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Ruslan Akhambayev[1], Saulesh Minazhova[2], Amangeldy Bekbayev[3], Assel Zhumatova[4], Dinara Ussipbekova[5]

# Enhancing energy efficiency in decentralized systems: a comprehensive approach to renewable energy use

Abstract: This article explores the principles of an integrated approach to enhance the efficiency of renewable energy utilization for small-scale, decentralized consumers, with a particular focus on Kazakhstan. The significance of this research lies in addressing the challenges faced by these consumers, including limited financial and technological resources, and proposing solutions that can reduce reliance on centralized energy systems, foster energy autonomy, and minimize environmental impacts. The study employs a multifaceted approach encompassing analytical, classification, functional, statistical, and synthesis methods to assess the effectiveness of renewable energy sources (RES), such as wind and solar power, in decentralized energy systems. Specifically, it identifies Kazakhstan's potential for wind energy, which exceeds solar energy in capacity, and regions with substantial renewable energy potential, such as Kyzylorda, North Kazakhstan, and Zhambyl. The economic assessments indicate that wind and solar power are cost-effective, with the electricity produced from wind stations being particularly competitive. The findings emphasize the potential for wind and solar power to meet a substantial proportion of the electricity demand in various

✉ Corresponding Author: Saulesh Minazhova; e-mail: saamiinaa70@hotmail.com

[1] Satbayev University, Kazakhstan; ORCID iD: 0000-0002-1707-7042; e-mail: rusakhambayevv@gmail.com

[2] Satbayev University, Kazakhstan; ORCID iD: 0000-0002-5461-2251; e-mail: saamiinaa70@hotmail.com

[3] Satbayev University, Kazakhstan; ORCID iD: 0000-0003-3520-1710; e-mail: amangeldyb43@outlook.com

[4] Satbayev University, Kazakhstan; ORCID iD: 0000-0001-9606-7557; e-mail: assel_zhumm@outlook.com

[5] Asfendiyarov Kazakh National Medical University, Kazakhstan; ORCID iD: 0009-0008-7025-9858; e-mail: di_ussipbekova@hotmail.com

regions, with wind farms having the capacity to satisfy entire regional needs. The study concludes that an integrated approach that combines technological, economic, and social factors can substantially enhance energy efficiency, decrease environmental footprints, and contribute to the sustainable development of local communities.

Keywords: sustainable energy systems, wind and solar energy efficiency, regional renewable potential, energy autonomy, clean energy transition

## Nomenclature and abbreviation

RES – Renewable Energy Sources
SPP – Solar Power Plants
WPP – Wind Power Plants

## Introduction

Incorporating renewable energy sources (RES) into the energy system is crucial for attaining sustainability and mitigating environmental repercussions in the current energy landscape. With the increasing global interest in sustainable and eco-friendly energy solutions, the development of innovative energy supply techniques for low-power decentralized users has emerged as an essential need. Renewable energy sources, such as solar and wind energy, present considerable promise, yet their optimal utilization necessitates a comprehensive approach that integrates technological, economic, social, and environmental aspects.

Emphasizing low-power decentralized consumers – who frequently encounter obstacles such as restricted financial means and technological access – presents a chance to diminish dependence on centralized energy systems, enhance energy autonomy, and reduce environmental impact. This can, thus, stimulate local economic expansion and promote sustainable development within the community. Confronting the obstacles associated with the use of renewable energy sources for these customers is thus of both practical and theoretical significance in fostering a sustainable and energy-efficient future.

According to Nurlanova et al. (2021), regional characteristics are significant factors in the context of utilizing renewable energy in low-rise residential structures. Every region possesses distinct climatic, geographical, economic, and socio-cultural attributes that can significantly influence the efficacy and demand for renewable energy. As a result, the effectiveness of renewable energy implementation in low-rise residential structures depends not only on the availability of resources but also on the adaptation of technologies to regional conditions, local economic feasibility, and the level of social acceptance, which collectively shape the success of renewable energy initiatives.

In the work of Petuchov et al. (2023), the authors highlight the need to develop more realistic models of cryogenic storage for comprehensive studies, as well as to pay more attention to the possibilities of cryogenic systems beyond power generation. As stated in the study, improving the air liquefaction process will significantly reduce energy costs per unit of production, increase the use of waste heat, and increase the energy recovery rate by up to 70%.

According to Tulegenova (2020), Kazakhstan is experiencing rapid growth in the renewable energy sector, driven by established institutional conditions such as development programs, legislative frameworks, and support mechanisms for the RES industry. Thanks to these measures, there has been a significant increase in the installed capacity of wind farms. Calculations indicate that wind farms exhibit superior productivity compared to other forms of renewable energy in Kazakhstan, significantly surpassing solar power generation. This variation is attributed to the unique geographical distribution of solar and wind energy resources across Kazakhstan.

Bulatov and Neshina's (2020) study examines the advancement of wind energy in Kazakhstan, proposing strategies to augment efficiency and achieve carbon neutrality. The author's work, which focuses on investments, energy storage technologies, and the role of governmental and international support, underlines the importance of a multifaceted approach in implementing RES projects. This viewpoint is further reinforced by Minazhova et al. (2023), who advocate for the establishment of renewable energy zones, integrating a range of technologies, including wind and solar, to enhance efficiency and stimulate innovation.

Zhumatova and Orynbasarov (2021) it is important to highlight that employing energy complexes utilizing renewable energy sources for Kazakhstan's traction power supply system holds substantial potential and represents a promising aspect in the sustainable development of transport infrastructure. Incorporating renewable energy sources into the traction power supply system can offer numerous notable advantages, such as decreased greenhouse gas emissions, decreased reliance on imported fuels, enhanced energy efficiency, and lowered operational expenses.

The objective of this article is to examine the principles of an integrated approach aimed at enhancing the effectiveness of utilizing renewable energy sources, particularly concerning low-power decentralized consumers. This approach considers technical, economic, social, and environmental factors with the aim of attaining energy independence, decreasing reliance on centralized systems, mitigating environmental impacts, and fostering sustainable development and economic efficacy on a local scale.

# 1. Materials and methods

The analytical method was instrumental in evaluating the efficacy and efficiency of implementing an integrated approach to utilizing renewable energy sources for low-power decentralized consumers. Research and data analysis have identified specific indicators and practical results associated with the implementation of this approach. With the help of statistical analysis, specific indicators of the effectiveness of the integrated approach were calculated. Percentage reductions in energy dependence on traditional energy sources, reductions in energy costs, and improvements in the ecological footprint were assessed. The obtained results facilitated an assessment of the efficacy of integrating renewable energy sources and highlighted areas that need further enhancement.

Through the functional method, a more detailed examination was conducted on the involvement of low-power decentralized consumers in utilizing renewable energy sources. The functional method allowed for an understanding of how these consumers contribute to reducing dependence on traditional energy sources. The structural-functional method aided in comprehending the specific roles and functions carried out by low-power decentralized consumers concerning the utilization of renewable energy sources. The structural-functional method allows an understanding of the relationship between the structure of the RES system and the functions performed by low-power decentralized consumers. By applying the synthesis method, it was possible to determine the optimal ways to combine different technologies and resources to improve the efficiency of the use of renewable energy sources for low-power decentralized consumers. The synthesis method has made it possible to create integrated systems that maximize the use of available resources and ensure efficient energy supply.

The study carried out a detailed disclosure of the theoretical component of the work, which allowed for an in-depth study of the basic principles and concepts associated with an integrated approach to the use of RES for low-power decentralized consumers. This included conducting an analysis of existing models, technologies, and methods. Based on the theoretical analysis, a methodology was developed, which was then applied in the practical part of the study. This included data collection, analysis of the obtained results, and subsequent optimization of the RES system. The theoretical component of the work provided the foundation for the implementation of an integrated approach in practice and contributed to the development of practical recommendations and solutions aimed at improving the efficiency of the use of renewable energy in this context.

The practical component of the study included several pilot projects and experiments aimed at installing and testing renewable energy systems for low-power decentralized consumers. These projects have collected a variety of data, including information on energy production, consumption, system efficiency, and other factors. The analysis revealed the advantages and limitations of these systems. Drawing from the obtained results, suggestions were crafted to enhance and optimize the utilization of renewable energy sources. The study of the practical component of the work led to the receipt of specific data and practical experience, which supplemented and confirmed the theoretical assumptions put forward in the study. This made it possible to formulate realistic recommendations and strategies aimed at improving the efficiency of RES use for low-power decentralized consumers.

## 2. Results

The proportion of renewable energy in worldwide electricity production is consistently increasing. As of 2024, renewable energy accounts for 6.43% of Kazakhstan's total electricity generation, with a capacity of 3,032 MW. In Almaty, projects like the Kapshagay Solar Power Plant and Samruk-Energy's transition to gas turbines indicate growing renewable energy adoption, though exact city-level data is limited (Smatayeva et al. 2024). An important factor contributing to its development is the policy of decarbonization of the economy, which emphasizes energy with a minimal carbon footprint. This aligns with the objectives of the Paris Agreement, which aims to limit global temperature rise by reducing greenhouse gas emissions and promoting sustainable energy solutions (United Nations… 2015). The increase in annual rates of electricity consumption underscores the relevance of research aimed at diversifying energy sources. Even with a significant reduction in prices for traditional energy sources, renewable energy remains in demand for large countries with vast territories, where the problem of centralized energy supply is relevant, and high costs for constructing power lines stimulate the use of autonomous power supply systems. This observation is supported by the statistical method used to analyze global electricity consumption trends. The modularity of renewable energy installations, primarily based on solar and wind energy, allows the creation of objects with different capacities, contributing to the development of this industry at the regional level and providing energy for a wide range of consumers, both within a single energy network and for autonomous systems.

At the moment, in the Republic of Kazakhstan, electricity is produced mainly using fossil hydrocarbon fuels. About 81% of the electricity produced comes from coal-fired power plants, which causes significant air pollution. In Almaty, the electricity generation situation is similar to the general trend in the country (Assanov et al. 2021). The distinctive feature of a sparse population density in the nation creates opportunities for the expansion of seasonal or permanent independent energy consumers, along with providing ample space for the establishment of renewable energy sources. The analytical method used in evaluating Kazakhstan's energy infrastructure highlights the challenges posed by centralized systems and the potential of renewable sources in addressing energy deficits (Sadykov et al. 2024). In the Republic of Kazakhstan, power generation capacities are grouped into multiple energy zones, and the transmission of energy between these zones incurs notable losses. The functional method was applied to assess the role of different energy zones and the transmission losses in Kazakhstan's aging infrastructure. The findings emphasize the need for enhanced local generation and distribution systems to mitigate losses. The aging network infrastructure, established during the Soviet era, stands as a primary factor contributing to the continuous rise in energy losses. As energy consumption increases and the Southern Energy Zone lacks sufficient capacity, addressing the issue of electricity transit from the "North to the South" becomes imperative. The industrial sector is the leading consumer of electricity in Kazakhstan, accounting for 58% of the total, followed by housing and communal services – 22%, losses for own needs – 14%, and agriculture – 1% (International Energy Agency 2021). Most industrial companies in Kazakhstan export their products to the world market, where the environmental image is currently given great attention, as it has an impact on investment attractiveness.

Kazakhstan has endorsed the Kyoto Protocol and established a legal framework that includes adopting state-supported mechanisms like auctions to encourage the growth of renewable energy. Synthesis methods were employed to combine policy analysis with capacity targets, revealing a clear path toward achieving up to 1,200 MW for wind and 1,100 MW for solar power by 2025 (Guliyev 2023; Aliyev and Aliyeva 2022).

In Almaty, there has been a favorable trend in the advancement of renewable energy sources from 2016 to 2020. New capacities were installed, and the generation of energy from renewable sources witnessed growth during this timeframe. Notably, substantial growth is noted in the wind energy sector, along with advancements in small hydroelectric power plants and solar power installations. Wind energy occupies a leading position among all renewable sources in Almaty. Favorable climatic conditions and the availability of natural resources make it possible to build wind turbines and use wind energy to generate electricity. This industry is experiencing active growth and plays a substantial role in the overall production of energy from renewable sources. Moreover, there has been a rise in the number of small hydropower plants in the area. They use the potential of river flows and watersheds to generate electricity. This strategy not only helps to boost the proportion of renewable energy but also fosters the growth of local economic and environmentally sustainable resources. Solar energy also has a significant impact on the progress of renewable energy sources in Almaty. The adoption of solar power plants and the usage of solar panels to generate electricity are increasingly becoming more popular. Due to its affordability and environmental friendliness, solar energy contributes to sustainable development and can reduce dependence on traditional energy sources. However, without energy storage, a stable energy supply cannot be ensured throughout the day and across different seasons. The upward trajectory in the progress of renewable energy sources in Almaty reflects the aspiration to establish an environmentally friendly and energy-sustainable urban infrastructure (Pablo-Romero et al. 2021).

Despite the unconventional circumstances for the vigorous growth of renewable energy, Kazakhstan actively promotes the advancement of this sector, particularly prioritizing wind and solar energy as key focus areas. However, assessing the potential of renewable sources in energy supply requires an analysis of the energy supply potential in various regions of Kazakhstan, with a specific focus on utilizing renewable energy sources. The energy supply potential represents the proportion of electricity that can be generated using renewable energy sources to meet energy requirements. When evaluating the potential for energy supply, factors such as energy demand, the effectiveness of renewable energy sources, restrictions on their deployment, and the competitiveness of renewable energy compared to conventional sources are taken into account.

As of the beginning of 2023, Kazakhstan has 207 operational power plants with a combined installed capacity of 219.01 GW (Demir et al. 2024). Significant energy shortages are found in many regions. Akmola region has the highest negative electricity balance, reaching 4,792 GW/h/year. The Pavlodar region serves as the primary generator and consumer of electricity within Kazakhstan, and it also acts as the primary exporter of this energy to other regions within the country. In the year 2020, the electricity exported to the Russian Federation totaled 3,566 GWh, while that to Central Asia amounted to 2.8 GWh (Table 1).

Table 1. The electricity generated from renewable energy-based plants in the Republic of Kazakhstan and its proportion in the overall electricity output

Tabela 1. Energia elektryczna wytworzona w elektrowniach wykorzystujących energię odnawialną w Republice Kazachstanu i jej udział w całkowitej produkcji energii elektrycznej

| Year | Renewable energy sources [million kWh] | | | | Share of electricity produced using RES in the energy balance [%] |
|---|---|---|---|---|---|
| | WPP | SPP | small hydropower plants | biomass thermal power plants | |
| 2018 | 271 | 86 | 81 | – | 0.98 |
| 2019 | 335 | 90 | 144 | – | 1.07 |
| 2020 | 398 | 138 | 242 | 1 | 1.26 |

Source: compiled by the authors based on data by Melnyk et al. (2020).

Studies have shown that on the territory of the Republic of Kazakhstan, specific energy production can reach values from 63 to 342 MWh/year/km$^2$ when using wind power plants (WPP) and from 41 to 68 MWh/year/ km$^2$ when using solar power plants (SPP) with photovoltaic modules (Figs 1 and 2). It is noticeable that the efficiency of wind stations exceeds the efficiency of solar stations by 1.5–5 times (when using selected types of photovoltaic modules and wind turbines).

Figures 1 and 2 illustrate the efficiency of WPP and SPP in terms of electricity generation, expressed in megawatt-hours per year per square kilometer (MWh/year/km$^2$). This unit represents the annual energy output per square kilometer of land, providing a standardized measure for comparing the efficiency of renewable energy installations across different regions. For example, a SPP with a capacity of 500 kWp installed on a 50 × 50 m plot (2,500 m$^2$) typically generates between 400 and 700 MWh per year. This estimate is based on an average capacity factor of 9–16%, considering regional variations in solar radiation and system efficiency. When scaled to a full square kilometer (1,000,000 m$^2$), the energy production is extrapolated accordingly, leading to values in the range of 41–68 MWh/year/km$^2$ for solar farms, as shown in Figure 2. This calculation assumes optimal land use and panel placement density, which may vary depending on specific geographic and technical conditions. For WPP, the energy

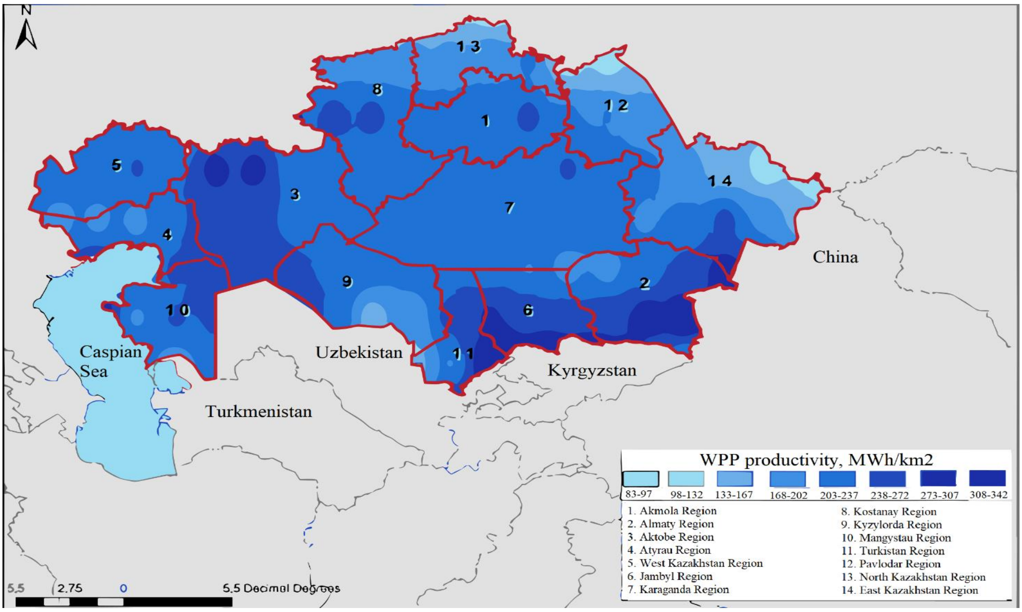


Fig. 1. Efficiency of wind power plants (WPPs) in relation to electricity generation [MWh/km$^2$] for 2020
Source: Ministry of Energy of the Republic of Kazakhstan (2023)

Rys. 1. Wydajność elektrowni wiatrowych (WPP) w odniesieniu do produkcji energii elektrycznej [MWh/km$^2$] dla 2020 r.

generation potential is significantly higher, reaching values between 63 and 342 MWh/year/km$^2$, as illustrated in Figure 1. This variation is due to the higher efficiency of wind energy conversion and the ability to space wind turbines over a larger area while still achieving high energy yields per unit of land.

In evaluating the potential for energy supply, it is imperative to consider a range of constraints, encompassing protected natural areas, forests, urban settlements, water bodies, and critical bird habitats. Furthermore, consideration should be given to factors that promote the adoption of wind and solar energy, such as the availability of power lines, road infrastructure, and electrical substations (Gernaat et al. 2021). Utilizing spatial analysis tools makes it possible to exclude areas where power plant construction is restricted and to pinpoint suitable locations for station placement. As part of this research, the impact of power lines was examined as a factor that contributes to the advancement of renewable energy sources. A limitation has been set specifying that allowable development areas must be within a maximum radius of 5 km from power lines. This is attributed to the elevated expenses associated with constructing such transmission lines. Following the conducted calculations, regions suitable for utilization as viable areas were identified. According to the data obtained, the regions of Karaganda (33,131 km$^2$ for wind farms and 34,271 km$^2$ for solar plants), Akmola (27,445 km$^2$ for wind farms and 29,357 km$^2$ for solar plants) and Pavlodar (22,111 km$^2$ for wind farms and 22,614 km$^2$ for solar stations) the regions

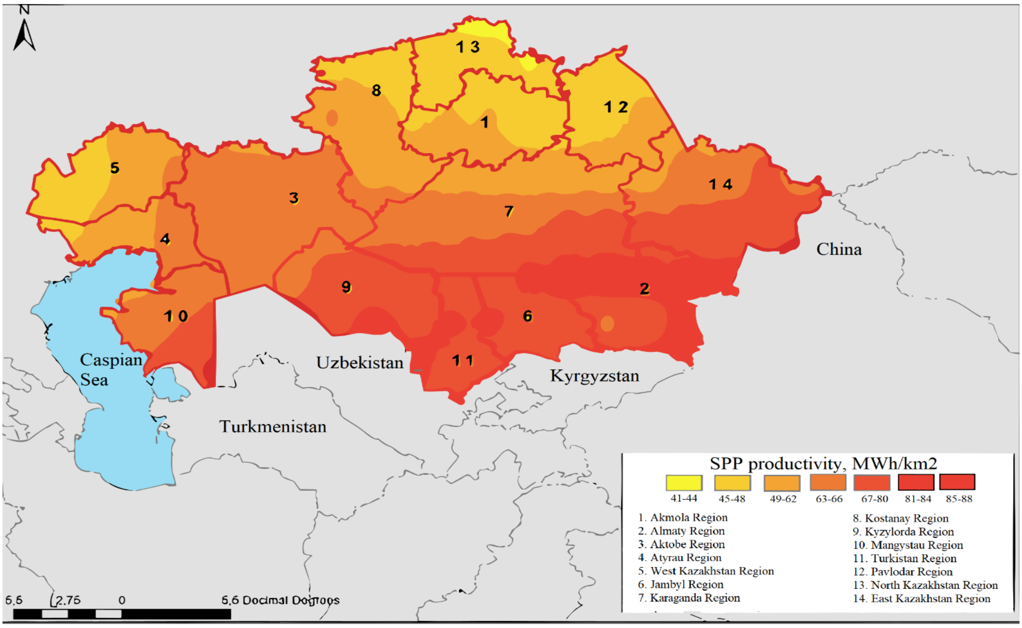


Fig. 2. Efficiency of solar power plants (SPP) in relation to electricity generation [MWh/km$^2$] for 2020
Source: Ministry of Energy of the Republic of Kazakhstan (2023)

Rys. 2. Wydajność elektrowni słonecznych (SPP) w odniesieniu do produkcji energii elektrycznej [MWh/km$^2$] dla 2020 r.

of Kazakhstan have significant land resources for the placement of stations operating on the basis of renewable energy sources. In the subsequent phase, computations were conducted to compare the electricity output from wind and solar installations with the electricity demand across different regions of Kazakhstan, using the determined available land areas. Utilizing all authorized areas, the aggregate energy supply potential for the entire Republic amounts to roughly 43% (equivalent to 44,975 GWh/year) for wind farms and 11% (around 11,023 GWh/year) for solar installations.

Upon scrutinizing the energy supply capacity within various regions, it becomes apparent that the yearly output from wind farms situated in authorized zones holds the potential to adequately fulfill the electricity requirements in regions characterized by relatively low overall consumption, such as North Kazakhstan and Kyzylorda regions. Significant potential for renewable energy supply is also evident in the Zhambyl, West Kazakhstan, Kostanay, and Akmola regions, where the percentage of electricity consumption replaced by renewables exceeds 65%, ranging from 1295 to 5898 GWh/year. The Kyzylorda, Zhambyl, and North Kazakhstan regions exhibit the most favorable conditions for deploying solar power plants. In these regions, the potential output from solar stations could range from 20% to 32% (equivalent to 544 to 873 GWh) of the total electricity demand. The levelized cost of electricity has been utilized as a significant metric for gauging the expenses associated with generating electricity from solar and wind farms.

Data regarding the initial investment and ongoing expenses associated with the establishment and functioning of wind farms was sourced from available estimations provided by international analytical organizations (Panagiotis et al. 2020). As a result of this analysis, the present value of electricity ranges from 30.64 to 42.47 tenge per kilowatt-hour for solar power plants and from 4.3 to 13.98 tenge per kilowatt-hour for wind farms. The indicated ranges are for stations with maximum and minimum capacity. The cost of electricity can vary significantly depending on the costs of logistics, but in this study, this component was not taken into account due to the impossibility of forecasting for different regions of Kazakhstan. The cost of electricity in the wholesale energy and capacity market in Kazakhstan, obtained from the results of trading in 2020, using traditional fuel sources is from 4.09 to 10.81 tenge per kilowatt-hour (Temirgaliyeva and Junussova 2020). The estimated cost of energy produced from solar and wind stations falls within a comparable range, given the approximations involved in the calculations. When analyzing the cost of electricity in relation to the tariffs for purchasing electricity by individuals and businesses across different regions of Kazakhstan, energy generated from wind and solar stations is least competitive in the Atyrau, Aktobe, and Pavlodar regions, while it is most competitive in the Almaty, Akmola, and Mangystau regions.

To improve the efficiency of using RES for low-power decentralized consumers in the city of Almaty, it is necessary to apply an integrated approach that includes several key activities. First, it is important to analyze the needs and capabilities of consumers in order to determine the optimal renewable energy technologies for specific conditions and requirements. This may include an assessment of solar and wind potential, as well as the availability of other RES resources. Secondly, there should be a promotion of information and education regarding the utilization of renewable energy, along with the implementation of training programs and the provision of guidance on installing and operating renewable systems. Additionally, it is crucial to establish adequate financing and support mechanisms, which may include incentives, subsidies, or financial aid to facilitate the installation of renewable energy systems. In addition, it is important to create the necessary infrastructure for the integration and networking of RES systems, as well as improve the management and monitoring system to ensure efficient use and maximize energy production. In general, the successful increase in the efficiency of RES use for low-power decentralized consumers requires an integrated approach that combines technical, informational, financial, and organizational measures. An optimal model for the management and control of renewable energy systems for small distributed consumers includes several key components for optimizing energy delivery, managing loads, and making more efficient use of renewable energy (Mahmud et al. 2020). Some of these components are presented here:

1. Monitoring and control of energy production. The best models use advanced monitoring systems that continuously monitor renewable energy production. This includes monitoring the operation of solar panels and wind turbines, as well as collecting and analyzing data on energy production. This data is used to develop control algorithms for the efficient distribution of the produced energy.
2. Predicting energy output. To enhance the efficiency of renewable energy source utilization, the model incorporates an energy production forecasting system. It allows for the prediction

of the future performance of photovoltaic and wind farms based on weather data and past performance. This forecast helps plan energy distribution and optimize system performance.

3. Load management. A key element of the optimal model involves managing loads to guarantee the effective utilization of renewable energy. This entails creating algorithms capable of managing and optimizing energy consumption based on the quantity of energy generated from renewable sources. For example, it is possible to automatically redistribute energy between different loads or manage the temporary shutdown of specific equipment during periods of low renewable energy performance.
4. Energy storage systems. Optimal models might incorporate energy storage systems that enable surplus energy from renewable sources to be stored and utilized later. This can help stabilize fluctuations in energy production and ensure power supply reliability during periods of low renewable energy activity. Energy storage approaches include batteries, compressed air, hydropower, and other technologies.
5. Monitoring and diagnostics. The model includes a monitoring and diagnostics system to ensure the reliable operation of the RES system. It includes continuous monitoring and analysis of renewable energy equipment's operation to identify potential problems and malfunctions. Predictive fault detection and timely repair reduce system downtime and improve reliability.

Implementing optimal management and control models for renewable energy systems among decentralized low-power consumers results in enhanced efficiency in utilizing renewable energy sources, decreased reliance on conventional energy sources, and the establishment of sustainable energy systems.

## 3. Discussion

The principles of an integrated approach aimed at enhancing the efficiency of renewable energy for small decentralized consumers are crucial in fostering the sustainable development of the energy system. Exploring this topic and examining research findings contribute to a deeper comprehension of the principles and actions required for the efficient utilization of renewable energy. Maximizing the variety and integration of various types of renewable energy sources is a fundamental principle of an integrated approach. This entails leveraging solar energy, wind energy, hydropower, and other resources to ensure a dependable and consistent energy supply. This approach reduces dependence on a single source and increases the sustainability of the energy system as a whole, ensuring its reliability and sustainability. In order to achieve optimal utilization of renewable energy, it is essential to employ advanced systems for monitoring, forecasting, and management. These systems enhance the efficiency of energy production and distribution from renewable sources by incorporating load management, equitable distribution, energy storage systems, and advanced control technologies. They provide maximum efficiency and reduce energy waste, contributing to the stability and reliability of the system.

Taking into account the characteristics and needs of low-power decentralized consumers is also an important principle. Tailoring the adaptation and integration of renewable energy sources into their energy systems on an individual basis enables the optimization of energy utilization. It guarantees the availability and dependability of energy supply. This may include autonomous systems, adaptive tariff models, and other solutions tailored to the specific needs and capabilities of low-power decentralized consumers. Positive research findings have validated the implementation of an integrated approach to enhance the efficiency of RES utilization for low-power decentralized consumers. This encompasses decreasing reliance on energy, enhancing environmental sustainability, lowering energy expenses, improving the overall sustainability of the energy system, and generating new prospects for local community development. This strategy fosters sustainable growth while mitigating adverse environmental effects. The RES management and control model includes production monitoring, forecasting, load management, energy storage systems, and equipment control. It optimizes energy distribution, allows planning energy needs, and uses renewable energy efficiently. Storage systems smooth out production fluctuations and ensure power supply reliability. Monitoring and diagnostics detect and prevent problems. This model is crucial in enhancing the effectiveness of renewable energy and advocating for sustainable energy advancement.

However, the successful implementation of these principles requires support from governments, the development of appropriate policies and regulations, and cooperation between various stakeholders, including manufacturers, consumers, research organizations, and the public. The discourse on this subject and the findings from the research contribute to establishing a foundation for devising effective strategies and practical solutions in utilizing renewable energy for small, decentralized consumers, thereby advancing toward a sustainable energy future. Diversifying the energy portfolio, training and raising awareness about renewable energy, stimulating innovation, developing cost-effective financing models, improving energy infrastructure and cooperation between countries – all these are important aspects of the efficient use of renewable energy for low-power decentralized consumers (Temirbaeva et al. 2024). These actions foster sustainable progress, enhance quality of life, and safeguard the environment.

In recent years, researchers have highlighted the essential function of low-power decentralized consumers in the shift to renewable energy systems. According to Chen et al. (2021), these users, by implementing renewable energy systems like solar panels or wind turbines on their properties, generate their electricity and diminish reliance on traditional energy sources. The capability for independent energy generation substantially enhances the resilience of the power grid. In instances of failures within centralized networks, decentralized energy systems guarantee an uninterrupted supply to their proprietors, hence enhancing the reliability and sustainability of the energy infrastructure. These contributions are essential for achieving overarching sustainability objectives, significantly influencing the global energy transition.

Moreover, Hoang and Nguyen (2021) contend that a fragmented strategy for renewable energy deployment is inadequate for realizing the complete potential of these resources. The need for a cohesive strategy is especially apparent when addressing the intricate, multiple issues of energy transition. Assessing the efficacy of renewable energy systems, including solar panels and wind turbines, is fundamental to this cohesive strategy. Utilizing data from real-time monitoring, stakeholders can enhance the distribution and consumption of renewable energy, consistent with the findings of Chege et al. (2020), who emphasize the critical importance of technological advances in surmounting prior obstacles to renewable energy adoption.

Ahmad et al. (2021) highlight the paramount significance of load control. Their research indicates that synchronizing energy usage with renewable energy production via innovative algorithms and control systems optimizes energy efficiency. This method is essential for reducing variations in energy output and consumption, therefore improving the sustainability of energy systems. These technologies maximize the use of renewable energy, diminishing dependence on conventional energy sources and aiding in the development of more efficient energy infrastructures.

According to Hannan et al. (2020), energy storage devices serve a supplementary function in ensuring the reliability of renewable energy sources. Such systems store surplus energy produced during high-output periods, offering a buffer during low-output intervals to guarantee a constant and stable supply. The advancement and use of energy storage technologies, especially lithium-ion batteries, have consequently become essential facilitators of the renewable energy transition. This innovation immediately enhances the performance of decentralized energy systems, assuring their reliability and consistency throughout time.

The regulatory framework is essential for promoting the extensive adoption of renewable energy technologies. Kozhageldi et al. (2022) contend that a strong legal and regulatory framework is essential for directing the adoption of integrated renewable energy systems. Such frameworks must encompass not only the technological and commercial aspects but also protect the rights and interests of consumers. As governments advance support for the renewable energy sector, it is crucial to integrate these technologies with existing policies to ensure long-term sustainability and broad acceptance.

According to Bourcet (2020), regulatory matters and economic mechanisms are significant in encouraging the growth and utilization of renewable energy sources among small decentralized consumers. These mechanisms aim to ease investment, offer financial assistance, and foster a conducive environment for renewable energy development. A crucial mechanism related to financing renewable energy projects involves offering low-interest loans and credit facilities to investors and developers. These financial tools promote the expansion of renewable energy infrastructure and lower the installation costs of equipment, thus making it more accessible for low-power decentralized consumers.

## Conclusions

Diversity and the combination of different types of RES are the key principles of an integrated approach to energy. This strategy entails utilizing a variety of energy sources together to attain maximum system efficiency and sustainability. Incorporating multiple energy sources such as solar, wind, and hydro enables the creation of a robust and dependable power supply, diminishing reliance on a single source and enhancing system resilience. According to studies, wind power plants in Kazakhstan demonstrate significantly higher energy efficiency than solar power plants. This is due to the geographical distribution of RES energy resources. The collected data was analyzed in order to assess the efficiency and reliability of the use of renewable energy sources for low-power decentralized consumers. The results confirm that an integrated approach contributes to increasing energy independence, reducing reliance on centralized energy systems, and minimizing environmental impact. The inclusion of advanced monitoring, forecasting, and management systems allows optimizing the production and distribution of energy from renewable energy sources. This includes load management, balanced power distribution, the use of energy storage systems, and the application of efficient control technologies. Studies on the application of an integrated approach show that such an approach helps to reduce energy dependency, improve the ecological footprint, reduce energy costs, increase the sustainability of the energy system, and create new opportunities for the development of local communities. The economic assessment of the generated electricity based on RES indicates its competitiveness. This opens up prospects for attracting investments and developing renewable energy projects for low-power decentralized consumers. In general, the study confirms that the principles of an integrated approach play an important role in improving the efficiency of RES use for low-power decentralized consumers. Further research in this area may be aimed at developing specific strategies and recommendations for the successful implementation of an integrated approach in practical settings and various geographic areas.

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Ruslan Akhambayev, Saulesh Minazhova, Amangeldy Bekbayev, Assel Zhumatova,
Dinara Ussipbekova

# Zwiększanie efektywności energetycznej w systemach zdecentralizowanych: kompleksowe podejście do wykorzystania energii odnawialnej

## Streszczenie

W niniejszym artykule przeanalizowano zasady zintegrowanego podejścia do zwiększenia efektywności wykorzystania energii odnawialnej przez małych, zdecentralizowanych konsumentów, ze szczególnym uwzględnieniem Kazachstanu. Znaczenie tych badań polega na sprostaniu wyzwaniom stojącym przed tymi konsumentami, w tym ograniczonym zasobom finansowym i technologicznym, oraz zaproponowaniu rozwiązań, które mogą zmniejszyć zależność od scentralizowanych systemów energetycznych, wspierać autonomię energetyczną i minimalizować wpływ na środowisko. W badaniu zastosowano wieloaspektowe podejście obejmujące metody analityczne, klasyfikacyjne, funkcjonalne, statystyczne i syntezy w celu oceny efektywności odnawialnych źródeł energii (OZE), takich jak energia wiatrowa i słoneczna, w zdecentralizowanych systemach energetycznych. W szczególności zidentyfikowano potencjał Kazachstanu w zakresie energii wiatrowej, który przewyższa moc energii słonecznej, oraz regiony o znacznym potencjale energii odnawialnej, takie jak Kyzylorda, Północny Kazachstan i Zhambyl. Oceny ekonomiczne wskazują, że energia wiatrowa i słoneczna są opłacalne, a energia elektryczna wytwarzana przez elektrownie wiatrowe jest szczególnie konkurencyjna. Wyniki podkreślają potencjał energii wiatrowej i słonecznej do zaspokojenia znacznej części zapotrzebowania na energię elektryczną w różnych regionach, przy czym farmy wiatrowe mogą zaspokoić całe regionalne potrzeby. W badaniu stwierdzono, że zintegrowane podejście łączące czynniki technologiczne, ekonomiczne i społeczne może znacznie zwiększyć efektywność energetyczną, zmniejszyć wpływ na środowisko i przyczynić się do zrównoważonego rozwoju lokalnych społeczności.

Słowa kluczowe: zrównoważone systemy energetyczne, efektywność wykorzystania energii wiatrowej i słonecznej, regionalny potencjał odnawialny, autonomia energetyczna, transformacja w kierunku czystej energii