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Energy Efficiency in Agricultural Power Systems: Economic Perspectives and Development Priorities

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Abstract. The growing demand for energy in agriculture highlights the need for efficient, sustainable, and economically viable power supply systems. In the context of Uzbekistan's agrarian transformation, improving energy efficiency has become a critical driver of productivity, competitiveness, and environmental sustainability. This study investigates the economic aspects of energy efficiency in agricultural power systems, emphasizing the challenges and opportunities in the Republic of Karakalpakstan. Using comparative analysis and statistical data from 2016 to 2024, the research identifies inefficiencies in current energy utilization and explores the potential for renewable energy integration. The paper develops a framework for evaluating energy efficiency from an economic perspective, focusing on investment optimization, cost reduction, and sustainability. The results demonstrate that the implementation of modern energy-saving technologies and innovative financing mechanisms can reduce production costs in agricultural enterprises by 12–18%, while simultaneously mitigating environmental impacts. The findings contribute to the formulation of regional strategies for the sustainable modernization of Uzbekistan's agropower infrastructure.

INTRODUCTION

Agriculture continues to be one of the most energy-consuming sectors of the economy, especially in developing nations where outdated technology and poor infrastructure limit productivity. In Uzbekistan, where agriculture plays a vital role in national GDP and employment, enhancing energy efficiency has emerged as a key focus for attaining sustainable economic development. The reliance of the agricultural sector on electricity for irrigation, processing, and storage imposes a significant energy burden that directly influences the cost structure and competitiveness of agribusiness operations.

In the last ten years, the Republic of Uzbekistan has implemented significant reforms focused on diversifying its energy sources and lessening the economic risk faced by rural sectors.

The shift to renewable energy sources—particularly solar and biogas—has grown more critical for agricultural production. As stated in the “Strategy for the Transition to a Green Economy for 2019 to 2030” [1], enhancing energy efficiency in the agropower sector is crucial for guaranteeing food security, safeguarding the environment, and fostering sustainable regional growth. The Republic of Karakalpakstan serves as a notably relevant example for examining agricultural energy efficiency because of its distinct climate and geographic features. Regular droughts, limited water supply, and distance from centralized power networks lead the area to rely heavily on localized energy options. Therefore, enhancing energy efficiency and implementing novel power supply systems has become essential for the economic stability of local farms and agricultural businesses.

Energy efficiency in agriculture involves a mix of technical, organizational, and financial strategies aimed at optimizing the yield for each unit of energy used [2]. It involves enhancing equipment efficiency, reducing losses during power transmission, and implementing renewable technologies appropriate for rural settings. From an economic perspective, energy efficiency signifies not just a decrease in operational expenses but also a chance to improve profitability and draw sustainable investment into rural sectors.

Given these considerations, the objective of this manuscript is to:

1. Analyze the prevailing conditions and economic ramifications of energy consumption within the agricultural sector of Uzbekistan;
2. Identify principal obstacles to enhancing energy efficiency in rural electrical systems;
3. Propose strategic recommendations aimed at the modernization of agricultural energy infrastructures in the Republic of Karakalpakstan.

The originality of this investigation resides in the synthesis of economic efficiency analysis with regional energy management frameworks, thereby yielding both pragmatic and policy-oriented implications. This research enriches the existing literature by providing empirical insights into the convergence of energy economics and agricultural modernization within the context of a transitioning economy.

EXPERIMENTAL RESEARCH

The experimental investigation was conducted to assess the economic efficiency of energy utilization in agricultural enterprises situated in the Republic of Karakalpakstan. The study employed a mixed-methodological approach that integrated statistical data analysis, field observations, and evaluations of energy performance in selected agricultural operations. The investigation encompassed the interval from 2016 to 2024, concentrating on the patterns of energy utilization, production efficiency, and investment metrics within the agropower domain. The subsequent critical variables were scrutinized:

- Electricity utilization per hectare of irrigated agricultural land (kWh/ha);
- Consumption of fuels and lubricants (liters per production unit);
- Output energy efficiency ratio (OER = agricultural output / total energy input);
- Proportion of energy expenses in overall production costs (%);
- Return on energy investment (REI).

Quantitative data were sourced from the State Committee of Statistics of the Republic of Uzbekistan, the Ministry of Agriculture, and regional reports from Karakalpakstan. Supplementary empirical data were acquired from three representative agricultural enterprises — Azamat Qaraqum, Raxat Mayshi, and Qidirmiyaz Qahraman — which were chosen based on their distinct energy frameworks and production focuses. The research indicated that farms consumed less energy in 2024 compared to 2016—approximately 13 out of 100 less. This occurred because they enhanced their irrigation systems and transitioned from diesel fuel to electric power. Nonetheless, the expenditures on energy continue to represent a significant portion of overall expenses, approximately 18 to 22 out of every 100. This indicates that there are still numerous opportunities for them to conserve more energy and reduce costs in the future (Table 1).

TABLE 1. Energy consumption of researched farms in Karakalpakstan

Indicator	2016	2020	2024
Energy consumption (kWh/ha)	540	510	468
Energy cost share (%)	22.4	20.1	18.7
Energy efficiency ratio (OER)	1.25	1.32	1.41
Average yield (thousand UZS/ha)	11,200	13,600	15,800

The adoption of energy-efficient irrigation methods and renewable energy devices (like solar-powered water pumps) resulted in a 12–18% increase in net farm profits. Moreover, farms that implemented automated systems for irrigation and equipment saw an additional 8% reduction in energy waste.

Empirical correlation analysis revealed a significant positive relationship ($r = 0.81$) between investments in energy efficiency technologies and overall farm productivity, reinforcing the notion that enhancements in energy efficiency directly contribute to financial growth in agriculture.

Karakalpakstan is a semi-arid region that has significant irrigation requirements and a substantial solar energy potential. The region's historic dependence on fossil fuel systems has limited agricultural profits due to variable energy prices and unreliable supply.

Pilot projects carried out from 2020 to 2024 under the “Green Energy for Rural Development” initiative demonstrated concrete results:

- 24% reduction in energy usage per hectare;
- 16% rise in total agricultural production;
- 10% reduction in CO₂ emissions for each ton of product.

This evidence confirms the importance of renewable energy in enterprises—particularly solar photovoltaic (PV) systems and biogas generators—as effective tools for improving both economic and environmental sustainability in agricultural operations.

The study utilized the ensuin equation to calculate the Economic Efficiency Coefficient (EEC) of energy-saving measures:

$$EEC = \frac{(C_0 - C_1)}{I} \times 100 \quad (1)$$

Where:

- C_0 — initial annual energy expenditures (UZS);
- C_1 — annual energy expenditures following modernization (UZS);
- I — total capital in energy-saving techniques (UZS).

In the studied farms, the average EEC was 17.6%, indicating that each 1 million UZS spent on energy efficiency resulted in roughly 176,000 UZS of annual savings. Taking into account the average payback time of 5.2 years, these projects can be deemed economically viable and appealing for both individual investors and public initiatives.

The experimental results indicate that enhancing energy efficiency in agricultural power systems yields substantial socio-economic advantages. Besides lowering costs, it improves resilience against energy disruptions and aids in promoting environmental sustainability.

Nonetheless, various limitations were recognized:

- Restricted availability of long-term funding for energy upgrades;
- Shortage of qualified technicians for servicing renewable systems;
- Partial implementation of digital monitoring tools on the farm.

Tackling these obstacles necessitates synchronized policy measures — such as favorable loans for energy-efficient technologies, tax breaks for renewable energy uptake, and enhanced training initiatives for rural energy administration.

RESULTS OF RESEARCH

The study revealed a distinct enhancement in the energy efficiency of agricultural power systems throughout Uzbekistan, with the Republic of Karakalpakstan acting as a notable case example. Statistical data from 2016 to 2024 revealed a 13.4% decrease in overall agricultural energy use, while production increased by 41%. This shows that agricultural economic growth can be attained through sensible and sustainable energy utilization.

Energy efficiency metrics, such as energy usage per hectare, share of energy costs, and output energy ratio (OER), showed improvement throughout the monitored timeframe. The examination showed that even small investments in contemporary power systems led to significant economic impacts, resulting in lower production unit costs and enhanced farm profitability (Table 2).

TABLE 2. Energy efficiency indicators of farms

Indicator	2016	2020	2024	Change (2016 and 2024, %)
Energy consumption (kWh/ha)	540	510	468	-13.3
Energy cost share in production (%)	22.4	20.1	18.7	-3.7
Output energy efficiency ratio (OER)	1.25	1.32	1.41	+12.8
Gross agricultural output (mln UZS)	11,200	13,600	15,800	+41.0

The financial analysis demonstrated that energy efficiency measures have a direct positive impact on profitability in agricultural enterprises. The application of solar-powered irrigation systems, low-voltage electric motors, and automated controls reduced total energy costs by 12–18%.

The regression analysis found a statistically significant positive correlation ($r = 0.81$) between the *level of investment in energy efficiency* and *farm profitability*.

The empirical model can be represented as:

$$Y = 0.21X_1 + 0.38X_2 + 0.27X_3 + \varepsilon \quad (2)$$

Where:

- Y = Farm profitability (gross margin),
- X_1 = Investment in energy efficiency technologies,
- X_2 = Energy consumption reduction rate,

- X_3 = Level of renewable energy use,
- ε = error term.

The model accounts for 84.5% of the variance ($R^2 = 0.845$) in profitability, indicating that energy efficiency and technological innovation are essential factors for economic sustainability in agriculture.

The Republic of Karakalpakstan exhibited reduced baseline efficiency levels because of climatic limitations and insufficient infrastructure development. Yet, farms that adopted focused energy upgrades saw considerable progress.

- Azamat Qaraqum Farm: 17% decrease in energy expenses per hectare, 12% rise in yield.
- Raxat Mayshi Farm: 14% decrease in diesel usage via hybrid irrigation methods.
- Qidirniyaz Qahraman Farm: 20% enhancement in OER from the implementation of solar-powered water pumps.

Taken together, these findings suggest that regional initiatives focused on renewable integration, technological advancement, and effective energy management can significantly boost agricultural competitiveness (Table 3).

TABLE 3. The cost-benefit analysis revealed that the average investment payback period for energy-saving technologies in agriculture is 5–6 years

Measure	Average Investment (mln UZS)	Annual Savings (mln UZS)	Payback Period (years)	Measure
Solar irrigation systems	45.0	8.0	5.6	Solar irrigation systems
Energy-efficient electric motors	28.0	5.2	5.3	Energy-efficient electric motors
Biogas installations	60.0	10.5	5.7	Biogas installations

This analysis supports the argument that energy efficiency projects are economically viable and socially beneficial, especially when supported by state subsidies, preferential loans, or public–private partnership (PPP) programs.

The findings suggest that national and regional energy policies must focus on:

1. Expanding access to renewable energy sources for rural producers;
2. Providing financial incentives (tax breaks, credit programs) for farms investing in energy efficiency;
3. Integrating digital monitoring and smart technologies in rural energy systems;
4. Strengthening research and education in agricultural energy management;
5. Promoting collaboration between government, private sector, and academia.

Such measures would not only enhance economic performance but also align Uzbekistan's agricultural development with the global sustainability goals set by the United Nations and the FAO.

TABLE 4. Result Summary of researches

Dimension	Result Summary
Economic	12–18% reduction in energy costs; 41% growth in productivity
Technological	Introduction of renewable and smart systems improved energy efficiency by 13%
Environmental	10% reduction in CO ₂ emissions per production unit
Investment	Average payback period: 5.2 years

CONCLUSIONS

The conducted research has demonstrated that energy efficiency plays a fundamental role in improving the economic sustainability of agricultural power systems. Empirical data from the Republic of Karakalpakstan confirm that the modernization of energy infrastructure, combined with investment in renewable energy and innovative technologies, can significantly increase both productivity and profitability in the agricultural sector.

Main Conclusions:

1. Energy efficiency is a key driver of agricultural modernization.

Between 2016 and 2024, total energy consumption per hectare in the studied farms decreased by 13.3%, while gross output increased by over 40%. This indicates that efficient energy utilization contributes directly to agricultural growth.

2. Economic efficiency and investment are strongly correlated.

Regression analysis ($R^2 = 0.845$) confirmed that investments in energy-saving technologies have a statistically significant positive effect on farm profitability. Each 1 million UZS invested generated around 176,000 UZS in annual savings, with an average payback period of 5–6 years.

3. Renewable energy integration yields both economic and environmental benefits.

Solar and biogas systems implemented under the “Green Energy for Rural Development” program led to a 16% growth in agricultural output and a 10% reduction in CO₂ emissions, supporting the dual goals of economic and ecological sustainability.

4. Karakalpakstan has high potential for renewable energy development.

Due to its geographic and climatic characteristics, the region is suitable for large-scale deployment of solar photovoltaic and hybrid energy systems in irrigation, water management, and rural processing facilities.

5. Institutional support and financing mechanisms remain critical barriers.

The lack of accessible long-term financing and limited technical capacity in rural areas restricts the widespread adoption of energy-efficient solutions. Without coordinated policy action, these limitations will continue to slow modernization.

Recommendations:

1. Develop a national framework for agricultural energy efficiency.

Establish clear energy performance standards and targets for agricultural enterprises, aligning with the Strategy for the Transition to a Green Economy (2019–2030).

2. Expand financial support instruments.

Introduce subsidized credit lines, leasing programs, and public–private partnerships (PPP) for renewable energy projects in rural areas.

3. Promote digital and smart technologies in energy management.

Implement IoT-based monitoring systems for irrigation, storage, and processing to optimize electricity consumption and reduce waste.

4. Enhance research and training.

Strengthen cooperation between universities, research centers, and agricultural enterprises to build human capital in energy management and green technology innovation.

5. Encourage regional pilot projects.

Karakalpakstan should serve as a model region for demonstrating integrated renewable energy systems in agriculture, combining economic, environmental, and social benefits.

6. Monitor and evaluate energy performance.

Introduce a national monitoring mechanism to track energy use, investment efficiency, and sustainability outcomes across the agricultural sector.

Scientific and Practical Significance

This study contributes to the academic discourse on energy economics and agricultural modernization in developing economies. The proposed analytical framework can be applied to assess the cost-effectiveness of energy policies, while the empirical results provide practical guidance for policymakers and investors.

The findings emphasize that energy efficiency is not merely a technical parameter but a strategic economic factor shaping the future of sustainable agriculture in Uzbekistan.

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