Decarbonization of Central Asian Economies in the Context of Achieving net Zero Targets

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Abstract: Achieving climate neutrality (Net Zero) has become a strategic priority for global climate stability and sustainable economic development. Central Asian countries, characterized by high dependence on fossil fuels and significant renewable energy potential, face both challenges and opportunities in the transition toward low-carbon economies. This study analyzes decarbonization prospects in Central Asia for the period 2026-2050 using scenario-based and institutional approaches. Three development scenarios are examined: Business-as-Usual (BAU), Moderate Energy Transition, and Net Zero by 2050. The analysis evaluates CO_2 emission trajectories, changes in the regional energy mix, sectoral contributions to emission reduction, and institutional readiness for energy transition. The results show that the BAU scenario maintains a carbon-intensive development path and widens the gap between actual emissions and climate targets. The Moderate Transition scenario slows emission growth but remains insufficient to achieve climate neutrality. In contrast, the Net Zero scenario demonstrates the potential to reduce regional CO_2 emissions by 80-90% through large-scale renewable energy deployment, energy system modernization, and consistent institutional reforms. The findings further indicate that governance quality, regulatory frameworks, investment conditions, and monitoring systems are critical determinants of successful decarbonization. Without institutional transformation, the region's technical potential for emission reduction cannot be fully realized. These results provide practical guidance for climate and energy policy development and support the design of long-term sustainable development and Net Zero transition strategies in Central Asia.

1 INTRODUCTION

1.1 Global Context of Decarbonization and the Net Zero Agenda (2026-2050)

In recent decades, climate change has evolved from primarily a scientific concern into a central determinant of global economic and environmental policymaking. The accelerated increase in atmospheric concentrations of greenhouse gases-primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)-is largely the result of industrial development based on extensive fossil fuel consumption. According to international assessments, the energy sector remains the largest source of anthropogenic emissions, accounting for more than two-thirds of global CO_2 emissions.

In this context, economic decarbonization is understood as a systemic and long-term transformation of production structures, energy systems, and institutional frameworks aimed at significantly reducing the carbon intensity of economic growth. Decarbonization is no longer viewed solely as an environmental objective but as a comprehensive structural transition affecting industrial policy, financial systems, technological innovation, and governance mechanisms.

The Net Zero concept-defined as achieving a balance between anthropogenic greenhouse gas emissions and their removal by mid-century-has become the cornerstone of the global climate agenda. Enshrined in the Paris Agreement and supported by a growing number of countries, including those with transition economies, the Net Zero target for 2050 is considered both an ecological imperative and a foundation for a new sustainable development paradigm. In this paradigm, economic growth, energy security, and climate resilience reinforce each other rather than conflict.

The period 2026-2050 is expected to represent the most intensive phase of the global energy transition. It is characterized by the simultaneous expansion of renewable energy sources, improvements in energy efficiency, electrification of transport and industry, deployment of low-carbon industrial technologies (such as hydrogen and carbon capture and storage), and restructuring of financial and institutional mechanisms.

This figure illustrates three global pathways:

- A continuation of fossil-fuel-dominated growth (BAU);
- A moderate decarbonization pathway aligned with current national commitments;
- A Net Zero pathway consistent with limiting global warming to 1.5°C.

The comparison highlights the decisive importance of early and coordinated policy actions. Delayed interventions significantly increase the cumulative emissions gap and raise the economic costs of transition in later decades.

For Central Asia, these global trends create both external pressures and strategic opportunities. As the global economy increasingly shifts toward low-carbon production standards, countries that fail to decarbonize may face declining competitiveness, carbon border adjustment mechanisms, and reduced access to sustainable finance. Conversely, proactive transition strategies can enhance energy diversification, technological modernization, and long-term economic resilience.

Thus, the analysis of decarbonization prospects in Central Asia must be situated within the broader global transformation of energy systems and institutional architectures. The following sections examine the regional specifics, scenario modeling results, and institutional conditions necessary for achieving Net Zero by 2050.

Figure 1 illustrates alternative trajectories of global carbon dioxide (CO_2) emissions over the period 2020-2050 under three energy transition scenarios: Business-as-Usual (BAU), Moderate Transition, and Net Zero by 2050.

The Business-as-Usual (BAU) scenario reflects the continuation of the current global energy structure, characterized by the dominant role of fossil fuels and limited deployment of low-carbon technologies. Under this pathway, global emissions stabilize or experience slight long-term growth, remaining significantly above levels consistent with climate neutrality.

The Moderate Transition scenario assumes gradual strengthening of climate monitoring mechanisms, expansion of renewable energy sources, and improvements in energy efficiency. As a result, emissions peak in the mid-2020s and subsequently decline steadily. However, the reductions achieved under this pathway are insufficient to reach climate neutrality by 2050.

The Net Zero scenario represents a trajectory aligned with the objectives of the Paris Agreement. It presupposes a deep transformation of energy and economic systems, including:

- accelerated deployment of renewable energy sources;
- electrification of end-use sectors;
- large-scale implementation of carbon capture and storage (CCS) technologies;
- comprehensive institutional and regulatory reforms [1]-[4].

Under this scenario, global CO_2 emissions begin a consistent decline after 2026 and approach net-zero levels by mid-century. Comparative analysis of these trajectories underscores the critical importance of early and coordinated climate action. Delayed policy measures substantially increase the scale of required structural transformations and the associated economic costs in later decades [5].

1.2 Energy Systems of Central Asian Countries in the Context of Market Transition

The countries of Central Asia-Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan-occupy a distinctive position within the global climate architecture. On the one hand, the region is characterized by a high dependence on fossil fuels, particularly coal, oil, and natural gas, which constitute the foundation of export revenues and energy security. On the other hand, Central Asia possesses considerable renewable energy potential, including solar, wind, and hydropower resources, as well as significant opportunities for improving energy efficiency in industry and the housing and utilities sector.

Table 1: Energy intensity and carbon intensity of gdp in central Asian countries (2020). Source: Author's calculations based on international energy and financial organization data [6], [7].

Country	Energy Intensity of GDP (kg oe/USD, 2017 PPP)	Carbon Intensity of GDP (kg CO_2/USD, 2017 PPP)
Kazakhstan	0.18	0.42
Uzbekistan	0.27	0.58
Kyrgyzstan	0.22	0.39
Tajikistan	0.30	0.31
Turkmenistan	0.35	0.75

The regional economies have largely inherited an energy-intensive production structure formed during the Soviet period. A high share of heavy industry and chemical production, aging infrastructure, and limited access to modern technologies contribute to elevated carbon intensity of GDP.

Table 1 demonstrates significant heterogeneity among the region's economies in terms of energy efficiency and carbon burden. Kazakhstan exhibits relatively lower energy intensity, reflecting a more diversified economic structure and comparatively higher technological development. In contrast, Tajikistan and Turkmenistan show substantially higher energy intensity levels, indicating the dominance of energy-intensive sectors and limited modernization of the production base.

Carbon intensity of GDP remains particularly high in countries with a strong hydrocarbon sector and fossil-fuel-based electricity generation. These figures indicate considerable potential for emission reductions through structural and technological transformation within long-term decarbonization strategies [6], [8].

At the same time, the region faces unique climate and environmental challenges. Accelerated glacier melting, increasing water scarcity, desertification, and a higher frequency of extreme weather events amplify the vulnerability of agriculture and energy systems. These factors make decarbonization not only a tool for fulfilling international commitments but also a critical component of adaptation strategy.

1.3 Institutional Frameworks and the Economics of Decarbonization

Economic decarbonization cannot proceed without appropriate institutional conditions. Institutions-both formal and informal rules, decision-making mechanisms, and incentive systems-determine the speed and depth of the energy transition.

In Central Asia, the institutional environment is characterized by:

- a strong state presence in the energy sector;
- limited competition;
- emerging but incomplete market mechanisms.

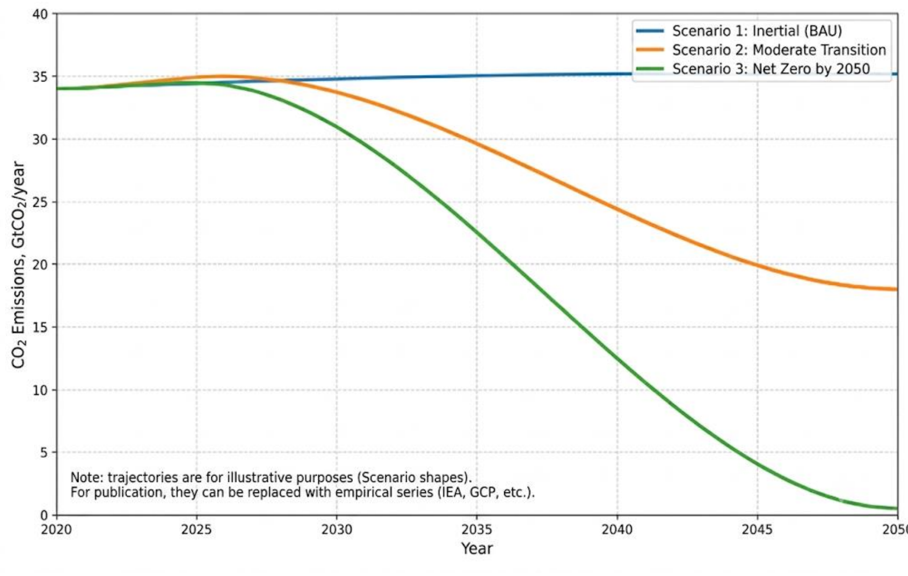

Figure 1: Global CO_2 emission dynamics under energy transition scenarios (2020-2050).

State-owned energy companies dominate extraction, processing, and distribution of energy resources. While this ensures strategic control over critical sectors, it may simultaneously reduce flexibility and limit innovation dynamics.

Key institutional barriers include (Fig. 2):

- continued subsidization of fossil fuels;
- limited transparency in tariff regulation;
- restricted access of private capital to energy markets;
- underdeveloped carbon pricing mechanisms.

These constraints can significantly slow down the decarbonization process.

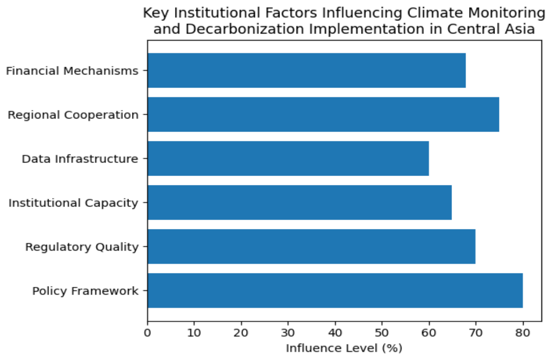

Figure 2: Key institutional factors influencing climate monitoring and decarbonization implementation in Central Asia.

The figure highlights the interaction between governance quality, regulatory frameworks, investment climate conditions, and public participation. It demonstrates that institutional modernization is a prerequisite for translating technical renewable energy potential into actual emission reductions.

Overall, the economic feasibility of achieving Net Zero in Central Asia depends not only on technological capacity but also on the effectiveness of institutional reform. Without parallel institutional transformation, even ambitious energy transition strategies may remain partially implemented. Figure 3 presents a conceptual framework of the institutional factors determining the pace and quality of decarbonization in Central Asian countries up to 2050. At the center of the scheme lies the strategic objective-achieving decarbonization goals and Net Zero-around which the key institutional blocks shaping the "implementation environment" of the energy transition are organized.

These core blocks include:

- Public sector reform and strategic governance under market conditions;
- Regulatory environment, including tariff policy, grid access, and electricity market rules;
- Price signals and subsidy reform, incorporating elements of carbon regulation.

Together, these components establish the predictability of rules, ensure policy coherence, and stimulate the reallocation of resources toward low-carbon technologies.

The right-hand side of the framework reflects factors related to resource provision and transformation capacity:

- Investment climate and access to finance, including green finance instruments.
- Innovation systems and human capital development.
- Data infrastructure and MRV systems (Monitoring-Reporting-Verification), ensuring transparency, accountability, and measurability of progress.

The lower block highlights regional coordination as an independent institutional dimension of particular importance for Central Asia. Due to interconnected energy systems, transboundary water management, and the need for harmonized standards and joint infrastructure projects, regional cooperation becomes a critical enabler of effective decarbonization.

Collectively, these elements form the institutional "architecture of transition," the quality of which determines the feasibility of accelerated decarbonization scenarios and the achievement of climate neutrality.

Most existing studies focus either on the technical potential of renewable energy sources or on the descriptive analysis of national strategies and climate commitments. Limited attention has been devoted to integrated Net Zero transition scenarios that explicitly incorporate regional institutional constraints and enabling conditions. Moreover, comparative analysis of Central Asian economies within a unified methodological framework remains rare, complicating the formulation of evidence-based regional policy recommendations.

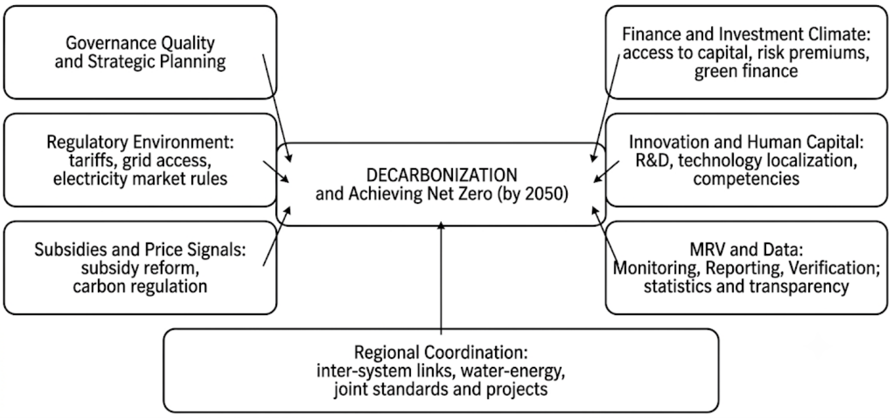

Figure 3: Institutional factors of decarbonization in Central Asian countries.

1.4 Literature Review and Identification of the Research Gap

Contemporary academic literature on decarbonization and Net Zero encompasses a wide range of themes, including energy system modeling, macroeconomic assessments of climate mitigation, and technological transition pathways. However, research specifically addressing the decarbonization of Central Asian economies remains fragmented and often limited to individual countries or specific sectors.

This situation reveals a clear research gap: the absence of an integrated scenario-based and institutional analysis of long-term decarbonization pathways in Central Asia up to 2050. The present study aims to address this gap.

1.5 Research Objective, Tasks, and Scientific Novelty

The objective of this article is to conduct a comprehensive analysis of the state and prospects of decarbonization in Central Asian economies in the context of achieving Net Zero targets by 2050, based on scenario and institutional approaches.

To achieve this objective, the study addresses the following tasks:

- Development of alternative energy and economic development scenarios for 2026-2050.
- Assessment of greenhouse gas emission trajectories and structural changes in the energy balance.
- Analysis of institutional conditions and constraints affecting decarbonization policy implementation.
- Formulation of recommendations to improve climate and energy governance and monitoring systems in Central Asia.

The scientific novelty of the study lies in the integration of scenario modeling and institutional analysis, enabling a more comprehensive understanding of potential Net Zero transition pathways in transition economies. Unlike existing studies, this research adopts a comparative regional perspective and explicitly incorporates institutional specificities, thereby enhancing the practical relevance of its findings.

1.6 Theoretical Foundations of Decarbonization and Net Zero Analysis

The theoretical foundation of decarbonization research lies at the intersection of sustainable development theory, energy economics, and institutional economics.

The concept of sustainable development, widely recognized after the publication of the Brundtland Commission report, emphasizes the balanced interaction of economic, social, and environmental dimensions of development [1], [9]. Within the climate agenda, this approach has evolved into the paradigm of low-carbon and climate-neutral growth. Energy-economic models applied in Net Zero analysis are based on long-term optimization of the energy mix, considering technological, resource, and institutional constraints [3]. These models enable the assessment not only of emission trajectories but also of macroeconomic impacts, including effects on employment, investment flows, and competitiveness.

Institutional economics highlights the role of formal rules, coordination mechanisms, and governance quality in ensuring the successful implementation of structural transformations [5], [7]. In transition economies such as those of Central Asia, institutional factors are particularly significant, as they determine the capacity to adapt global climate objectives to national contexts.

1.7 Scenario Approach as a Tool for Long-Term Transformation Analysis

Scenario analysis is widely used in studies of energy transition and decarbonization as a tool for addressing long-term uncertainty [6], [7]. Unlike forecasts, scenarios do not aim to predict the future precisely; rather, they construct alternative development trajectories reflecting different combinations of technological, economic, and environmental drivers. In the context of Central Asia, the scenario approach enables comparison between:

- An inertia-based development path preserving the current fossil-fuel-dominated structure;
- Accelerated transformation pathways involving large-scale renewable deployment, enhanced energy efficiency, and systemic energy reforms [7].

This approach facilitates a comprehensive understanding of trade-offs between economic growth, climate commitments, and social stability.

1.8 Role of International Commitments and Regional Cooperation

International climate agreements play a critical role in shaping national decarbonization strategies. The Paris Agreement institutionalized nationally determined contributions (NDCs), granting Central Asian countries flexibility in choosing mitigation instruments and timelines.

However, increasing global climate ambition and the expansion of cross-border carbon regulation mechanisms-such as carbon border adjustment measures-intensify external pressure on carbon-intensive economies in the region [8].

Regional cooperation among Central Asian countries could significantly reduce transition costs through coordinated infrastructure development, technology exchange, and harmonized institutional approaches [10], [11]. Nevertheless, the current potential of regional climate and energy cooperation remains underutilized, requiring deeper analytical attention.

1.9 Justification of the Time Horizon (2026-2050)

The selected time horizon reflects the logic of global climate policy and the structural nature of energy transformation. The period 2026-2050 represents the decisive phase during which institutional and technological foundations for climate neutrality must be established [7], [12].

For Central Asian countries, this period coincides with active economic modernization and infrastructure expansion. This creates both risks-such as locking in carbon-intensive trajectories-and opportunities for transitioning toward more sustainable development models [13].

A long-term analytical perspective allows for the assessment of cumulative institutional effects and avoids underestimation of delayed climate policy impacts.

1.10 Article Structure

The article follows the IMRAD structure.

- The Introduction substantiates the relevance of the topic, formulates the research objectives, and identifies the research gap.
- The Methods section presents the scenario and institutional methodology, including data sources and assumptions.
- The Results section provides quantitative findings supported by tables, figures, and diagrams.
- The Discussion section compares the findings with existing literature and formulates practical policy recommendations for decarbonization in Central Asia.

2 METHODS

2.1 Overall Research Design and Methodological Framework

This study is based on a comprehensive methodological approach combining quantitative and qualitative methods to assess long-term decarbonization pathways in Central Asia (2026-2050). The mixed-methods design reflects the multidimensional nature of energy transition, encompassing technological, economic, and institutional transformations [14].

The methodological framework consists of three interrelated analytical levels:

1) Scenario modeling of energy and economic development.
2) Calculation and comparison of greenhouse gas emission trajectories, primarily CO_2.
3) Institutional analysis of factors determining the feasibility of different decarbonization pathways.

Figure 4 presents the logical scheme of the research methodology, illustrating the sequence of analytical stages and the interconnections between the applied methods.

Figure 4 depicts the logical and sequential structure of the research methodology applied to analyze the decarbonization of Central Asian economies over the period 2026-2050. The scheme reflects the integration of scenario-based modeling and institutional analysis, starting from the formulation of the research objective and the selection of input data, and ending with the synthesis of findings and the development of policy recommendations. This methodological framework enables a systematic linkage between quantitative calculations of the energy balance and CO_2 emissions and a qualitative assessment of the institutional environment that determines the feasibility of alternative energy-transition pathways.

A distinctive feature of the scheme is the explicit separation between the stages of scenario design (BAU, Moderate Transition, and Net Zero) and the analytical modeling blocks, which enhances transparency of assumptions and reproducibility of results. Institutional analysis is embedded as an independent and equally important component of the methodology, emphasizing that achieving Net Zero targets depends not only on technological parameters but also on the quality of public governance, regulatory instruments, and the investment environment. In this sense, the proposed scheme establishes an integrated analytical architecture for the study and provides the basis for interpreting the results [7], [15].

The choice of the 2026-2050 time horizon is determined by the objective of climate neutrality, as reflected in international agreements and national strategies adopted by most countries worldwide. This period is expected to represent the most intensive phase of the energy transition, requiring substantial investment, institutional reform, and a rethinking of prevailing models of economic growth [16]. For Central Asian countries, this timeframe coincides with an active modernization of energy infrastructure, which makes the assessment of alternative development trajectories particularly relevant.

The spatial scope of the study covers five Central Asian countries: Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan. Despite differences in resource endowments, levels of economic development, and institutional structures, these countries share a common historical trajectory in the formation of their energy systems and face similar challenges in the context of decarbonization. This enables the region to be treated as a comparable analytical space and supports cross-country comparative analysis [17], [18].

A key principle of the methodological design is data and result comparability. To ensure comparability, all macroeconomic and energy indicators are converted into consistent measurement units, primarily using purchasing power parity (PPP), while calculations employ harmonized emission factors and energy-equivalence coefficients [17], [19]. This approach reduces the risk of bias associated with differences in national statistical systems.

2.2 Scenario Analysis: Development and Parameterization of Decarbonization Scenarios

Scenario analysis is employed as the core instrument for assessing potential decarbonization pathways for Central Asian economies under conditions of high uncertainty in long-term development. Unlike deterministic forecasts, scenarios allow researchers to examine alternative futures that reflect different combinations of policy choices, technological progress, and institutional change [4], [15]. In this study, three baseline scenarios were developed to serve as the analytical basis for comparing potential pathways toward Net Zero.

Scenario 1: Business-as-Usual (BAU) assumes the continuation of current trends in the energy sector and limited changes in the institutional environment. Under this scenario, the energy balance remains predominantly fossil-fuel-based, while the diffusion of renewable technologies and improvements in energy efficiency remain moderate. CO_2 emissions stabilize or continue to increase in the long run, making climate neutrality unattainable [18], [20].

Scenario 2: Moderate Energy Transition reflects a gradual strengthening of climate and energy monitoring, including expanded deployment of renewable energy, tariff-regulation reform, and a progressive phase-out of fossil-fuel subsidies. This scenario assumes that emissions peak in the medium term and subsequently decline; however, Net Zero is not achieved by 2050 [21].

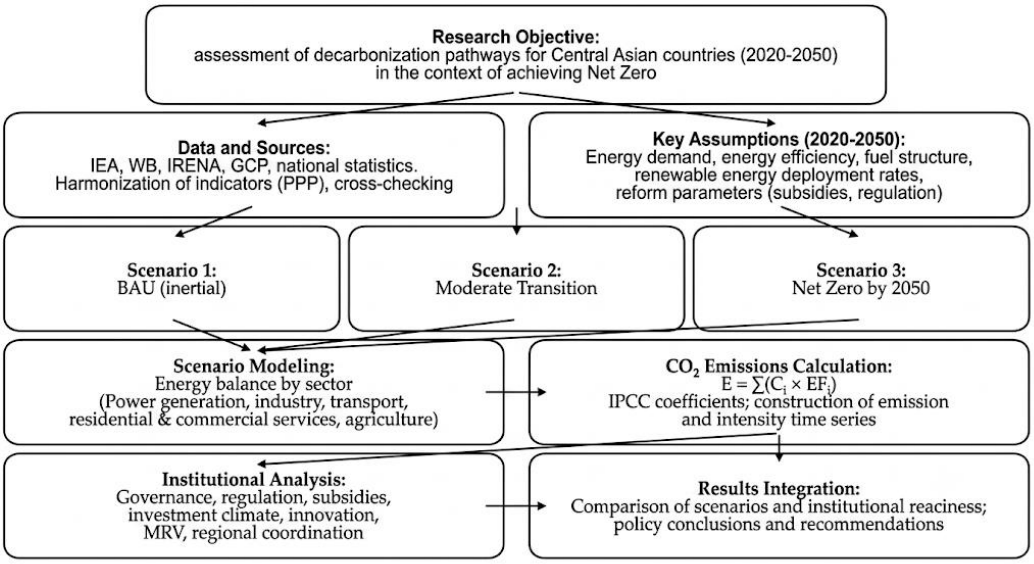

Figure 4: Logical flowchart of the research methodology.

Table 2: Key parameters of decarbonization scenarios for Central Asian economies. Source: author's compilation based on scenario approaches and recommendations of the IPCC, IEA, and IRENA [15], [8], [22]-[24].

Parameter	Business-as-Usual (BAU)	Moderate Energy Transition	Net Zero by 2050
Energy demand growth	High, consistent with historical trends	Moderate, with gradual slowdown	Constrained due to efficiency and structural change
Share of renewables in electricity by 2050, %	15-20	35-45	60-70
Coal use	Remains high	Gradual decline	Nearly fully phased out
Role of natural gas	Dominant in the energy mix	Transitional ("bridge fuel")	Limited, partly with CCS
Energy-efficiency improvement	Minimal	Moderate	High across all sectors
Electrification of final consumption	Limited	Partial (transport, housing/communal sector)	Large-scale (industry, transport, buildings)
CCS technologies	Virtually not applied	Pilot projects	Targeted deployment in energy-intensive sectors
Institutional reforms	Absent or fragmented	Partial and gradual	Comprehensive and systemic
Investment in low-carbon technologies	Low	Medium	High, with private and international participation
Climate neutrality	Not achieved	Not achieved	Achieved by 2050

Scenario 3: Net Zero by 2050 represents the most ambitious development pathway and requires a profound structural transformation of energy and economic systems. It includes accelerated renewable-energy deployment, broad electrification of final energy consumption, the development of carbon capture and storage (CCS) technologies, and comprehensive institutional reforms. This scenario is aligned with recommendations by the IPCC and the International Energy Agency and requires significant upfront investments and strong policy coordination [14], [22].

The main scenario parameters-including energy-demand growth rates, renewable-energy shares, energy-efficiency improvements, and carbon-intensity trajectories-are summarized in Table 2. These parameters are used in subsequent calculations of emissions and economic impacts.

Table 2 synthesizes the key parameters used to construct alternative decarbonization scenarios for Central Asian economies and highlights fundamental differences between the BAU pathway, the moderate transition scenario, and the Net Zero-by-2050 scenario. The parameters cover energy-demand dynamics, energy-mix structure, renewable-energy uptake, the scale of end-use electrification, and the depth of institutional reform. Such structuring enables clear scenario comparisons and helps identify the main levers driving differences in outcomes.

The table indicates that the BAU scenario preserves a carbon-intensive development model with minimal institutional change, whereas the moderate transition scenario implies a partial transformation of energy systems without achieving climate neutrality. By contrast, the Net Zero scenario is characterized by comprehensive change, including rapid renewable deployment, large-scale energy-efficiency improvements, and systemic institutional reforms. These parameters provide the basis for scenario-based modeling of CO_2 emissions and for assessing the feasibility of climate-neutrality pathways in Central Asian countries [15], [22].

Comparative dynamics of key indicators across the three scenarios are visualized using charts and graphs, which makes it possible to clearly demonstrate differences between inertial development and accelerated transition trajectories. This approach increases transparency of assumptions and facilitates interpretation of scenario-analysis results [24], [25].

2.3 Energy Modeling and Greenhouse-Gas Emissions Accounting

To quantify the implications of decarbonization scenarios, the study applies a simplified energy-economic modeling approach based on a balance representation of energy systems and coefficient-based greenhouse-gas emissions accounting. This approach is widely used in regional studies where access to detailed integrated assessment models is limited, yet transparency of assumptions and reproducibility are required [24].

The modeling framework is grounded in an energy balance in which total final energy consumption is represented as the sum of consumption across major economic sectors: power generation, industry, transport, the residential and residential and municipal sector (housing/communal) sector, and agriculture. For each sector, the structure of energy carriers (coal, oil, natural gas, renewables) is specified, enabling the estimation of total CO_2 emissions in accordance with the IPCC methodology [2], [7].

Emissions are calculated using the following relationship: $E = \Sigma (C_i \times EF_i)$, where E is total CO_2 emissions, $\mathbf{C}_i$ is consumption of fuel type i, and EF_i is the corresponding emission factor. Emission factors are taken in line with IPCC guidelines and international energy-agency recommendations, ensuring comparability with other studies [11], [13].

Within the scenario framework, parameters of energy demand and balance structure vary by scenario. The BAU scenario assumes the continuation of current demand-growth trends and limited changes in fuel structure. The moderate transition and Net Zero scenarios incorporate higher energy-efficiency improvement rates, increased renewable shares, and a reduction in the use of carbon-intensive fuels [7], [23]. The main sectoral assumptions are presented in Table 3.

Table 3: Core sectoral assumptions for energy modeling (2026-2050) [14], [16], [23].

Sector	Key assumptions (2026-2050)
Power generation	Gradual reduction in coal-fired generation; accelerated growth of renewables (solar, wind, hydropower); deployment of energy storage; grid-efficiency improvements and lower transmission losses.
Industry	Energy-efficiency gains through equipment modernization; partial electrification of processes; adoption of low-carbon technologies in energy-intensive industries (metals, cement); limited CCS use under Net Zero.
Transport	Gradual shift from internal combustion engines to electric and hybrid vehicles; development of public transport; use of alternative fuels (hydrogen, biofuels) in freight and aviation segments.
Residential and commercial sector	Improved building energy efficiency; expanded electric heating and heat pumps; reduced direct use of coal and natural gas; implementation of energy-efficient building standards.
Agriculture	Limited growth in energy consumption; improved efficiency in fuel and electricity use; partial electrification of agricultural machinery; reduced indirect emissions through optimization of water and land resources.

Table 4: Institutional readiness indicators for decarbonization in Central Asian countries [8], [20], [26]-[29].

Institutional block	Main assessment indicators
Public governance and strategic planning	Existence of long-term low-carbon strategies; integration of climate goals into national development plans; interagency coordination of climate policy.
Regulatory environment of energy markets	Transparency of tariff regulation; degree of competition in electricity markets; access of independent producers to infrastructure; availability of renewable support mechanisms.
Subsidies and price signals	Scale of fossil-fuel subsidies; extent to which external environmental costs are internalized in energy prices; presence/absence of carbon-pricing elements.
Investment and financial climate	Availability of long-term finance; development of green-finance instruments; investment risks; participation of international financial institutions.
Innovation and human-capital capacity	R&D expenditure in energy; workforce training and retraining programs; localization of low-carbon technologies; science-industry linkages.
MRV systems and statistical base	Existence of emissions MRV systems; quality of energy and climate statistics; transparency and accessibility of data.
Regional cooperation	Participation in regional energy and climate initiatives; coordination of cross-border infrastructure projects; harmonization of standards and regulations for decarbonization.

Table 3 summarizes the key sectoral assumptions used to develop decarbonization scenarios for Central Asia over 2026-2050. The assumptions reflect expected structural changes in energy consumption, technological development, and fuel mix across sectors, accounting for sector-specific characteristics and mitigation potential. In power generation, the focus is on phasing down coal and accelerating renewables, whereas in industry and transport the main drivers are energy efficiency, electrification, and low-carbon technologies. In the residential/communal and agricultural sectors, transformation is assumed to be more moderate but systemic, aiming to reduce direct fossil-fuel use and improve energy-use efficiency. Collectively, these assumptions underpin the calculation of scenario trajectories of CO_2 emissions and the assessment of Net Zero feasibility under the region's institutional and resource constraints [7], [16], [23].

To improve analytical clarity, modeled results are aggregated into time series of CO_2 emissions for 2026-2050 and compared across scenarios using graphical methods (see Fig. 3). This allows identification of critical divergence points between trajectories and helps assess time windows for implementing the most effective policy measures [7], [16].

2.4 Methodology of Institutional Analysis

Quantitative results from scenario modeling are complemented by an institutional analysis aimed at assessing the feasibility of alternative decarbonization pathways under Central Asian conditions. The institutional analysis builds on the new institutional economics perspective, which conceptualizes institutions as a set of formal rules, coordination mechanisms, and informal practices that shape economic behavior [20], [27].

The study identifies key institutional blocks previously presented in Figure 4, including the quality of public governance, the regulatory environment of energy markets, the system of price incentives, the investment climate, innovation and human-capital capacity, and monitoring, reporting, and verification (MRV) infrastructure. For each block, a set of indicators is defined to enable comparative assessment across the region [7], [28]. The evaluation of institutional factors is primarily qualitative-to-quantified. This means expert assessments and international rating data are converted into comparable scales, enabling the integration of institutional parameters into the overall analytical framework [18], [29]. Composite indicators of institutional readiness for decarbonization are presented in Table 4.

2.5 Data Sources and Validation Procedures

The empirical basis of the study includes data from leading international organizations, including the International Energy Agency, the World Bank, the International Renewable Energy Agency, and the Global Carbon Project, as well as official statistics from national agencies of Central Asian countries. Using multiple sources increases reliability and reduces the risk of systematic error [20], [30].

To ensure consistency and comparability, cross-validation and harmonization procedures are applied to time series. When discrepancies arise, priority is given to internationally recognized sources, and identified inconsistencies are analyzed and documented. This approach is consistent with best practices in empirical research on energy systems and climate policy [4], [19].

2.6 Study Limitations and Uncertainties

Despite the comprehensive methodological design, the study has several limitations. First, scenario modeling inherently involves substantial uncertainty, particularly regarding the pace of technological progress and the depth of institutional reforms. Second, the aggregated nature of the model does not fully capture intra-sector heterogeneity and subnational specificities within individual countries [15], [31].

Nevertheless, the combined use of scenario analysis and institutional assessment provides an integrated view of potential decarbonization pathways and supports the development of well-grounded conclusions and recommendations for long-term climate policy in Central Asian countries [8], [20].

3 RESULTS

3.1 Scenario Trajectories of CO_2 Emissions in Central Asian Countries (2026-2050)

The scenario-modeling results demonstrate fundamentally different CO_2-emissions trajectories for Central Asian countries depending on the chosen development pathway. Under the Business-as-Usual (BAU) scenario, total regional emissions exhibit a persistent tendency toward growth or stagnation at a high level throughout the study period. This is driven by the continued dominance of fossil fuels in the energy mix and limited improvements in energy efficiency. Such a trajectory creates a substantial gap between observed emissions dynamics and the Net Zero objectives embedded in international climate agreements [4], [9].

In the Moderate Energy Transition scenario, emissions reach peak levels in the medium term (late 2020s to early 2030s), followed by a gradual decline. However, the rate of reduction is insufficient to achieve climate neutrality by 2050. These results corroborate findings in the literature that incremental climate-policy measures, absent deep structural reforms, may slow emissions growth but do not deliver the scale of reductions required for Net Zero [15], [32].

The Net Zero scenario is characterized by the sharpest and most sustained decline in CO_2 emissions after 2025. In this case, total regional emissions decrease by more than 80-90% by 2050 relative to the 2020 level, consistent with trajectories compatible with the Paris Agreement. Figure 5 clearly illustrates the divergence of scenario pathways and underscores the critical role of early and large-scale policy measures.

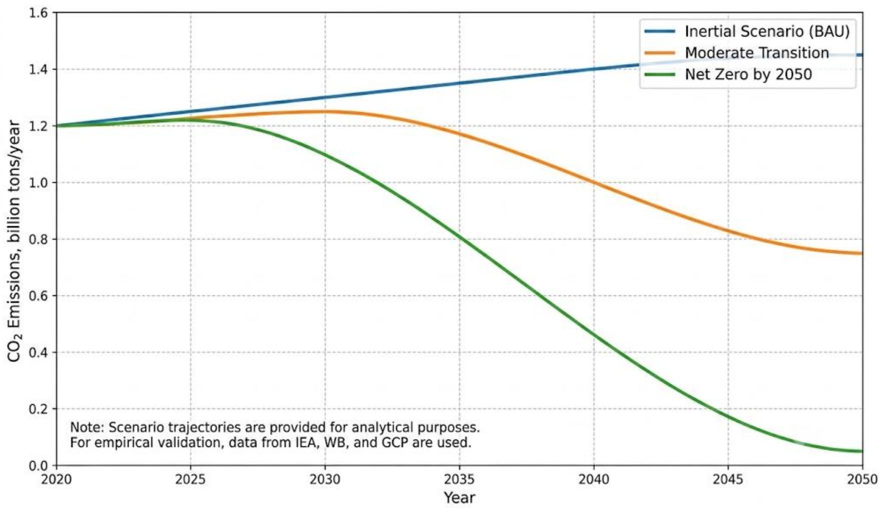

Figure 5: CO_2 emissions trajectories in Central Asian countries by scenario (2020-2050).

Figure 5 presents the evolution of aggregate carbon dioxide (CO_2) emissions in Central Asian countries over 2020-2050 under three development scenarios: Business-as-Usual (BAU), a Moderate Energy Transition, and a Net Zero pathway. The BAU scenario is characterized by a sustained increase in emissions throughout the entire period, reflecting the persistence of a carbon-intensive energy mix and limited diffusion of low-carbon technologies. Under the Moderate Transition scenario, emissions peak in the late 2020s and subsequently decline gradually; however, the pace of reduction remains insufficient to achieve climate neutrality by 2050. This trajectory indicates the limited effectiveness of partial and weakly coordinated climate-policy measures [4], [25], [33].

By contrast, the Net Zero scenario follows a fundamentally different pathway, marked by a sharp and sustained decline in CO_2 emissions after 2026 and convergence toward near-zero levels by 2050. Such dynamics are feasible only under conditions of deep energy-system transformation, large-scale deployment of renewable energy, extensive electrification of end-use demand, and comprehensive institutional reforms. The comparison across scenarios clearly demonstrates that delaying active decarbonization efforts substantially increases the required rate of emissions reductions in later years and raises the economic and social costs of transition, underscoring the critical importance of early and consistent climate monitoring and policy implementation in Central Asian countries [7], [34], [35].

3.2 Structural Changes in the Energy Balance

Modeling results indicate that progress toward decarbonization targets is largely determined by structural transformation of the energy balance. Under the BAU scenario, the shares of coal, oil, and natural gas in total primary energy consumption remain dominant, thereby reinforcing the region's high carbon intensity. At the same time, renewable energy expands only marginally and does not exert a systemic effect on emissions reduction [20], [36].

A qualitatively different pattern emerges under the Moderate Transition and Net Zero scenarios. The share of renewable energy-particularly solar and wind generation-rises substantially, most notably in the power sector. In parallel, coal use declines and the role of natural gas gradually decrease in the long run. Table 5 summarizes the scenario-based changes in the energy-balance structure of Central Asian countries by 2050.

Table 5: Energy-balance structure in Central Asian countries by scenario, % (2050).

Energy source	BAU	Moderate Transition	Net Zero by 2050
Coal	28	15	3
Oil	26	22	8
Natural gas	32	28	14
Renewables	12	32	60
Other sources (incl. nuclear and imports)	2	3	15

Source: author's scenario-modeling results based on IEA, IRENA, and national statistical sources [4], [7], [36], [37].

Table 5 highlights fundamental differences in the energy-balance structure across scenarios by 2050. Under BAU, fossil fuels remain dominant, with a combined share exceeding 85%, implying the entrenchment of a carbon-intensive growth model and limited scope for substantial CO_2 reductions. Even under a Moderate Energy Transition, coal, oil, and natural gas retain a significant share despite the notable expansion of renewables, suggesting that gradual and fragmented climate-policy measures can only partially reconfigure regional energy consumption patterns [11], [38], [39].

In the Net Zero scenario, the energy balance exhibits a qualitatively different configuration, characterized by the dominance of renewables, whose share reaches approximately 60% by 2050. The sharp reduction in coal and oil use, combined with a declining role for natural gas, reflects the depth of structural change required to achieve climate neutrality. The increased share of other energy sources-including low-carbon baseload options and cross-border supplies-also underscores the importance of energy-system diversification and regional cooperation. Overall, the results indicate that Net Zero targets in Central Asian countries are achievable only through accelerated renewable deployment, infrastructure modernization, and sustained institutional reforms [20], [40], [41].

The findings further suggest that, without accelerated renewable-energy development and modernization of the power sector infrastructure, achieving Net Zero becomes practically unattainable. These conclusions are consistent with global assessments by the International Energy Agency, supporting the broader relevance of the identified patterns [18], [37].

3.3 Sectoral contributions to emissions reductions

Sectoral results indicate that the largest contributions to CO_2-emissions reductions under the Net Zero scenario are delivered by the power sector and industry. The power sector plays a pivotal role through decarbonization of generation and the subsequent electrification of end-use demand in other sectors of the economy. Figure 7 illustrates the distribution of sectoral contributions to total emissions reductions by 2050.

Figure 6 illustrates country-level differences in CO_2 emissions reductions under the Net Zero scenario by 2050, highlighting the strongest reductions in Tajikistan and Kyrgyzstan. Figure 6 highlights fundamental differences in the structure of the energy balance in Central Asian countries depending on the selected development pathway by 2050. Under the Business-as-Usual (BAU) scenario, fossil fuels retain a dominant position, with their combined share exceeding 85%, thereby reinforcing a carbon-intensive growth model and limiting the scope for substantial CO_2 emissions reductions. Even under the Moderate Energy Transition scenario, coal, oil, and natural gas continue to account for a significant proportion of the energy mix, despite the noticeable expansion of renewable energy sources. This confirms that gradual and fragmented climate-policy measures are capable of only partially transforming the region's energy-consumption structure [8], [38], [39].

By contrast, the Net Zero scenario exhibits a qualitatively different configuration of the energy balance, characterized by the dominance of renewable energy, whose share approaches approximately 60% by 2050. The substantial decline in coal and oil use, together with the reduced role of natural gas, reflects the depth of structural transformation required to achieve climate neutrality. At the same time, the increasing share of other energy sources-including low-carbon baseload capacities and cross-border electricity supplies-underscores the importance of energy-system diversification and enhanced regional cooperation. Overall, the results suggest that achieving Net Zero targets in Central Asian countries is feasible only through accelerated renewable-energy deployment, infrastructure modernization, and consistent institutional reforms [40], [41].

In the transport sector, significant emissions reductions are achieved through the electrification of passenger vehicles and the introduction of alternative fuels in freight and aviation segments. In the residential and communal sector, emissions decline as a result of improved building energy efficiency and the transition to low-carbon heating systems. Collectively, these measures generate a multiplier effect that amplifies decarbonization outcomes across the entire economy [20], [42].

3.4 The Role of Institutional Factors in Scenario Implementation

A comparison of quantitative scenario-modeling results with institutional indicators (see Table 4) reveals a strong relationship between institutional quality and the feasibility of accelerated decarbonization pathways. Countries with more advanced strategic planning frameworks and regulatory environments demonstrate a greater capacity to implement Moderate Transition and Net Zero scenarios, whereas institutional constraints significantly increase transformation costs and implementation risks [7], [43].

Particularly critical are factors related to the investment climate, regulatory transparency, and the existence of effective monitoring, reporting, and verification (MRV) systems. The analysis shows that, without parallel institutional reforms, even substantial technical potential for renewable energy does not guarantee the achievement of decarbonization targets. This finding underscores the necessity of an integrated policy approach combining technological deployment with institutional strengthening measures [8], [44].

Figure 6, 7 and Table 6 demonstrate substantial cross-country differentiation in the scale of CO_2 emissions reductions across Central Asian states under the Net Zero scenario. The highest relative reductions are observed in Kyrgyzstan and Tajikistan, largely due to their initially high shares of low-carbon hydropower and comparatively lower dependence on carbon-intensive industrial sectors. In contrast, Kazakhstan and Uzbekistan require deeper structural transformations-including accelerated power-sector decarbonization and modernization of energy-intensive industries-to achieve comparable reductions, reflecting a more complex pathway toward climate neutrality [14].

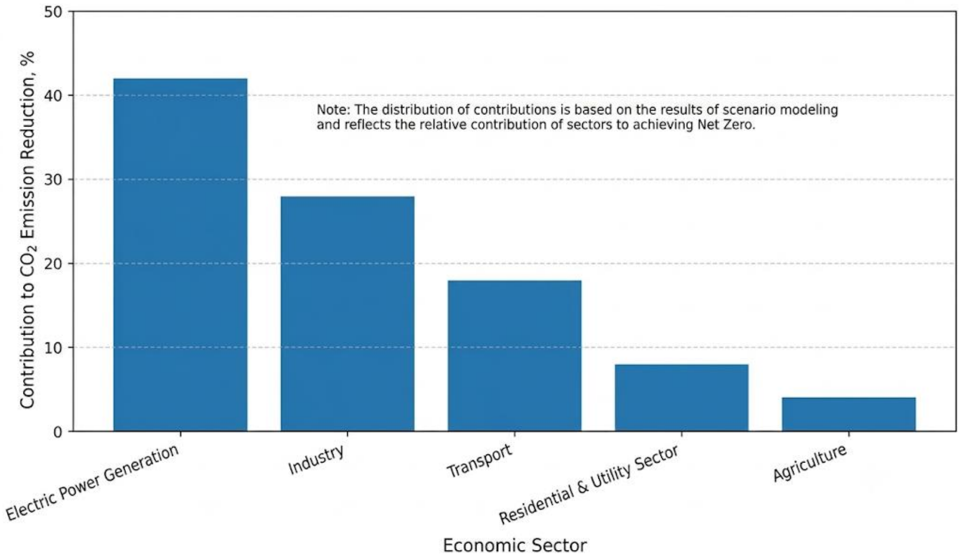

Figure 6: Sectoral contributions to CO_2 emissions reductions under the Net Zero scenario, %.

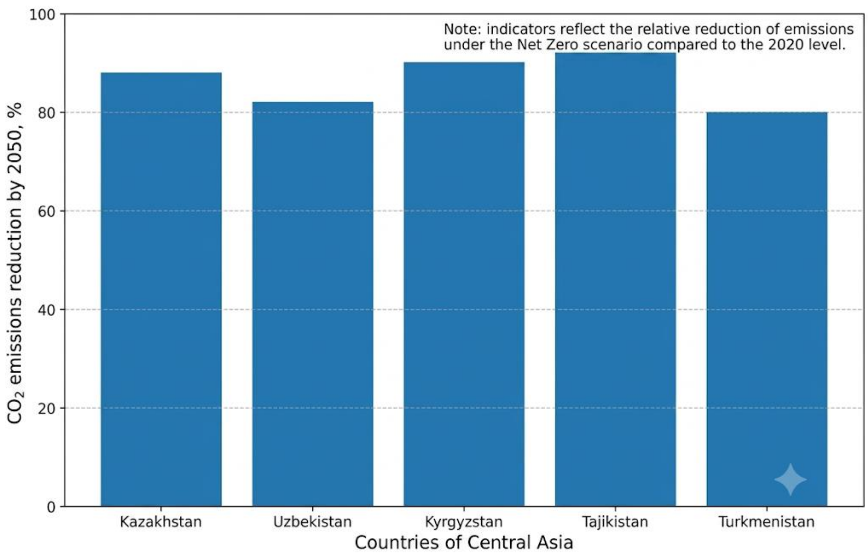

Figure 7: CO_2 emissions reductions by Central Asian countries under the Net Zero scenario by 2050, %.

Table 6: Comparative dynamics of CO_2 emissions reductions in Central Asian countries under the Net Zero scenario (2026-2050). Source: author's scenario-modeling results based on IEA, World Bank, and national statistical data [20], [45], [46].

Country	CO_2 emissions reduction by 2050 compared to 2020, %	Key drivers of reduction
Kazakhstan	88	Power-sector decarbonization, renewable energy expansion, industrial modernization
Uzbekistan	82	Rapid solar deployment, energy-efficiency improvements, tariff-policy reforms
Kyrgyzstan	90	High hydropower share, electrification of final energy demand
Tajikistan	92	Dominance of low-carbon hydropower, limited carbon-intensive industry
Turkmenistan	80	Methane-leak reduction, improved gas-sector efficiency, diversification of generation

In Turkmenistan, the relative emissions reduction is less pronounced compared to other countries in the region, reflecting the economy's strong dependence on natural gas and its export-oriented energy model. Nevertheless, modeling results indicate that even under such structural conditions, targeted measures-such as methane-leak mitigation, efficiency improvements in gas infrastructure, and gradual diversification of the energy mix-can generate substantial progress toward Net Zero. Overall, the findings confirm that climate neutrality in Central Asia is technically achievable but requires differentiated national strategies that account for country-specific resource endowments and institutional capacities [24], [27].

4 DISCUSSION

4.1 Comparison with International Research

The results obtained in this study are broadly consistent with the findings of leading international organizations and academic research on decarbonization and Net Zero pathways. Reports by the IPCC and the International Energy Agency emphasize that achieving climate neutrality requires early and rapid emissions reductions in the power sector, followed by large-scale electrification of final energy consumption [7], [18], [47]. The scenario analysis for Central Asian countries confirms the general validity of this pattern, demonstrating the dominant contribution of power-sector decarbonization to total CO_2 reductions under the Net Zero scenario.

At the same time, the identified decarbonization trajectories exhibit region-specific features distinguishing Central Asia from advanced economies. In particular, higher dependence on fossil fuels and limited access to investment capital result in steeper and more costly emissions-reduction pathways in later periods when policy action is delayed. This finding aligns with comparative research highlighting the disproportionately high costs of a "late transition" for emerging and transition economies [48].

4.2 Institutional Constraints and Opportunities for Accelerated Decarbonization

One of the central conclusions of this study is the critical role of the institutional environment in determining the feasibility of decarbonization pathways. Even where substantial technical potential for renewable energy exists, weak regulatory frameworks, inefficient subsidy systems, and limited transparency in energy markets significantly slow the pace of transition. This observation is consistent with the institutional economics literature, which emphasizes that institutional quality is a key determinant of long-term economic and technological development [14], [49].

In Central Asian countries, institutional barriers are primarily manifested in the continued subsidization of fossil fuels, limited competition in electricity markets, and fragmented climate-policy frameworks. However, the analysis also indicates that targeted institutional reforms-such as tariff regulation reform, development of robust monitoring, reporting, and verification (MRV) systems, and mobilization of private capital-can substantially reduce the overall costs of decarbonization and enhance its social acceptability [8], [16], [50], [51].

4.3 Cross-country Differentiation and the Need for Tailored Strategies

The comparative analysis reveals significant heterogeneity in initial conditions and transition pathways among Central Asian countries. States with a high share of low-carbon electricity generation (notably Kyrgyzstan and Tajikistan) benefit from structural advantages that enable deeper emissions reductions at relatively lower transformation costs. Conversely, hydrocarbon-exporting economies face more complex trade-offs between climate objectives and economic stability [52].

These differences underscore the need for tailored national decarbonization strategies rather than uniform regional solutions. At the same time, enhanced regional coordination and joint implementation of cross-border infrastructure projects could reduce aggregate transition costs and strengthen the resilience of Central Asia's energy systems [19], [53].

4.4 Policy and Economic Implications

The study's findings have important implications for climate and energy policy in Central Asian countries. First, they highlight the necessity of shifting from declarative climate commitments toward the implementation of coherent and coordinated policy measures. Second, the modeled scenarios underscore the importance of early investments in low-carbon infrastructure, as delayed action leads to sharply increasing required rates of emissions reduction in later decades [20], [54].

From an economic perspective, decarbonization should not be perceived solely as a source of costs. With appropriate institutional support, the energy transition can serve as a driver of technological modernization, economic diversification, and enhanced long-term competitiveness. This is particularly relevant for Central Asian countries undergoing structural transformation [4], [55].

4.5 Limitations and Directions for Future Research

Despite the robustness of the results, their interpretation should consider certain limitations. The aggregated nature of the scenario modeling does not fully capture intra-country regional disparities or the social dimensions of transition. Moreover, institutional change is inherently difficult to quantify and depends heavily on political will and external factors [7], [56].

Future research should focus on a more detailed assessment of the socio-economic impacts of decarbonization, including effects on employment, inequality, energy poverty, and energy security. The development of more granular models incorporating subnational specificities within Central Asian countries would further enhance the analytical and practical relevance of policy recommendations [57].

CONCLUSIONS

This study provides a comprehensive assessment of decarbonization prospects in Central Asian economies in the context of achieving Net Zero targets by 2050, employing an integrated scenario and institutional approach. The findings indicate that long-term regional development trajectories fundamentally depend on the depth and consistency of energy and institutional reforms. The Business-as-Usual (BAU) pathway reinforces a carbon-intensive growth model and widens the gap between actual emissions trends and international climate objectives, whereas accelerated transition scenarios demonstrate the potential for substantial CO_2 reductions under conditions of early and coordinated policy action [8], [58].

The Net Zero scenario illustrates that Central Asian countries collectively possess the technical capacity to approach climate neutrality. However, realization of this pathway requires profound structural transformation of energy systems. Power-sector decarbonization plays a central role, generating multiplier effects through electrification of industry, transport, and residential sectors. Without accelerated renewable-energy deployment and infrastructure modernization, Net Zero targets remain practically unattainable [59], [60].

A core contribution of this research lies in its emphasis on the institutional dimension of the energy transition. The analysis demonstrates that the quality of governance, regulatory transparency, effective price signals, and robust MRV systems are as critical as technological solutions. Even substantial renewable-energy potential cannot ensure successful decarbonization in the presence of institutional weaknesses. This underscores the need to embed climate policy within a broader framework of institutional reform and sustainable-development strategy [25], [61]-[72].

Comparative analysis across Central Asian countries reveals marked heterogeneity in starting conditions and transition capacities. Countries with high shares of low-carbon generation enjoy structural advantages, while hydrocarbon-dependent economies face more complex trade-offs between climate goals and macroeconomic stability. Accordingly, effective decarbonization requires differentiated national strategies tailored to specific resource endowments, institutional capacities, and socio-economic contexts [72].

From a policy perspective, the results highlight the critical importance of early investment in low-carbon infrastructure and coherent institutional reform. Delayed action significantly increases the required pace of emissions reduction in later periods and amplifies associated economic and social costs. At the same time, decarbonization represents not only a climate obligation but also an opportunity for technological upgrading, economic diversification, and enhanced long-term competitiveness in Central Asia [35], [69]-[72].

In conclusion, achieving Net Zero in Central Asian countries is a complex yet feasible objective, contingent upon ambitious climate policies, sustained institutional reforms, and strengthened regional cooperation. Future research should further explore the socio-economic dimensions of decarbonization and develop more detailed modeling frameworks that account for intra-country regional specificities, thereby enhancing the scientific and policy relevance of the findings.

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