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Green Development and Regional Energy Security: A Multidimensional Case Study Analysis of the Rogun Hydropower Plant in Tajikistan

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Abstract – Endowed *with one of the most substantial hydropower potentials in Central Asia, the region is strategically positioned to advance its transition to a low-carbon energy future. Hydropower currently contributes over 95% of the region's electricity generation; however, a considerable share of its potential remains underexploited. This paper provides a comprehensive analysis of the role of hydropower in fostering sustainable development, with a focus on the economic, environmental, and social dimensions of expanding this renewable energy source. Utilizing a detailed assessment of the existing hydropower infrastructure, this study identifies key barriers, including financing constraints, and regional cooperation challenges, while simultaneously highlighting the opportunities for scaling up hydropower production.*

A case study of the Rogun Hydropower Plant is presented, illustrating that the project could increase electricity generation by over 3,600 MW, effectively reducing national energy deficits by 40% and providing a potential for surplus export to neighboring regions. The findings underscore the critical importance of overcoming financial and governance obstacles to fully capitalize on hydropower resources. Moreover, the study emphasizes the necessity for robust long-term planning, the development of innovative financing mechanisms, and enhanced multilateral cooperation to secure the sustainable deployment of hydropower resources. These strategies are essential to ensuring the long-term resilience of hydropower as a cornerstone of regional energy security and climate mitigation.

Key Words: **Electricity generation, Sustainable Development, Environmental Impact, and Energy Security**

1. INTRODUCTION

Hydropower is widely recognized as a key renewable energy source that can significantly contribute to mitigating climate change by reducing reliance on fossil fuels. However, its sustainability is highly debated due to the complex trade-offs between energy production and environmental and social impacts. The sustainability of hydropower projects, particularly large-scale ones, has been assessed using multiple frameworks that integrate economic, environmental, social, and governance (ESG) factors [1]. In the context of Tajikistan, where hydropower constitutes the majority of electricity production, it is essential to evaluate these factors comprehensively to determine how to maximize the benefits of hydropower while addressing the potential risks.

Recent studies have emphasized the economic benefits of hydropower, particularly in developing countries. For Tajikistan, hydropower offers the potential for economic growth, industrialization, and energy security. However, studies also highlight the macroeconomic challenges associated with large-scale hydropower projects, particularly the capital-intensive nature of plants like Rogun and the country's limited access to international finance [2]. Furthermore, the economic viability of such projects depends on the ability to balance construction costs, operational efficiency, and long-term revenue from electricity exports [3].

When assessing hydroelectric power plant projects, environmental sustainability is a crucial factor. In the fight against climate change, hydroelectric power is acknowledged as a clean and sustainable energy source that helps lower greenhouse gas emissions. Greenhouse gas emissions can be decreased by large-scale initiatives like the Rogun Hydroelectric Power Plant (Rogun HPP) [2]. In addition, the Rogun HPP is strategically significant for Tajikistan and all of Central Asia. Because hydroelectric electricity replaces conventional fossil fuel power plants and balances intermittent sources like solar and wind, these factors contribute to a decrease in CO2 emissions. As a result, Rogun guarantees energy security and regional economic growth in addition to helping to improve the climatic conditions. The Rogun HPP may successfully demonstrate how energy development and environmental preservation can coexist in harmony by upholding international standards and a strong environmental management framework.

Social sustainability is also a critical component of hydropower assessments, particularly in areas where communities are displaced or impacted by environmental

changes. Large hydropower projects often lead to the displacement of local populations, which necessitates careful planning and execution of resettlement policies [4]. The social impacts of hydropower projects can also include changes in livelihood opportunities, access to water, and regional inequalities. For the Rogun Hydropower Plant, the potential displacement of communities and the need for equitable compensation and community participation in decision-making are central social concerns that must be addressed through inclusive governance frameworks.

Finally, governance mechanisms play a pivotal role in ensuring the sustainability of hydropower projects [5]. Effective governance is essential for managing financial, environmental, and social risks, as well as for fostering transparency and accountability in project implementation.

The aim of this study is to conduct a comprehensive, multidimensional analysis of the Rogun Hydropower Plant in Central Asia, with a focus on its role in enhancing regional energy security and advancing green development. Specifically, the study seeks to evaluate the economic, environmental, social, and governance aspects of the Rogun Hydropower Plant, providing actionable recommendations for ensuring its sustainable contribution to the region's energy future [6]. To achieve this, the study will assess the economic impact of the Rogun Hydropower Plant, including its potential to reduce energy deficits, increase electricity exports, and contribute to long-term economic growth. Additionally, the environmental sustainability of the plant will be evaluated, considering its effects on water resources, biodiversity, and ecosystem health, as well as its capacity to mitigate greenhouse gas emissions compared to fossil fuel-based energy generation [7].

The social implications will also be examined, particularly the impact on local communities, the resettlement process, employment generation, and improved access to energy in rural areas. Furthermore, the study will analyze the governance and financing mechanisms essential for the sustainable development of the plant, focusing on overcoming challenges related to governance, financing, and regional cooperation. Ultimately, the study aims to provide strategic recommendations for optimizing hydropower development in Central Asia, emphasizing the importance of integrated long-term planning, robust financial models, and international collaboration [8].

2. Hydropower Potential in Tajikistan

Tajikistan's hydropower resources are among the largest in the world, ranking it highly in terms of generation capacity per square kilometer and per capita. The country's rivers, particularly the Vakhsh, Amu Darya, and Syr Darya, provide a rich source of renewable energy that can be exploited through the construction of hydropower plants. Despite this, Tajikistan has only tapped into a small fraction of its hydropower potential. Current estimates suggest that Tajikistan has the capacity to generate over 527 billion kWh of electricity annually, which is three times the current electricity consumption in Central Asia [9].

As of 2025, Tajikistan's total installed hydropower capacity has grown to approximately 6,000 MW, reflecting ongoing investments and modernizations that position the country as a key player in Central Asia's renewable energy landscape, though it remains behind global leaders like Brazil, China, and Canada in absolute terms [6].

The Rogun Hydropower Plant, under construction since the 1980s, is set to become the largest hydropower station in Central Asia once completed 10]. With an estimated capacity of 3,600 MW and an expected annual output of 17 billion kWh, Rogun is expected to significantly reduce Tajikistan's energy deficit and increase electricity exports to neighboring countries [11]. According to estimates, Tajikistan's neighboring countries face substantial electricity deficits measured in the hundreds to thousands of megawatts (MW), particularly during winter peak demand. Uzbekistan, Afghanistan, and Kyrgyzstan are among the nations that border Tajikistan and experience significant seasonal electricity shortages, particularly in the winter, as a result of their excessive reliance on erratic hydropower, poor infrastructure, and growing demand that exceeds supply. Along with these countries, Pakistan also faces similar shortcomings [12].

Afghanistan, whose power system remains underdeveloped and highly import-dependent, is estimated to face shortfalls of roughly 300–500 MW during peak winter months, when heating demand rises sharply, and domestic generation is insufficient. Uzbekistan, despite having a larger and more diversified power system, regularly experiences seasonal deficits ranging from 1,000 to 2,000 MW in winter, driven by surging residential heating demand, aging thermal infrastructure, and constraints in fuel supply. Kyrgyzstan, like Tajikistan, relies heavily on hydropower and suffers from low reservoir levels in winter, resulting in electricity shortages of approximately 400–700 MW during peak periods [13]. Pakistan, although not a direct neighbor to Tajikistan, faces comparable structural challenges; during high-demand seasons-particularly winter evenings and summer heat waves-its power shortfall has historically ranged from 2,000 to over 5,000 MW, affecting both households and industry. Collectively, these deficits underscore a regional pattern in which winter demand consistently exceeds available supply, highlighting the urgent need for cross-border power trade, grid modernization, and diversification away from exclusive dependence on seasonal hydropower [14].

Tajikistan's hydropower potential is not only crucial for meeting domestic energy needs but also for positioning the

country as a key player in the regional energy market. The country's role as an energy exporter could contribute to economic growth, particularly through trade agreements with neighboring nations and the implementation of cross-border energy infrastructure. In particular, Tajikistan's participation in regional initiatives, such as the Central Asia-South Asia Electricity Transmission and Trade Project (CASA-1000), can facilitate the export of surplus energy, boosting the country's economic development and fostering regional cooperation [15].

Furthermore, Tajikistan's position as a major energy hub in the region is reinforced by the current unified Central Asian Power System (CAPS), which has ready-made high-voltage transmission infrastructure from the Soviet era that enables instantaneous electricity exchanges among Tajikistan, Uzbekistan, Kyrgyzstan, and Kazakhstan [16].

The underutilization of Tajikistan's hydropower potential presents a significant opportunity for the country. The expansion of hydropower capacity, including both large-scale projects like Rogun and smaller, decentralized hydropower systems, could help ensure energy security, reduce reliance on imported fossil fuels, and address the power shortages that affect rural communities [17].

Table 1: Major Hydropower Plants in Tajikistan

Hydropower Plant	Owner	Capacity (MW)	River
Nurek HPP	Barki Tojik	3000	Vakhsh
Sangtuda HPP-1	Sangob (Iran)	670	Vakhsh
Baipaza HPP	Barki Tojik	600	Vakhsh
Golovnaya HPP	Barki Tojik	240	Vakhsh
Kairakum HPP	Barki Tojik	126	Syr Darya
Pereadnaya HPP	Barki Tojik	29.95	Vakhsh Canal
Pamir-1 HPP	Pamir Energy	28	Gunt
Centralnaya HPP	Barki Tojik	15.1	Vakhsh Canal
Varzob HPP-2	Barki Tojik	14.7	Varzob
Varzob HPP-1	Barki Tojik	9.5	Varzob

Source: Investments in the Water and Energy Complex of Central Asia, Eurasian Development Bank, Almaty, 2021, p. 13.

2.1. The Role of Hydropower in Sustainable Development

Hydropower is central to Tajikistan's energy strategy and its broader goal of sustainable development. Hydropower offers numerous economic, environmental, and social benefits, making it a critical component of Tajikistan's green energy transition. This section will explore how hydropower contributes to Tajikistan's economic growth, energy security, and environmental sustainability.

Using Central Asia as an example, the development of the energy sector can ensure rapid economic growth not only for Tajikistan, but also for neighboring countries through the export of cheap, environmentally friendly energy [18].

Economic Contributions

Hydropower in Tajikistan plays a crucial role in the country's economic development. As the primary source of electricity, hydropower supports industries such as manufacturing, agriculture, and services, all of which are essential to the country's economic growth. The availability of low-cost, renewable electricity is essential for industrialization, particularly in energy-intensive sectors such as mining and textiles. Hydropower also offers significant export potential, allowing Tajikistan to generate revenue from the sale of electricity to neighboring countries such as Afghanistan, Pakistan, and Uzbekistan [19].

Beyond energy generation, the development of hydropower infrastructure generates employment opportunities, both during the construction phase and through ongoing maintenance and operations. It also fosters the development of ancillary industries, including the construction sector, equipment manufacturing, and research and development. Furthermore, the development of hydropower projects can stimulate regional economic cooperation, particularly in the context of cross-border energy trade and infrastructure development [18].

Agricultural development in Central Asian countries depends largely on the water resources of the Amu Darya and Syr Darya rivers, which provide irrigation, sustainable agriculture, and seasonal employment.

According to the Interstate Commission for Water Coordination (ICWC), the total water withdrawal limit for the Syr Darya will be 4.2 billion m^3 by 2026. Water distribution remains uneven: Kazakhstan will receive 460 million m^3, Kyrgyzstan 47 million m^3, Tajikistan 365 million m^3, while Uzbekistan will receive the largest share—3.347 billion m^3 (79.3%). This distribution is driven by the need to maintain environmental flows and prevent soil salinization in the river's lower reaches [20].

Despite high water inflows into the upper reaches of the Syr Darya (6.119 billion m^3, or 119% of the norm), a number of reservoirs received significant volumes: Toktogul - 500 million m^3, Andijan - 320 million m^3, Charvak - 428 million m^3, and Shardara - 576 million m^3. This requires coordinated water releases to maintain sanitary flows, which simultaneously reduces resources for irrigated agriculture [21].

At the same time, Tajikistan did not experience water shortages in 2025: the country received 9.8 billion m^3 from

the Amu Darya, using approximately 83% of the established limit. This ensured the stable operation of reservoirs, prevented drought, and ensured sustainable irrigation of farmland, supporting rural employment and incomes.

Kazakhstan, located in the lower reaches of the Syr Darya River, will face a reduction in water resources: during the non-growing season, the volume of incoming water will be almost halved compared to 2025 levels (460 million m^3 versus 909 million m^3). In response, predictive reservoir operating modes and water redistribution measures are being developed, allowing farmers to adapt cropping patterns and reduce the risk of crop losses [22].

Overall, water availability remains a key factor in the region's agricultural development. Although coordinated water resource management helps reduce the risk of drought and maintain irrigation, lower river reaches, particularly in Kazakhstan, remain the most vulnerable to water shortages [6].

Environmental Benefits

Hydropower is a key driver of Tajikistan's environmental sustainability. As a renewable energy source, hydropower reduces the country's reliance on fossil fuels, mitigating the environmental degradation associated with coal, oil, and natural gas extraction. Hydropower has a significantly lower carbon footprint than conventional power generation technologies, and its use can help Tajikistan meet its climate goals, including reducing greenhouse gas emissions in line with international climate agreements.

In addition to reducing carbon emissions, hydropower contributes to water management and flood control, particularly in regions vulnerable to seasonal flooding. Large dams like Rogun can help regulate river flows, provide irrigation for agriculture, and ensure a steady water supply for both human consumption and ecosystem preservation. Tajikistan's vast network of rivers offers the potential for integrating hydropower with other forms of water resource management, enhancing both energy production and environmental resilience [23].

Tajikistan's hydropower infrastructure, located in the upper reaches of the Amu Darya and Syr Darya river basins, plays a key role in regulating the water balance of the Central Asian region, contributing to sustainability and preventing further depletion of the Aral Sea.

In particular, the Nurek reservoir on the Vakhsh River (a tributary of the Amu Darya) operates in a mode of regulated releases, smoothing out fluctuations in flow and accumulating reserves during intense glacier melting (in August-September 2025, the inflow reached 115% of the norm), which prevents water shortages during periods of variable flow and ensures a stable water supply for irrigation and the population of downstream countries.

Similarly, the "Bakhri Tojik" reservoir on the Syr Darya, jointly used by Tajikistan, Kazakhstan, and Uzbekistan since May 2025 based on a trilateral protocol, is being transformed into a coordinated flow management system.

During the winter (non-irrigation) period, when the demand for water for irrigation decreases, Tajikistan significantly reduces releases from the reservoirs of the Vakhsh cascade and the Syr Darya: for example, in 2024–2025, the volume of additional releases amounted to almost 1.8 billion m^3 above the plan to maintain sanitary and ecological flow in the riverbed and prevent salinization and desertification of downstream territories [24].

These measures immediately ensure the preservation of the Aral Sea and its deltas: in 2025–2026, 4.2 billion m^3 of water are planned to be allocated specifically for the Aral Sea (half in the winter-spring period), plus an additional 800 million m^3 for sanitary and ecological releases into the irrigation systems of the Aral Sea region. Thus, Tajikistan's position in the upper reaches of the river and its hydropower facilities provide a buffer against seasonal fluctuations in water flow, contributing to short-term cooperation within the framework of the Interstate Water Management Coordination Commission (ICWC) and preventing environmental disasters in the Aral Sea basin.

Social Impact and Energy Access

The social benefits of hydropower in Tajikistan are equally important. As a source of renewable energy, hydropower can provide reliable electricity to remote and underserved communities, reducing energy poverty and improving living standards. In rural areas, where energy access is limited, hydropower development can facilitate the provision of electricity to homes, schools, healthcare facilities, and businesses. This, in turn, can drive socio-economic development, improve health outcomes, and provide better opportunities for education.

However, the social impacts of hydropower development must also be carefully considered. Large hydropower projects often require the displacement of local communities, and ensuring fair compensation, resettlement,

and access to social services is essential. Tajikistan must implement robust resettlement policies, following international best practices, to mitigate the social consequences of hydropower projects. Effective community engagement and participation in decision-making are essential for ensuring that the benefits of hydropower are shared equitably among all stakeholders [25].

Access to drinking and irrigation water in Central Asian countries is largely determined by the regulation of the flow of the transboundary Amu Darya and Syr Darya rivers by Tajikistan's hydropower facilities. In downstream countries-Uzbekistan, Turkmenistan, and the southern regions of Kazakhstan-where the majority of the population lives in rural areas and is employed in agriculture, this regulation directly impacts the standard of living, food security, and socioeconomic stability of millions of people. During the non-growing season (winter), despite its own energy needs, Tajikistan increases water releases from the Vakhsh Cascade and Syr Darya reservoirs to maintain sanitary and environmental flows downstream. In 2024–2025, the volume of additional releases exceeded the planned volume by almost 1.8 billion m^3, preventing riverbed salinization and critical downstream water shortages. The Nurek Reservoir effectively smoothed out fluctuations in the Amu Darya's flow, accumulating the necessary reserves during the period of intense glacier melt (up to 115% of normal in August–September 2025), ensuring a stable water supply to fields and settlements downstream without major disruptions [26].

Ecological releases are particularly important for preserving the Aral Sea and the Aral Sea region: 4.2 billion m^3 of water are allocated specifically for the Aral Sea and its delta in 2025–2026 (half of this is allocated during the winter-spring period), as well as an additional 800 million m^3 for sanitary and environmental needs of the irrigation systems of the Dashoguz velayat (Turkmenistan), Khorezm region, and Karakalpakstan (Uzbekistan). This is critical for preserving floodplain ecosystems and providing water to the region's population, which is already suffering from shortages.

Tajikistan's hydropower infrastructure thus serves as a key instrument for regional water management, directly determining access to water and quality of life in rural areas of downstream Central Asian countries [27].

2.2. **Strategies for Enhancing Green Energy Development**

For Tajikistan to fully capitalize on its hydropower potential, the country must adopt a multifaceted strategy that addresses the financial, environmental, and governance challenges associated with large-scale hydropower development. This section discusses the key strategies that Tajikistan can adopt to ensure the sustainable development of its hydropower sector.

Financial and Governance Reforms

One of the critical obstacles to hydropower development in Tajikistan is securing sufficient financing. Hydropower projects, especially large-scale ones like Rogun, require significant investment, and Tajikistan's national budget is already stretched thin due to other development priorities. To overcome this challenge, Tajikistan must explore diverse financing options, including public-private partnerships, international loans, and green bonds. Engaging in regional and international funding initiatives will be crucial in ensuring the completion of ongoing projects and the initiation of new ones [29].

Additionally, Tajikistan must strengthen its governance framework to ensure transparency and accountability in hydropower development. Effective project management, coupled with stringent anti-corruption measures, will enhance investor confidence and ensure that the benefits of hydropower are distributed equitably.

However, Tajikistan's public-private partnership (PPP) mechanism for implementing projects is underdeveloped, especially for hydropower projects. First and foremost, Tajikistan needs to liberalize its energy sector to alleviate significant burdens on the state budget. This year alone, 20% of the budget is allocated to the construction of the Rogun hydroelectric power station. Widespread use of PPPs could alleviate this burden on the country's budget and reallocate it toward addressing equally important social issues [29].

Macroeconomic Risks

Large-scale hydropower projects in Tajikistan, such as the Rogun Dam, are exposed to significant macroeconomic risks. These include fluctuations in exchange rates, inflation, and overall economic growth. For instance, depreciation of the national currency can increase the local cost of imported equipment and materials, while inflation can erode the real value of government and investor contributions. Additionally, dependence on hydropower revenue for budgetary planning exposes the country to revenue volatility, especially in years of low water inflow due to climatic variability.

Debt Sustainability

Hydropower projects require massive upfront investments, often financed through long-term loans from international institutions or bilateral agreements. High levels of debt can strain Tajikistan's public finances, especially if projected revenues from energy exports or domestic electricity sales are delayed or underperform.

Debt sustainability assessments must consider the ability to meet principal and interest payments without jeopardizing social spending or other development priorities [28]. Maintaining a sustainable debt-to-GDP ratio is crucial to ensure that hydropower investments do not compromise fiscal stability.

Non-Performing Investments

Large hydropower projects are vulnerable to becoming non-performing investments if they face construction delays, technical inefficiencies, or lower-than-expected output. Factors contributing to this risk include insufficient project management capacity, environmental constraints, and unforeseen hydrological variability. Non-performing projects tie up significant capital without delivering expected returns, thereby reducing investor confidence and potentially deterring future investment.

Long-Term Investment Horizons

Hydropower projects typically have long gestation periods, often spanning decades from planning to full operational capacity. This long-term horizon increases exposure to political, economic, and technological changes that can alter project viability. Investors and governments must account for shifts in energy demand, regional energy markets, and climate conditions over these extended periods to ensure the sustainability of returns.

Project Cost Escalation Risks

Cost escalation is a common challenge in large hydropower projects. Factors include rising material and labor costs, delays in construction, and unforeseen technical difficulties. Climate-related factors, such as extreme floods or droughts, can also drive up costs by requiring additional infrastructure or mitigation measures. Without effective risk management and contingency planning, project budgets can overrun, potentially leading to funding shortfalls and delays in commissioning [30].

Together, these factors highlight why financial and governance reforms, including diversified financing, robust project oversight, and risk mitigation strategies, are essential for the sustainable development of Tajikistan's hydropower sector.

Regional Cooperation and Energy Integration

Regional cooperation is essential for maximizing the benefits of hydropower development in Tajikistan. The Central Asian region is home to several countries with significant hydropower potential, and the development of a regional energy market could provide mutual benefits. Tajikistan, along with its neighbors, should work to harmonize energy policies, share resources, and develop joint energy infrastructure projects. The CASA-1000 project, which aims to connect Tajikistan and Kyrgyzstan with Pakistan and Afghanistan through an energy transmission network, is a promising example of regional collaboration. Expanding such initiatives could position Tajikistan as a regional energy hub [30].

Tajikistan and its neighbors can maximize hydropower production, balance seasonal electricity supply, and lower regional energy shortfalls by working together within the Central Asian Energy System. Initiatives such as the CASA-1000 project show how Central Asia may become a connected and mutually beneficial regional energy market through coordinated energy policies and shared infrastructure.

Technological Innovation and Modernization

Technological innovation is another critical factor in enhancing the efficiency and sustainability of Tajikistan's hydropower sector.

Based on available data from government and energy-sector reporting, Tajikistan has implemented a substantial number of energy infrastructure and modernization projects, including those in hydropower:

Since 2001, Tajikistan has completed 36 energy projects in the broader energy sector (which includes construction and modernization of hydroelectric plants, power lines, grid upgrades, and related infrastructure). These are directly linked to improving generation capacity and reliability. -[31]

In addition, the government is actively implementing another 18 projects currently under way. These ongoing projects also encompass modernization and new capacity expansion in hydropower and transmission infrastructure. -[6]

Specific major hydropower modernization efforts include the complete rehabilitation of all six units at the Qairokkum Hydropower Plant (increasing capacity and resilience) and the ongoing multi-year modernization of units at the Nurek Hydropower Plant, both of which are central to Tajikistan's efforts to enhance winter generation capacity and system reliability [32].

Taken together, these figures indicate that more than 50 projects related to energy production, grid modernization, and hydropower infrastructure-many of which involve technological upgrades-have been implemented or are in active development in Tajikistan's energy sector, including significant investments in hydropower modernization [6].

A notable example is the comprehensive rehabilitation of the Nurek Hydropower Plant, where aged turbines and auxiliary equipment are being replaced with high‑efficiency

units; by August 2024, four of the nine generating units had been modernized and reconnected to the grid, and additional turbine upgrades were underway through 2025, with the project expected to increase total capacity from approximately 3 015 MW to about 3 375 MW upon full completion [33].

In parallel, the Kairakkum Hydropower Plant in Sughd region completed modernization of all six of its hydroelectric units by November 2025, increasing the station's capacity from 126 MW to 174 MW and boosting annual electricity generation from roughly 650 million kWh to about 900 million kWh.

By the end of 2025, these projects - including the multi‑phase rehabilitation of Nurek and the complete upgrade of Kairakkum - represent the core modernization initiatives implemented to date, contributing to improved operational performance, reduced maintenance costs, and enhanced energy output, while laying the foundation for future integration of smart grid technologies and advanced monitoring systems to optimize generation and distribution.

In Tajikistan, electricity losses remain a significant obstacle to the efficient use of hydropower potential and stable energy supply. According to the Ministry of Energy and Water Resources, the total level of losses in the energy system in 2024 amounted to approximately 20% of the electricity produced, meaning that every fifth kilowatt-hour of generated energy is lost before reaching the end consumer.

This situation is largely due to the inefficient state of distribution networks and commercial losses (including theft and unaccounted consumption). In the country's distribution networks, commercial losses in 2024 were recorded at approximately 21.6%, while independent experts believe that the actual level of losses may exceed 40% without system modernization.

In the capital Dushanbe, progress was made in reducing losses during the first half of 2025, and this figure decreased to 16.9%, however, it remains significantly higher than international standards and limits the ability of power grids to effectively support the growth of the agricultural and industrial sectors.

Thus, modernization of distribution networks, the introduction of smart metering and control systems, and combating commercial losses are critically important elements for increasing the efficiency of Tajikistan's energy sector and ensuring the sustainable development of the economy as a whole [34].

The integration of smart grid technologies, energy storage systems, and advanced monitoring tools can optimize the distribution and management of electricity, particularly during periods of peak demand. Tajikistan should also invest in research and development to explore the potential for micro-hydropower projects, which could provide decentralized energy solutions for remote areas.

3. Materials and methods

3.1 Study Area

Tajikistan is a landlocked, mountainous country located in Central Asia, with its vast river systems such as the Vakhsh, Amu Darya, and Syr Darya offering significant hydropower potential. The Rogun Dam, situated upstream from the Nurek Dam on the Vakhsh River serves as a central focus of the study. This region is part of Tajikistan's central mountainous area, which is characterized by challenging terrain and significant seasonal variations in water flow, particularly influenced by glacier melt and precipitation patterns. The environmental characteristics of this region, such as water availability, biodiversity, and ecosystem health, are crucial for understanding the sustainability of hydropower projects.

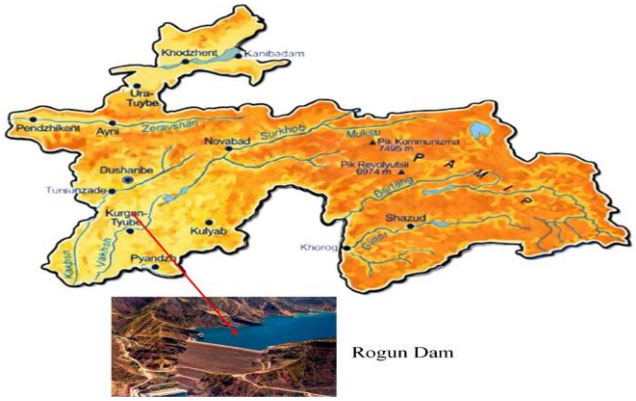


Fig – 1: Shows the map of the study area

3.2 Methods

This study employs a mixed-methods approach to explore the hydropower development landscape in Tajikistan, integrating qualitative and quantitative data analysis to examine the economic, environmental, and social implications of expanding hydropower infrastructure. The methodology is designed to provide a comprehensive understanding of Tajikistan's hydropower potential, incorporating data from primary sources, such as stakeholder interviews and site observations, alongside secondary data obtained from government reports, industry publications, and international studies. The research utilizes both statistical modeling and sustainability assessment frameworks to quantify and visualize key metrics, ensuring a holistic evaluation of Tajikistan's green energy development.

3.2.1. Research Design

The research design is based on an exploratory and explanatory framework that combines qualitative insights with quantitative analysis. This integrated approach allows the study to explore the factors driving hydropower development in Tajikistan and to identify key trends and challenges in the sector. The exploratory aspect seeks to uncover emerging issues, such as the role of governance and financial constraints, while the explanatory aspect aims to establish the relationships between hydropower expansion and broader sustainability goals, such as energy security, economic development, and environmental protection.

Additionally, the research takes a longitudinal perspective, examining historical trends in hydropower development in Tajikistan and projecting future needs and opportunities. The study assesses the current state of Tajikistan's hydropower sector, particularly in terms of installed capacity, production, and social and environmental impacts, and uses this baseline to evaluate the sustainability of future developments.

3.2.2. Data Collection

Data were collected from a combination of primary and secondary sources to ensure a comprehensive understanding of the hydropower sector in Tajikistan.

Primary data were gathered through interviews and site visits. Semi-structured interviews were conducted with key stakeholders in Tajikistan's energy sector, including government officials, energy policymakers, engineers involved in hydropower projects, environmental experts, and representatives from international financial institutions such as the World Bank and the Asian Development Bank. These interviews provided rich qualitative insights into the challenges, opportunities, and governance frameworks surrounding hydropower development in Tajikistan.

In addition to interviews, site visits were conducted to hydropower plants, including Nurek, Sangtuda, and Rogun. These visits allowed for firsthand observations of plant operations, environmental management practices, and community interactions, offering a deeper understanding of the on-the-ground realities of hydropower development in Tajikistan. Site visits also facilitated discussions with plant operators, local authorities, and affected communities, contributing to the evaluation of social impacts and the effectiveness of mitigation measures.

Secondary data were collected from a range of sources, including government publications, international energy reports, and academic literature. These sources provided valuable quantitative data on hydropower capacity, energy consumption, and environmental performance. Project documentation, such as feasibility studies, environmental and social impact assessments (ESIAs), and financial reports from key hydropower projects in Tajikistan, were also reviewed to provide detailed insights into the development, financing, and environmental impacts of these projects.

4. Data Analysis

The data analysis process combined qualitative coding, quantitative modelling, and visual representations to assess the sustainability of hydropower development in Tajikistan. This analysis was structured around four main dimensions: economic viability, environmental sustainability, social impact, and risk management.

4.1. Qualitative and Quantitative Analysis

The qualitative data collected from interviews and site visits were analyzed using thematic coding to identify key patterns related to governance, financial challenges, environmental risks, and social impacts. This approach allowed for the identification of recurring themes and insights that provide a deeper understanding of the factors influencing hydropower development in Tajikistan. Key themes included the role of international financing, governance issues, and the effectiveness of environmental mitigation measures.

To provide a robust empirical foundation for the study, statistical models were developed to analyze energy production and demand in Tajikistan. Historical data on electricity consumption, population growth, and industrial development were used to forecast future energy demand, which was then compared to the potential hydropower supply from existing and planned projects. A linear regression model was applied to project future energy consumption trends based on demographic and economic indicators.

Additionally, energy shortfall calculations were performed to assess the gap between hydropower production and energy demand, particularly during periods of low water flow in the winter months. This calculation identified the need for supplementary power sources or energy imports to meet seasonal electricity demand. Graphical representations of energy supply and demand curves were created to visualize this gap, providing a clear depiction of the challenges facing Tajikistan's energy security.

4.2. Environmental Sustainability Modeling

The environmental analysis focused on assessing the carbon emissions reduction potential of hydropower compared to fossil fuel-based power generation. A carbon footprint model was used to calculate the reduction in CO2 emissions that would result from Tajikistan's hydropower projects. The emissions savings were quantified by applying standard emission factors for coal and natural gas power

plants (as reported by the IEA). The formula for CO2 savings was applied to each hydropower project:

$$CO_2 Saving\left(\frac{tons}{year}\right) = \left\{ \begin{array}{l} Electricity\,Output\left(\frac{kwh}{year}\right) \times \\ Emission\,Factor\left(\frac{tons}{kwh}\right) \end{array} \right\}$$

The results were presented in bar charts below in Figure 4, comparing the emissions reductions of hydropower projects against fossil fuel alternatives.

4.3 Sustainability Assessment:

An integrated Sustainability Assessment Framework (SAF**)** was used to evaluate the economic, environmental, and social sustainability of hydropower projects. The framework was adapted to suit Tajikistan's context, incorporating sustainability indicators related to financial viability, environmental impact, social acceptance, and risk management. These indicators were scored based on expert assessments and data derived from the project documents.

The Strengths**,** Weaknesses**,** Opportunities**,** and Threats (SWOT) analysis was used to identify internal and external factors that affect the sustainability of hydropower projects in Tajikistan. This analysis highlighted strengths such as the country's vast hydropower potential, weaknesses related to financial constraints, opportunities for regional energy integration, and threats stemming from political instability and environmental challenges.

- Strengths (Internal factors)- This section could highlight the advantages of the Rogun project, such as its potential to increase electricity generation capacity, improve energy security, and reduce dependence on fossil fuels. It can also emphasize the project's alignment with national energy strategies and the country's long-term sustainability goals.

- Weaknesses (Internal factors)- The weaknesses section will visually outline the internal challenges, such as high initial investment costs, financing challenges, outdated infrastructure, and regulatory hurdles that could delay or affect the long-term operational efficiency of Rogun.

- Opportunities (External factors)- This section can highlight the opportunities for regional energy integration, including Tajikistan's potential as an energy exporter to neighboring countries like Afghanistan and Pakistan. It can also include opportunities for international cooperation, technological advancements in hydropower, and green financing options that could support the development of the project.

- Threats (External factors)- The threats section would capture the external risks to the sustainability of the project, such as political instability, competition for water resources, environmental degradation, and the potential impacts of climate change on water flow.

4.4. Graphical Representations and Visualization

Throughout the analysis, graphical tools were employed to present the results clearly. These included:

✓ Energy Supply and Demand Graph

These graphs illustrate the gap between projected hydropower output and energy demand in Tajikistan. They also highlight the seasonal fluctuations in energy availability and the risks associated with this dependence on hydropower.

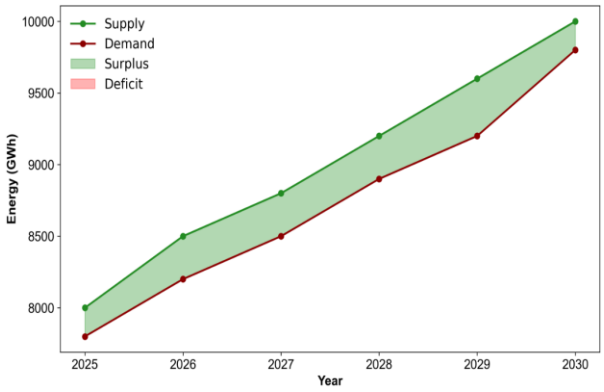


Fig – 2: Shows energy supply vs demand in Tajikistan

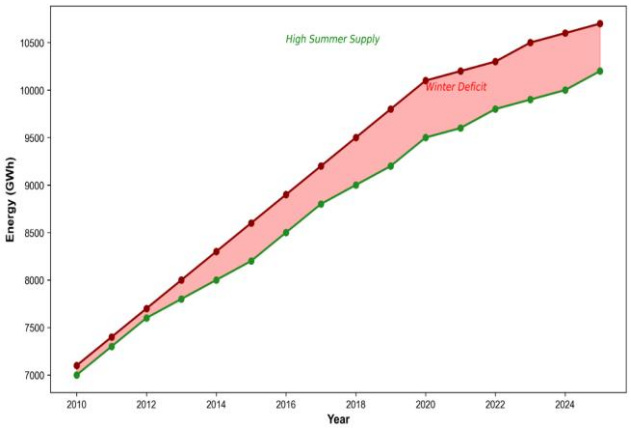


Fig – 3: Present seasonal variations and their implications

✓ CO2 Emission Reduction Graph (Bar Chart)

The compares the CO2 savings from hydropower projects versus fossil fuel generation. Example data for CO2 emissions saved.

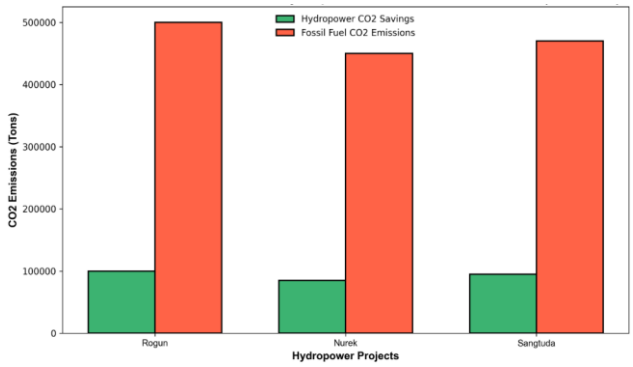


Fig – 4: Describes CO2 savings (in tons) for hydropower vs fossil fuel plants

Alternative Scenario: CO2 Emissions from Coal-Fired Electricity Production in Tajikistan

$$CO_2 Saving\left(\frac{tons}{year}\right) = \left\{ Electricity\ Output\left(\frac{kwh}{year}\right) \times \right.$$
$$\left. Emission\ Factor\left(\frac{tons}{kwh}\right) \right\}$$

The formula calculates CO2 savings (in tons) as the difference between emissions from a fossil fuel alternative (e.g., coal) and the actual hydropower generation:

CO_2 Savings (tons) = [Electricity Output (MWh) × Coal Factor (tons/MWh)] - [Electricity Output (MWh) × Hydro Factor (tons/MWh)].

This represents the emissions avoided by using hydropower instead of coal.

Step 1: Determine Tajikistan's Relevant Electricity Output

- Annual total electricity generation (2024): 22.43 TWh (or 22,430,000 MWh).
- Hydropower share: 89%, equating to approximately 20 TWh (or 20,000,000 MWh) from hydropower. (Note: Some sources cite up to 98%, but 89% is a conservative estimate reflecting recent diversification into coal and gas for winter reliability.)

- In the alternative scenario, we calculate emissions as if this 20,000,000 MWh were produced by coal-fired plants instead.

Step 2: Select Emission Factors

- Coal factor: A standard emission factor for coal-fired power plants is 0.92 tons of CO2 per MWh. This is an average derived from global and regional data, accounting for variations in coal type and plant efficiency (typically ranging from 0.82 to 1.0 tons/MWh). For context, this includes lifecycle emissions like mining and transport but focuses on operational combustion.

- Hydro factor (for reference in savings calculation): Approximately 0.024 tons of CO2 per MWh, based on median global values for reservoir-based hydropower in temperate regions like Tajikistan (accounting for methane from reservoirs and construction). This is very low compared to fossil fuels.

Step 3: Calculate Alternative CO2 Emissions

- Alternative emissions from coal = Hydropower Output (MWh) × Coal Factor (tons/MWh).
- Plugging in the values: 20,000,000 MWh × 0.92 tons/MWh = 18,400,000 tons of CO2 annually.
- This represents a hypothetical where coal replaces hydropower, leading to significantly higher emissions. For scale, this is equivalent to the annual CO2 output of about 4 million passenger vehicles or the carbon sequestration of roughly 215 million tree seedlings grown for 10 years (using EPA equivalencies for illustration).

Step 4: Compare to Current Scenario and Calculate Savings (for Context)

- Current emissions from hydropower = 20,000,000 MWh × 0.024 tons/MWh = 480,000 tons of CO2 annually (a fraction of the alternative).
- CO2 savings (using the formula) = [20,000,000 × 0.92] - [20,000,000 × 0.024] = 18,400,000 - 480,000 = 17,920,000 tons avoided annually.

- This savings highlights hydropower's environmental advantage, equivalent to removing about 3.8 million cars from the road each year.

Sensitivity Analysis (to Account for Variability)

- If using a lower coal factor (e.g., 0.85 tons/MWh for more efficient plants): Alternative emissions = 20,000,000 × 0.85 = 17,000,000 tons.

- If using a higher coal factor (e.g., 1.0 tons/MWh for subcritical plants common in developing regions): Alternative emissions = 20,000,000 × 1.0 = 20,000,000 tons.
- If hydropower share is 98% (higher estimate): Output = 22,000,000 MWh, alternative emissions ≈ 20,240,000 tons (using 0.92 factor).

This range (17-20 million tons) shows the calculation's robustness, but actual values depend on plant specifics.

✓ Sustainability Radar Chart

A radar chart was used to visually represent the sustainability performance of hydropower projects across various dimensions (economic, environmental, social, and risk management), enabling a quick comparison of their relative strengths and weaknesses.

Fig – 6: Shows a radar chart visualizes the Sustainability performance of hydropower projects

A radar chart is a visual tool for visualizing the multidimensional sustainability of hydropower projects, allowing several key parameters to be assessed simultaneously. It helps policymakers, investors, and other stakeholders quickly identify project strengths and weaknesses, as well as their overall sustainability.

Figure 6: Sustainability Radar Chart – Key Parameter Indicators. The chart includes axes representing the key sustainability components: economic feasibility, environmental impact, social impact, risk management, governance and transparency, and technical and operational performance. Indicators are typically rated on a scale (e.g., 0 to 10), forming a polygon, where a larger, more symmetrical shape indicates a higher level of sustainability, and dips indicate problem areas. For hydropower projects in general and in Tajikistan in particular, economic feasibility is generally rated high due to low operating costs, long service life, and potential for revenue from domestic consumption and electricity exports, including through the CASA-1000 initiative. Environmental performance remains mixed: despite low carbon emissions, risks associated with changes in river flow, biodiversity, and methane emissions remain, but modern environmental standards allow for higher ratings.

Social impact is determined by the balance between population resettlement, job creation, and increased access to electricity; comprehensive resettlement and community development programs significantly improve this indicator. Risk management encompasses seismic, hydrological, financial, and geopolitical threats and is enhanced by quality planning and insurance mechanisms. Governance and transparency, including anti-corruption measures and stakeholder participation, are critical to investor confidence.

Technical and operational efficiency are linked to the quality of design, the implementation of modern technologies, and adaptation to seasonal and climatic variations. The radar chart for Tajikistan's hydropower development strategy shows strong economic and technical performance, coupled with historically weaker, but improving, social, environmental, and governance aspects. The Rogun and modernized Nurek hydropower projects demonstrate that targeted reforms and international cooperation are gradually improving the sustainability profile.

Overall, this visualization highlights the need for an integrated approach: sustainable hydropower development in Tajikistan requires balanced progress across all key areas to ensure long-term environmental, social, and economic benefits.

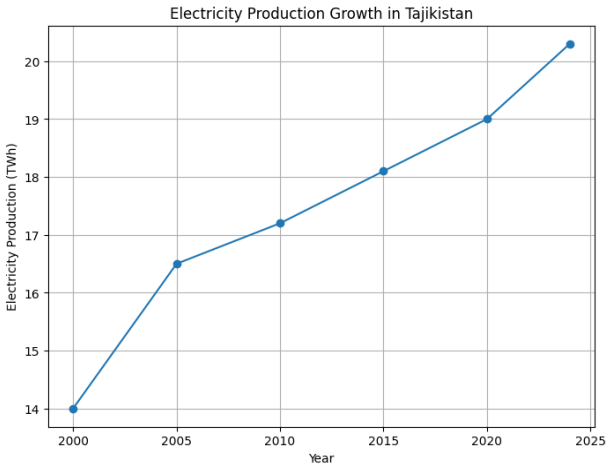
5. Analysis and Discussion

The Energy Supply vs. Demand Graph for Tajikistan, spanning the period from 2010 to 2025, provides invaluable insights into the country's dependence on hydropower to meet its electricity needs, as well as the associated challenges and opportunities. The graph highlights seasonal variations in energy supply and demand, which arise from Tajikistan's reliance on hydropower, a source of energy influenced by the seasonal fluctuations in water flow, particularly from glacial melt and rainfall. During the summer months, river flows peak, resulting in increased energy generation from hydropower plants. This is reflected in the green-shaded surplus areas in the graph, where supply exceeds demand. The excess energy produced during these months presents a significant opportunity for Tajikistan to export electricity to neighboring countries, such as Afghanistan, Pakistan, and Uzbekistan, thus contributing to regional energy security. The export potential is further supported by regional initiatives like the CASA-1000 project, which aims to enhance electricity trade between Central Asia and South Asia. Exporting surplus energy not only contributes to regional cooperation but also generates economic benefits for Tajikistan, providing a source of revenue that can be reinvested into infrastructure development and further energy projects. This opportunity, however, is highly dependent on the development of effective transmission infrastructure and regional agreements, as noted by [31].

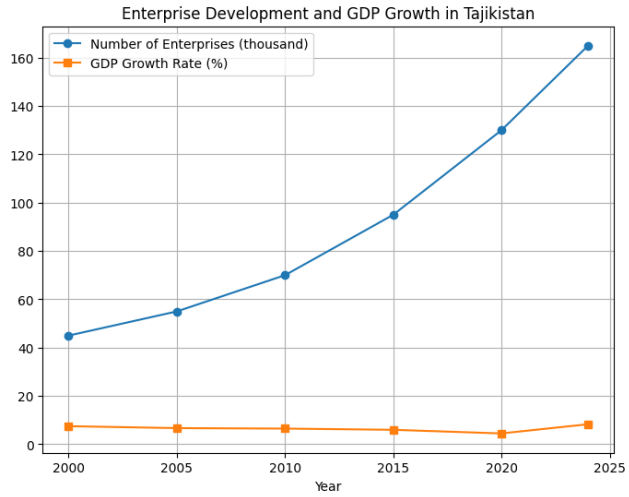
However, the graph also reveals a significant challenge: the winter deficit in energy supply. As river flows decline during the winter months, hydropower generation drops, leading to an energy shortfall. The red-shaded areas in the graph highlight this mismatch, where demand exceeds supply, leading to potential energy shortages. This seasonal fluctuation poses a risk to Tajikistan's energy security, as the country remains heavily reliant on hydropower without a diversified energy portfolio. The seasonal energy deficit, particularly in the winter, suggests that Tajikistan must address this vulnerability through energy diversification. The need to reduce dependence on hydropower is echoed in [34], which argues that nations dependent on hydropower must incorporate alternative renewable energy sources, such as solar and wind power, to stabilize their energy systems. These alternatives could provide consistent energy

generation throughout the year, complementing hydropower's seasonal production and mitigating the risk of energy shortages during critical months. Furthermore, energy storage systems such as pumped hydro storage or battery storage could play an essential role in balancing the supply-demand gap by storing excess energy produced during high-flow periods and releasing it during peak demand or low-flow months. This strategy, discussed by [5], could reduce the vulnerability of Tajikistan's energy system and provide more reliable power to meet growing demand.

The steady increase in energy demand over the period from 2010 to 2025, as shown in the graph, reflects the growing economy of Tajikistan, particularly in industrial sectors such as mining, manufacturing, and agriculture, which are energy-intensive. In addition, urbanization and population growth have led to increased demand for electricity, with the demand curve consistently trending upward from 7,100 GWh in 2010 to 10,700 GWh in 2025. This increasing demand, as highlighted in previous works by [48], reflects the broader economic and social developments in Tajikistan. As the economy continues to grow, especially in energy-intensive sectors, the country will require a more diversified energy mix to meet its rising electricity needs. The existing hydropower capacity is insufficient to meet this growing demand during critical periods, particularly in winter, when water flow is low. This mismatch between supply and demand further highlights the need for diversification and the development of additional energy sources, as discussed by, who noted the challenges of relying on a single energy source to meet increasing demand in rapidly developing economies [35].



Source: author's illustration based on data from Agency on statistic (www.stat.tj/en)



Source: author's illustration based on data from Agency on statistic (www.stat.tj/en)

Tajikistan supplemented its inherited hydropower base with new capacity expansions and systematic modernization of existing facilities during the time of independence, as seen in Figures 1 and 2, resulting in a considerable increase in effective energy generation. Increased private investment in actual economic sectors and entrepreneurship were made possible by the ensuing improvement in energy reliability, which in turn supported steady GDP development [38].

The green-shaded surplus areas on the graph, indicating periods of excess hydropower generation, present an opportunity for Tajikistan to export electricity to neighboring countries. This surplus, especially during the summer months when water flow is at its peak, can be utilized to meet the growing energy demand in countries like Afghanistan, Pakistan, and Uzbekistan, which face significant energy shortages. Energy export is not only an opportunity for Tajikistan to enhance regional energy cooperation but also to diversify its economy, which remains heavily reliant on agriculture and remittances [36]. By exporting electricity, Tajikistan could generate revenue, which can be reinvested into the country's energy infrastructure, including the development of renewable energy sources such as solar, wind, and potentially geothermal power [49]. These developments, as [39] suggest, would help reduce Tajikistan's vulnerability to seasonal fluctuations in hydropower production and contribute to the overall economic growth of the country. The export of energy, through projects like CASA-1000, is a strategic move that could position Tajikistan as a regional energy hub and enhance its geopolitical standing in Central Asia and beyond [43].

The policy implications emerging from this analysis point to several key actions that Tajikistan must take to ensure the long-term sustainability and security of its energy system. Energy diversification is crucial to mitigate the risks associated with seasonal hydropower fluctuations.

Tajikistan should explore the integration of solar and wind power, which would complement the variable nature of hydropower production. Additionally, the development of energy storage systems will be vital in storing surplus energy during high-flow periods and providing a reliable energy supply during the winter deficit. As in this [36] emphasized, expanding grid infrastructure will improve not only the export capacity but also the overall reliability and efficiency of the national grid. This would also support the integration of alternative renewable energy sources and enhance the country's role in the regional energy market.

Strengthening regional energy cooperation remains essential for maximizing the benefits of Tajikistan's hydropower surplus. Collaborative efforts through projects like CASA-1000 and other energy agreements will help optimize energy exports and integrate Tajikistan into the broader Central Asian energy grid. As T. J. Menzel [40] noted, regional cooperation can enhance energy security and stabilize energy prices across Central Asia, contributing to the overall economic development of the region.

In terms of winter energy management, Tajikistan should explore energy imports from neighboring countries or invest in thermal backup power systems to ensure that critical sectors such as healthcare, industry, and households can continue to operate without significant disruptions. These backup systems would provide a safeguard during periods of high demand or low hydropower generation [37].

Finally, long-term sustainability considerations must be taken into account. Climate change poses a significant risk to the hydropower sector, particularly due to its potential effects on glacial melt and seasonal precipitation patterns. Climate adaptation strategies and water management policies will be crucial to ensuring the long-term viability of hydropower as a primary energy source [41]. Furthermore, addressing the social impacts of hydropower development, including resettlement and the displacement of agricultural land, is critical for maintaining social acceptance and ensuring the long-term success of hydropower projects. Ensuring fair compensation and involving local communities in the decision-making process will be essential for fostering sustainable development, as emphasized by [42].

In conclusion, the analysis of the Energy Supply vs. Demand Graph for Tajikistan from 2010 to 2025 highlights both the opportunities and risks associated with the country's dependence on hydropower. The seasonal variations in energy supply and demand underscore the need for energy diversification, robust infrastructure investment, and enhanced regional cooperation. Addressing these challenges through strategic diversification, energy storage, and climate adaptation policies will be crucial for ensuring the long-term sustainability and resilience of Tajikistan's energy system [43-47].

6. Conclusion

This study provides a comprehensive analysis of Tajikistan's energy supply and demand dynamics, focusing on the critical role of hydropower in meeting the country's electricity needs. The findings underscore the significant seasonal fluctuations in energy production due to the country's reliance on hydropower, which is heavily influenced by seasonal water flow variations from glacier melt and rainfall. While Tajikistan enjoys periods of surplus energy during the summer months, the winter deficit in energy supply poses a serious risk to energy security, particularly as demand continues to rise in line with economic growth, industrialization, and urbanization.

The analysis emphasizes the vulnerability of Tajikistan's energy system to seasonal fluctuations, underlining the urgent need for energy diversification. The reliance on hydropower, while crucial for the country's energy generation, is not sufficient to meet the growing demand during critical periods, especially in the winter. Therefore, integrating alternative renewable energy sources such as solar and wind power, alongside the development of energy storage systems, will be essential to stabilize the supply and ensure energy security year-round. The potential for energy exports presents a key opportunity to enhance regional energy cooperation, reduce dependency on imports, and foster economic growth, particularly through initiatives like CASA-1000.

Moreover, regional collaboration and investment in infrastructure, including the modernization of grid systems and the development of energy storage solutions, are critical for optimizing the use of surplus energy and ensuring reliable energy distribution both domestically and across borders. As Tajikistan continues to position itself as a regional energy hub, enhancing cross-border energy cooperation will further integrate its energy system into the broader Central Asian energy market.

Long-term sustainability considerations, particularly in the face of climate change, necessitate climate adaptation strategies to safeguard the future viability of hydropower. Additionally, addressing the social impacts of hydropower projects, including resettlement and the displacement of agricultural land, will be vital for ensuring the successful and equitable development of hydropower resources. Managing these challenges through fair compensation and community involvement will be crucial for maintaining social acceptance and ensuring the continued support for such projects.

In conclusion, while Tajikistan's hydropower resources present a significant opportunity for sustainable energy development, addressing the challenges associated with seasonal energy supply fluctuations, increasing energy demand, and social and environmental impacts is imperative. By diversifying its energy mix, investing in

infrastructure, and enhancing regional cooperation, Tajikistan can secure its energy future, optimize the use of its hydropower potential, and contribute to the long-term sustainable development of Central Asia.

Future research should focus on assessing the impacts of climate change on hydropower production, integrating alternative renewable sources like solar and wind into the energy mix, and exploring socio-economic impacts of hydropower projects, particularly related to resettlement. Further studies on regional energy cooperation and energy trade within Central Asia are also crucial to optimize Tajikistan's energy export potential and ensure efficient integration into regional grids. This will help build a sustainable and resilient energy future for Tajikistan.

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