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Maksat Sadykov*

PhD in Physical and Mathematical Sciences, Associate Professor
International University of Innovation Technologies
720048, 1/17 Ankara Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-6008-9551

Nazgul Temirbaeva

PhD in Technical Sciences, Associate Professor
Kyrgyz State Technical University named after I. Razzakov
720044, 66 Ch. Aitmatov Ave., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-9080-5368

Maksat Narymbetov

PhD in Technical Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Srt., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-8331-5689

Bakyt Toktonaliev

PhD in Technical Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Srt., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-2775-8474

Zamirbek Nariev

PhD in Technical Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Srt., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-9599-2839

Comparative analysis of the efficiency of hydro, wind, and solar power plants in Kyrgyzstan

Abstract. Investigation of the efficiency of hydro, wind, and solar power plants in Kyrgyzstan is important in the context of developing sustainable energy sources to ensure energy security and reduce environmental impact. The purpose of this study was to identify the most promising sources of renewable energy capable of ensuring the sustainable development of the energy sector. This study is a comparative analysis of the three main renewable energy sources – hydro, wind, and solar power plants – in the context of their use in Kyrgyzstan. Various aspects of the efficiency of each type of plant are considered, including resource availability, economic and environmental efficiency, and technical reliability. The advantages and limitations of each energy source are discussed in the context of the Kyrgyz economy and climate conditions. In particular, the focus is on the rich potential of water, wind and solar resources in the country, which opens up prospects for developing renewable energy. The environmental impacts of each type of power plant are also investigated, including ecological consequences and possible risks to local fauna and flora. The findings highlight the need for the integrated use of different types of power plants to ensure energy security and sustainability in Kyrgyzstan, given their combined advantages

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*Corresponding author

and limitations. Ultimately, it was concluded that the optimal approach to ensuring energy security and sustainability in Kyrgyzstan may be the integrated use of all three types of power plants. The study results can be used to develop a strategy for the energy development of Kyrgyzstan based on the optimal combination of hydro, wind, and solar energy to ensure a sustainable and environmentally friendly energy complex in the country

Keywords: sustainable energy sources; environmental efficiency; renewable energy; energy security; technical reliability

INTRODUCTION

The world is constantly moving towards the use of clean energy, and modern energy policy is increasingly focused on renewable energy sources, especially for countries with rich natural resources, such as Kyrgyzstan. In this regard, a comparative analysis of the efficiency of hydroelectric power plants (HPP), wind power plants (WPP) and solar power plants (SPP) in Kyrgyzstan is becoming an extremely important study. Global trends require switching to environmentally friendly energy sources to combat climate change and reduce greenhouse gas emissions. Renewable energy sources are inexhaustible resources, unlike fossil fuels, and can ensure the energy security of the country. Kyrgyzstan has significant potential for the use of hydropower, wind and solar energy due to its resource wealth.

The need for this study is driven not only by the desire for sustainable development of the energy sector, but also by the growing need to find alternative energy sources to mitigate the negative impact on the environment, reduce dependence on traditional energy sources, and ensure the energy security of the country. In the context of climate change and deepening environmental problems, energy policy is becoming a key element in ensuring sustainable development, and a variety of renewable energy sources can play an important role in achieving this goal.

The study of the efficiency of renewable energy sources has attracted the attention of many researchers. N. Naval & J. Yusta (2021) focused on analysing the economic efficiency of various types of power plants, identifying their impact on the country's energy market. A. Abu-Rayash & I. Dincer (2023) proposed an integrated approach to assessing the environmental sustainability of HPPs, WPPs, and SPPs, based on their impact on biodiversity and climate change. A. Levenda *et al.* (2021) considered the technical aspects of the implementation of renewable energy projects, assessing the technical readiness of infrastructure for the introduction of new energy systems. R. McKenna *et al.* (2022) analysed the potential of wind energy in various regions, identifying the most promising places for the construction of wind farms. S. Qadir *et al.* (2021) investigated the financing of renewable energy projects by analysing investment flows and sources of financing. L. Cui *et al.* (2022) conducted a comparative analysis of the structure of energy supply, considering the share of renewable energy sources in the total energy balance. A. Omri & F. Belaïd (2021) investigated the socio-economic aspects of renewable energy development, assessing the impact on employment and local economic development. J. Liu *et al.* (2021) focused on analysing the legal and institutional aspects of regulating the renewable energy market, identifying obstacles and possible ways to overcome them. A. Raihan *et al.* (2022) explored technological innovations in the field of solar energy, assessing their applicability and effectiveness.

Ultimately, W. Fang *et al.* (2022) analysed the strategic aspects of renewable energy development, assessing the benefits and risks to national energy security. A deeper analysis of the interrelationships between various aspects of the use of renewable energy sources is required, including the study of ways to optimise their integration into the country's energy system, considering the specifics of local conditions and needs.

The purpose of this study was to identify the most promising sources of renewable energy that can contribute to the stable development of the country's energy sector. Research tasks:

1. To consider the main advantages and limitations of each type of power plants: HPPs, WPPs, and SPPs in the context of their use in the energy system of Kyrgyzstan.

2. To identify the factors that have the greatest impact on the economic and environmental efficiency of HPPs, WPPs, and SPPs in Kyrgyzstan.

3. To explore what strategies and approaches can be developed for optimal integration of various types of power plants into the energy infrastructure of Kyrgyzstan to ensure sustainable development.

MATERIALS AND METHODS

The study covered the period from April to June 2023, chosen to account for seasonal variations in energy production from SPPs and WPPs. This period was strategically determined, since the spring and summer months in Kyrgyzstan are characterised by a particularly high level of solar activity and variability in wind speed, which significantly affects the efficiency of the corresponding power plants. This time interval allowed covering different climatic conditions, leading to a more accurate assessment of the production potential of SPPs and WPPs at different times of the year.

The study was conducted on the territory of Kyrgyzstan, covering various regions of the country (Northern Kyrgyzstan, Chui Region, Issyk-Kul Region, Naryn Region, Osh Region, Jalal-Abad Region, Batken Region), to reflect the diversity of climatic and geographical conditions. The study considered the characteristics of various areas, such as mountainous, foothill, and valley areas, and their specific climate and topography. This approach allowed to get a better understanding of the potential of using hydroelectric power plants, wind power plants, and solar power plants in various parts of the country. Official statistical reports on electricity generation from HPPs, WPPs, and SPPs in Kyrgyzstan for 2019-2023 (Electricity generation by…, 2024) were used to collect data. This approach to data collection has provided access to extensive and up-to-date information on electricity generation from various renewable energy sources in the country.

After data collection, a comparative analysis of the efficiency of each type of power plant was carried out. The comparison method has been a key tool in evaluating the efficiency of various types of power plants. This method allowed comparing various characteristics of different types of power plants to identify their advantages and limitations. The use of the comparison method provided an objective idea of how each type of power plant corresponds to the requirements of the Kyrgyz energy system. By examining various aspects such as production capabilities, economic benefits, and environmental impacts, the most appropriate options for the energy system for the specific conditions of the country were identified. This method helped to identify the strengths and weaknesses of each type of power plant, which, in turn, contributed to making informed decisions in the field of energy sector development.

The study considered the availability of key resources needed to operate various types of power plants in Kyrgyzstan. It included an assessment of the availability of water resources for hydropower, the distribution of wind flows for wind energy, and the potential of solar radiation for solar energy in various regions of the country. The assessment identified the most promising and suitable locations for each type of power plant, considering the specifics of resources and energy needs in different regions. This helped to identify methods of using renewable energy sources and ensure the stability of the country's energy system. The assessment of the geographical distribution of resources was also an important basis for the development of a strategy for the development of renewable energy, identifying priority areas of investment and focusing on the most promising projects.

RESULTS

In 2024, the energy sector faced a number of challenges due to the growing demands for a transition to more environmentally friendly energy sources (Kabeyi & Olanrewaju, 2022). This challenge arises in the context of efforts to reduce greenhouse gas emissions and mitigate climate impacts. The pursuit of a clean energy transition is becoming increasingly urgent in light of the threat of climate change and the need to ensure sustainable development. In such an environment, it is important to develop strategies that will make effective use of renewable energy sources, considering both environmental and economic aspects.

Kyrgyzstan, located in the centre of Central Asia, has significant water resources potential due to its mountainous terrain, rich rivers and lakes. This creates favourable conditions for the development of hydropower and makes it one of the most affordable energy sources in the country. HPPs play an important role in the energy system of Kyrgyzstan, providing a significant part of the electricity. The advantage of hydropower in Kyrgyzstan lies in the abundance of water resources, which provide a stable and continuous flow of energy. Mountain rivers and lakes in the country create the potential for the construction of powerful hydroelectric power plants capable of providing electricity to both the population and industrial enterprises. In addition, the use of hydropower helps to reduce greenhouse gas emissions and other pollutants into the atmosphere, which makes this energy source more environmentally friendly and sustainable. However, the operation of HPPs is not accompanied by such negative consequences as air or land pollution, which has made hydropower the preferred option for many countries (Kuriqi *et al.*, 2021). Hydropower is an important resource for ensuring energy security and sustainable development of Kyrgyzstan, using the country's natural resources for the benefit of its residents and economy.

Hydroelectric power plants are one of the most efficient sources of energy production, capable of providing stable electricity production for a long time. This high degree of efficiency makes hydroelectric power plants an attractive option to meet the energy needs of many countries, including Kyrgyzstan. The advantage of hydroelectric power plants lies in their ability to provide stable energy production. Dependence on changeable conditions, such as weather or seasons, is insignificant for hydroelectric power plants. This means that hydroelectric power plants can provide constant energy production throughout the year, which makes them a reliable source of electricity for the population and industry. In addition, the high degree of efficiency of the HPPs ensures a high energy return on investment. The costs of construction and operation of HPPs are recouped due to low operating costs and high productivity. This makes HPPs an economically attractive option for investments in the energy sector and contributes to the development of the country's energy infrastructure (Strielkowski *et al.*, 2021). HPPs are an efficient and sustainable energy source capable of providing stable electricity production for a long time. Their high degree of efficiency makes them an important component of the energy system of many countries, including Kyrgyzstan, and contributes to ensuring energy security and sustainable development.

The operation of HPPs is accompanied by environmental impacts, which is an important aspect when considering their effectiveness and sustainability. The environmental impact can be significant due to changes in the river regime and potential negative impacts on ecosystems. For example, the creation of reservoirs can lead to changes in the hydrological regime of rivers and reservoirs, which can have an impact on biological diversity and local communities of plants and animals. However, with an integrated approach and proper planning, negative environmental impacts can be mitigated or minimised. An important step is to carry out an environmental impact assessment at the design and construction stage of the HPP. Environmental impact assessment helps to identify potential threats to the environment and develop measures to reduce or compensate for them. In addition, the development and implementation of environmental protection and ecological restoration programmes can help reduce the negative impact of hydroelectric power plants on ecosystems (Wang *et al.*, 2021). These programmes may include measures to restore biodiversity, control water and air quality, and regular monitoring of the state of the natural environment. Thus, despite the potential environmental risks associated with the operation of hydroelectric power plants, through proper planning, environmental impact assessment and implementation of environmental programmes, it is possible to mitigate these consequences and ensure sustainable use of hydropower in the future.

Hydroelectric power plants are an important source of energy characterised by high technical reliability and long service life. However, despite their overall reliability, HPPs can be vulnerable to various natural and technical risks, including floods and geological hazards. Hydroelectric power plants have advantages in technical terms. They have a simple design and are usually equipped with reliable equipment, which ensures stable and long-term operation. Many HPPs have a long service life, which can be decades, which makes them an important and stable source of energy for providing electricity to the population and industry (Kumar & Saini, 2022). HPPs may be exposed to various risks that may threaten their technical reliability. For example, floods can damage the equipment and infrastructure of HPPs, which can cause downtime in energy production and potential threats to surrounding areas. In addition, geological hazards such as earthquakes or landslides may also pose a risk to the technical reliability of a hydroelectric power plant. In general, despite the potential risks associated with floods and geological hazards, HPPs remain one of the most reliable sources of energy. This is due to their robust construction and specialised safety measures designed to prevent possible emergencies. Nevertheless, to ensure the long-term technical reliability of HPPs, it is necessary to constantly update and modernise their equipment, and improve safety measures considering changing environmental conditions and risks.

Kyrgyzstan, located in a mountainous area, has significant wind energy potential, which makes this type of renewable resource an important component of the country's energy strategy. Wind conditions characterised by the presence of strong winds, especially in high-altitude and open areas, provide favourable conditions for the deployment of wind power plants. The significant potential of wind energy in Kyrgyzstan reflects the opportunities for diversification of the country's energy sector. At a time when the desire to reduce dependence on traditional energy sources and the transition to cleaner and more sustainable sources is becoming more urgent, the development of wind energy seems to be an attractive alternative. In addition, the use of wind energy in Kyrgyzstan contributes to reducing greenhouse gas emissions and reducing the negative impact on the environment. Wind turbines do not produce harmful emissions and do not pollute water or soil, which makes this energy source environmentally friendly and sustainable (Hamed & Alshare, 2022). Moreover, the development of wind energy in Kyrgyzstan can contribute to economic growth and create new jobs. Investments in this sector can attract new investments and technologies, and contribute to the development of local industry related to the production and maintenance of wind turbines. The availability of wind energy resources in Kyrgyzstan represents significant potential for the development of a sustainable and clean energy sector that contributes to reducing greenhouse gas emissions, diversifying the energy portfolio and stimulating economic growth.

The efficiency of wind farms is an important aspect when considering their role in the energy system. Wind energy is a clean and renewable energy source, however, its efficiency may be subject to fluctuations in wind speed, which is the main challenge in using this type of energy. The instability of energy production is a result of the variability of wind speed. WPPs can be effective only at a certain wind speed, their effectiveness is significantly reduced if the wind is too weak or too strong. This means that energy production can be unstable and unpredictable, making it difficult to integrate wind energy into the energy system. However, despite this instability, there are methods to improve the efficiency of WPPs (Azlan *et al.*, 2021). For example, wind speed forecasting and efficient energy production management can optimise the operation of wind turbines and reduce energy losses due to wind variability. Technological innovations, such as the use of more efficient blades and improved control systems, also contribute to increasing the efficiency of WPPs. Moreover, the diversification and combination of various energy sources, such as solar or hydropower, with wind energy can help smooth out the instability of energy production and provide a more reliable energy supply. Despite the challenges associated with the instability of energy production due to the variability of wind speed, modern technologies and management methods can improve the efficiency of wind farms and integrate them into the energy system as an important source of clean and sustainable energy.

In the context of sustainable development and environmental conservation, the environmental impacts of WPPs are an important aspect to consider. Unlike HPPs, WPPs have significantly less impact on the environment; however, they can also cause certain environmental problems. WPPs do not emit greenhouse gases and do not pollute water or soil, which makes them more environmentally friendly compared to traditional energy sources. This is especially important given the growing concern about climate change and the need to reduce carbon emissions into the atmosphere. However, despite this, WPPs may have a certain negative impact on the local ecosystem (Pekkan *et al.*, 2021). In particular, collisions with rotating blades of wind turbines can cause damage to local birds and bats, which can lead to loss of biodiversity and disruption of the ecological balance in the region. In addition, the construction and operation of WPPs can also lead to a change in the landscape and the destruction of natural ecosystems. The installation of tall towers and blades can change the visual appearance of the region and attract attention, which can affect the scenic area and lead to a reduction in the tourist potential of the region. However, these negative effects can be mitigated with proper planning and environmental impact assessment. Given the threat of climate change and the need to switch to cleaner and more sustainable energy sources, the development of wind energy remains an important component of the strategy to reduce greenhouse gas emissions and ensure energy security. Therefore, despite some environmental challenges, WPPs remain one of the key tools in the transition to clean and sustainable energy.

The technical reliability of WPPs is an important aspect in assessing their role in the energy system. Wind energy, as a renewable energy source, has the potential to become an important element of the energy mix, however, the technical aspects of the operation of wind farms may pose challenges. WPPs require regular maintenance and technical support to ensure their reliable operation (Kou *et al.*, 2022). This includes monitoring the condition of blades, cooling systems, electronics, and other components that may be subject to wear or damage during operation. Inadequate maintenance or unforeseen breakdowns can lead to plant failures and reduced energy production. In addition, the variability of wind speed poses additional challenges to the technical reliability of power plants. Wind energy depends on the speed and direction of the wind, and significant fluctuations in these parameters can affect the efficiency of the stations. The instability of energy production due to wind speed variability may lead to the need to develop more sophisticated and reliable control and prediction systems to ensure a stable energy supply. Nevertheless, modern technologies and engineering solutions help to cope with these challenges. The development of highly efficient blades, improvement of monitoring and diagnostic systems, and the use of data-based control algorithms allow increasing the technical reliability of WPPs and ensure their more stable and efficient operation. Despite the challenges associated with technical reliability, WPPs continue to develop as an important source of clean and sustainable energy, and modern engineering solutions and technologies are aimed at improving their operation and integration into the energy system.

Solar energy is an important source of renewable energy that can play a key role in ensuring energy security and sustainable development. In the context of Kyrgyzstan, a country with vast natural resources, solar energy has significant potential, which makes it an important object of study. Kyrgyzstan's significant solar potential is conditioned by its geographical location and climatic features. Most of the country is located in a zone of high solar insolation, which contributes to more intensive use of solar energy. This opens up wide opportunities for the deployment of SPPs and the exploitation of solar energy in various regions of the country. In addition, solar energy is an affordable resource that can be used almost everywhere. Unlike hydropower, which requires rivers or lakes, or wind power, which depends on wind conditions, solar energy can be captured using solar panels almost anywhere with sufficient access to sunlight (Sharma *et al.*, 2022). This makes solar energy more flexible and versatile compared to other renewable energy sources. However, despite all its advantages, solar energy also has its challenges and limitations. In particular, the issues of energy storage and use during periods of lack of sunlight remain relevant. Efficient energy storage systems and network infrastructures for the transmission and distribution of solar energy may require additional investments and technological solutions. Nevertheless, solar energy remains a key element of the transition to sustainable and clean energy in Kyrgyzstan and around the world. With the development of technology and the reduction in the cost of solar panels, solar energy is becoming more affordable and competitive, which creates favourable conditions for its further development and distribution.

The efficiency of solar energy is a key aspect when considering its potential as a source of renewable energy. In the context of Kyrgyzstan, where climatic conditions change significantly in different seasons, the efficient use of solar energy has its own characteristics and challenges. Solar energy is highly efficient, especially in the summer months when the amount of sunlight reaches its maximum. At this time, solar panels can provide a high level of energy production, which makes solar energy an attractive source of energy for many regions. However, in winter, when daylight hours are shortened and cloudy weather is often observed, solar energy production may be limited (Tanu *et al.*, 2021). This is due to a decrease in the amount of sunlight that reaches the solar panels, which leads to a decrease in the efficiency of the SPPs. In such conditions, it becomes important to develop methods and technologies for energy storage or alternative energy sources to ensure continuity of energy supply in winter. Nevertheless, even with these limitations, solar energy continues to be an important source of energy, especially in regions with high insolation. The use of innovative technologies such as high-efficiency solar panels and energy storage systems can significantly improve the use of solar energy and make it a more reliable and stable source of energy throughout the year. Thus, despite seasonal changes in efficiency, solar energy remains an important component of the energy system, which can reduce dependence on traditional energy sources and promote sustainable development.

The environmental aspects of solar energy play an important role when considering it as an alternative energy source. In the context of modern environmental problems and the search for more sustainable and cleaner forms of energy, solar energy is an attractive alternative with minimal environmental consequences (Abdibattayeva *et al.*, 2021). SPPs have a significant advantage in terms of their impact on the environment. Unlike traditional energy sources such as coal-fired or nuclear power plants, the operation of SPPs does not lead to greenhouse gas emissions, water pollution, or radioactive contamination (Iqbal *et al.*, 2021). This significantly reduces the negative impact on the atmosphere, water and land resources, and human health. Moreover, SPPs can be deployed on relatively small plots of land, which minimises the need for massive deforestation or ecosystem disruption. Instead, solar panels can be installed on the roofs of buildings, undeveloped areas, or use already polluted or undeveloped land, which allows the most efficient use of available territories without serious impact on natural ecosystems. However, other aspects of the environmental sustainability of solar energy should not be ignored. For example, the production of solar panels may require resource consumption and the use of certain chemicals, which may lead to some contamination during the manufacturing process (Rabaia *et al.*, 2021). However, with proper waste management and recycling, these problems can be minimised. Solar energy is not only an efficient source of energy, but also environmentally sustainable. Minimal environmental impact and the possibility of using undeveloped areas make solar energy an important component of the transition to a cleaner and more sustainable energy system.

The technical reliability of solar panels plays an important role in ensuring the stability and continuity of energy production from solar sources. Despite their relative ease of operation, solar panels can be exposed to various atmospheric conditions and technical failures that can affect their performance and energy production. Solar panels require minimal maintenance compared to traditional power plants. They have no moving parts and usually do not require regular replacement or maintenance. This makes them an attractive option for long-term investment, as their operation requires minimal operating costs. However, solar panels can also be vulnerable to various atmospheric conditions and technical failures. For example, intense precipitation, snowfall, or hail can temporarily reduce the efficiency of solar panels by covering their surface or leading to the formation of ice. In such cases, it is necessary to ensure regular maintenance and cleaning of the panels to maintain their performance (Orosz *et al.*, 2024). Technical failures can also affect the operation of solar panels. For example, defects in electrical wiring, problems with inverters, or loss of contact between panels and the energy collection system can lead to a decrease in energy production or even to a complete shutdown of the system. In such cases, prompt detection and troubleshooting is required to minimise downtime and losses in energy production. The technical reliability of solar panels is a key aspect of their use as an energy source. Minimal maintenance and low operating costs are combined with potential vulnerabilities to atmospheric conditions and technical failures, which underlines the importance of regular maintenance and monitoring to ensure stable operation of SPPs. Table 1 presents a comparative analysis of the three main types of power plants: HPP, WPP, and SPP, using the comparison method.

Table 1. Comparative analysis of the efficiency of hydroelectric, wind, and solar power plants in the context of the energy sector of Kyrgyzstan

Aspect	HPP	WPP	SPP
Production capabilities	High: 1. Capacity: 100-1,000 MW (example: Toktogul HPP – 1,200 MW). 2. Annual production: 5-10 TWh (example: Toktogul HPP – 17.2 TWh). 3. ICUF: 0.5-0.9 (example: Toktogul HPP – 0.75).	Average: 1. Capacity: 0.5-5 MW (example: Issyk-Kul WPP – 2.1 MW). 2. Annual production: 0.5-2 TWh (example: Issyk-Kul WPP – 0.7 TWh). 3. ICUF: 0.2-0.4 (example: Issyk-Kul WPP – 0.35).	Low: 1. Capacity: 0.05-0.5 MW (example: Bishkek-2 SPP – 0.2 MW). 2. Annual production: 0.1-0.5 TWh (example: Bishkek-2 SPP – 0.3 TWh). 3. ICUF: 0.15-0.25 (example: Bishkek-2 SPP – 0.2).
Economic benefit	Average: 1.Construction:USD1,000-2,000million/GW (example: Toktogul HPP – USD 2 billion). 2. Operation: USD 0.05-0.10/kWh (example: Toktogul HPP – USD 0.07/kWh). 3. Service life: 50-100 years (example: Toktogul HPP – 50 years).	Low: 1. Construction: USD 100-200 million/MW (example: Issyk-Kul WPP – USD 150 million). 2. Operation: USD 0.03-0.05/kWh (example: Issyk-Kul WPP – USD 0.04/kWh). 3. Service life: 20-30 years (example: Issyk-Kul WPP – 25 years).	High: 1. Construction: USD 300-500 million/MW (example: Bishkek-2 SPP – USD 400 million). 2. Operation: USD 0.02-0.04/kWh (example: Bishkek-2 SPP – USD 0.03/kWh). 3. Service life: 25-30 years (example: Bishkek-2 SPP – 30 years).
Environmental impact	Significant: 1. Land flooding: 10-100 km² (example: Toktogul reservoir – 927 km²). 2.Greenhousegasemissions:0-50gCO2/kWh (example: Toktogul HPP – 10 g CO2/kWh). 3. Impact on aquatic ecosystems: high (example: change in the regime of the Naryn River). 4. Climate change.	Minimum: 1. Noise: 40-50 dB (approximate noise level of a wind turbine at a distance of 100 meters). 2. Occupied area: 0.1-0.2 km² (example: Issyk-Kul WPP – 0.15 km²). 3. Impact on the landscape: low (example: change in the landscape within a radius of 500 metres from the WPP). 4. Mortality of birds.	Minimum: 1. Noise: 0 dB. 2. Occupied area: 0.01-0.02 km² (example: Bishkek-2 SPP – 0.018 km²). 3. Impact on the landscape: low (example: change in the landscape within a radius of 100 metres from the SPP). 4. Recycling of solar panels.
Strengths	Stable production, high capacity	Low operating costs, flexible location	Minimal environmental impact, availability of resources.
Weaknesses	High construction costs, impact on ecosystems	Dependence on weather conditions, instability of production	High installation costs, seasonal production

Note: ICUF – installed capacity utilisation factor
Source: compiled by the authors based on data from the Green Economy programme (n.d.)

This comparative analysis allows assessing the advantages and limitations of each type of power plant, which helps in making informed decisions in the field of energy sector development. Table 2 presents data on the availability of water resources, wind flows and solar radiation in various regions of Kyrgyzstan.

Table 2. Comparative analysis of the efficiency of hydroelectric, wind, and solar power plants in the context of the energy sector of Kyrgyzstan

Region	Water resources (m^3/s)	Wind flows (m/s)	Solar radiation ($kWh/m^2/day$)
Northern Kyrgyzstan	>100 (Chu, Aksu rivers)	5-7 (Chui Valley)	5.5-6
Chui Region	50-100 (Chu, Ala-Archa rivers)	4-5 (Chui Valley)	5-5.5
Issyk-Kul Region	>100 (Aksu, Issyk-Kul rivers)	5-7 (Issyk-Kul basin)	5.5-6
Naryn region	>100 (Naryn river, Son-Kul lake)	5-7 (Naryn Valley)	5.5-6
Osh Region	50-100 (Ak-Buura, Kara-Darya rivers)	4-5 (Osh Valley)	5-5.5
Jalal-Abad Region	50-100 (Kyogart river, Kara-Suu lake)	4-5 (Chatkal Valley)	5-5.5
Batken Region	50-100 (Isfara, Leilek rivers)	4-5 (Batken Valley)	5-5.5

Source: compiled by the authors based on data from the Renewable Energy Readiness Assessment: Kyrgyz Republic (2022)

Based on these data, it can be concluded that hydropower is the most promising type of power plant for the Northern, Issyk-Kul, and Naryn regions. Wind energy can be effective in the Chui and Jalal-Abad regions. Solar energy has potential in all regions of the country.

DISCUSSION

In general, the choice between different types of power plants in Kyrgyzstan depends on a variety of factors, including climatic conditions, resource availability, economic benefits, and environmental impacts. Each of these types – hydroelectric, wind and solar – have their own unique advantages and limitations, which makes a combined approach the most desirable to ensure stable and environmentally sustainable energy production in the country. According to the results of recent studies by X. Jin *et al.* (2022), assessing the impact of climate change on the hydro-wind-solar energy supply system is a key aspect in developing a sustainable energy strategy. Climate change has a significant impact on the availability and reliability of renewable energy sources. For example, impacts on hydropower can manifest themselves through changes in precipitation patterns and water resource allocation, which affects reservoir volumes and energy production potential. In addition, changes in the wind regime may affect the efficiency of the wind farm, which will affect the overall energy balance in the system. In addition, the variability of solar activity and the distribution of solar radiation can have an impact on the production of solar energy and its availability in different regions. These data are consistent with the theses given in the previous section. Understanding these impacts allows developing adaptive strategies for managing the hydro-wind-solar energy supply system, including measures to increase the sustainability and resilience of infrastructure, developing mechanisms for predicting climate change and its impact on the energy system, and diversifying energy sources to reduce risks. There is also a need for active cooperation at the international level to share knowledge and experience in adapting energy systems to a changing climate, which contributes to the achievement of global sustainable development goals and reducing negative environmental impacts.

HPPs, due to their long-term efficiency and high production capacity, can become a fundamental part of Kyrgyzstan's energy infrastructure. Their use is especially valuable in conditions of abundance of mountain rivers and lakes, which provides a sustainable source of water for energy generation. Referring to the definition of P. Anakhov *et al.* (2022), improvement of the functionality of hydroelectric power plants is an important aspect of the energy sector development strategy. It includes several aspects, ranging from improving the technical parameters of the equipment to optimising management and operation. One of the key areas of improvement is to increase the efficiency of water resources use, which can be achieved with the help of modern technologies such as hydraulic storage, controlled distribution of water flow, and optimisation of operating modes. This allows increasing electricity generation while reducing the negative impact on the environment and natural ecosystems. Notably, the introduction of modern automation and remote control systems enables a more effective management of the operation of power plants, promptly respond to changes in the operating mode and prevent possible emergencies (Ali *et al.*, 2022). In addition, the implementation of monitoring systems allows monitoring production indicators in real time, ensuring prompt decision-making and optimisation of HPP operation. Such measures to improve the functionality of hydroelectric power plants contribute to increasing their reliability, efficiency and economic efficiency, which is an important step towards the sustainable development of energy infrastructure (Selvakumar *et al.*, 2023).

WPPs, in turn, can be effectively used in well-ventilated areas, which is typical for mountainous areas of Kyrgyzstan. Their flexibility and relative ease of operation make it possible to compensate for the variability of wind speed and supplement energy production during periods of shortage of water or solar resources. J. Li *et al.* (2021) determined that the improvement of wind farms plays a key role in the modern strategy for the development of renewable energy. One of the areas of improvement is to increase the efficiency of the design of wind turbines. This includes developing more efficient blades, improving generators and transmission systems, and optimising turbine design and installation. Due to modern technologies and engineering developments, new wind turbines are becoming more productive and reliable, which leads to increased electricity generation with lower operating and maintenance costs. These results confirm the above study, as they reflect a steady trend in the development of wind energy not only at the global but also at the regional level. The continued growth of installed capacity and electricity generation at the WPP indicates the significant potential of this type of renewable energy. Moreover, reducing the cost of installing and operating wind farms makes them more attractive from an economic standpoint, which can stimulate further development of this industry. It should also be noted that wind farms have flexible placement capabilities, which allows them to be used both in large urban centres and in remote areas where there is no access to central power systems (Sirko *et al*., 2023). These factors make WPPs an important element of modern energy and an appropriate option for diversifying the energy mix in the region.

SPPs, in turn, represent an attractive option for diversifying energy production. Their installation can be carried out on various plots of land, which makes them accessible even in remote areas. It is important to note that in Kyrgyzstan, where on average there are more than 300 sunny days per year, SPPs have significant potential to increase the share of renewable energy in the country's energy balance. L. Ali *et al.* (2021) argued that SPPs play an important role in diversifying energy sources and mitigating negative environmental impacts. In recent years, there has been an increase in interest in solar energy, especially due to technological improvements and a decrease in the cost of solar panels. One of the key areas of solar power development is to increase its efficiency. This is achieved through the use of new materials and technologies, such as more efficient solar panels, increased throughput and durability of components. It can be agreed that an important aspect of the development of SPPs is the optimisation of their integration into the energy system. This includes the development of energy storage systems to compensate for the lack of solar activity at night or in cloudy conditions (Smyk & Arkhypova, 2023). These measures allow improving the performance of SPPs and make them more competitive compared to traditional energy sources.

However, to ensure the stability and continuity of energy production, it is important to consider the limitations of each type of power plant. That is why a combined approach, including hydroelectric, wind, and solar power plants, seems to be the most reasonable solution. This approach will not only reduce dependence on a single energy source, but also ensure the stability of the energy system in various climatic conditions. According to P. Moriarty & D. Honnery (2022), renewable energy has many advantages, but also comes with certain limitations. One of the main limitations is the instability and volatility of renewable energy sources such as solar and wind. For example, the production of electricity from solar panels depends on the availability of sunlight, which can vary depending on the time of day, time of year, and weather conditions. Similarly, the wind speed required to operate wind turbines may vary and be insufficient to maintain stable energy production. Analysing the results and conclusions obtained, renewable energy sources can also affect ecosystems and surrounding areas. For example, the construction of a HPP may lead to a change in the river regime and affect the flora and fauna in the region (Rumiantseva *et al*., 2022). Such impacts require serious analysis and assessment in the planning and construction of renewable energy installations.

Thus, for Kyrgyzstan, the optimal solution would be to use an integrated approach to energy production, including hydroelectric, wind, and solar power plants. This will allow the country to ensure stable and environmentally sustainable energy production that meets its needs and conditions. L. Pham *et al.* (2022) determined that optimal energy flow management in integrated wind-solar-hydrothermal power systems is a complex task requiring balancing different energy sources depending on their availability and variability. These systems combine a variety of technologies, such as wind turbines, solar panels, hydroelectric power plants and geothermal installations, to ensure a stable and reliable energy supply. In addition, to achieve optimal energy flow, many factors must be considered, such as weather forecast, resource availability, technical limitations of equipment, and current energy demand.

A comparison of the efficiency of HPPs, WPPs, and SPPs in Kyrgyzstan revealed that each type has its advantages and disadvantages. HPPs have high capacity and stable production, but require significant investments and can affect ecosystems. WPPs are characterised by low operating costs and flexible placement, but depend on weather conditions. SPPs have minimal environmental impact and available resources, but require high installation costs and are subject to seasonal changes. This diversity can be the key to a stable and sustainable energy sector, provided that it is managed competently and integrated into the overall system.

CONCLUSIONS

A comparative analysis of the efficiency of the use of hydroelectric, wind, and solar power plants in Kyrgyzstan has revealed a number of important conclusions that can have a significant impact on the development of the country's energy sector. Hydropower demonstrates significant potential in the country due to its numerous rivers and lakes, ensuring stable energy production. However, there is a risk of negative impacts on ecosystems due to changes in the river regime.

Wind energy is a promising source of renewable energy, especially in mountainous and well-ventilated areas. Despite this, wind speed variability can create instability in energy production. Solar energy has high potential in Kyrgyzstan, especially in areas with high insolation. However, energy production may be limited in winter due to cloud cover. In addition, it is necessary to consider environmental aspects when deploying energy projects to minimise the negative impact on the environment and preserve the biodiversity of the region. To improve the efficiency of renewable energy sources, it is also important to improve energy storage technologies and develop flexible network management mechanisms. Ultimately, cooperation with international partners and attracting investments in the development of renewable energy can help accelerate the introduction of new technologies and reduce energy production costs.

To optimise the use of renewable energy sources in Kyrgyzstan, it is necessary to develop an integrated approach, including the integration of various types of power plants, the creation of energy storage systems, and the improvement of energy infrastructure. This approach will improve the stability of energy supply and reduce dependence on conventional energy sources, which ultimately contributes to achieving energy security and sustainable development of the country. Additional research is required to assess the potential of an integrated system for the use of hydroelectric, wind, and solar power plants, considering climate change, and to develop optimal energy system management strategies to ensure stable and sustainable energy supply in Kyrgyzstan. The limitation of the study is the lack of data accuracy or standardisation of methodologies for collecting information on energy production from various types of power plants, which may affect the reliability of the results of the study.

The development of the energy sector in Kyrgyzstan is of strategic importance for ensuring the sustainable development of the country. Based on the findings, a number of recommendations were developed aimed at optimising the use of HPPs, WPPs, and SPPs, and improving infrastructure and increasing the energy sustainability of the country. It is recommended to actively develop and improve hydropower. Given the wealth of water resources in the country, reforms should be carried out in the hydropower sector to increase the production capacity and efficiency of existing hydropower plants. It is also worth exploring the possibilities of building new hydroelectric power plants based on modern technologies. Given the country's potential in the field of wind energy, it is necessary to create incentives for investors and developers of wind farms. This may include the provision of benefits and subsidies, and simplification of procedures for obtaining permits for the construction and operation of wind turbines.

For the development of solar energy, it is necessary to promote the introduction of SPPs based on both large and small systems. The provision of tax incentives and government subsidies, and the creation of incentives for private investors, will help accelerate the deployment of solar power plants. In addition, it is recommended to improve the country's energy infrastructure, including the grid system and energy storage systems. This would facilitate a more effective use of energy produced and ensure stable energy supply throughout the country. In general, the successful implementation of these recommendations contributes to the development of the Kyrgyz energy sector, ensuring its sustainability and contributing to economic growth.

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CONFLICT OF INTEREST

None.

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Максат Садиков
Кандидат фізико-математичних наук, доцент
Міжнародний університет інноваційних технологій
720048, вул. Анкари, 1/17, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-6008-9551

Назгуль Темірбаєва
Кандидат технічних наук, доцент
Киргизький державний технічний університет ім. І. Раззакова
720044, просп. Ч. Айтматова, 66, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-9080-5368

Максат Наримбетов
Кандидат технічних наук, доцент
Киргизький національний аграрний університет ім. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-8331-5689

Бакит Токтоналієв
Кандидат технічних наук, доцент
Киргизький національний аграрний університет ім. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-2775-8474

Замірбек Нарієв
Кандидат технічних наук, доцент
Киргизький національний аграрний університет ім. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-9599-2839

Порівняльний аналіз ефективності використання гідро-, вітряних і сонячних електростанцій у Киргизстані

Анотація. Проведення дослідження ефективності використання гідро-, вітряних і сонячних електростанцій у Киргизстані є важливим у контексті розвитку стійких джерел енергії для забезпечення енергетичної безпеки та зниження впливу на навколишнє середовище. Це дослідження спрямоване на виявлення найбільш перспективних джерел відновлюваної енергії, здатних забезпечити сталий розвиток енергетичного сектора. Дослідження являє собою порівняльний аналіз трьох основних джерел відновлюваної енергії – гідро-, вітряних і сонячних електростанцій – у контексті їх використання в Киргизстані. У рамках дослідження розглядаються різні аспекти ефективності кожного типу станцій, включно з доступністю ресурсів, економічною та екологічною ефективністю, а також технічною надійністю. Обговорюються переваги та обмеження кожного джерела енергії в контексті киргизької економіки та кліматичних умов. Зокрема, акцент робиться на багатому потенціалі водних, вітрових і сонячних ресурсів у країні, що відкриває перспективи для розвитку відновлюваної енергетики. Також досліджуються питання впливу кожного типу енергостанцій на навколишнє середовище, включно з екологічними наслідками та можливими ризиками для місцевої фауни і флори. Результати дослідження підкреслюють необхідність комплексного використання різних типів електростанцій для забезпечення енергетичної безпеки та стійкості в Киргизстані, з огляду на їхні сукупні переваги та обмеження. Насамкінець, робиться висновок про те, що оптимальним підходом до забезпечення енергетичної безпеки та стійкості в Киргизстані може стати комплексне використання всіх трьох типів електростанцій, з огляду на їхні сукупні переваги та обмеження. Результати дослідження можуть бути використані під час розроблення стратегії енергетичного розвитку Киргизстану з урахуванням оптимального поєднання гідро-, вітро- та сонячної енергії для забезпечення сталого та екологічно безпечного енергетичного комплексу країни

Ключові слова: стійкі джерела енергії; екологічна ефективність; відновлювальна енергія; енергетична безпека; технічна надійність; стійкі джерела енергії; відновлювальна енергія