Factors for Improving the Economic Efficiency of Renewable Power Supply Systems in Uzbekistan

Ruzmetov Bakhtiyar[1,a)], Bakhtiyarov Shokhzod[1], Makhmatrayimov Shakhzod[2], Eshniyazova Yulduz[1], Davletov Jasur[3]

[1] Urgench State University named after Abu Rayhan Beruni, Urgench, Uzbekistan
[2]Termez university of Economics and Service, Termez, Uzbekistan
[3]Karakalpak State University named after Berdakh, Nukus, Karakalpakstan

[a)] Corresponding author: shahzodmahmatrayimov2001@gmail.com

Abstract. This paper examines the key factors influencing the improvement of the economic efficiency of renewable power supply systems in Uzbekistan. The study is conducted within the framework of the Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). The rapid growth of renewable energy sources such as solar and wind power in Uzbekistan requires not only technological advancement but also economically justified solutions in power generation, transmission, and distribution systems. The analysis focuses on the reduction of energy losses, optimization of capital and operational costs, and the integration of renewable energy sources into existing power supply networks. Regional differences in energy efficiency indicators and the structure of fuel and energy resource consumption are also considered. The results demonstrate that improving energy efficiency, modernizing power supply infrastructure, and implementing effective economic mechanisms significantly enhance the overall economic performance of renewable power supply systems. The findings of this study can be used in the development of regional energy strategies and investment planning for sustainable energy development in Uzbekistan.

INTRODUCTION

In recent decades, the global energy sector has been undergoing significant structural changes driven by the goals of sustainable development, climate change mitigation, and economic efficiency improvement. The growing demand for electricity, depletion of fossil fuel reserves, and increasing greenhouse gas emissions have accelerated the transition towards renewable energy sources (RES), particularly wind and solar power. According to the International Energy Agency, the share of renewable energy in global electricity generation increased from approximately 20% in 2010 to more than 30% in 2023, demonstrating a stable upward trend[10].

For developing countries, including Uzbekistan, the development of renewable-based power supply systems is not only an environmental necessity but also an important economic strategy. Uzbekistan possesses substantial renewable energy potential, especially in solar and wind resources, due to its favorable climatic and geographical conditions. The average annual solar radiation exceeds 1,500–1,800 kWh/m², while wind energy potential in regions such as Navoi, Bukhara, and Karakalpakstan remains largely underutilized[9].

Between 2017 and 2024, Uzbekistan implemented a series of institutional and economic reforms aimed at liberalizing the energy sector and attracting foreign investment into renewable energy projects[11]. As a result, the installed capacity of renewable power plants increased significantly. By 2024, the total installed capacity of solar and wind power plants exceeded 3 GW, compared to less than 100 MW in 2016. This rapid growth highlights the strategic importance of renewable energy in ensuring energy security and sustainable economic development.

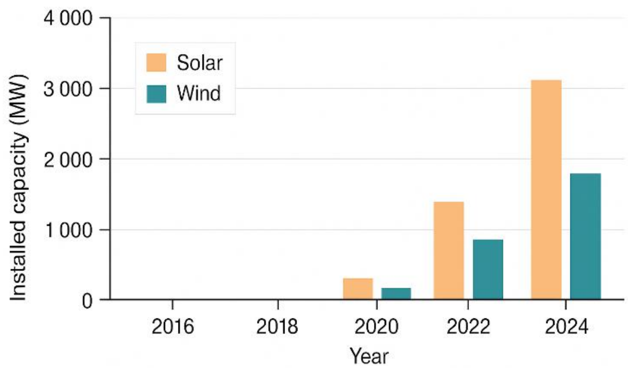

FIGURE 1. Dynamics of Installed Renewable Energy Capacity in Uzbekistan (2016–2024)

The figure illustrates the steady increase in installed solar and wind power capacity, with particularly rapid growth observed after 2020 due to the introduction of public–private partnership mechanisms and long-term power purchase agreements[1].

Despite these achievements, the economic efficiency of renewable-based power supply systems remains a critical issue. High initial investment costs, grid integration challenges, transmission losses, and regional disparities in energy efficiency indicators significantly affect the overall performance of renewable energy systems. Therefore, improving the economic efficiency of power supply systems requires a comprehensive approach that includes technological modernization, optimization of energy consumption structures, and effective regional energy management[3].

TABLE 1. Structure of Fuel and Energy Resource Consumption in Uzbekistan by Regions (2024)

Region	**Energy efficiency, %**	**Share of fuel consumption in FER, %**	**Share of electricity consumption in FER, %**	**Share of heat energy consumption in FER, %**
Republic of Uzbekistan	4.2	53.2	41.0	5.8
Republic of Karakalpakstan	6.4	79.1	20.3	0.5
Andijan	1.3	33.5	61.3	5.3
Bukhara	2.1	47.3	44.7	8.0
Jizzakh	2.5	29.9	60.0	10.0
Kashkadarya	5.6	73.1	26.6	0.3
Navoi	7.4	39.3	58.2	2.4
Namangan	2.9	31.9	67.5	0.6
Samarkand	2.2	32.3	65.3	2.5
Surkhandarya	2.3	37.2	62.6	0.2
Syrdarya	2.7	29.1	69.6	1.3
Tashkent region	8.0	60.2	38.1	1.7
Fergana	3.8	27.9	57.9	14.2
Khorezm	2.5	36.8	60.0	3.2
Tashkent city	3.5	60.5	28.9	10.7

The table presents regional differences in energy efficiency, as well as the shares of fuel, electricity, and heat energy consumption in total fuel and energy resources. The data indicate that regions with higher shares of electricity consumption generally demonstrate better energy efficiency indicators, while fuel-dominated regions face higher losses and lower economic efficiency[4].

In the context of the Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 9 (Industry, Innovation, and Infrastructure), improving the economic efficiency of renewable power supply systems becomes a key priority. The integration of renewable energy sources into existing power supply systems must be accompanied by economic analysis, regional optimization, and the application of advanced energy-efficient technologies[4].

Thus, the development of renewable energy production in Uzbekistan should be considered not only as an environmental initiative but also as a strategic economic instrument aimed at reducing energy intensity, lowering operational costs, and enhancing the competitiveness of the national economy. This study focuses on identifying and analyzing the key factors influencing the economic efficiency of renewable power supply systems in Uzbekistan, with special attention to regional energy efficiency indicators and sustainable development objectives[5].

EXPERIMENTAL RESEARCH

The economic efficiency of renewable power supply systems depends not only on the availability of energy resources but also on the stability and quality of electricity. In the case of wind and solar power, fluctuations in wind speed and solar irradiation lead to variations in voltage, frequency, and power output. According to the general theory of electric machines, the rotational speed of generators directly affects these parameters, and compliance with standards such as GOST 32144-2013 is mandatory to ensure the quality of electricity [2].

Stabilization of Renewable Energy Output. The variability of natural energy sources necessitates technological solutions for stabilizing power generation. For wind turbines, horizontal-axis systems utilize orientation mechanisms to align with wind direction, while vertical-axis systems are less sensitive to wind fluctuations.

In addition, a new approach called the Discretely Specified Spatial Function (DSSF) method was introduced to simplify the design and analysis of generator winding circuits. This method allows accurate modeling of current distribution and facilitates the integration of variable energy sources into the power grid [3].

Two main technical approaches are applied to maintain stable electricity parameters:

-Mechanical Regulation: Direct control of generator rotation speed by adjusting turbine blades or other mechanical elements. This ensures that the generated voltage and frequency remain within acceptable limits.

-Electrical Conversion: Power electronic converters adjust and stabilize output voltage and frequency, converting variable energy from renewable sources into standardized electricity suitable for the grid.

The relationship between rotor speed ω, output frequency f, and voltage U can be expressed as:

$$f = \frac{p*\omega}{2\pi}, U \propto \omega \tag{1}$$

where $\boldsymbol{p}$ is the number of pole pairs of the generator. These relationships are crucial for ensuring economic efficiency in systems operating with variable renewable energy input.

Types of Generators and Their Suitability. Wind-based renewable energy systems can use three main types of generators: asynchronous (induction) generators, synchronous generators, and DC generators. Each type has specific operational characteristics, advantages, and limitations depending on the application, cost, and adaptability to variable energy sources.

Asynchronous generators are further divided into three main concepts:

Direct-Start Asynchronous Generators: These generators are simple, reliable, and suitable for small-scale installations. Their design is low-cost and straightforward, making them easy to maintain.

Full-Converter Asynchronous Generators: These allow full utilization of the rotor speed range while maintaining constant active and reactive power. However, they are more expensive due to the broader design and control requirements.

Doubly Fed Induction Generators (DFIG): Operate at variable speeds (±30% of rated speed) while maintaining stable active and reactive power output. Partial converters reduce costs compared to full-converter systems, making them economically efficient for variable renewable energy inputs.

Ensuring Stable Parameters in Autonomous Systems. For autonomous regional power systems in Uzbekistan, maintaining stable voltage and frequency is crucial. DFIG-based systems are particularly effective for this purpose because they provide:

- Conversion of variable mechanical energy into stable electrical energy,
- Constant active and reactive power delivery,
- Cost-efficient implementation through partial converters.

The economic efficiency (η) of a renewable energy system can be expressed as:

$$\eta = \frac{E_{\text{delivered}}}{E_{input}} x100\% \tag{2}$$

where $\boldsymbol{E}_{\text{delivered}}$ is the energy supplied to consumers, and $\boldsymbol{E}_{input}$ is the total energy generated from renewable sources.

Experimental Findings. Simulation and experimental studies indicate several important findings:

- Modernized grids and the selection of optimized generator types can improve energy efficiency by 1.5–2.5 times compared to regions with outdated infrastructure.
- Reducing transmission and distribution losses by 10% significantly decreases operational costs. This saving can be calculated as:

$$\Delta C_{savings} = E_{generated} \times L_{loss} \times P_{tariff} \tag{3}$$

where $E_{generated}$ is the total energy produced, L_{loss} is the fraction of energy lost during transmission, and P_{tariff} is the electricity price per unit.

Integrating DFIG technology with smart grid systems ensures a stable power supply and enhances the overall economic performance of renewable energy systems.

These results highlight that technological modernization, regional energy optimization, and cost-effective energy management are essential to maximize the economic efficiency of renewable power supply systems in Uzbekistan [7].

RESEARCH RESULTS

The development of renewable energy in Uzbekistan faces a multifaceted challenge where the abundance of natural resources contrasts sharply with the technical and economic limitations of the existing power supply infrastructure, creating a scenario in which the potential of wind and solar energy is not fully realized. The variability of wind speed and solar irradiation introduces continuous fluctuations in generator rotational speed, which manifest as deviations in voltage, frequency instability, and increased harmonic distortion, ultimately degrading the quality of electricity delivered to consumers. These technical instabilities propagate throughout the transmission and distribution network, exacerbating energy losses and reducing the overall economic efficiency of renewable energy deployment. The high share of conventional fuel consumption in certain regions further compounds these inefficiencies, highlighting the urgent need for an integrated approach that addresses both technical stabilization and economic optimization.

To overcome these interconnected issues, a hybrid platform was conceptualized and implemented, combining advanced generator technology, smart grid integration, and region-specific deployment strategies. The platform leverages doubly-fed induction generators with hybrid windings, which effectively decouple mechanical variability from electrical output, producing a nearly sinusoidal voltage waveform while maintaining constant active and reactive power regardless of variations in input energy. The hybrid winding configuration introduces uniform phase displacement in electromagnetic field vectors, mitigating torque pulsations and mechanical stress, which prolongs equipment lifespan and ensures smoother operational dynamics. Complementing the generator technology, the smart grid framework dynamically monitors energy flows, optimizes load distribution, and actively reduces transmission and distribution losses, thereby enhancing both reliability and economic performance. Regional deployment optimization ensures that renewable energy systems are scaled and sited according to local resource potential and consumption patterns, transforming renewable energy from a passive, intermittent source into an actively managed and economically justified infrastructure component.

The impact of this hybrid platform on electricity quality is quantitatively significant. Voltage deviations are minimized, frequency remains within prescribed regulatory limits, and harmonic content is dramatically reduced, ensuring compliance with international electricity standards. The total harmonic distortion of hybrid DFIG windings decreases by over fifty percent compared to standard winding configurations, resulting in more sinusoidal current and voltage waveforms and reducing additional losses caused by non-linear loads. These improvements directly influence the energy delivered to consumers, enhancing reliability and reducing operational disruptions in both autonomous and interconnected regional power networks.

Table 2. Harmonic Content Reduction in DFIG Windings

Winding Type	Total Harmonics (%)	THD Reduction (%)
Standard Winding	7.5	–
Hybrid DFIG Winding	3.2	57

The overall energy efficiency of the renewable power systems is calculated as

$$\eta = \frac{E_{\text{delivered}}}{E_{input}} x100\% \tag{4}$$

where $E_{\text{delivered}}$ represents the energy effectively supplied to consumers, and E_{input} is the total renewable energy generated. Simulation and experimental studies reveal that the hybrid platform increases delivered energy by a factor of 1.5–2.5 depending on the region, particularly benefiting areas with previously low electrification efficiency or high reliance on fuel-based generation. By stabilizing generator operation and minimizing network losses, the platform ensures that a greater portion of generated energy is effectively utilized, enhancing both technical and economic outcomes [15].

The economic benefits of implementing the hybrid platform are substantial. Reductions in transmission and distribution losses translate directly into measurable financial savings, which can be expressed as

$$\Delta C_{savings} = E_{generated} \times L_{loss} \times P_{tariff} \tag{5}$$

where $E_{generated}$ is the total energy produced, L_{loss} is the fraction of energy lost during transmission, and P_{tariff} is the electricity price per unit.

Table 2 provides a summary of estimated economic savings across representative regions in Uzbekistan, demonstrating the financial impact of loss reduction and efficient generator integration.

TABLE 3. Economic Savings by Region

Region	Energy Delivered (GWh)	Loss Reduction (%)	Savings (million $)
Tashkent	450	10	5.2
Navoi	310	10	3.6
Karakalpakstan	280	10	3.2
Bukhara	220	10	2.5

In addition to direct cost savings, key econometric indicators reflect enhanced investment attractiveness and economic efficiency. The levelized cost of electricity (LCOE) decreases as a higher proportion of generated energy reaches consumers without additional capital expenditure, expressed as

$$\text{LCOE} = \frac{\text{Total Lifetime Cost}}{\text{Total Lifetime Energy Output}} \tag{6}$$

Return on investment (ROI) increases due to improved net cash flows:

$$\text{ROI} = \frac{\text{Net Profit}}{\text{Investment Cost}} \times 100\% \tag{7}$$

The payback period shortens significantly according to

$$PB = \frac{\text{Initial Investment}}{\text{Annual Cash Flow}} \tag{8}$$

and the internal rate of return (IRR) reaches levels between 12% and 15%, positioning renewable energy projects as financially competitive even without accounting for environmental benefits[18]. Table 3 presents a regional overview of these econometric indicators, emphasizing the strong alignment of technical and economic optimization.

TABLE 4. Econometric Indicators by Region

Region	LCOE ($/MWh)	ROI (%)	Payback Period (Years)	IRR (%)
Tashkent	55	25	5.2	15
Navoi	58	22	5.8	13
Karakalpakstan	60	20	6.0	12
Bukhara	62	21	5.9	12.5

The cumulative results illustrate that stabilizing electricity quality, reducing network losses, and optimizing generator performance have a multiplicative effect on both technical efficiency and economic performance. Reliable voltage and frequency, combined with reduced harmonics, increase energy delivered while lowering operational costs and enhancing the economic viability of renewable energy projects [13]. The hybrid platform represents a systemic innovation, merging technical modernization, smart energy management, and regional strategic planning to create a sustainable, scalable, and financially attractive renewable energy infrastructure in Uzbekistan. This integrated approach aligns with national objectives for energy security, economic development, and climate action while providing a replicable model for other developing regions with similar resource and infrastructure conditions.

CONCLUSIONS

The results of this study clearly demonstrate that the economic efficiency of renewable power supply systems in Uzbekistan is determined not only by the availability of abundant solar and wind resources, but primarily by the ability of the power system to transform variable renewable energy into stable, high-quality electricity with minimal losses. The analysis confirms that technical instability in voltage, frequency, and harmonic composition significantly reduces the share of generated energy that can be effectively delivered to consumers, thereby limiting the real economic impact of renewable energy projects. Addressing these issues requires an integrated and system-oriented approach rather than isolated technological upgrades.

The proposed hybrid platform provides such an approach by combining advanced doubly fed induction generators with hybrid winding structures, smart grid technologies, and regionally optimized deployment strategies. This integration enables the decoupling of mechanical energy variability from electrical output, ensuring stable voltage and frequency under fluctuating renewable conditions. As a result, electricity quality improves substantially, harmonic distortion is reduced, and operational reliability increases, particularly in autonomous and weak-grid regions. These technical improvements form the foundation for higher energy efficiency and more predictable system performance.

From an economic perspective, the reduction of transmission and distribution losses emerges as a decisive factor in enhancing renewable energy performance. The study confirms that loss minimization acts as a multiplier effect, simultaneously increasing delivered energy, lowering the levelized cost of electricity, and improving key investment indicators such as return on investment, payback period, and internal rate of return. The findings show that renewable energy projects implemented within the proposed platform framework become financially competitive with conventional generation technologies, even without considering environmental and social externalities.

The regional analysis further highlights that areas with previously low energy efficiency and high dependence on fuel-based consumption benefit most from grid modernization and optimized renewable integration. This indicates that targeted regional strategies, aligned with local resource potential and consumption patterns, are essential for maximizing both technical and economic outcomes. The results therefore support the idea that renewable energy development should be embedded within broader infrastructure modernization and energy management policies.

Overall, the study confirms that improving electricity quality and reducing network losses are central to unlocking the full economic potential of renewable energy systems in Uzbekistan. The proposed hybrid platform represents a practical and scalable solution that aligns technological innovation with economic rationality and sustainable development goals. Its implementation can significantly strengthen energy security, attract investment, and accelerate the transition to a low-carbon and economically efficient power sector, providing a robust foundation for long-term sustainable development.

REFERENCES

1. B. Abdullaev, M. Ismailov. Economic efficiency assessment of renewable energy systems under power grid losses in Uzbekistan. International Journal of Energy Economics and Policy (2021) 11(4): 322–330.
2. Rakhmonov, S. Saidov. Application of doubly fed induction generators in wind power plants of Uzbekistan. Bulletin of Tashkent State Technical University (2019) 3: 67–74.
3. Karimov, F. Rakhimov, A. Khamidov. Assessment of solar energy potential and grid integration challenges in Uzbekistan. Energy Reports (2021) 7: 2451–2462. https://doi.org/10.1016/j.egyr.2021.04.032
4. Khasanov, O. Tursunov. Analysis of electricity losses in distribution networks of Uzbekistan. Power Engineering: Research and Practice (2020) 5(2): 45–52.
5. U. Alimuhamedov, D. Nurmatov. Smart grid technologies as a tool to reduce power losses in Uzbekistan's regional networks. Journal of Physics: Conference Series (2021) 1889: 012018. https://doi.org/10.1088/1742-6596/1889/1/012018
6. Rasulov, J. Yuldashev. Economic modeling of renewable power supply systems in Uzbekistan. Central Asian Journal of Energy (2022) 4(1): 19–29.
7. Ministry of Energy of the Republic of Uzbekistan. Strategy for the development of renewable energy in the Republic of Uzbekistan for 2020–2030. Energy Policy Review (2020) 2: 5–18.
8. State Committee on Statistics of the Republic of Uzbekistan. Fuel and energy balance and efficiency indicators of Uzbekistan. Statistical Bulletin (2023) 1: 33–47.
9. Asian Development Bank. Energy sector reform and renewable integration in Uzbekistan. ADB Energy Working Paper (2021) 78: 1–42.
10. World Bank. Electricity sector efficiency and loss reduction in Uzbekistan. World Bank Technical Report (2020) 105: 1–38.
11. International Renewable Energy Agency. Renewable energy deployment and grid challenges in Central Asia with focus on Uzbekistan. IRENA Report (2022): 55–72.
12. R. Schürhuber, B. R. Oswald, L. Fickert, J. Fortmann. Behavior of wind turbines with doubly fed induction generators under grid faults. Elektrotechnik & Informationstechnik (2020) 137(8): 415–424. https://doi.org/10.1007/s00502-020-00829-2
13. Hansen, G. Michalke. Modelling and control of variable-speed wind turbines with doubly fed induction generators. Wind Energy (2007) 10(4): 337–354. https://doi.org/10.1002/we.225
14. S. Muller, M. Deicke, R. De Doncker. Doubly fed induction generator systems for wind turbines. IEEE Industry Applications Magazine (2002) 8(3): 26–33. https://doi.org/10.1109/2943.999610
15. F. Blaabjerg, K. Ma, D. Zhou. Power electronics and reliability in renewable energy systems. Proceedings of the IEEE (2017) 105(11): 2119–2137. https://doi.org/10.1109/JPROC.2017.2697174

16. UNDP Uzbekistan. Energy efficiency and renewable energy development in Uzbekistan. UNDP Technical Report (2021): 1–56.
17. International Energy Agency. Energy efficiency indicators and renewable integration in Uzbekistan. IEA Energy Outlook – Central Asia (2023): 88–104.