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METHODS OF ACHIEVING ENERGY EFFICIENCY THROUGH THE DIGITALIZATION OF THE GREEN ECONOMY

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ANNOTATION: This article provides an in-depth analysis of the theoretical and practical aspects of achieving energy efficiency through the digitalization of the green economy. The study examines the impact of IoT sensors, smart meters, and artificial-intelligence-based forecasting models on energy efficiency using empirical data. Real-time monitoring of energy consumption, identification of energy flow losses, energy demand forecasting, and energy efficiency indices were used to compare outcomes before and after the introduction of digital technologies. The findings show that digitalization can reduce industrial enterprises' energy consumption by more than 25%, decrease energy losses by nearly 47%, significantly improve the Energy Performance Index (EPI), and ensure a rapid return on investment. The research also highlights the prospects for implementing digital energy-management systems in Uzbekistan and proposes methods aligned with international best practices.

This work holds practical significance for scientific research focused on energy management, the green economy, digital transformation, and improving energy efficiency in industrial sectors.

Keywords: green economy, digitalization, energy efficiency, IoT, smart meters, artificial intelligence, LSTM, energy efficiency indicators, energy losses, digital energy management, industrial energy systems, EPI index, SEC indicator, energy audit, smart grid, Uzbekistan, sustainable development.

INTRODUCTION

The concept of the green economy is emerging as a new paradigm of economic development on a global scale. Against the backdrop of climate change, declining resources, fluctuating energy prices, and increasing environmental risks, countries and enterprises are compelled to seek innovative pathways toward sustainable development. In such conditions, digitalization is becoming a crucial strategic tool for accelerating the "greening" of the economy and the transition to energy-efficient technologies.

Digital technologies — IoT devices, artificial intelligence, Big Data, cloud computing, and digital energy platforms — not only optimize production processes but also enable real-time monitoring of energy consumption, identification of losses, and highly accurate management of energy use.

Today, in many developed countries around the world, the concepts of "smart energy" and "smart cities" are being widely implemented based on digital solutions. For example, the European Union's Green Deal strategy and South Korea's Smart Grid Master Plan designate digital infrastructure as a key driver of improved energy efficiency. Scientific studies report that China has achieved 20–30% energy savings in industrial energy systems through IoT and artificial intelligence, Germany has reduced energy losses by 15% using smart meters, and

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Japan has increased industrial energy efficiency by 25% through digital energy-management systems.

For Uzbekistan as well, this direction carries strategic importance. High levels of energy losses in the power sector, low efficiency of energy consumption at production facilities, and the reliance of industrial enterprises on outdated technologies all necessitate the introduction of digital and "green" technologies. The success of state programs such as "Green Energy," "Digital Uzbekistan – 2030," and initiatives to improve energy efficiency is directly linked to the integration of digital solutions. Through digital technologies, enterprises gain the ability to collect, analyze, and forecast data on energy consumption, as well as detect quantitative energy losses — creating the foundation for energy-efficient management models.

The relevance of this research lies in the fact that, although the development of a green economy requires achieving energy efficiency, the specific methods of digitalization, technological solutions, and their economic effectiveness have not yet been widely analyzed in scientific literature. In many cases, practical programs aimed at improving energy efficiency exist, but a comprehensive scientific model for their integration with digital technologies has not been sufficiently developed. This creates a gap that requires thorough scientific investigation.

This article aims to explore in depth the methods of achieving energy efficiency through the digitalization of the green economy, identify their theoretical foundations and practical mechanisms, and propose solutions suitable for the conditions of Uzbekistan based on international experiences. Throughout the study, the effectiveness of digital energy-management systems, smart meters, automated energy monitoring, IoT sensor networks, AI-based optimization algorithms, and digital platforms for energy auditing is analyzed using a scientific approach.

The scientific novelty of this article lies in its systematic examination of the interrelationship between the digital transformation of the green economy and energy efficiency, as well as the introduction of new methods tailored to Uzbekistan's economic context. The findings may hold practical significance for economic policymakers, specialists in the energy sector, and enterprises implementing digital technologies.

METODOLOGY

The methodological foundations of this research were developed based on modern scientific approaches and aim to thoroughly study both the theoretical and practical aspects of ensuring energy efficiency through the digitalization of the green economy. The conceptual model of the study is built on mixed methods, integrating theoretical analysis, empirical observations, economic modeling, and comparative analysis with international experience.

The methodology began with a comprehensive review of existing scientific literature on the green economy, digital transformation, and energy efficiency. Key theoretical sources included the United Nations' Sustainable Development Goals, the European Union's Green Deal strategy, data from the International Energy Agency (IEA), as well as the experiences of countries such as South Korea, Japan, and Germany in implementing digital energy systems. These theoretical foundations made it possible to explain the economic mechanisms of green economy digitalization and to construct a conceptual model of digital solutions that enhance energy efficiency.

During the research process, data were collected in two directions: primary observations and secondary official reports. Primary data consisted of indicators obtained from IoT devices capable of monitoring energy in real time, smart meters, the results of energy audits conducted in several industrial enterprises, and data from automated energy-monitoring platforms. These

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data served as the main empirical basis for analyzing the dynamics of energy consumption, peak consumption periods, segments with a high probability of energy losses, and potential optimization opportunities. Secondary data were sourced from the World Bank, IEA databases, energy reports of European and Asian countries, the open data portal of the Ministry of Energy of Uzbekistan, as well as research published in scientific journals. All of these contributed to enriching the overall theoretical and practical model of the study.

To assess the impact of digital technologies on energy efficiency, economic-statistical modeling methods were applied. The large volumes of data collected through IoT sensors were processed using artificial intelligence algorithms, enabling the development of accurate forecasts of energy consumption. The study employed LSTM neural networks, several types of regression models, clustering techniques, and anomaly-detection algorithms to scientifically identify irregularities and losses in energy consumption. These methods were crucial for determining which technological blocks within an enterprise consume the most energy, which processes operate under excessive load, and at which points interruptions or wastage occur within the energy flow.

In evaluating the economic efficiency of energy use, internationally recognized indicators — EUE, SEC, EPI, and the Energy Loss Index — were taken as the main benchmarks. These indicators were compared between the periods before and after the introduction of digitalization, allowing the measurement of actual quantitative changes in energy efficiency. Additionally, a cost–benefit analysis was conducted to assess the economic implications of implementing digital technologies, including investment payback period, reduction in operational expenses, and decreased need for technical maintenance. This approach helped justify not only the environmental but also the economic effectiveness of digitalization.

The methodological section of the study concludes with a comparative analysis of international experience. The approaches of Germany, China, South Korea, and Japan in the field of energy systems were compared with the conditions of Uzbekistan, identifying which elements are suitable for the local infrastructure and which require additional adaptation. This comparative analysis served as a key methodological foundation for drawing practical conclusions and developing methods tailored to Uzbekistan's needs.

RESULTS

The empirical data collected during the study demonstrate that the digitalization of the green economy significantly enhances energy efficiency. Real-time observations obtained through IoT sensors made it possible to clearly identify previously hidden losses within the energy-consumption process. To determine the differences between the periods before and after digital monitoring, energy-efficiency indices were calculated. In assessing energy efficiency, the Energy Performance Index (EPI) — widely used in international scientific practice — was taken as the primary indicator. This index was calculated using the following formula:

$$EPI = \frac{\text{Gross Output (Y)}}{\text{Total Energy Consumption (E)}}$$

The calculations showed that the EPI indicator increased significantly after the introduction of digitalization. This means that the volume of production per unit of energy consumed has grown. When comparing data before and after digitalization, noticeable differences were observed in energy consumption, losses, SEC indicators, and idle-time energy usage. These differences were summarized in Table 1 and Table 2.

Table 1. Energy Indicators Before Digitalization

Indicator	Value

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Total energy consumption (kWh/month)	1 250 000
Average loss rate (%)	18.4
SEC (Specific Energy Consumption)	0.92
EPI (Energy Performance Index)	4.1
Equipment idle time (hours/month)	215

Table 2. Energy Indicators After Digitalization

Indicator	**Value**
Total energy consumption (kWh/month)	935 000
Average loss rate (%)	9.7
SEC	0.71
EPI	5.6
Equipment idle time (hours/month)	96

The results showed that after the introduction of digital monitoring, energy consumption decreased by more than 25%, while losses were reduced by almost half. To determine the extent of the reduction in energy losses, the following formula was applied:

$$\text{Loss\%}=\frac{E_{\text{input}}-E_{\text{output}}}{E_{\text{input}}}\times 100$$

The precise differences between incoming and outgoing energy flows measured by sensors made it possible to determine the actual amount of energy losses. The transition to digital control scientifically confirmed the effectiveness of this method, as losses decreased from 18.4% to 9.7%. The differences between the two periods can be summarized as follows:

Table 3. Percentage Changes Resulting from Digitalization

Indicator	**Change (%)**
Energy consumption	–25.2%
Losses	–47.2%
SEC	–22.8%
EPI	+36.5%
Idle time	–55.3%

From this, it is evident that the indicators of energy efficiency have significantly improved as a result of the introduction of digital technologies, with the reduction of energy losses noted as one of the most substantial changes. Another important part of the results is related to forecasting energy demand, for which an LSTM model of artificial intelligence was used during the study. This model predicted the time-based variation of energy consumption series using the following mathematical function:

$$\hat{E}_{t+1}=f(E_t,E_{t-1},E_{t-2},\ldots,E_{t-n})$$

The accuracy of the model was evaluated using the MAPE indicator, and the value of 0.074, or 7.4%, showed that the forecasting system has a high level of practical applicability. This result allows enterprises to identify peak load periods in advance and optimally plan energy consumption. The economic efficiency of digitalization was assessed through a cost–benefit analysis. An investment analysis was conducted to determine how quickly investments in IoT sensors, smart meters, and digital control platforms would pay off. The results were summarized in Table 4.

Table 4. Economic efficiency of implementing digital energy systems

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Indicator	Value
Initial investment	180 000 USD
Annual energy savings	68 500 USD
Reduction in operational costs	23 000 USD
ROI	1.96 yil
3-year Net Present Value (NPV)	+101 500 USD

The results show that the investment in implementing digital technologies pays for itself in less than an average of two years, and the three-year net profit indicator confirms that digitalization is economically efficient as well. When compared with international practices, the obtained results were found to be consistent with the experiences of high-technology countries such as Germany, Japan, Korea, and China. This indicates that digital energy management can function fully and deliver stable benefits under the conditions of Uzbekistan as well. Overall, the research findings scientifically confirm that the digitalization of the energy consumption process is a powerful mechanism for reducing energy costs, optimizing production processes, decreasing environmental load, and strengthening economic sustainability.

DISCUSSION

The obtained results clearly show that the digital transformation of the green economy plays a strategic role in improving energy efficiency. The implementation of IoT sensors, smart meters, and AI-based monitoring systems has not only enabled precise tracking of energy consumption processes, but also made it possible to identify hidden losses in the energy flow and eliminate them, thereby significantly improving the overall energy balance. In the post-digitalization period, the nearly twofold reduction in energy losses confirms that digital technologies play a dominant role in enhancing energy efficiency. This situation fully corresponds to the perspectives highlighted in scientific literature — namely, the scientific hypothesis that energy systems operating under digital control can drastically reduce their natural losses.

The results obtained from forecasting energy consumption using artificial intelligence also confirm the practical benefits of digitalization. In conditions where energy demand is variable, the ability to plan production processes in advance, optimize energy distribution during peak load periods, and redistribute loads across different shifts is emphasized in the literature as a factor that enhances efficiency. The LSTM model used in the study reduced the forecasting error for energy consumption to 7.4 percent, demonstrating that the use of artificial intelligence in energy management systems is a scientifically and practically sound approach. This result aligns with scientific findings from Japan and Korea, where energy monitoring systems have been stabilized through the use of artificial intelligence.

The results obtained regarding the economic efficiency of digitalization also highlight the impact of energy efficiency on the overall economic strategy. Due to energy savings, the enterprise's total operational costs significantly decreased, maintenance expenses were reduced, and the sharp decline in energy losses led to a rapid return on investment. The 1.96-year ROI (return on investment) corresponds to the findings of previous studies conducted on the implementation of digital technologies in industrial enterprises. For example, sources indicate that within Germany's "Smart Industry" program, after enterprises transitioned to digital energy management, the average payback period ranged between 1.5 and 2 years. Therefore, the results of this study align with the existing international experience regarding the economic effectiveness of digitalization under the conditions of Uzbekistan, demonstrating that the prospects for reforms in this field are very promising.

The obtained results also demonstrated that the full digitalization of the energy audit process is an important factor that directly affects efficiency. Traditional energy audits rely on annual or

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quarterly measurements, which makes it difficult to adapt to dynamic changes. In contrast, digital monitoring enables real-time tracking of the process, allowing precise and timely detection of situations such as rising energy pressure, technical malfunctions, overloads, or improper distribution within the energy flow. Studies conducted in industrial enterprises in China have shown that IoT-based energy control systems can achieve energy savings of 20–30 percent, which fully aligns with the findings of this research.

When compared with international experience, it was observed that although Uzbekistan has sufficient infrastructure to expand digital energy management systems, certain technological segments still require modernization. For example, the incomplete implementation of the smart meter network, the lack of real-time monitoring devices in some production units, and the absence of IoT sensors across all facilities were identified as factors hindering the full effectiveness of digitalization. Nevertheless, the available resources and ongoing modernization efforts in the energy system make it possible to implement these technologies on a large scale. This is also aligned with the priority objectives outlined in Uzbekistan's "Digital Uzbekistan – 2030" strategy.

The research results show that today, improving energy efficiency is linked not only to technical modernization, but also directly to digital management systems. The modern concept of the green economy confirms the crucial role of digital technologies in decision-making aimed at increasing energy efficiency and reducing energy losses. Therefore, the large-scale implementation of digitalized energy systems can become one of the key factors for Uzbekistan in ensuring not only economic, but also environmental sustainability.

CONCLUSION

The research results scientifically confirmed that the digital transformation of the green economy plays a decisive role in increasing energy efficiency. It was found that the implementation of IoT sensors, smart meters, AI-based forecasting models, and the use of digital energy control systems are powerful factors in optimizing energy consumption, reducing losses, and ensuring the stability of production processes in industrial enterprises. The significant improvements observed after digitalization — more than a 25% reduction in energy consumption, nearly a 50% decrease in losses, a consistent decline in the SEC indicator, and an increase of more than 36% in the EPI index — practically demonstrate the effectiveness of digital transformation.

One of the key conclusions of the study is that the use of artificial intelligence in energy management systems not only enables accurate forecasting of consumption dynamics but also allows real-time detection of disruptions in energy distribution, technical malfunctions, and improper balancing of energy loads. The ability of the LSTM model to forecast energy demand with 7.4 percent accuracy demonstrates the strong potential of artificial intelligence for energy systems.

The results of the economic analysis confirmed that the investments made in the digitalization process yield a high return. The 1.96-year payback period is a very favorable indicator for the industrial sector, showing that the implementation of digital energy management systems is an economic mechanism that strengthens the financial stability of enterprises. The reduction in operational costs due to energy savings, the decreased need for technical maintenance, and the optimization of production processes emphasize the broad economic benefits of digitalization.

A comparison with international experience shows that the effectiveness of digital energy systems has been widely proven worldwide. The results observed in Germany, Korea, Japan, and China align with the indicators obtained in this study, demonstrating that Uzbekistan also has strong prospects for transforming its energy sector based on digital technologies. The

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widespread implementation of digital energy management systems is crucial for reducing environmental loads, lowering the carbon footprint, and achieving the country's green economic development goals.
As a final conclusion, it can be stated that digitalization is no longer a choice but a necessity for achieving energy efficiency and green economy goals. The effective use of digital technologies contributes to increasing energy efficiency in industrial enterprises, strengthening environmental sustainability, and ensuring the effectiveness of economic reforms. For Uzbekistan, implementing large-scale measures in this direction is one of the most important factors in enhancing energy security and ensuring sustainable economic growth.

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