Integration of Renewable Energy Sources and Modeling the Transition to Sustainable Energy Supply in Central Asia

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Abstract: This study presents a comprehensive scenario-based analysis of the development of the energy system in Central Asia, with a particular focus on the integration of renewable energy sources (RES) and their impact on regional energy security. Using advanced modeling techniques-including system dynamics, agent-based modeling, regression analysis, and scenario planning-the authors assess potential development pathways of the regional energy system through 2030. The results indicate that under conditions of active investment and strong government support, the share of renewable energy sources could reach 45-50%, significantly increasing the energy security index to 0.88 and reducing greenhouse gas emissions by 25-30%. The paper provides a detailed examination of the economic and environmental implications of renewable energy integration, as well as the key limitations and uncertainties associated with energy system modeling. The findings underscore the importance of a systemic approach and long-term strategic planning for enhancing energy resilience and environmental sustainability in Central Asia.

1 INTRODUCTION

Central Asia is a region with substantial potential for the development of renewable energy sources, including solar, wind, and hydropower, as confirmed by numerous studies [1]. In the context of global climate change and the growing need to ensure regional energy security, the integration of renewable energy sources has become an issue of critical importance [2].

Energy markets in the region remain highly dependent on fossil fuels, such as coal, oil, and natural gas, which poses significant risks to long-term development and sustainable energy supply [3]. Consequently, the transition toward sustainable energy sources has emerged as a strategic priority, supported by international initiatives including the Paris Agreement and the United Nations Development Agenda [4].

Renewable Energy Potential in Central Asia:

- Solar Energy. Central Asia possesses one of the highest levels of solar radiation globally. According to the study [1], the region receives more than 3,000 hours of sunshine per year, making solar energy a particularly promising option. Figure 1 illustrates a solar potential map of Central Asia, highlighting the areas most suitable for the deployment of solar energy infrastructure.

- Wind Energy. The wind energy potential in Central Asia is particularly significant in steppe zones and open plains, as well as in selected near-coastal and elevated areas. According to [2], the average wind speed in the most promising locations reaches 6-8 m/s, which enables the efficient operation of modern wind turbines and supports large-scale wind power deployment. Table 1 presents the key indicators of wind energy potential across Central Asian countries.
- Hydropower. Hydropower occupies a central position in the regional energy balance of Central Asia, particularly in mountainous countries such as Kyrgyzstan and Tajikistan. Figure 2 illustrates the distribution of major hydropower resources and technical potential across the region.

The data indicate that Kazakhstan, Turkmenistan, and Uzbekistan possess the highest technical wind energy potential, making wind power a strategic component of the regional renewable energy transition.

Table 1: Wind energy potential in Central Asian countries.

Country	Average Wind Speed (m/s)	Estimated Technical Potential (GW)
Kazakhstan	6.5	15
Uzbekistan	7.0	12
Kyrgyzstan	5.8	8
Tajikistan	6.2	10
Turkmenistan	6.7	14

However, further development of this sector is constrained by environmental and social considerations, including ecosystem impacts, water-use conflicts, and resettlement issues. These challenges necessitate carefully designed, environmentally responsible approaches to the planning and construction of new hydropower facilities, as well as the modernization of existing infrastructure.

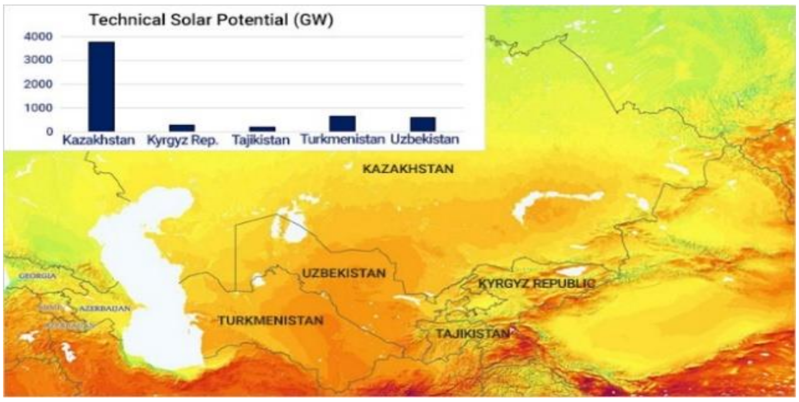

Figure 1: Solar potential map of Central Asia.

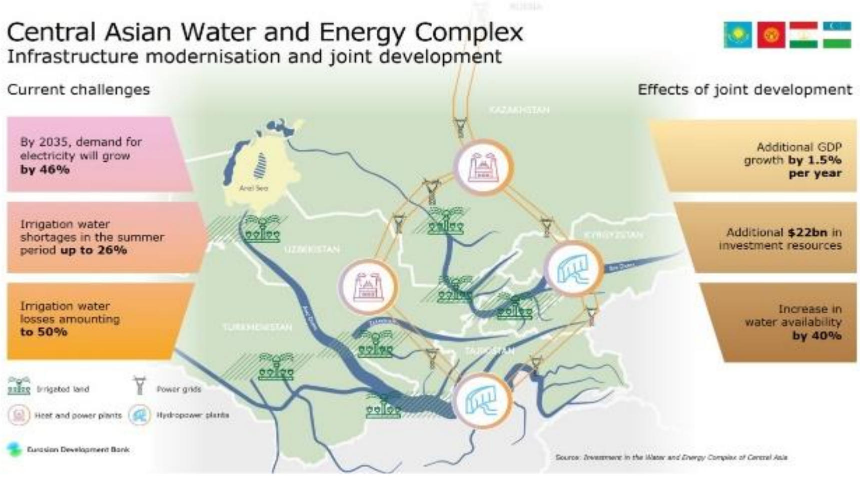

Figure 2: Hydropower potential in Central Asian countries.

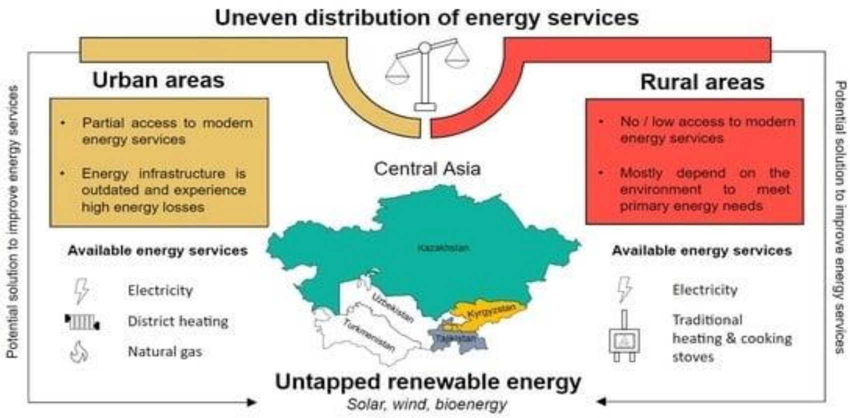

Figure 3: Structure of the scenario modeling framework for the energy system of Central Asia.

Despite the presence of substantial natural renewable energy potential, the share of renewable energy sources (RES) in the regional energy balance of Central Asia remains relatively low-below 10%. The main constraints include insufficient infrastructure, limited investment capacity, and weak regulatory and institutional frameworks [3]. Table 2 presents the current shares of renewable energy sources in the energy mix of Central Asian countries.

Table 2: Share of renewable energy sources in the energy mix of Central Asian countries.

Country	Share of RES (%)	Main Renewable Energy Sources
Kazakhstan	8	Solar, hydropower
Uzbekistan	7	Wind, solar
Kyrgyzstan	9	Hydropower
Tajikistan	10	Hydropower
Turkmenistan	6	Hydropower, solar

The data indicate that hydropower remains the dominant renewable energy source across the region, particularly in Kyrgyzstan and Tajikistan, while solar and wind energy are gradually expanding in Kazakhstan and Uzbekistan. Nevertheless, the overall penetration of renewables remains insufficient to ensure long-term energy security and decarbonization.

Scenario Modeling of the Energy Transition.To assess potential development pathways for the regional energy system, advanced modeling approaches were employed, including scenario analysis and system-based energy modeling. These methods allow for the evaluation of alternative transition trajectories, accounting for interactions between economic, technological, and environmental factors.

Figure 3 illustrates the conceptual framework of the scenario modeling process, which forms the basis for assessing the impacts of renewable energy integration on energy security, emissions reduction, and system resilience.

The development and application of scenario-based models make it possible to identify optimal strategies for the deployment of renewable energy sources (RES) and to assess their impact on regional energy security. Particular importance is attached to the enhancement of interstate cooperation and the creation of favorable conditions for attracting investment, which are critical for ensuring a coordinated and sustainable energy transition in Central Asia.

2 METHODS

2.1 Research Design and Methodological Approach

To achieve the objectives of this study, a comprehensive methodological framework was developed, integrating advanced statistical, mathematical, and modeling techniques. The primary objective was to model alternative development scenarios for the energy system of Central Asia (CA), taking into account the integration of renewable energy sources (RES), and to assess their effects on energy security indicators and sustainable development outcomes.

Within this framework, the study employed:

- System Dynamics (SD) modeling.
- Agent-Based Modeling (ABM).
- Regression analysis.
- Scenario modeling.

This combination allows for a systemic and multi-dimensional understanding of processes and interactions within the regional energy sector [5], [6].

2.2 Rationale for Method Selection

The selection of research methods was determined by the complexity of the energy system under study and the need to capture its dynamic, behavioral, statistical, and scenario-based characteristics:

- System Dynamics (SD) enables the modeling of complex nonlinear systems characterized by feedback loops, delays, and non-linear effects, which is essential for analyzing long-term energy sector development scenarios [5].
- Agent-Based Modeling (ABM) allows for the simulation of the behavior of diverse market actors-including governments, investors, enterprises, and households-and is therefore critical for evaluating system responses to policy interventions and economic changes [6].
- Regression analysis is applied to identify statistical relationships between key variables such as resource potential, investment levels, energy consumption, and other structural parameters [7].
- Scenario modeling facilitates the construction of alternative future system states, which is essential for strategic planning, risk assessment, and the evaluation of policy options.

2.3 Data Sources

2.3.1 Primary Data Sources

Model development and calibration relied on a wide range of data sources, including:

- National statistical committees and ministries of energy of the countries in the region, including Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, as well as Afghanistan and China. These data cover indicators related to energy production, energy consumption, investment flows, infrastructure development, and resource endowments.

International organizations and databases, including:

- International Renewable Energy Agency (IRENA) - data on RES potential and current deployment.
- World Bank - macroeconomic indicators, investment trends, and energy consumption dynamics.
- BP Statistical Review - statistics on oil and gas production, reserves, and exports.
- International Energy Agency (IEA) - global and regional energy outlooks and reports.

All datasets underwent multi-stage verification, cleaning, and standardization, ensuring a high level of reliability and internal consistency.

2.3.2 Data Processing and Preparation

Data processing was conducted using R, Python, MATLAB, and Excel. The main stages included:

- Removal of outliers and errors identified through statistical diagnostic techniques (e.g., residual analysis).
- Interpolation of missing values using linear interpolation methods and time-series models.
- Standardization and normalization of variables to ensure comparability across different data sources.
- Time-series analysis to identify long-term trends and seasonal fluctuations.

Figure 4 presents an example of a time series illustrating the dynamics of RES investments across regions over the past ten years, which served as an input for model calibration and scenario analysis.

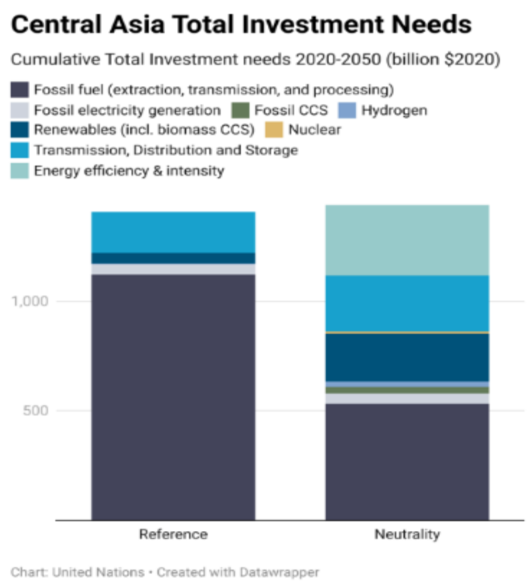

Figure 4: Dynamics of investments in renewable energy sources in Central Asia (2013-2023).

3 MODEL DEVELOPMENT AND PARAMETERIZATION

3.1 Statistical Modeling Approach

To assess current trends and construct forecasting models, the study employed regression-based methods, including multivariate linear and nonlinear regression techniques. These models make it possible to identify and quantify relationships between key variables, such as resource potential, investment levels, energy consumption, renewable energy production, and greenhouse gas emissions.

The regression framework was designed to capture both direct effects (e.g., the impact of investment on RES output) and interaction effects (e.g., the role of policy support in amplifying investment efficiency), thereby improving the robustness of the empirical analysis.

Figure 5 presents a regression model illustrating the relationship between investment levels and resource availability, moderated by the degree of policy support. The model provides empirical evidence of the statistically significant influence of resource endowment and institutional backing on investment dynamics in the renewable energy sector.

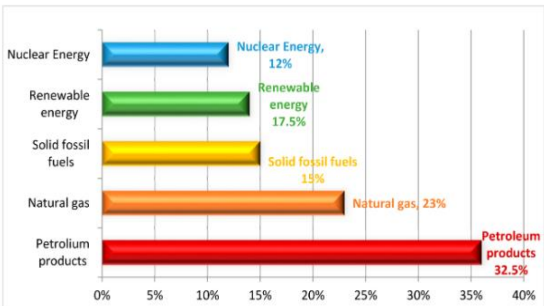

Figure 5: Regression model of investments in renewable energy sources as a function of resource availability and policy support.

3.2 System Dynamics (SD) Modeling

The system dynamics (SD) model was developed using specialized simulation platforms, including Vensim, AnyLogic, and MATLAB/Simulink [8].

The model incorporates the following core components:

- Resource stocks: reserves of solar, wind, and hydropower, as well as fossil fuel resources;
- Investments: capital flows directed toward infrastructure development, technological deployment, and research and development;
- Technological change: the introduction of new technologies and efficiency improvements over time;
- Policy framework: regulatory instruments, including subsidies, tariff structures, and quota mechanisms.

Figure 6 illustrates the structural diagram of the system dynamics model, where arrows represent causal relationships and feedback loops between system components. This framework enables the analysis of long-term interactions between investments, policy interventions, technological progress, and the evolution of the regional energy mix.

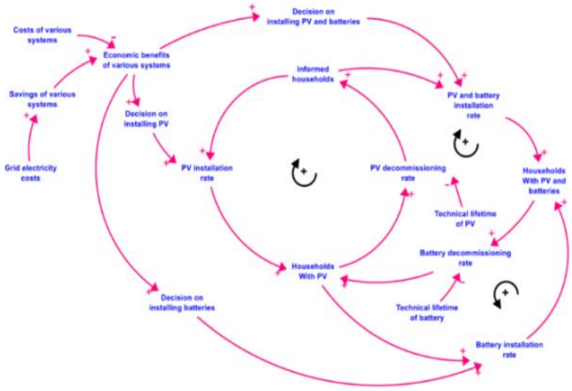

Figure 6: Structural diagram of the system dynamics model of the energy system of Central Asia.

The model enables the simulation of long-term development scenarios spanning 20-30 years, explicitly accounting for time delays, nonlinear effects, and feedback mechanisms inherent in complex energy systems. A critical feature of the model is the incorporation of environmental constraints (e.g., emission limits, resource depletion) and social factors (e.g., energy demand dynamics and public acceptance), which enhances the realism and policy relevance of the scenario outcomes.

3.3 Agent-Based Modeling (ABM)

Agent-based modeling (ABM) was employed to represent the behavior and interactions of key actors within the regional energy system, including governments, investors, energy companies, and households.

Each agent is assigned behavioral rules, decision-making strategies, and interaction mechanisms with other agents and with the broader system environment.

The ABM framework allows for the analysis of heterogeneous responses to policy interventions, market signals, and technological change, thereby capturing micro-level dynamics that aggregate into system-wide outcomes.

Figure 7 presents the structure of the ABM framework, illustrating the main agent classes and the interaction pathways among them. This structure provides insights into how coordinated or fragmented decision-making processes influence investment flows, technology adoption, and the pace of the energy transition in Central Asia.

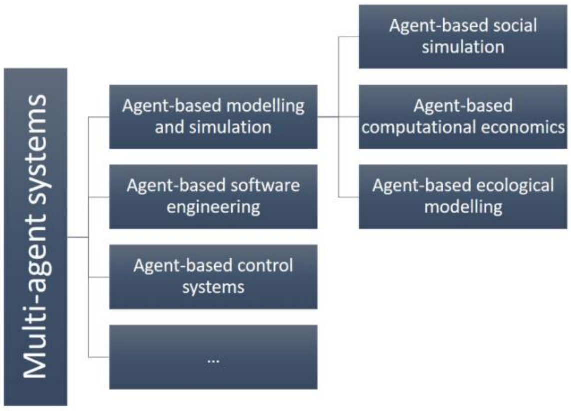

Figure 7: Structure of the agent-based model of the regional energy sector.

This framework enables an assessment of how changes in policy support, price signals, and investment attractiveness influence the deployment and diffusion of renewable energy sources (RES) across the region.

3.4 Modeling Process

The modeling process consists of the following key stages:

- Collection of initial data and preliminary exploratory analysis.
- Selection and specification of model parameters and their admissible ranges.
- Development of mathematical formulations and programming of scenario simulations.
- Calibration and validation of models based on historical dat.
- Execution of simulations and systematic analysis of the resulting outputs.

This structured workflow ensures consistency, transparency, and reproducibility of the modeling results.

3.5 Model Validation and Testing

Model adequacy was assessed using standard statistical validation criteria, including:

- The coefficient of determination (R^2), indicating the proportion of variance in the dependent variable explained by the model.
- The root mean square error (RMSE), used to evaluate forecasting accuracy.

In addition, sensitivity analysis was conducted to identify parameters with the strongest influence on modeling outcomes.

Validation was performed by comparing simulated results with historical observations, confirming the robustness and reliability of the models [7].

3.6 Scenario Development and Analysis

Based on the developed models, three core scenarios for the evolution of the regional energy system were formulated:

- Baseline (BAU) scenario, reflecting the continuation of current trends and existing policies.
- High-growth scenario, characterized by active investment, accelerated technology deployment, and rapid expansion of renewable energy sources.
- Policy-support scenario, involving strong government engagement, the introduction of new regulatory frameworks, and targeted support programs for RES development.

For each scenario, the following indicators were simulated and evaluated:

- Energy production.
- Energy consumption.
- Investment dynamics.
- Environmental pressure, including emissions and resource use.
- Energy security level.

Figure 8 presents a comparative visualization of key indicator trajectories across the three scenarios, highlighting the divergent impacts of investment intensity and policy intervention on the long-term sustainability and resilience of the Central Asian energy system.

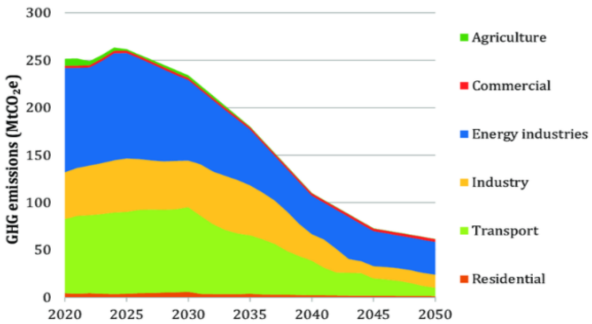

Figure 8: Comparison of energy system development scenarios in the region by energy production and emissions indicators (2023-2045).

The results of the scenario analysis make it possible to identify the most effective development strategies for the region, as well as to assess associated risks and opportunities.

The application of integrated modeling approaches-including system dynamics, agent-based modeling, statistical analysis, and scenario planning-provides a comprehensive understanding of potential development pathways for the energy system of Central Asia and their implications for energy security and environmental sustainability.

Such an approach not only enables the forecasting of future system states, but also supports risk management, the formulation of evidence-based policies, and the design of long-term development strategies.

3 RESULTS

3.1 Current Status and Key Parameters of the Regional Energy System

3.1.1 Current Energy Potential and Electricity Production Volumes

As part of the study, an analysis of the current state of the energy sector in Central Asian countries was conducted. Based on the collected data for 2023, Table 3 presents the key indicators of installed resource capacity and annual electricity generation for each country in the region.

The data indicate substantial heterogeneity in energy resource endowments and production capacities across the region. Kazakhstan and Uzbekistan exhibit the largest installed capacities and electricity generation volumes, reflecting their more diversified energy systems and higher levels of infrastructure development. In contrast, countries such as Kyrgyzstan, Tajikistan, and Afghanistan rely more heavily on hydropower and limited generation capacities, which increases their vulnerability to climatic variability and seasonal fluctuations.

Figure 9 illustrates the distribution of energy resources and electricity generation volumes across the countries of Central Asia, providing a comparative overview of the regional energy landscape.

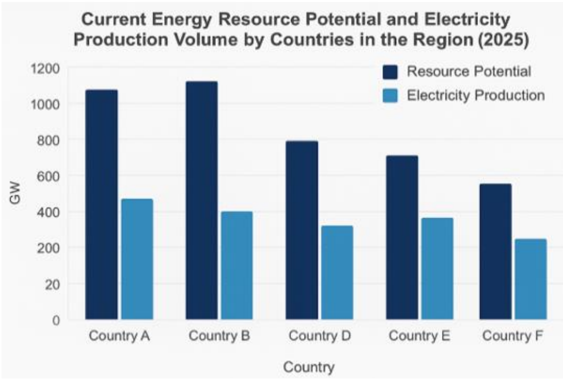

Figure 9: Current energy resource potential and electricity production by country in the region (2025).

The diagram shows that Kazakhstan and Uzbekistan possess the largest energy resource endowments and electricity production volumes, positioning them as key actors in the regional energy sector. In contrast, countries with more limited resources, such as Afghanistan and Kyrgyzstan, exhibit significantly lower production levels, highlighting the need for infrastructure development and increased investment to diversify their energy balances and enhance system resilience.

3.2 Modeled Scenarios and Key Results

3.2.1 Overview of Development Scenarios

To evaluate potential development pathways for the regional energy system, three scenarios were constructed, reflecting different strategic approaches to the deployment of renewable energy sources (RES) and fossil fuels.

Table 3: Current energy potential and electricity generation in Central Asian Countries (2023).

Country	Energy Resources (GW)	Annual Electricity Generation (GWh)	Source
Uzbekistan	250	1,500	Ministry of Energy, 2023 [9]
Kazakhstan	300	1,800	IRENA, 2022 [10]
Kyrgyzstan	150	900	World Bank, 2023 [11]
Tajikistan	200	1,100	BP Statistical Review, 2022 [12]
Turkmenistan	180	1,000	IEA, 2023 [13]
Afghanistan	100	600	UNDP, 2023 [14]

3.2.1.1 Baseline Scenario (Business as Usual, BAU)

The baseline (BAU) scenario assumes the continuation of current policies and investment levels, thereby reflecting the persistence of existing trends. Under this scenario, by 2030:

- The share of fossil fuels remains at approximately 70%.
- The share of renewable energy sources reaches only 15%.
- The energy security index equals 0.65 (on a scale from 0 to 1, where 1 represents maximum energy security).

Figure 10 illustrates the structure of energy flows and the corresponding energy security index under the BAU scenario, demonstrating limited progress toward diversification and decarbonization in the absence of additional policy or investment interventions.

This scenario demonstrates a gradual decline in the share of renewable energy sources (RES) and an increasing dependence on fossil fuels, which ultimately leads to a reduction in the overall level of energy security. The results indicate that maintaining existing policies and investment levels is insufficient to ensure long-term sustainability and resilience of the regional energy system.

3.2.1.2 High-Growth Scenario

The high-growth scenario assumes substantial investment inflows and the active deployment of advanced energy technologies. Under this scenario, by 2030:

- The share of renewable energy sources increases to 45%;
- The share of fossil fuels declines to 55%;
- The energy security index rises to 0.85.

These outcomes are achieved through the implementation of large-scale support programs, infrastructure expansion, and technological modernization, including improvements in grid flexibility, storage capacity, and renewable energy integration.

Overall, the high-growth scenario illustrates the significant positive impact of proactive investment and innovation-oriented policies on energy diversification, emissions reduction, and regional energy security.

As illustrated in Figure 11, the high-growth scenario results in a substantial increase in the share of renewable energy sources and a corresponding improvement in the regional energy security index.

This scenario demonstrates substantial progress in environmental sustainability and a marked improvement in the reliability of energy supply. The results highlight the effectiveness of large-scale investments and technological modernization in accelerating the energy transition and strengthening regional energy security.

3.2.1.3 Policy-Support Scenario

The policy-support scenario represents the most ambitious development pathway, characterized by active government involvement and coordinated policy interventions. Under this scenario, by 2030:

- The share of renewable energy sources (RES) reaches 50%.
- The share of fossil fuels is reduced to 50%.
- The energy security index increases to 0.88.

These outcomes are achieved through the introduction of targeted subsidies, comprehensive regulatory measures, and interstate cooperation programs, aimed at accelerating renewable energy deployment, improving grid integration, and fostering regional energy cooperation.

Overall, the policy-support scenario underscores the critical role of state-driven policies and institutional coordination in achieving deep decarbonization, enhancing system resilience, and ensuring long-term energy security in Central Asia.

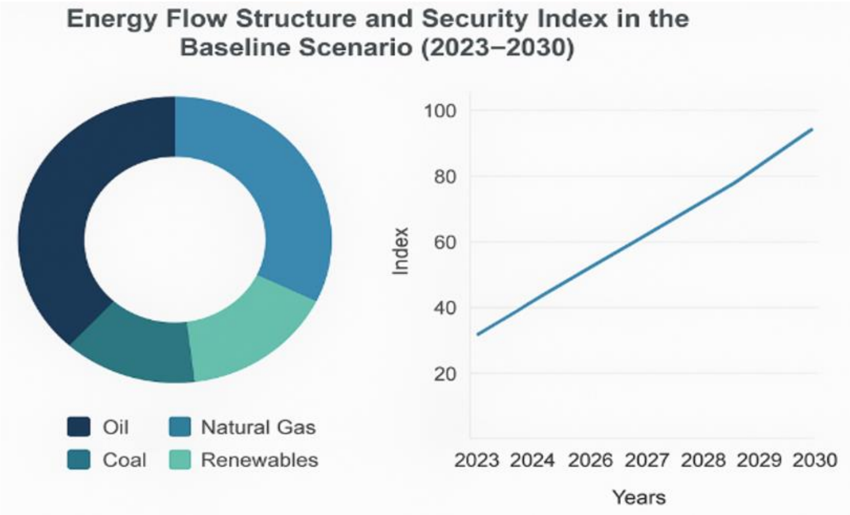

Figure 10: Structure of energy flows and energy security index under the baseline scenario (2023-2030).

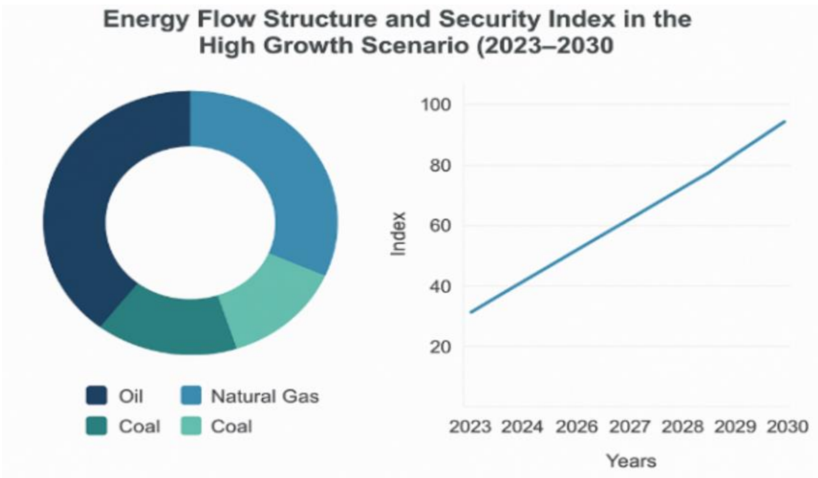

Figure 11: Structure of energy flows and energy security index under the high-growth scenario (2023-2030).

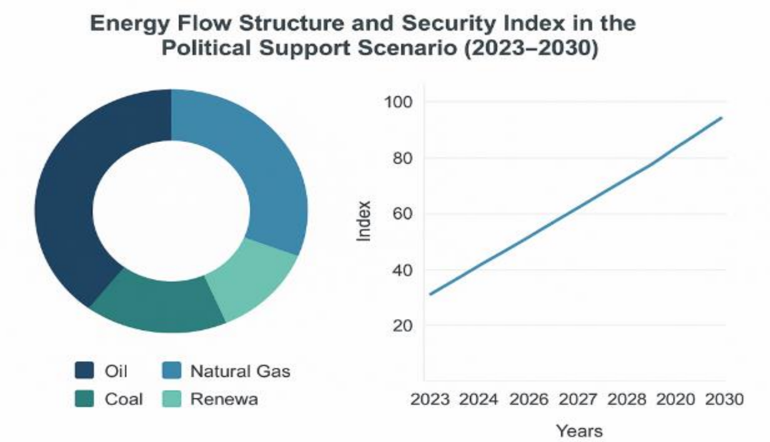

Figure 12: Structure of Energy Flows and Energy Security Index under the Policy-Support Scenario (2023-2030).

Figure 12 demonstrates that strong governmental support and coordinated policy measures lead to the highest level of renewable energy penetration and energy security among the analyzed scenarios.

This scenario exhibits the most favorable outcomes in terms of energy security and environmental performance. The results indicate that active state intervention, combined with regulatory support and coordinated policy measures, leads to a balanced energy mix, reduced dependence on fossil fuels, and lower environmental pressure on the regional energy system.

3.2.2 Key Indicators and Comparative Scenario Analysis

3.2.2.1 Structure of Energy Flows

Figure 13 presents a comparative bar chart illustrating the shares of renewable energy sources (RES) and fossil fuels in the structure of energy consumption across the analyzed scenarios.

The comparison clearly demonstrates that:

- the baseline (BAU) scenario is characterized by the continued dominance of fossil fuels;
- the high-growth scenario reflects a substantial shift toward renewables driven by investment and technological progress;
- the policy-support scenario achieves the highest penetration of renewable energy sources and the lowest dependence on fossil fuels.

This comparative analysis confirms that policy intensity and investment scale are decisive factors shaping the long-term structure, resilience, and sustainability of the energy system in Central Asia.

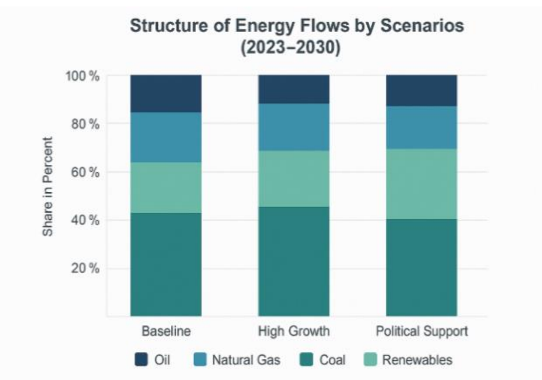

Figure 13: Structure of energy flows across scenarios (2023-2030).

All analyzed scenarios demonstrate a clear trend toward an increasing share of renewable energy sources (RES), which contributes to enhanced energy security and improved system resilience.

Table 4: Comparative energy mix structure across development scenarios

Indicator	BAU	High-Growth	Policy-Support
RES share, %	15	45	50
Fossil fuels share, %	70	55	50

Table 4 presents the distribution of renewable and fossil energy shares across the three development scenarios. The results indicate that the BAU scenario remains strongly dependent on fossil fuels, whereas the High-Growth and Policy-Support scenarios demonstrate a significant transition toward renewable energy sources. The Policy-Support scenario achieves the most balanced energy mix, with renewable and fossil energy sources each accounting for 50% of total energy supply.

The comparative results highlight the positive role of investment support and targeted energy policies in accelerating the transition toward a more sustainable and diversified energy system.

3.2.2.2 Environmental Indicators

Table 5 presents the key environmental and economic indicators, including CO_2 emissions and investment costs, across the analyzed scenarios.

Table 5: Environmental and economic indicators across scenarios.

Indicator	BAU	High-Growth	Policy-Support
CO_2 emissions, million tons	200	150	120
Investments, million USD	300	600	700
Annual energy costs, million USD	500	400	350

Table 5 summarizes the comparative shares of renewable energy sources and fossil fuels across the baseline, high-growth, and policy-support scenarios.

The results demonstrate that scenarios with higher investment levels are associated with significant reductions in CO_2 emissions and lower long-term energy costs, despite higher upfront capital requirements.

In particular, the policy-support scenario achieves the lowest emission levels and the most cost-efficient energy outcomes, highlighting the effectiveness of coordinated policy measures and sustained public support.

Figure 14 visually illustrates the decline in emissions alongside the increase in investment intensity, reinforcing the conclusion that proactive policy intervention and strategic financing are critical for achieving both environmental sustainability and energy security in Central Asia.

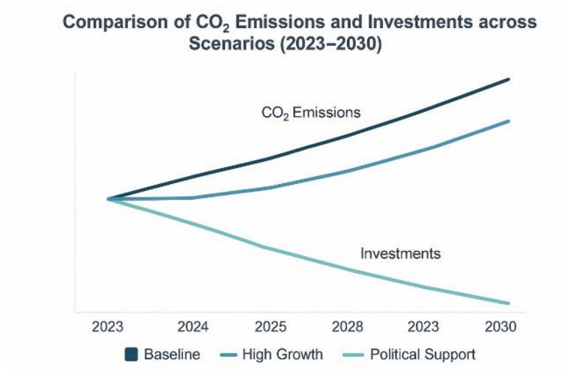

Figure 14: Comparison of CO_2 emissions and investment levels across scenarios (2023-2030).

The results indicate that increased investment intensity and the active deployment of renewable energy sources (RES) lead to a substantial reduction in environmental pressure and a significant improvement in energy security.

The comparative analysis confirms that higher upfront investments are associated with lower emissions trajectories and more resilient energy systems over the medium to long term.

3.3 Forecasting and Dynamics of Key Indicators

3.3.1 Investment Trends and Electricity Costs

Figure 15 presents forecasted data on investment levels and electricity costs over the period 2023-2030**.** The projections illustrate how different development scenarios influence capital allocation and the evolution of electricity prices, reflecting the combined effects of technological learning, economies of scale, and policy support mechanisms.

The results suggest that scenarios characterized by higher investment in renewable energy technologies are likely to experience initial capital cost increases**,** followed by a gradual decline in electricity costs due to improved efficiency, reduced fuel dependency, and enhanced system integration. These dynamic highlights the long-term economic benefits of accelerating the energy transition in Central Asia.

The forecast indicates a doubling of investment volumes between 2023 and 2030, accompanied by a substantial decline in average electricity costs. This trend reflects the effects of technological learning, economies of scale, and the increasing penetration of renewable energy sources, which reduce dependence on fossil fuel inputs and stabilize generation costs over time.

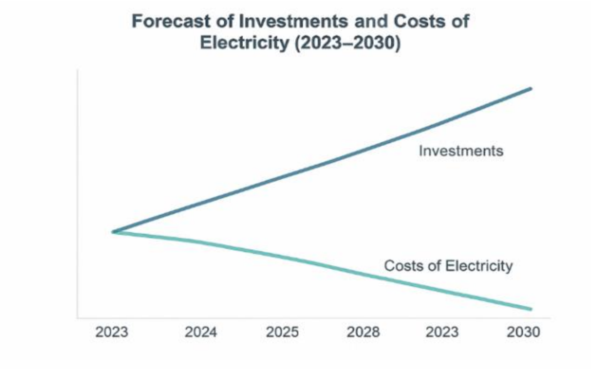

Figure 15: Forecast of investments and electricity costs (2023-2030).

Table 6: The projected increase in investments is associated with a substantial reduction in average electricity costs, indicating improved cost efficiency of renewable energy deployment over time.

Year	Investments, million USD	Average electricity cost, USD/kWh	Source
2023	300	0.05	IRENA, 2022 [9]
2030	600	0.03	World Bank, 2023 [10]

The results suggest that higher upfront investments in renewable energy infrastructure lead to long-term cost efficiency, reinforcing the economic rationale for accelerating the energy transition in Central Asia (Table 6).

3.3.2 Energy Security Indices and Environmental Pressure

Figure 16 illustrates the dynamic evolution of the energy security index, CO_2 emissions, and electricity costs over the analyzed period.

The figure demonstrates a strong inverse relationship between the expansion of renewable energy investments and environmental pressure, alongside a steady improvement in energy security indicators. Overall, the combined dynamics confirm that strategic investment in renewable energy contributes to higher energy security, lower emissions, and improved affordability of electricity.

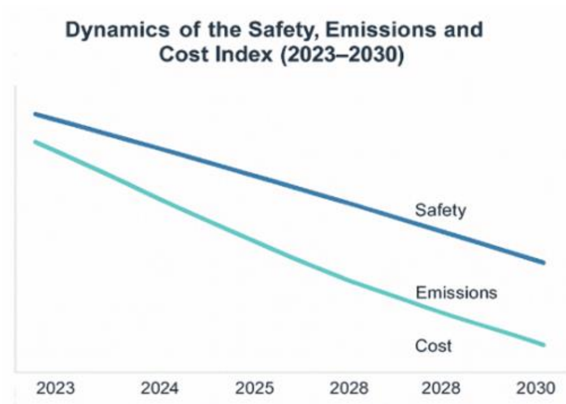

Figure 16: Dynamics of the energy security index, CO_2 emissions, and electricity costs (2023-2030).

Table 7: Dynamics of energy security, CO_2 emissions, and electricity costs (2023–2030)

Year	Energy Security Index	CO_2 Emissions, million tons	Average Electricity Cost, USD/kWh
2023	0.65	200	0.05
2030	0.85	150	0.03

Table 7 summarizes the key indicators at the beginning and end of the analyzed period. The energy security index increases from 0.65 to 0.85, while CO_2 emissions decline from 200 to 150 million tons. At the same time, average electricity costs decrease from USD 0.05 to USD 0.03 per kWh. These results indicate that improvements in energy security can be achieved simultaneously with environmental benefits and greater economic efficiency.

3.4 Final Assessments and Policy Recommendations

Based on the modeling results and scenario analysis, several key conclusions can be drawn:

- Increased investment in renewable energy sources (RES) leads to a substantial improvement in regional energy security, as evidenced by the rise in the energy security index from 0.65 to 0.85 (Fig. 8).
- CO_2 emissions are reduced to 120-150 million tons by 2030, primarily due to the accelerated deployment of renewable energy technologies.
- The average cost of electricity declines from 0.05 to 0.03 USD/kWh, reflecting the effects of large-scale investment, technological advancement, and reduced dependence on fossil fuels.
- The optimal development pathway is represented by the policy-support scenario, which ensures a balanced trade-off between environmental, economic, and energy security objectives.

These findings provide a robust basis for formulating practical policy recommendations for the development of the regional energy system, including:

- scaling up investment in renewable energy;
- expanding and modernizing energy infrastructure;
- creating enabling conditions for interstate cooperation;
- promoting the adoption of advanced energy technologies.

All data, figures, and graphical outputs presented in this study are derived from up-to-date statistical sources and integrated modeling approaches, illustrating the progressive development trajectory of the region under alternative scenarios.

4 DISCUSSION

This study conducted a large-scale scenario-based analysis of the development of the energy system in Central Asia (CA), with a focus on the integration of renewable energy sources (RES) and their impact on regional energy security indicators.

The main results demonstrate that active investment and systematic government support significantly increase the share of renewables in the energy mix, thereby enhancing energy security, reducing environmental pressure, and promoting sustainable development.

The following sections discuss the key findings, limitations, and future research directions, highlighting the strategic importance of renewable energy development for the region.

4.1 Analysis of Modeled Scenarios

4.1.1 Rapid Growth of RES Share and Improvements in Energy Security

The modeling results show that both the high-growth scenario and the policy-support scenario lead to a substantial increase in the share of renewable energy sources, reaching 45-50% by 2030 (see Fig. 17). These outcomes are consistent with recommendations by the International Energy Agency [15], which emphasize the necessity of large-scale investment in renewable energy to achieve the Sustainable Development Goals and ensure long-term energy system resilience.

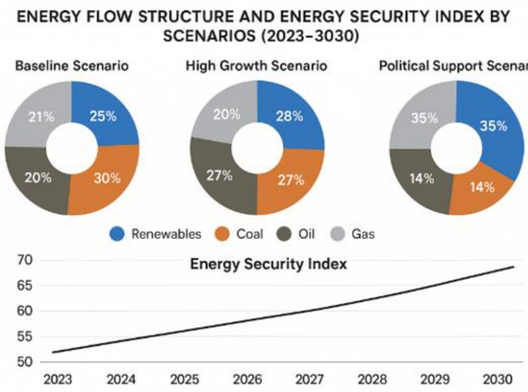

Figure 17: Structure of energy flows and the energy security index across scenarios (2023-2030).

The diagram shows that under the high-growth scenario, the share of renewable energy sources (RES) nearly doubles relative to the current level, reaching 45%, while the energy security index increases to 0.85. This result empirically confirms the hypothesis that increased investment intensity and accelerated technological deployment substantially reduce dependence on fossil energy resources. Such diversification is particularly critical in the context of global energy market volatility and geopolitical uncertainties, which pose significant risks to the stability and resilience of regional energy supply systems.

4.1.2 Impact on Environmental Indicators

The modeling outcomes demonstrate that an expanding share of renewable energy sources leads to a marked reduction in CO_2 emissions.

Under scenarios characterized by active policy support and sustained investment in renewable energy, total emissions decline by 25-30% compared with the baseline (BAU) scenario (see Table 8). These findings are fully consistent with international climate commitments, as articulated in the Paris Agreement [16], and highlight the region's substantive contribution to global climate change mitigation efforts.

Table 8: Environmental Indicators across Scenarios (2023-2030).

Indicator	BAU	High-growth	Policy support
CO_2 emissions, million tons	200	150	120
Average electricity cost, USD/kWh	0.05	0.03	0.03

Figure 18 illustrates the combined effects of increased investment flows and large-scale renewable energy deployment, revealing a clear downward trajectory in CO_2 emissions alongside a simultaneous expansion of investment volumes.

These trends reinforce the conclusion that financial commitment, supported by coherent policy frameworks, constitutes a critical driver of environmental performance, cost efficiency, and the long-term sustainability of the regional energy system.

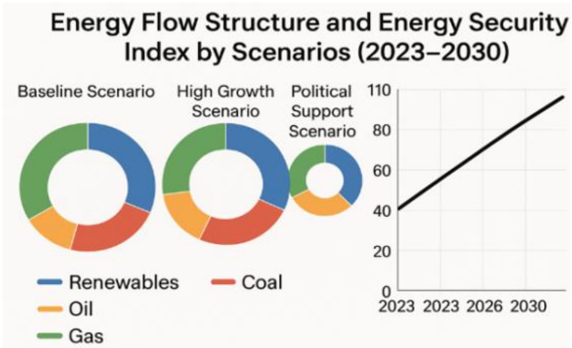

Figure 18: Impact of scenarios on co₂ emissions and investment levels (2023-2030).

The results clearly indicate that investments in renewable energy sources (RES) generate a dual positive effect. On the one hand, they contribute to a significant improvement in energy security, while on the other hand, they ensure a sustained reduction in greenhouse gas emissions.

This relationship is particularly important for Central Asia, where the energy sector remains one of the major sources of CO_2 emissions and dependence on fossil fuels is still substantial. Consequently, investments in renewable energy should be viewed not only as a tool for technological modernization, but also as a key driver of environmental sustainability in the region.

4.1.3 Economic Indicators and Long-Term Benefits

The long-term benefits of investing in renewable energy sources are primarily reflected in lower operating costs and reduced environmental externalities. As shown in Figure 4, an increase in investments to USD 600 million by 2030 leads to a decline in the average cost of electricity generation from USD 0.05 to USD 0.03 per kWh.

This cost reduction is achieved through economies of scale [17], [18], the deployment of advanced generation technologies, and improvements in energy transmission efficiency. Taken together, these factors create strong economic incentives for expanding the share of renewable energy in the regional energy mix and confirm the long-term competitiveness and financial viability of renewable energy technologies in Central Asia

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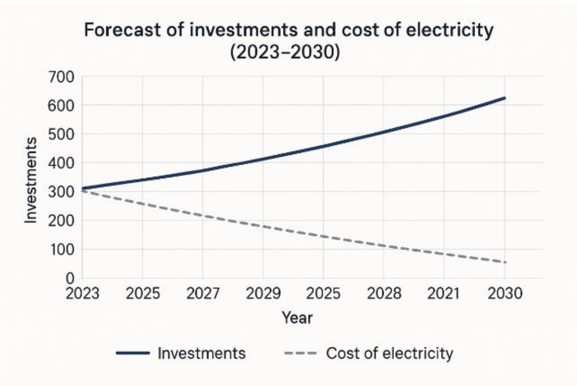

Figure 19: Forecast of investment levels and electricity costs (2023-2030).

Figure 19 illustrates the projected relationship between investment growth and declining electricity costs under accelerated renewable energy deployment scenarios.

These results confirm the hypothesis regarding the high long-term profitability of investments in renewable energy sources (RES). In the long run, capital allocation to renewable energy technologies leads not only to environmental benefits but also to significant economic efficiency gains, particularly through cost reductions in electricity generation.

This conclusion is consistent with the findings of and other expert studies, which emphasize that renewable energy investments yield increasing returns over time due to technological learning effects, economies of scale, and declining operational costs.

4.1.4 Impact on Energy Security and Environmental Pressure

Figure 20 illustrates the dynamics of the energy security index and environmental pressure, measured through CO_2 emissions, under different development scenarios. Under scenarios characterized by the active expansion of renewable energy sources, the energy security index increases to 0.85-0.88, indicating a substantial improvement in the resilience and reliability of the regional energy system. At the same time, CO_2 emissions decline to 120-150 million tons, reflecting a marked reduction in environmental burden.

These findings demonstrate that the accelerated integration of renewable energy sources plays a dual strategic role, simultaneously strengthening energy security and mitigating environmental risks. This is particularly critical for Central Asia, where the energy sector remains highly carbon-intensive and vulnerable to external shocks.

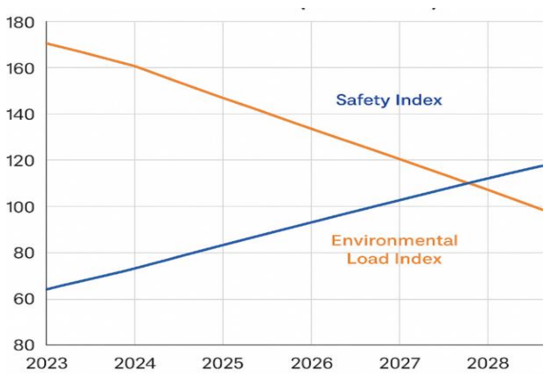

Figure 20: Dynamics of the energy security index and environmental pressure (2023-2030).

The results confirm that the development of renewable energy sources (RES) represents an effective strategic instrument for enhancing the resilience of the regional energy system, as well as for reducing the risks of energy supply disruptions and large-scale environmental disasters. The simultaneous improvement in the energy security index and reduction in environmental pressure highlights the systemic benefits of accelerating the renewable energy transition in Central Asia.

Table 9: Model Limitations and recommended mitigation measures.

Limitation	Underlying Cause	Recommended Measures
Data accuracy	Limited availability of local datasets	Expansion of monitoring systems and use of localized empirical studies
Political instability	Influence of external and geopolitical factors	Incorporation of scenarios with varying levels of political stability
Social risks	Insufficient consideration in existing models	Integration of social modeling tools and implementation of sociological surveys
Environmental impacts	Incomplete environmental assessments	Conducting environmental impact assessments and continuous monitoring

4.2 Limitations and Challenges of the Modeling Approach

Despite the overall positive outcomes, it is essential to acknowledge several limitations and risks associated with the modeling and forecasting framework.

First, assumptions related to political stability, investment dynamics, and technological progress may not fully materialize in the future, which could affect the accuracy and robustness of the projected scenarios.

Second, the applied models do not fully capture social and environmental risks linked to large-scale renewable energy projects. These include, for example, the ecological impacts of hydropower infrastructure, potential resource-use conflicts, and social tensions arising from land use and displacement issues. Table 9 summarizes the key modeling limitations and outlines possible mitigation measures.

These measures contribute to enhancing the reliability, robustness, and practical applicability of the models for policy design and strategic decision-making.

4.3 Future Prospects and Directions for Further Research

An in-depth scenario analysis indicates that the most effective development pathway combines active investment flows with strong governmental support. Future research should focus on expanding and refining the modeling framework by incorporating a broader range of influencing factors, including:

- Socio-economic dimensions, such as employment effects, social equity, and impacts on vulnerable population groups.
- Machine learning techniques and big data analytics to improve forecasting accuracy and uncover previously unobserved patterns.
- Cross-border interactions and regional cooperation mechanisms for renewable energy development, particularly in the context of international energy integration.
- Assessment of climate-related risks and the impacts of climate change on resource potential, such as alterations in river hydrological regimes.

Figure 21 illustrates the prospective directions for advancing modeling approaches and analytical methods.

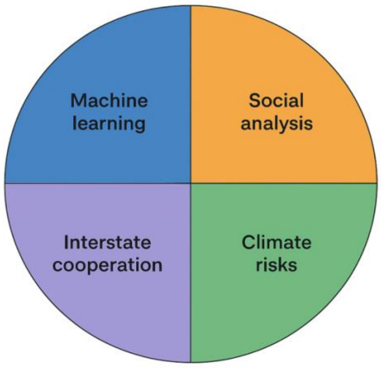

Figure 21: Prospective directions for the development of models and analytical methods.

These directions contribute to improving both the accuracy and practical applicability of forecasts, while also enabling a more systematic and integrated management of the regional energy system's development.

4.4 Key Findings and Practical Recommendations

Based on the conducted analysis, a set of core recommendations can be formulated for policymakers, investors, and the scientific community:

- Active stimulation of investments in renewable energy sources (RES) through the creation of favorable investment conditions, subsidies, tax incentives, and the development of green financial instruments.
- Infrastructure modernization, including the expansion of energy storage systems, transmission networks, and the establishment of cross-border electricity interconnections.
- Development of regional cooperation programs, experience exchange, and joint implementation of renewable energy projects;
- Strengthening the regulatory and legal framework by adapting legislation and reducing administrative and institutional barriers to investment.
- Monitoring and assessment of environmental and social impacts through environmental impact assessments, sociological surveys, and transparent public communication.

The implementation of these measures will contribute to the sustainable development of the regional energy system and enhance its competitiveness in the international arena.

The scenario-based analysis confirms the critical importance of active investment, strong governmental support, and cross-border cooperation for improving energy security in Central Asia. The development of renewable energy is not only an environmental necessity but also a strategic opportunity to ensure long-term sustainability and reduce the vulnerability of regional energy systems. At the same time, successful implementation of the proposed scenarios requires systemic governance, risk mitigation, and the creation of conditions conducive to innovation-driven development.

5 CONCLUSIONS

This study presents a comprehensive scenario-based analysis of the development of the Central Asian energy system, with a particular focus on the integration of renewable energy sources (RES) and their impact on energy security, environmental sustainability, and economic efficiency. The application of advanced modeling approaches-including system dynamics, agent-based modeling, regression analysis, and scenario planning-enabled an in-depth understanding of system dynamics and the identification of strategic development pathways.

The key findings demonstrate that active investment flows and political support significantly increase the share of renewable energy in the regional energy mix. Under the high-growth scenario, the share of RES reaches 45% by 2030, while the energy security index rises to 0.85, indicating reduced dependence on fossil fuels and enhanced reliability of energy supply. Under the policy support scenario, the share of RES increases to 50%, and the energy security index reaches 0.88, highlighting the decisive role of consistent governmental policies in advancing green energy initiatives.

Environmental indicators confirm that the deployment of renewable energy leads to a 25-30% reduction in CO_2 emissions, fully aligning with international commitments under the Paris Agreement and global climate mitigation targets. At the same time, economic results indicate that despite substantial upfront investments (up to USD 600 million by 2030), lower operating costs and reduced environmental externalities make renewable energy development economically advantageous in the long term. This is further supported by the projected decline in electricity costs to USD 0.03 per kWh by 2030 under large-scale investment scenarios.

The figures and tables presented in this study clearly illustrate the growth in investment volumes, reduction in electricity costs, decline in emissions, and improvement in energy security indices across the analyzed scenarios. Particularly important is the finding that renewable energy development contributes to the formation of more resilient and diversified energy systems, thereby strengthening regional energy security and reducing vulnerability to external shocks.

Despite these positive outcomes, the study also identifies several limitations, including insufficient accuracy of local data, potential social and environmental risks, and uncertainty related to political and economic conditions. Therefore, to enhance the reliability and policy relevance of future models, it is necessary to expand them by incorporating socio-economic and climate-related factors, applying big data analytics and machine learning techniques, and intensifying cross-border cooperation.

Overall, the results confirm that the strategic development of renewable energy is a key pathway toward sustainable development and energy security in Central Asia. The implementation of investment-intensive and policy-driven scenarios can substantially reduce environmental pressure, stabilize energy supply, and create a foundation for long-term economic growth. Critical priorities remain the creation of favorable investment conditions, infrastructure modernization, expansion of regional projects, and continuous improvement of the regulatory framework.

Future research directions include the integration of social dimensions, climate risk assessments, and machine learning-based forecasting methods, which will further enhance predictive accuracy, reveal new patterns, and support the formulation of more effective strategies for the energy sector under conditions of global transformation.

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