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

Maksat Sadykov*
PhD in Physical and Mathematical Sciences, Professor
International University of Innovation Technologies
720020, 1/17 Ankara Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-6008-9551

Zhanarbek Osmonov
Postgraduate Student
Kyrgyz National Agrarian University named after K.I. Skryabin
720064, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-9304-9844

Ysman Osmonov
Doctor of Technical Sciences, Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720064, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-6569-7684

Urmat Karasartov
PhD in Technical Sciences, Senior Lecturer
Kyrgyz National Agrarian University named after K.I. Skryabin
720064, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-5753-4308

Renewable energy sources in Kyrgyzstan and energy supply to rural consumers

Abstract. The study assesses the potential of renewable energy sources in Kyrgyzstan and explores their application to provide energy to rural consumers. This study used an approximation of the parabolic function of solar radiation change, statistical processing of data on the average annual water flow of small rivers, as well as calculation of the volume of manure produced and its processing into biogas and bio fertilisers to assess their potential in agriculture and environmental impact. Kyrgyzstan, located between 40 and 68° north latitude, has evenly distributed solar radiation, small rivers and biomass, which have significant renewable resources. The distribution of solar radiation on the territory corresponds to the normal law of the monthly average mathematical expectation of 175.79 kWh/(m^2*month) and a standard deviation of 92.44 kWh/(m^2*month). On average, each square metre of a solar power plant can produce 0.451 kWh of energy. The intervals of average water discharge between the small rivers of Kyrgyzstan follow a power law distribution with a mathematical expectation of 3.112 m^3/s and a standard deviation of 2.46 m^3/s.

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*Corresponding author

With a natural water flow rate of 0.652 m^3/s, a low-pressure micro-hydroelectric power plant (with a water head of 1 to 2 m) can generate up to 8.95 kW of power. The total consumption of biogas by an average farm in Kyrgyzstan and its consumption for heating raw materials in a bioreactor during the cold season ranges from 16.34 to 18.93 kg/hour. This demand for biogas is met by producing domestic feedstock (animal manure) using compact biogas plants with reactors of up to 20 m^3. These facts indicate that the use of the above-mentioned renewable energy sources in Kyrgyzstan can provide autonomous power supply to remote rural consumers and contribute to solving existing environmental problems, as well as energy-saving

Keywords: solar energy sources; solar collectors; watercourses; micro-hydroelectric power plants; biological resources

INTRODUCTION

The use of renewable energy sources not only meets humanity's energy needs but also serves as a means of combating global greenhouse gas pollution. The continued development of renewable energy sources through the creation of new energy storage technologies will lead to a reduction in the role of traditional centralised energy systems. The practice of autonomous power supply increases its reliability and stimulates the revision of the "base load" concept in favour of the "distribution load" concept. This trend is more efficient in meeting energy supply needs, especially in rural areas, given their remoteness from centralised power transmission networks. The intensive development of agriculture, as well as other sectors of the economy, leads to a significant increase in energy consumption. The demand for electricity, heat and cold for production and domestic needs of rural producers is constantly growing. Solutions should be found for the disposal of large volumes of agricultural waste, especially manure. It is necessary to address the issue of autonomous power supply to rural producers, as it is unprofitable to lay centralised power lines to remote areas with low power consumption.

Kyrgyzstan has significant solar energy resources that can be used to generate electricity using solar panels and collectors. At the same time, the country has an abundance of water resources, including rivers and streams, which can be used to generate energy through small hydroelectric power plants. In addition, Kyrgyzstan has significant biomass reserves, such as animal manure and vegetable waste, which can be used for biogas and biodiesel production. These resources are distributed evenly throughout the country and can be easily developed for energy production (Shakulikova & Akhmetov, 2021). The problem of lack of affordable energy consumption in rural areas of Kyrgyzstan is relevant due to the instability of the centralised energy supply and limited access to energy for agricultural needs. P. Florio *et al.* (2021) investigated the potential of solar energy and proposed a methodology for assessing solar potential using geographic information systems. T.S. Kishore *et al.* (2021) analysed the use of small hydropower plants in rural areas and assessed their impact on energy supply. C. Bumharter *et al.* (2023) considered the potential of biomass and conducted a study on the development of technologies for processing manure into biogas. J. Zhao *et al.* (2022) analysed the economic efficiency of using renewable energy sources in rural areas. M.M. Kamal *et al.* (2022) studied the impact of wind energy on rural energy supply and proposed strategies for its use.

Y. Majeed *et al.* (2023) analysed solar and wind energy as alternative sources for sustainable agricultural development. K.K. Jaiswal *et al.* (2022) explored the environmental and social aspects of renewable energy in rural areas. K. Mehta *et al.* (2021) analysed the energy needs of Kyrgyz agriculture and proposed strategies to optimise the use of renewable energy sources. G. Li *et al.* (2022) studied the possibility of using solar collectors for heat supply. Erdiwansyah *et al.* (2021) proposed a model for the integration of various renewable energy sources to ensure a reliable and sustainable energy supply in rural areas of Kyrgyzstan. Additional research is needed on the social and economic sustainability of renewable energy projects in rural areas, as well as an analysis of technological solutions and infrastructure needs for the successful integration of renewable energy into Kyrgyz agriculture.

The study aims to assess the potential of renewable energy sources in Kyrgyzstan and to investigate their application in providing energy supply to rural consumers. Research goals:

1. Identify the main obstacles to the introduction of renewable energy sources in rural areas of Kyrgyzstan.

2. Employ formulas, reactions and expressions to accurately determine the adsorption and chemical bonding parameters of sulphur-containing gases in the mine atmosphere.

3. Confirm the effectiveness of the proposed methods and improve safety and environmental cleanliness in mines based on the results of measurements and observations in the field, as well as analysis of the use of various technologies.

MATERIALS AND METHODS

Kyrgyzstan, located between 40 and 68° N latitude, has domestic solar energy resources, which were estimated based on data from the Ministry of Energy and Industry of the Kyrgyz Republic (2022). The graphical representation of the dependence of solar radiation (P_c) on geographical latitude (T) over the course of a year forms a parabolic function (Fig. 1).

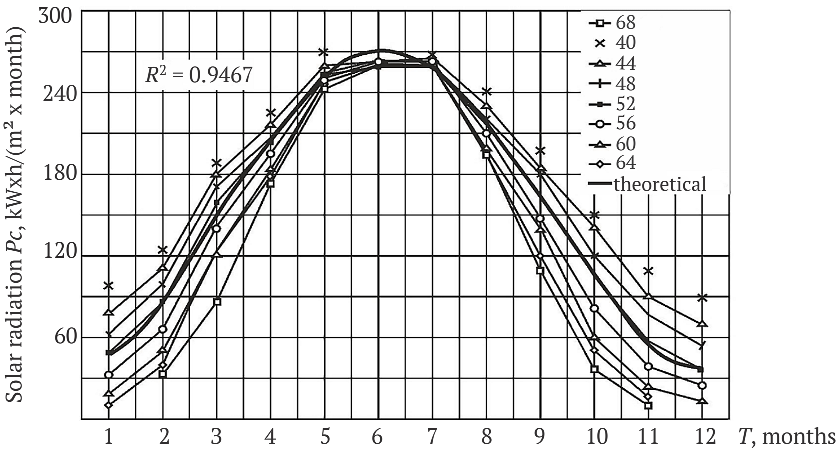

Figure 1. The variation of solar radiation (P_c)
with geographical latitude (deg N) during the year(T) is represented by the function P_c=f(T)
Source: compiled by the authors based on the Ministry of Energy and Industry of the Kyrgyz Republic (2022)

This function corresponds to a normal distribution law, which means that the distribution of solar radiation in Kyrgyzstan is described as follows (1):

$$f(P_c) = \frac{1}{92.44\sqrt{2\pi}} \exp\left[\frac{(P_C-175.79)^2}{2(92.44)^2}\right]. \quad (1)$$

With an average value of 175.79 kW∗h (m²∗month) and standard deviation σ = 92.44 kW∗h/(m²∗month). Using the Lagrange formula (Pasetto *et al*., 2021), the parabolic function P_c = f(T) was approximated, after which an empirical equation was chosen to describe the distribution of solar radiation in Kyrgyzstan during the year (2):

$$P_c = -9.26T^2 + 115.27 * T - 90.68. \quad (2)$$

Table 1 shows the calculations of solar radiation P_c by month throughout the year.

Table 1. Data on the estimated solar radiation P_c are presented by month of the year

Solar radiation	Months of the year											
	1	2	3	4	5	6	7	8	9	10	11	12
P_c,*kWh/(m²*month)	15.3	109	171.8	222.2	254.1	268.6	262.5	238.8	196.7	136	56.8	39.9
P'_c,*kWh/m²	0.042	0.302	0.417	0.617	0.705	0.743	0.729	0.663	0.546	0.378	0.158	0.11

Source: compiled by the authors based on Erdiwansyah *et al.* (2021)

The highest amount of solar radiation is observed during the months of May, June and July, it varies from 254.1 to 268.6 kW∗h/(m²∗month) or from 0.705 to 0.743 kW∗h/m². From January to April, solar radiation gradually increases (from 0.042 to 0.617 kW∗h/m²), while from August to December it decreases (from 0.663 to 0.11 kW∗h/m²). The average value of solar radiation during the year is 0.451 kW∗h/m², which means that each square metre of solar power plant is capable of generating 0.451 kW∗h of energy. The grazing season in Kyrgyzstan is in May-July, when the highest amount of solar radiation is observed, making the use of solar power plants during this period the most efficient. In addition, autonomous power supply is justified in pastureland conditions due to the remoteness of consumers from centralised power grids, which are inefficient. The main characteristics of water discharge in small rivers of Kyrgyzstan were studied based on the analysis of annual averages and coefficients of variability. It was found that four of these rivers have an average flow of more than 10 m³/s with coefficients of variability ranging from 0.12 to 0.15, while six rivers have an average flow of more than 4 m³/s with coefficients of variability ranging from 0.14 to 0.18 (World Bank, 2024). Sixteen rivers have an average water discharge of more than 2 m³/s with coefficients of variability ranging from 0.11 to 0.14, while the majority, namely 23 rivers, have an average water discharge of less than 2 m³/s with coefficients of variability of up to 0.3. There is a tendency for the coefficient of variability and its range to increase with a decrease in water flow in small rivers.

The analysis of statistical data on the average annual water discharge in 49 small rivers of Kyrgyzstan, ranging from 0.11 to 12.4 m³/s, was used to identify the regularities of this indicator's distribution in these rivers and present them in the form of a typical distribution curve, as shown in Figure 2.

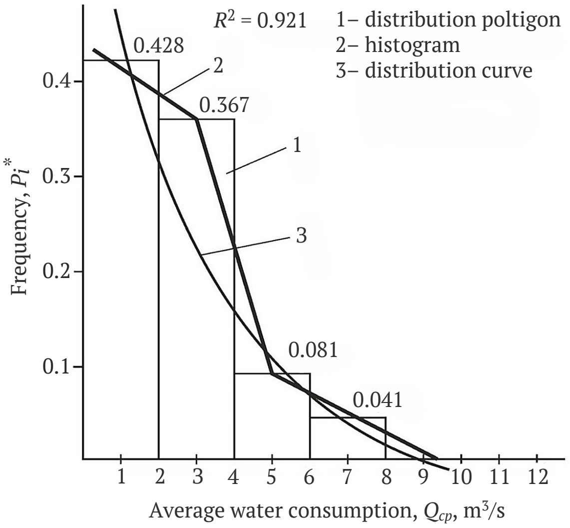

Figure 2. Graph illustrating the distribution of average annual water discharge in small rivers of Kyrgyzstan (49 rivers in total)
Source: compiled by the authors based on the Ministry of Energy and Industry of the Kyrgyz Republic (2022)

The distribution of intervals of average water discharge between small rivers in Kyrgyzstan corresponds to the exponential law (3):

$$f(Q_{av}) = 0.6388 * e^{-0.266*Qav}. \quad (3)$$

The average value is 3.112 m^3/s, and the standard deviation is 2.46 m^3/s. Kyrgyzstan's small rivers with an average water discharge (Q_{av} = 3.112 ± 2.46 m^3/s) are evenly distributed throughout the country, especially on pastures.

The estimated volume of manure produced by all types of farm animals in Kyrgyzstan per year reaches approximately 5.6 million tonnes (Ministry of Water Resources, Agriculture and Processing Industry of the Kyrgyz Republic, 2021). By processing it using biogas technology, it is possible to produce about 110 million m^3 of biogas and 5.5 million tonnes of biological fertiliser. This data was used to provide rural producers with 30% more biogas and fertilise 1300 thousand ha of arable land, which will increase crop yields by 15-20%. In addition, this approach will prevent the emission of about 214 million m^3 of greenhouse gases, including methane and carbon dioxide.

RESULTS

The supply of energy to rural consumers is a significant challenge in many countries, including Kyrgyzstan, due to the remoteness of some rural areas and the lack of infrastructure. In such circumstances, ensuring continuous and stable access to energy can be a challenge. However, renewable energy sources (RES) offer unique opportunities to address this problem. Renewable energy sources such as solar, wind and hydropower have the potential to become a key component of rural energy infrastructure. One of the main reasons for this is the fact that many rural areas have large open spaces and access to natural resources, which are essential for the deployment of renewable energy. For example, solar panels can be installed on rooftops or in open fields, converting sunlight into electrical energy (Asrami *et al.*, 2021). Wind turbines can be located on hills or high ground, harnessing the power of the wind to generate electricity. Hydropower can be generated through the construction of small hydropower plants on streams or small rivers.

One of the main advantages of renewables for rural areas is their potential to provide a decentralised energy supply. This means that rural communities can become more energy-independent, without relying solely on centralised energy transmission systems from remote sources (Streimikiene *et al.*, 2021). Decentralisation ensures access to energy for rural consumers even in the event of problems with the centralised power grid. However, despite all the advantages, the use of renewable energy for rural energy supply can also face some challenges. For example, investments in renewable energy infrastructure and technologies can be expensive and require significant upfront capital. In addition, environmental aspects, such as the impact on the local ecosystem when building hydroelectric power plants or wind turbines, must be considered. Overall, despite the challenges, renewable energy sources represent a promising solution for ensuring sustainable and affordable energy supply in rural areas. Modern technologies and development strategies can help to maximise the use of renewable energy potential, which will lead to improved quality of life and economic development of rural communities in Kyrgyzstan.

Kyrgyzstan, located in the centre of Central Asia, is a unique combination of mountain ranges, valleys and river systems. This landscape creates favourable conditions for the development of hydropower, especially when using the resources of small rivers. With the focus on environmental sustainability and energy security, the construction of small hydropower plants (SHPPs) on these rivers is becoming an important aspect of the country's energy sector development. It is necessary to address the richness of the mountain rivers that permeate the territory of Kyrgyzstan. These rivers offer enormous potential for power generation. Due to their small scale and relative accessibility, small river resources are a reliable source of energy that can supply both urban and rural areas. There are many advantages to building a hydropower plant (Ahmed *et al.*, 2022). They usually have a low cost compared to large hydropower plants, which makes them economically viable and affordable. In addition, SHPPs have a small ecological footprint and low heat losses, making them more environmentally friendly and sustainable than traditional energy sources. An important advantage of SHPPs is their flexibility and scalability. They can be easily integrated into existing infrastructure and used for local service, which is especially important for remote and rural areas. This helps to develop the social and economic potential of these areas and improve the quality of life of their residents. However, there are some limitations to the use of small hydropower plants. For example, there may be issues related to environmental change and the impact on the biodiversity of river ecosystems. These issues require serious analysis and planning to minimise negative consequences. In conclusion, small river resources represent a valuable source of energy for Kyrgyzstan. Harnessing this potential, combined with modern technologies and sustainable practices, can contribute to the country's development, ensuring a stable and environmentally friendly energy future for all its citizens.

Kyrgyzstan, with its vast natural resources, such as mountain ranges and abundant sunshine, has significant opportunities for solar energy development. In the southern regions of the country, where the intensity of solar radiation is higher, solar energy can become an important source of electricity for both urban and rural consumers. It is worth noting the huge potential of solar energy in Kyrgyzstan. The average duration of sunshine in the country is more than 2200 hours per year, making it one of the sunniest countries in the region (Karatayev *et al.*, 2022). This potential can be used to install solar panels on the roofs of buildings, as well as in specially designated areas, which will allow efficient collection and conversion of solar energy into electricity. The development of solar energy has several advantages. One of the key advantages is the ability to diversify energy sources. At a time when many countries are facing energy challenges due to their reliance on traditional sources such as coal or gas, solar energy can be a sustainable source that helps reduce this dependence. It is also worth noting the environmental component of solar energy. Unlike traditional energy sources, such as coal or oil, solar energy production does not result in greenhouse gas emissions or pollution (Kaewpraek *et al.*, 2021). This reduces the negative impact on the climate and preserves natural resources for future generations. The introduction of solar energy can contribute to the social and economic development of a country. The creation of jobs in the design, manufacture and installation of solar systems, as well as the development of local markets and services, will help improve the lives of local people and contribute to the development of rural areas. In conclusion, solar energy represents a promising source of energy for Kyrgyzstan. Maximising this potential will allow the country to reduce its dependence on traditional energy sources, reduce the negative impact on the environment and contribute to the sustainable development of the national energy sector.

In today's world, when the problems of energy security and climate change are becoming increasingly relevant, the development of renewable energy sources is becoming a priority for many countries, including Kyrgyzstan. One of these potential sources is biomass, including manure, which can be effectively used to produce biogas or biodiesel, which are important alternative energy sources (Zhu *et al.*, 2021). Rural areas of Kyrgyzstan have significant manure reserves due to the presence of substantial livestock counts. This opens prospects for the use of biomass for energy purposes. The process of converting manure into biogas or biodiesel not only enables the disposal of livestock waste but also the production of a valuable energy resource that can be used to generate electricity. The use of biomass in the energy sector has significant environmental benefits. Unlike traditional energy sources such as coal or oil, the production of biogas or biodiesel from manure not only does not generate additional greenhouse gas emissions but also helps to reduce the total amount of carbon emissions into the atmosphere. This reduces the negative impact on the environment and mitigates the effects of climate change.

An important advantage of using biomass in the energy sector is its social significance, especially for rural areas. In these areas, access to traditional energy sources is often limited, leading to inequalities in energy access. The use of biomass mitigates this inequality by providing local people with access to clean and affordable energy, which contributes to their social and economic development. In conclusion, the use of biomass, including manure, in Kyrgyzstan's energy sector is an important step towards sustainable development and energy security. This approach not only contributes to reducing greenhouse gas emissions and protecting the environment but also provides social and economic benefits to rural areas by improving their living standards and providing access to energy.

An experiment was carried out with a single-circuit solar water heater equipped with a thermosyphon. The inner diameters of the tube and cover are 47 and 58 mm, respectively, and the length is 1.8 metres. The water tank has a capacity of 140 litres. The angle of the south-facing solar collector is 30° from the horizon. Geographic coordinates of the location: 77°E, 42°N. The study aimed to estimate heat losses from the solar collector to the environment during the heating period (air temperature range +12...-12°C), to determine the efficiency and thermal power of the solar collector. At the beginning of the heating season, at an ambient temperature of 12°C, the heat loss coefficient is estimated at U_L = 7.77W/m²*h, and a temperature of -12°C, this coefficient increases and amounts to U_L=12.67W/m²*h (Fig. 3).

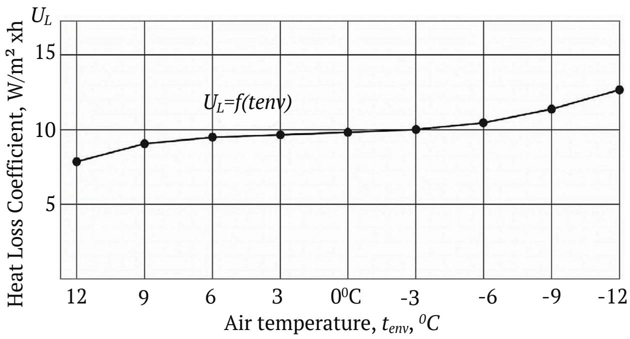

Figure 3. Graph of heat loss coefficient versus ambient temperature

Source: compiled by the authors based on Erdiwansyah *et al.* (2021).

The result of the product of the total heat loss coefficient (U_L) and the absorber panel efficiency (F') of the solar collector (U_L*F') is within the permissible range: from

4.9 to 10.1 W/(m²∗C°), which is in line with standard data (Grob *et al.*, 2021). According to Figure 4, the average daily efficiency of the solar collector is $\eta_{days} = 0.36$, and its thermal output is equal to $P_{ex} = 0.26$ kWh.

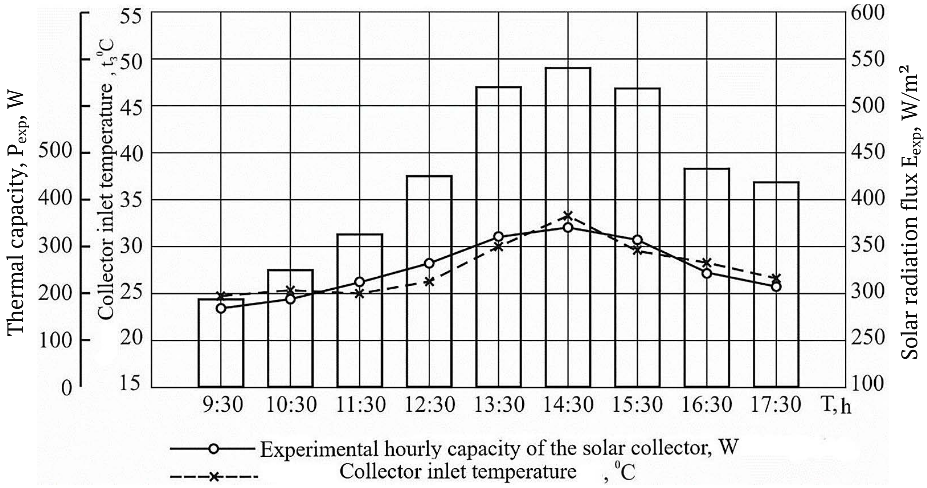

Figure 4. Graphs of the dependence of the water inlet temperature [$t_3 = f(T)$], solar radiation flux [$E_{exp} = f(T)$] and heat output [$P_{exp} = f(T)$] on the heating time of the heat carrier T

Source: compiled by the authors

The following theoretical framework was used in the course of experiments and calculations (4):

$$F' * U_L = \frac{G * C(t_{out} - t_{in})}{A(\bar{t}_{ex} - t_{env})}, \tag{4}$$

where: F' and U_L – the coefficients of absorption panel efficiency and heat loss, respectively; G – the water flow rate through the solar collector, expressed in kilograms per hour; C – the heat capacity of water, measured in watt-hours per kilogram °C; t_{out} and t_{in} – the temperatures of the water at the outlet and inlet of the solar collector, respectively; A – the area of the heat-accepting surface, expressed in square metres; the average liquid temperature is defined as the half-sum of the water temperatures at the inlet and outlet of the solar collector, measured in degrees Celsius; t_{env} – the ambient temperature, expressed in °C (5):

$$Q_s = F_R * S_{sc}[E(\tau\alpha)_e - U_L(t_{in} - t_{env})], \tag{5}$$

where: Q_s – the amount of useful energy per hour measured in kilowatt-hours (kWh); $S_{sc}[E(\tau\alpha)_e]$ – the amount of solar energy falling on the surface of the solar collector per hour, measured in kilowatt-hours (kWh);$S_{sc}[U_L(t_{in} - t_{env})]$ – the amount of energy that is lost to the environment per hour, measured in kilowatt-hours (kWh); F_R – heat transfer coefficient (FR); S_{sc} – solar collector area, measured in square metres (m²); E – solar radiation flux density on the surface of the solar collector, measured in kilowatt-hours per square metre (kWh/m²); $(\tau\alpha)_e$ – optical performance factor (OPF), showing the reduced absorption capacity of the solar collector.

$$F_R = \frac{G * C}{U_L}\left[1 - \exp\left(\frac{U_L * F *}{G * C_p}\right)\right], \tag{6}$$

where: C^P – the specific heat capacity of the pipe material in kilojoules per kilogram of degree Celsius; F^* – the solar collector area utilisation factor, which is defined as the product of 0.98 and the solar collector area (F^*=0.98∗Sgk) (Uçkan & Yousif, 2020).

$$\eta_{days} = \frac{\sum Q_s}{E_{ex} * S_{sc}}, \tag{7}$$

where: η_{days} – average daily efficiency of the solar collector, reflecting the average efficiency of the solar collector during the day; $\sum Q_s$ – total amount of useful energy received in the solar collector per day, measured in kilowatt-hours (kWh); E_{ex} – solar radiation flux density on the surface of the solar collector during its operation, measured in kilowatt-hours per square metre (kWh/m²).

$$P_{ex} = E_{ex} * S_{sc} * \eta_{days}, \tag{8}$$

where: η_{days} – the thermal capacity of the solar collector, measured in kilowatt-hours (kWh). During the tests of the low-pressure micro-hydroelectric power plant, the generated electric power was recorded: for average water consumption (Q_{av} = 3.122 m³/s); P = Q_{av}∗H∗g∗η = = 3112(1…2)∗9.81∗0.7 = 21.4…42.8 kW; for minimum water consumption (Q_{av} = 3.112 - 2.46 = 0.652 m³/s); P = 4.48…8.95 kW. During the tests, the study noted that water pressure fluctuations amounted to 1…2 metres. With minimal water consumption, the low-pressure micro-hydroelectric power plant can produce sufficient electrical power to meet the needs of the farm in pasture conditions for both production and domestic purposes.

The micro-hydroelectric power plant uses a double Blankey turbine (Nasir, 2021). The load is regulated by connecting the generator output to the "Power voltage inverter". The average total consumption of biogas and its consumption for heating raw materials in a bioreactor for the auxiliary needs of an average farm at low air temperature ranges from 16.34 to 18.93 kilograms per hour. The distribution of biogas consumption by consumer category is shown in Table 2.

Table 2. Consumption of biogas by the farm and its use for own needs (in particular, for heating biomass in the reactor)

Consumers of biogas	Biogas demand per day, m^3	Hourly biogas consumption kg/h
1	2	3
Gas cooker three meals a day for a family of 8	5.2...6.24	1.134...1.36
Heating devices at home (total living area of the farmer's house 148 m^2)	22.2...29.6 (t_{env}...-10°C) 31.0...34.04 (t_{env}=-11...-15°C) 36.0...38.48 t_{env}=>-16°C)	11.716...14.081
Heating devices for cow barn heating	23.04	1.92*1.2=2.304
Bioreactor heating device (bioreactor volume 17.93 m^3)	8.08	0.985*1.2=1.182

Source: compiled by the authors

The introduction and development of renewable energy sources in Kyrgyzstan have the potential not only to provide energy to rural areas but also to significantly change the country's energy landscape, leading to a reduction in dependence on traditional energy sources such as coal and oil. This has several advantages and benefits from both an environmental and socio-economic perspective, contributing to sustainable development. The development of renewable energy sources, such as hydropower, solar and wind energy, and biomass, has the potential to significantly reduce Kyrgyzstan's dependence on imported conventional energy sources. This reduction in dependence on volatile coal and oil markets helps to ensure the country's energy security, reducing economic risks and increasing its self-sufficiency. The development of RES contributes to the improvement of the environmental situation in the country (Shahbaz *et al.*, 2021).

Traditional energy sources, such as coal and oil, are often associated with air and soil pollution, greenhouse gas emissions and ecosystem destruction. In contrast, renewable energy sources are clean sources of energy that do not cause significant environmental damage. This reduces the negative impact on the climate and natural resources, which is a key aspect of sustainable development. An important advantage of renewable energy development is its social benefits. The introduction of renewable energy sources helps to create new jobs in the design, manufacture, installation and maintenance of renewable energy equipment. This helps to develop local economies and support entrepreneurship, especially in rural areas, which often experience high unemployment and economic underdevelopment (Riva *et al.*, 2022).

In conclusion, the development of renewable energy sources in Kyrgyzstan has great potential to improve the energy, environmental and social situation in the country. This contributes to sustainable development, enhancing international competitiveness and improving the quality of life of citizens. The introduction of these technologies should be a priority for the Kyrgyz government and encourage investment in this promising area.

DISCUSSION

Kyrgyzstan has significant natural resources, such as solar energy and hydropower potential, and is uniquely positioned to become an important player in the renewable energy market. The use of renewable energy sources to power rural Kyrgyzstan is a significant strategy with several potential benefits and challenges. This was also investigated by Erdiwansyah *et al.* (2021), where the results confirmed that a comprehensive study of renewable energy sources is key to developing effective energy strategies. This includes not only analysing the technical aspects and potential of different types of renewable energy, such as solar, wind and hydro but also considering the socio-economic and environmental factors that influence their deployment and use. Classification of different RES sources and identification of their main characteristics provide a better understanding of which energy sources can be most efficient in the specific conditions of a country or region. T.Z. Ang *et al.* (2022) also determined that one of the main challenges faced by researchers and practitioners in the field of RES is the need to develop integrated approaches to their implementation. This includes not only the development of new technologies and improvement of existing ones, but also the creation of appropriate infrastructure, development of legislation and regulations, and public education campaigns. In addition, it is important to address the potential social and economic impacts of renewable energy to minimise the negative aspects and maximise the positive. It is worth noting that to overcome these problems and effectively develop the renewable energy sector, it is important to propose a comprehensive approach, including measures to stimulate investment in renewable energy, develop innovative technologies, improve energy education and training, and create a favourable legislative and regulatory environment (Bacherikov *et al.*, 2024). This is the only way to ensure a sustainable and environmentally friendly energy supply for future generations.

It should be noted that Kyrgyzstan has a huge potential for the use of renewable energy. Located in a mountainous area with abundant sunlight and wind, the country has favourable natural conditions for the deployment of solar and wind power plants. In addition, the presence of rivers and streams provides the potential for the construction of small hydropower plants, which complements the energy mix. Many researchers, including J.N. Meier *et al.* (2023), addressed this aspect. The deployment of solar and wind power plants is an important aspect of the transition to sustainable and environmentally friendly energy. Solar power plants use solar panels to convert sunlight into electrical energy. They can be placed on the roofs of buildings, in open fields, and on special plots intended for solar farms. The development of solar energy helps to diversify the energy mix, reduce carbon emissions and create new jobs (Shram & Kachan, 2023). Wind power plants use wind energy to generate electricity. They are usually installed on open plains or on the shores of seas and oceans where winds are strong and stable. The development of wind power can reduce domestic dependence on traditional energy sources such as coal and oil and reduce our negative impact on the environment. A study conducted by M.R. Elkadeem *et al.* (2022) highlights the importance of deploying solar and wind power plants as a key step towards sustainable development and reducing environmental pollution. Accelerated technology development, as well as support from governments and investors, can help accelerate this process and achieve a cleaner and more efficient energy future. These results confirm the above study, as they demonstrate that the deployment of solar and wind power plants has the potential to be a key solution to addressing climate change and reducing dependence on fossil fuel-based energy sources. Efforts to develop such technologies can lead to improved air quality, reduced greenhouse gas emissions and contribute to a more sustainable energy system.

One of the main advantages of using renewable energy in rural areas is the possibility of providing a decentralised energy supply. Instead of relying on centralised transmission networks to transmit energy from distant sources, rural communities can be more independent by being able to produce personal energy on-site (Ismayilov *et al.*, 2019). This is especially important in remote areas where the construction and maintenance of centralised energy systems may be too expensive and impractical. B. Zakeri *et al.* (2021) addressed this phenomenon, noting that rural communities can become more energy-independent without relying solely on centralised transmission systems from distant sources. Decentralised energy supply improves rural area flexibility and adaptability to different conditions, including changes in energy consumption or failures in centralised networks. A study by Y.H. Ha & S.S. Kumar (2021) confirms that the use of decentralised energy supply using renewable energy sources contributes to improving energy security in rural areas. They can avoid the risks associated with interruptions in energy supply due to technical failures or lack of fuel for traditional energy systems. This is especially true in remote rural areas, where restoration of power supply after disasters can take considerable time due to difficult access and limited resources (Yaremova *et al.*, 2024). Thus, decentralised energy supply using renewable energy sources can increase the sustainability and reliability of the energy system in rural areas, which will lead to an improvement in the quality of life and economic development of these areas. Comparing the data obtained during the research, it is possible to note that decentralised energy supply based on renewable energy sources not only increases the sustainability of rural energy systems but also helps to reduce dependence on traditional energy sources such as coal or oil. This ensures a reliable energy supply that is not subject to fluctuations in fuel prices or the risk of interruptions in supply due to technical failures for rural communities.

However, there are also some challenges in using renewable energy to supply rural consumers in Kyrgyzstan. One of them is affordability. Investments in renewable energy infrastructure and technologies can be costly and may not be affordable for some rural communities without support from the state or international organisations (Matiichuk, 2022). L. Li & S. Zhang (2021) concluded that one of the main challenges in the use of renewable energy is instability and uncertainty. Wind and solar resources fluctuate depending on the time of day, weather conditions and seasons, which can lead to uneven energy production. This requires the development of efficient energy storage systems or alternative energy sources to compensate for the volatility. In addition, a study by Q. Yang *et al.* (2021) determined that the cost of renewable energy technologies is decreasing, but there is still a need for significant investment, especially in developing countries. This may be an obstacle to large-scale deployment of renewable energy without additional support and incentives from the government or international organisations. The study results analysis determined that, despite the challenges, the use of renewable energy represents an important step towards a sustainable and environmentally friendly energy future. Addressing these challenges requires a comprehensive approach and cooperation between government agencies, the private sector and the public.

In conclusion, the use of renewable energy sources to supply rural Kyrgyzstan is a promising solution with several potential benefits. However, for the successful implementation of this strategy, financial, socio-cultural and technical aspects need to be addressed, as well as support from the government and international partners. Lastly, the development of renewable energy in rural areas can contribute to sustainable development, reduce inequality and improve the quality of life of the rural population in Kyrgyzstan.

CONCLUSIONS

The analysis of solar energy resources and small rivers in Kyrgyzstan using mathematical statistics methods has provided valuable data. The distribution of solar radiation and water discharge in small rivers in Kyrgyzstan is characterised by significant fluctuations in both space and time. This highlights the need for flexibility and adaptation in the development and use of systems based on these resources.

The study showed that solar power installations have the potential to generate significant amounts of energy, although there is some room for improvement. This confirms the importance of further research and development in this area. The assessment of the potential of small rivers for power generation also demonstrates their significant potential. However, to optimally utilise this potential, efficient and environmentally sustainable small hydropower technologies need to be developed and implemented.

Finally, the results of the study highlight the importance of biogas technologies for agriculture. They can provide not only energy for domestic needs but also serve as an important source of heat for various agricultural processes. However, there are challenges, such as the affordability of technologies and infrastructure, as well as the instability of energy supplies due to fluctuations in renewable resources. In general, the results obtained indicate the wide potential of renewable energy and biogas technologies for the development of sustainable and environmentally friendly energy in Kyrgyzstan. However, to maximise their use, it is necessary to address the specifics and limitations of each resource, as well as to conduct further research and development in this area.

One of the limitations of this study is the limited amount of data on the actual use and efficiency of renewable energy technologies and biogas systems in rural Kyrgyzstan. The economic feasibility and potential social and environmental impacts of introducing renewable energy technologies and biogas systems in rural Kyrgyzstan need to be further studied.

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CONFLICT OF INTEREST

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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 Садиков*

Кандидат фізико-математичних наук, професор
Міжнародний університет інноваційних технологій
720020, вул. Анкара, 1/17, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-6008-9551

Жанарбек Осмонов

Аспірант
Киргизький національний аграрний університет імені К.І. Скрябіна
720064, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-9304-9844

Ісман Осмонов

Доктор технічних наук, професор
Киргизький національний аграрний університет імені К.І. Скрябіна
720064, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-6569-7684

Урмат Карасартов

Кандидат технічних наук, старший викладач
Киргизький національний аграрний університет імені К.І. Скрябіна
720064, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-5753-4308

Відновлювані джерела енергії Киргизстану та енергопостачання сільських споживачів

Анотація. Це дослідження оцінює потенціал відновлюваних джерел енергії в Киргизстані та досліджує їх застосування для забезпечення енергопостачання сільських споживачів. Для цього дослідження використовувалися апроксимація параболічної функції зміни сонячної радіації, статистичне опрацювання даних про середньобагаторічні витрати води малих річок, а також розрахунок обсягу гною, що виділяється, і його переробка на біогаз і біодобрива для оцінки їхнього потенціалу в сільському господарстві та впливу на екологію. У Киргизстані, розташованому між 40 і 68° північної широти, рівномірно розподілені сонячна радіація, малі річки та біомаса, що мають значні поновлювані ресурси. Розподіл сонячної радіації на території відповідає нормальному закону із середньомісячним математичним очікуванням 175,79 кВт*год/(м^2*місяць) і середньоквадратичним відхиленням 92,44 кВт*год/(м^2*місяць). У середньому, кожен квадратний метр геліоенергетичної установки здатний виробляти 0,451 кВт*год енергії. Інтервали середньої витрати води між малими річками Киргизстану відповідають показовому закону розподілу з математичним очікуванням 3,112 м^3/с і середньоквадратичним відхиленням 2,46 м^3/с. Під час природного зниження витрати води до 0,652 м^3/с, низьконапірна мікрогідроелектростанція (з напором води від 1 до 2 м) може генерувати енергію потужністю до 8,95 кВт. Загальне споживання біогазу середньостатистичним фермерським господарством у Киргизстані та його витрата для підігріву сировини в біореакторі в холодні періоди року коливається від 16,34 до 18,93 кг на годину. Цей попит на біогаз задовольняється за рахунок виробництва власної сировини (гною тварин) за допомогою компактних біогазових установок з реакторами об'ємом до 20 м^3. Ці факти свідчать про те, що використання вищезазначених поновлюваних джерел енергії в Киргизстані може забезпечити автономне енергопостачання віддалених сільських споживачів і сприяти розв'язанню наявних екологічних проблем, а також енергозбереженню

Ключові слова: джерела сонячної енергії; сонячні колектори; водотоки; мікрогідроелектростанції; біологічні ресурси