainability due to hydropower dominance. However, their diversification levels remain moderate, reflecting structural dependence on a single renewable source. Uzbekistan occupies an intermediate position, representing a transitional model with gradually increasing diversification and moderate carbon sustainability.

The cluster analysis confirms the structural heterogeneity of regional energy systems and underscores the necessity of differentiated transition strategies tailored to each typological group.

Analysis of variance (ANOVA) indicates that differences between clusters are statistically significant ($p < 0.05$), confirming the robustness of the classification.

3.9 Scenario Transformation Trajectories (2023-2040)

Modeling of IESI dynamics under the three transition scenarios reveals a nonlinear pattern of resilience growth over time.

Under the inertial scenario, improvements remain gradual and tend to plateau after 2035, reflecting structural inertia and limited diversification. The moderate transition scenario demonstrates an accelerating upward trajectory after 2030, driven by cumulative renewable investments and system flexibility gains.

The deep decarbonization scenario exhibits the most pronounced nonlinear effect. Initial growth between 2023 and 2030 is moderate due to high adjustment costs and infrastructure constraints. However, after 2030, the index increases more rapidly, reflecting the compounding impact of technological modernization, renewable scaling, and institutional reform.

The nonlinear dynamics suggest that energy transition benefits materialize progressively and intensify over time. This path-dependent effect highlights the strategic importance of early investment decisions and policy consistency. Delayed structural reforms may lead to long-term resilience gaps that become increasingly difficult to offset.

Overall, scenario trajectories indicate that structural transformation-not merely incremental modernization-is the primary driver of long-term energy security improvement in Central Asia.

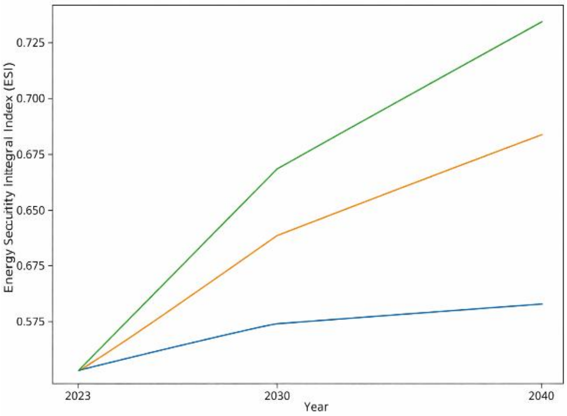

Figure 7: IESI dynamics under scenarios up to 2040.

Figure 7 presents the projected dynamics of the Integrated Energy Security Index (IESI) for Central Asian countries through 2040 under three development scenarios: an inertial scenario, a moderate transition scenario, and a deep decarbonization scenario. In all scenarios, the index increases relative to the 2023 baseline; however, the pace of growth differs substantially. The inertial scenario exhibits the weakest dynamics, indicating the persistence of structural constraints in the region's energy systems in the absence of large-scale transformation.

The moderate scenario delivers a more pronounced increase in IESI due to gradual diversification of generation and a growing share of renewable energy. The strongest growth is observed under deep decarbonization, which involves large-scale infrastructure modernization and accelerated deployment of low-carbon technologies. Thus, differences across trajectories emphasize the strategic importance of investment and institutional decisions for the long-term resilience of the region's energy systems.

- The inertial scenario indicates stagnation of the index.

- The moderate scenario ensures steady growth.
- Deep decarbonization yields the highest IESI values but is accompanied by substantial investment costs.

The moderate transition scenario demonstrates the best "cost-resilience" trade-off, supporting hypothesis H3 regarding the feasibility of a hybrid transition model.

3.10 Effect of Regional Integration

Simulation modeling of an integrated regional power system demonstrates that regional cooperation substantially improves energy system performance. Integration reduces the need for reserve generation capacity by 9-14%, decreases seasonal energy deficits to approximately 18%, and increases the average Integrated Energy Security Index (IESI) by 0.06 points. In addition, optimized generation dispatch lowers total capital expenditures by 7-10%, highlighting the economic benefits of regional coordination and shared infrastructure.

3.11 Key Empirical Findings

The empirical results indicate that generation diversification is the most influential determinant of energy system resilience. The expansion of renewable energy sources strengthens long-term energy security, although its effectiveness depends on adequate institutional and regulatory support. Furthermore, regional integration generates significant synergistic effects by improving system reliability and reducing infrastructure costs. Overall, the findings suggest that a hybrid energy transition model, combining renewable energy deployment with conventional generation and enhanced regional cooperation, represents the most feasible pathway for Central Asian countries.

4 DISCUSSION

4.1 Interpretation of Key Results and Contribution to the Scholarly Debate

The findings confirm that, for Central Asian countries, energy security in the context of the transition is determined not so much by absolute resource endowment as by the structural resilience of energy systems-generation diversification, flexibility, reserve capacity, and the institutional ability to manage shocks. The identified positive relationship between diversification (D) and IESI (Fig. 5) is consistent with studies showing that dependence on a single dominant resource increases systemic risks-whether price-related, technological, or infrastructure-related [10].

At the same time, cross-country differences reveal an important "transition paradox": high carbon resilience (C) (e.g., in hydropower-based systems of Kyrgyzstan and Tajikistan) does not necessarily imply higher overall energy security. Hydro-oriented models are sensitive to hydrological variability, seasonality, and climate factors, which constrains supply resilience without sufficient interconnections and reserve generation [9], [10], [14]. Therefore, low-carbon performance should be treated as a component of security, but not as its full substitute.

4.2 Comparison with International Research and Practices

Scenario trajectories of IESI through 2040 (Table 7; Fig. 7) indicate that an "inertial" pathway leads to stagnation in resilience, whereas moderate and deep-decarbonization scenarios result in substantially higher levels of energy security. This logic aligns with international energy transition planning practices: accelerated renewable deployment requires grid modernization, storage, and market mechanisms; otherwise, a higher RES share does not translate into higher system resilience [27]. In the case of Uzbekistan, the results are consistent with research emphasizing "cost-optimal pathways" and the institutional conditions for implementing power sector development plans, as well as policy recommendations for solar energy and transition governance [28].

At the same time, the regional specificity of Central Asian countries makes direct replication of EU or East Asian models methodologically inappropriate. Unlike advanced energy markets-where carbon pricing and deep liberalization are key drivers-Central Asia faces critical constraints related to grid bottlenecks, the capital intensity of modernization, and institutional barriers (regulation, tariffs, banking risk, long-term offtake guarantees), [29]. This helps explain why the moderate scenario is often "optimal" in terms of resilience gains relative to investment requirements, whereas deep decarbonization demands accelerated development of financial and grid mechanisms.

4.3 Regional Integration as an "Amplifier" of the Energy Transition

One of the most important conclusions is the systemic effect of integration: modeling indicates that IESI increases when cross-border exchange and reserve sharing expand. In 2024, the World Bank Group, together with Masdar and the Government of Uzbekistan, signed a financial package to fund a 250-MW solar photovoltaic plant with a 63-MW battery energy storage system, marking Central Asia's first renewable energy initiative with an integrated BESS component [30]. Additional analytical materials on electricity trade and market development within regional initiatives also highlight the need to modernize cross-border lines and trading rules to improve reliability and economic efficiency [27].

Integration matters not only as "trading kilowatt-hours," but also as a mechanism for reducing system costs: joint peak coverage, reserve sharing, reduced need for excessive capacity, and more efficient integration of variable generation (wind/solar) through a broader balancing area. In this sense, cross-border transmission projects and initiatives-including the export of summer hydropower surpluses to neighboring markets (e.g., CASA-1000)-show that regional cooperation can enhance both energy security and the investment attractiveness of low-carbon generation [8].

4.4 Institutional Recommendations: "Hybrid Transition" as a Realistic Strategy

Based on IESI results and scenario analysis, the most justified strategy for the region is a hybrid transition combining three directions:

1) accelerated deployment of renewables (solar/wind) where resource quality and cost-effectiveness are highest (primarily Kazakhstan, Uzbekistan, Turkmenistan);
2) modernization of conventional generation and efficiency improvements (lower emission intensity, technological upgrading, demand-side management);
3) development of grid infrastructure, storage, and markets to increase flexibility and integrate renewables [34].

The practical feasibility of this logic is supported by rising financing for "green" projects: for example, in 2024 the EBRD financed major renewable energy and battery storage projects in Uzbekistan, including a 300 MW solar plant with 75 MWh battery storage in the Kashkadarya region and a 500 MWh battery energy storage system in the Tashkent region [31]. At the same time, international "just transition" recommendations emphasize the importance of social and labor aspects (reskilling, local value chains, regional employment), without which accelerated transition may generate internal sustainability risks [13].

Overall, the key priorities for improving IESI include:

- reforming tariff and market architecture (transparent grid access rules, predictable procurement mechanisms/auctions);
- accelerated modernization of grids and dispatch (SCADA/digitalization) [33];
- development of storage and flexible capacities;
- regional rules for trading and balancing (reserves, emergency support, seasonal exchanges).

4.5 Geoeconomic Implications: Risks and Opportunities for Central Asian Countries

The energy transition changes the structure of regional revenues and external economic relations. For hydrocarbon exporters, a key medium-term risk is a potential decline in external demand and the rise of "carbon barriers" in trade, reinforcing the need for economic diversification and improved domestic energy efficiency [29]. At the same time, the growth of renewables and storage creates new dependencies-on technology, equipment, rare-earth materials, and capital. Therefore, the technological independence component (L) becomes a critical element of energy security, while localization of services and competencies becomes a central industrial policy priority [17], [31], [32].

On the other hand, the region has a window of opportunity: development of a regional electricity market and cross-border infrastructure can transform Central Asia into a hub for interregional electricity trade (including supplies to neighboring markets when surpluses exist) and increase the attractiveness of large "green" projects by expanding market size and reducing system risks [8], [18], [27], [30]. In this sense, energy integration becomes not only a reliability tool but also a geoeconomic asset.

4.6 Research Limitations and Directions for Further Work

Key limitations relate to heterogeneity of national statistics, differences in accounting methods for emissions and generation, and limited availability of comparable data on reserves, network losses, and technology localization. In addition, scenario estimates through 2040 are sensitive to assumptions regarding investment rates, cost of capital, and timelines for grid modernization [6]. Future research should expand the model by: (i) explicitly incorporating network constraints (power flow constraints), (ii) assessing reliability (SAIDI/SAIFI), (iii) adding indicators of affordability and energy poverty, and (iv) more detailed assessment of climate risks for hydropower generation [9], [10].

5 CONCLUSIONS

This study provided a comprehensive analysis of the relationship between the energy transition and energy security in Central Asian countries, taking into account structural asymmetries of their energy systems, resource specificity, and the potential for regional integration. The developed and tested integral energy security model (IESI)-including components of generation diversification, reserve capacity, technological localization, and carbon resilience-enabled a quantitative assessment of national energy system resilience and identification of the key drivers of transformation.

Empirical results show that the most significant driver of energy security is diversification of the generation structure. Countries with a more balanced energy portfolio demonstrate higher values of the integral index. At the same time, low-carbon performance-while improving long-term resilience-does not constitute a sufficient condition for energy security without adequate reserve and grid infrastructure. Cluster analysis confirms three regional typologies-export hydrocarbon-based, transitional gas-based, and hydropower-based-implying the need for differentiated transition strategies.

Scenario modeling through 2040 indicates that an inertial pathway leads to stagnation in resilience indicators, whereas moderate and decarbonization scenarios ensure substantial IESI growth. However, deep decarbonization requires significant investment and institutional modernization. Under constrained access to capital, the most realistic strategy for the region is a hybrid transition model combining renewable development, modernization of conventional generation, and intensified regional cooperation.

Practical recommendations include:

1) accelerated development of solar and wind generation in countries with the greatest resource potential;
2) modernization of grid infrastructure and implementation of digital control systems;
3) deployment of energy storage and flexible capacities;
4) establishment of a regional electricity market and harmonization of regulatory frameworks;
5) increased technological localization and development of national competencies.

The scientific contribution lies in developing an adapted integral energy security assessment model for transition economies with resource asymmetry. The practical significance of the work is the formation of an analytical foundation for designing national energy strategies and mechanisms of regional integration.

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