

Boosting of Dissipated Renewable Energy Systems Towards Sustainability in Kazakhstan

Guldana KHABDULLINA^{1*}, Dace PAULE², Ieva PAKERE³, Asset KHABDULLIN⁴,
Dagnija BLUMBERGA⁵

¹*Kostanay Regional University, Baytursynov Street 47, Kostanay, Kazakhstan*

^{2,3,5}*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, Latvia*

⁴*Seifullin Kazakh Agro-Technical Research University, Zhenis avenue, 62, Astana, Kazakhstan*

Received 19.08.2024; accepted 04.10.2024

Abstract – The study aims to develop a methodology for selecting and justifying a multi-energy hub based on renewable energy sources for agricultural complex. The methodology has an international dimension and was tested for the pilot case of the study in an agricultural site in Kazakhstan. The methodology consists of two parts. With the help of the *EnergyPro* software package, simulation of technical and economic analysis and optimization of energy hub operation for several different energy generation units was carried out. During the simulation, four different scenarios of an energy hub based on solar and wind energy, biomass and heat pump as well as coal-based fossil energy sources were considered. The second part of the methodology was based on the economic justification of climate-neutral technological solutions using multi-energy hubs in the agriculture sector. Climate neutrality diagram was created by use of GHG emission trading experience for a detailed technical and economic analysis and selection of the best renewable sources from various installation sites. Results show that the most promising and cost-effective option is the scenario with an integrated wind park, heat pump and biomass boiler.

Keywords – Agriculture decarbonisation; energy hub; renewable energy sources.

Nomenclature

CHP	Cogeneration	–
HP	Heat pump	–
GHG	Greenhouse gases	–
I	Specific investments	EUR/tCO ₂
K	Capital investments	EUR
MILP	Mixed Integer Linear Program	–
n	energy efficiency of energy production	–
R	Emission factor	tCO ₂ /MWh
RES	Renewable energy sources	–
TES	Thermal energy storage	–
Q	Energy demand	MWh/year

* Corresponding author.
E-mail address: guldana.abdukhalyykyzy@gmail.com

1. INTRODUCTION

Agriculture is a significant contributor to global carbon emissions, and decarbonizing the sector presents complex challenges. Each farming operation is unique, requiring tailored approaches that account for specific circumstances. To address this complexity, scenario-based modelling tools are often used to simulate potential solutions. Despite these variations, the overarching goal remains the same: to promote sustainability through the adoption of green technologies and more environmentally responsible farming practices [1]–[3]

One key knowledge gap in agriculture is the lack of comprehensive data on energy use, which is often fragmented. This highlights the need for standardized methods for data collection and analysis [4]. Energy security is another critical issue, influenced by both geopolitical and sustainability concerns [1]. It can be improved through on-site renewable energy generation, energy storage systems, and increased energy efficiency. Efforts should focus on reducing energy consumption in ways that are both reasonable and feasible [1], [5], [6]. Given that energy demand in agriculture is expected to rise with population growth, analysing current practices is essential to identify sustainable solutions [1].

Traditional energy sources are gradually losing their status for more efficient development of the world economy. Humanity is now paying attention to the development of renewable energy sources (RES) which do not pollute the environment with GHG emissions and allow the future use of limited fossil resources [5]. This is the main reason for the increase in investment and the use of RES [6]. Over the past ten years, the importance of renewable energy technologies as a replacement for environmentally harmful fossil fuel technologies in the decarbonization strategies of many countries has increased markedly [7]. For example, the European Union's aims in the decarbonization strategies of many countries have increased markedly [7]. The European Union aims to significantly increase its renewable electricity generation capacity, with a target of 45 % renewable electricity generation by 2030 [8]. Similarly, the United States has set a target of reaching 80 % of its electricity generation from RES by 2030 [9]. India aims to meet half of its energy needs from renewable energy sources by the same year [10]. In addition, China is discussing targets to increase the share of low-carbon energy in electricity generation to 40 % by 2030 [11]. Solar and wind energy can be produced alongside crops on the same land, creating a mutually beneficial situation. This approach not only generates electricity but also provides farmers with a stable, long-term income source. A study by the Department of Energy indicates that wind energy alone could create 80 000 jobs in the agricultural sector in the USA, contributing \$ 1.2 billion in income for farmers [12].

Kazakhstan is a resource-rich economy that is heavily dependent on its oil, gas, coal, and uranium, resources [13]. The economy of Kazakhstan is energy-intensive, which is due to both objective and subjective circumstances. At power plants, 65 % of equipment has been in operation for more than 20 years, and 31 % for more than 30 years. The depreciation of electric grid equipment is 60–80 % [14]. The current capacity RES in Kazakhstan is ~1.47 GW or 6.2 % of the total installed capacity.

Previous studies have shown that the renewable energy capacity installed now will fully cover the impending electricity shortage in the country [15]. These sources have huge potential, especially in the agricultural sector, where there is an urgent need for renewable energy because Kazakhstan is a major producer of livestock and grain. There are 76.5 million hectares of agricultural land in the country, of which 61 % are permanent pastures and 32 % are arable land. Wheat, the main agricultural crop of the country, is produced in the amount of 10–17 million tons per year. Barley, oats, corn, and rice are also grown. Improving

agricultural productivity, as well as the quality of the environment, is essential for long-term development [16].

However, the previous studies show that decarbonization of the agricultural sector at large is complex due to the individuality of each farming situation, which means that each case has to be considered on its own merits and scenarios must be simulated using modelling tools, but the idea remains the same: to promote sustainability through green technologies and a more environmentally responsible way of farming [1]–[3]. As one of the knowledge gaps, the lack of data on energy use in agriculture and its fragmentation is identified, which points to the need for standardised methods in both data collection and analysis [4]. Energy security is also a key issue in the agricultural sector, both from a geopolitical and a sustainability perspective [1]. It can be enhanced by various types of on-site renewable energy generation and energy storage systems, with an emphasis on energy efficiency, assessing energy consumption in terms of what is both reasonable and feasible to reduce [5]. As energy consumption in this sector is only expected to increase due to a growing population, it is important to analyse the current situation to find solutions to make it more sustainable [6].

In recent years, interest and discussions around combining renewable energy production with agricultural systems have also increased significantly. Studies are increasingly showing that certain designs, through for instance incorporating agrivoltaics or innovative bioenergy solutions in agricultural systems, can increase renewable energy use [4]. This can be implemented with low-carbon electricity, specifically for irrigation, for instance, all diesel pumps can be converted to electrical, as well as generally renewing and upgrading the technologies and equipment already in place although regional development and agricultural carbon emissions have a contradictory correlation [2], [18]. A case study for Canada, for instance, shows that over 84 % of total electricity demand can be met by agrivoltaics on agricultural land [19]. It was also concluded that this method could eliminate all fossil fuel electricity production in Canada, which indicates the major potential of this technology, provided that additional research and scenarios for specific regions and crops are carried out.

To improve the flexibility of energy supply with renewables, short-term or seasonal thermal storage solutions can be integrated. Also, electric batteries can be used to balance electric grids. Significant research was devoted to the use of thermal power plants and thermal energy storage in regional energy systems, the study of their impact on the functioning and integration of RES. Eid *et al.* [20] conducted an extensive analysis identifying 165 articles covering a wide range of topics related to energy storage, spanning applications from building systems to meeting peak energy load needs. Integration of storage units has made the energy generation systems more complex.

The wider need for power and heat sector coupling both in agriculture and other economies has led to the smart energy system concept, an energy system in which smart grid, heating, cooling and gas networks are combined and coordinated [21]. Smart energy systems aim to balance energy demand and production, increasing the efficiency of the network and reducing its carbon footprint. An energy hub that can be defined as the place where the production, conversion, storage and consumption of different energy carriers takes place, is a promising option for integrated management of multi-energy systems. It allows sectioning the complex energy system into manageable nodes and optimizing the energy system operation. Within the energy hubs, the demand can be covered by different energy carriers to reach the lowest operation costs and higher reliability. Optimal operation of energy hubs allows for improving network connectivity, increasing the sources of energy available at the time they manage demand flows along the areas of the appliance [22].

Previous research has utilized the energy hub approach to investigate the optimal charging and discharging of thermal storage in the presence of intermittent RES and variable electricity

prices within the multisource energy system [23]. The operation algorithms of multi-energy hubs are mainly driven by electricity prices and RES availability with less focus on other possible control algorithms, e.g. grid or heating network demand and supply conditions. Several authors have presented different programming models to analyse the potential flexibility of smart energy systems and energy hubs which allow to identification of optimal technological solutions [24]. These models allow the evaluation of different technology pathways, energy policies, and scenarios for a given region or country. However, previous research concludes that there are high levels of uncertainty in energy hub operation due to variable RES generations and end-users' energy demand schedules. Utilizing the benefits of smart grids and energy hubs requires an integrated modelling and management framework. Therefore, the main aim is to identify different technical solutions for agricultural energy hubs by considering renewable power generation and energy storage options.

The article is devoted to the analysis of the development of the agricultural and energy sector of Kazakhstan to deal with the dual situation. On the one hand, it is important to use local fossil resources for the development of the national economy, but on the other hand, to reduce the impact of global warming, the country's climate neutrality goals lead to the sustainable development of the industrial subsector of the agricultural sector.

2. METHODOLOGY

The methodology algorithm includes three large blocks, which are the main components of the energy hub evaluation model (see Fig. 1).

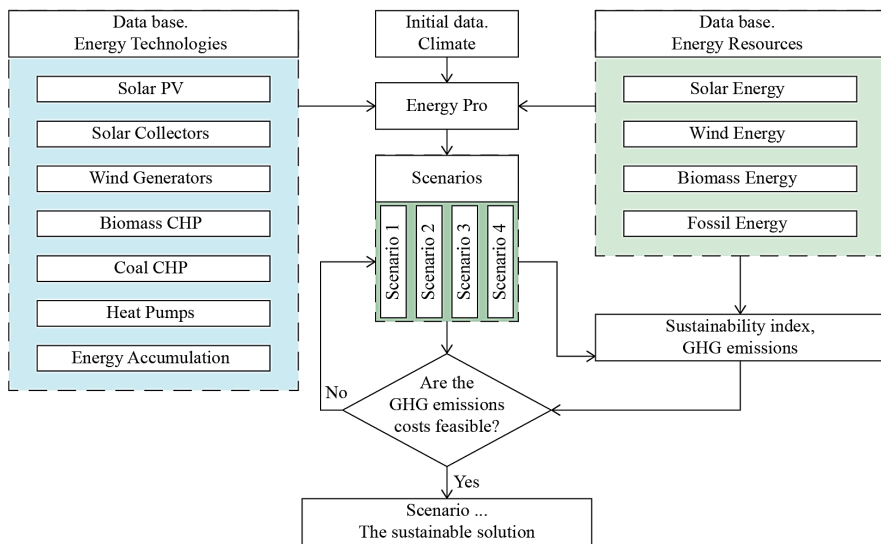


Fig. 1. Methodology framework and main steps.

The first block is the input data on the energy demand including heat and power consumption. Additionally, the information on available energy resources, technologies and limitations has been gathered. Further, the user of the model defines several energy-hub alternative scenarios by comparing available energy resources and technologies. Scenario 1 and Scenario 2 analyse different RES solutions for solar and wind integration with coal-

assisted boilers or cogeneration (CHP). Scenario 3 focuses on full decarbonization with biomass and wind energy production, but Scenario 4 is used as a Reference or Business-as-usual scenario with which the RES solutions are compared.

Further, the cost-optimal operation of each alternative by using *EnergyPro* software is identified. The most important parameter for comparing different alternatives is the emitted greenhouse gas (GHG) emissions which depend on the fossil fuel share in the energy hub. The best future development scenario for the analysed agriculture complex is found when the lowest GHG emissions are reached.

2.1. Case Study

The agricultural site in Kazakhstan has been used as a Case study. The Kazakh energy sector produced 340.8 million tons of CO₂ in 2021, of which 80 % came from the energy sector from heat and power production due to low efficiency, ageing and network assets. In this regard, the government signed a strategy for achieving carbon neutrality of the Republic of Kazakhstan until 2060 [17]. Kazakhstan has significant untapped opportunities for the growth and use of various RES, such as solar energy, wind energy, hydropower, and biomass. Therefore, the government expects the total share of renewable energy production to rise to 15 % of total energy supply and up to 50 % by 2050 [17].

Some support mechanisms have been already implemented. By the Law of the Republic of Kazakhstan supporting the use of RES, clean energy producers can sell generated electricity from renewable energy sources in the public network, at special tariffs through the Settlement and Financial Center for Support of Renewable Energy Sources, which guarantees the purchase of electrical energy from renewable energy sources [18].

The Kostanay region, the village of Stepnoye, was chosen as an ideal place for the implementation of renewable energy solutions. The village has 50 houses. The village's main energy consumer is the agriculture complex, which covers the cereal and livestock sectors (400 heads of horses, 957 heads of cattle, 356 heads of sheep). In this regard, the enterprise in Stepnoye uses effective cleaning equipment for grain harvested from the fields, the total capacity of which is 32 kW. The other main energy consumers are water preparation stations, boiler houses, machine stations and others resulting in a total electric capacity of 441 kW. Electricity consumption is 440 MWh/year. Agricultural equipment operates cyclically and depending on the harvest. The farm, grain threshing floor elevator, mill, machine and tractor station operate during the harvest season for about 2–3 months depending on the amount of harvest. Water intake and forage harvesting shops operate throughout the year. The consumption of thermal energy in the village as a whole, depending on the work premises and residential buildings during the heating season is 1172 MWh/year. Since the village of Stepnoye is a decentralized district, the main task is to compensate for the required capacity with renewable energy sources, while creating a micro-complex.

By 2030, the company's management plans to build a meat processing plant with a capacity of 10 tons per day, as well as construction of a dairy plant with a capacity of 30 tons per day. For the operation of the meat processing plant, it is planned to purchase refrigeration equipment, cutters, a thermal chamber, a meat grinder, a minced meat mixer, a syringe, and a clipper, which has a total capacity of 265 kW. Equipment operating time: refrigeration equipment and thermal chambers operate periodically; all other equipment operates intermittently. The total consumption of electricity is 460 MWh/year. The total heat consumption by the meat processing plant during the heating season is 964 MWh/year.

For the operation of the dairy plant, it is planned to purchase pasteurizers, microfuge, separator, separator for cheese, butter former, etc., for which the total capacity of the equipment is 135 kW. It is planned to accept 10 tons of milk per day (on average). The equipment will operate at intervals from 1 hour to 12 hours per day depending on its

operational function. The total electricity consumption will be 600 MWh/year. The total heat consumption of the dairy plant during the heating season is 1350 MWh/year.

As listed above, the enterprise will have several areas of development to improve the quality of life of the villagers of Stepnoye with the help of renewable energy sources. The total installation load of electricity is 1841 kW and for heat is 1500 kW. As shown in Table 1, the total electricity demand is 1500 MWh/year and for heat is 3486 MWh/year.

TABLE 1. TOTAL DEMAND OF THE ENERGY SOURCE OF ENTERPRISE

Energy consumer	Electricity, MWh/year	Thermal energy, MWh/year
Residential buildings	440	1172
Meat processing plant	460	964
Dairy plant	600	1350
Total	1500	3486

2.2. Energy Hub Optimisation

For accurate modelling and application of the complex, the *EnergyPro* program was used. *EnergyPro* serves as a tool designed to economically evaluate options in the energy sector. It involves sophisticated modelling of alternative behaviours in the energy system to understand the business implications, which are influenced by factors such as markets, taxes, subsidies, and more [13]. *EnergyPro* is a software solution designed to manage and optimize energy projects. It is widely used in the renewable energy sector, including wind, solar, and hydropower projects [14], [15].

With the help of the *EnergyPro* software package, simulation of technical and economic analysis and optimization of complex energy projects from several different power units was carried out. The program optimizes the operation of the plant, including energy storage following technical and financial parameters, to provide detailed specifications to meet specific energy needs, including heating, cooling and electricity use. It also provides the user with a detailed financial plan in a standard format, allowing the user to calculate and report emissions for the proposed project.

The *EnergyPro* energy systems model functions as a priority simulation model. It calculates the marginal production costs for all units at each time stage within the planning horizon, usually on an hourly basis throughout the year. This calculation, used in the analysis in this article, is based on factors such as operating costs, revenues, and dynamic electricity and gas prices.

Production costs include potential revenues, that is, the cost of heat production at a CHP is determined by fuel costs, variable operating and maintenance costs, and revenues from the supply of electricity to the grid. The units are then distributed or arranged in ascending order of production costs, ensuring that new production does not disrupt previously planned production [17].

They are also divided into analytical and Mixed Integer Linear Program (MILP)-based dispatching methods. The analytical dispatching method in *EnergyPro* involves assigning a priority number to each energy conversion technology at each time step. During the optimization period, the analytical dispatch mode works by first activating the technologies with the lowest priority number, ignoring the chronological order of the time steps, except when the priority numbers are identical. This activation process continues until all energy needs are met during the optimization period. Energy storage devices are used to transfer

energy between time steps while respecting user-defined technical constraints, such as those related to energy storage and conversion units.

When *EnergyPro* calculates these figures, the main goal is to minimize the total cost of heat production in the simulated power system. This is achieved by using the short-term marginal cost of heat production for each unit in each hour as a priority number [18]. The MILP approach includes constraints such as minimal loads. These constraints reflect the daily challenges faced by power plant operators, who have extensive experience in dealing with the complexities, nonlinearities, and constraints inherent in the day-to-day operation of power plants [19].

2.3. Energy Hub Scenarios

The simulations considered four different energy hub scenarios based on solar energy [19] and wind energy [20], biomass [21] and heat pump, battery, boiler and coal. Since renewable energy sources are unstable, except for wind energy in the area, complementary options for renewable energy sources are assumed. During the period when solar radiation is absent or reduced, the wind turbine and biomass will compensate for its absence. In systems that run entirely on renewable energy sources, as well as in existing transition systems, thermal energy storage (TES) is crucial to balance energy demand and supply [22]. It also allows heat pumps (HP) to optimize their performance, considering the dynamics of the electricity market and providing flexibility [23].

TABLE 2. Overview OF ENERGY HUB SCENARIOS

Technical parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Heat demand, MWh per year	3486	3486	3486	3486
Power demand, MWh per year	1500	1500	1500	1500
Solar power plant, MW _{power}	5	5	–	–
Wind power plant, MW	2	–	4	–
Heat pump, MW	1	1	1	–
Coal boiler, MW	5	7	–	–
Fossil CHP, MW	–	–	–	12
Biomass CHP, MW	–	–	8	–
Thermal storage, MWh	46	46	–	–
Electricity storage, MW _{power}	0.9	–	–	–

In all scenarios, the energy hub is designed to cover the heat demand of 3486 MWh/year (the required space heating for 50 one-family houses with an average of 100 m²) and power demand of 1500 MWh/year.

Table 2 shows the overview of the analysed scenarios. In Scenario 1, a solar photovoltaic field with an installed production capacity of 5 MW and a wind turbine with an installed capacity of 2 MW are the main electricity sources. A heat pump of 1 MW is used as a heat source. In addition, a battery of 0.90 MWh and a thermal storage tank with a storage capacity of 46 MWh are considered. A coal boiler with an installed capacity of 5 MW is used as an additional heat source.

In Scenario 2, only solar photovoltaic fields with an installed capacity of 5 MW, and heat pumps with an installed capacity of 1 MW are used as renewable sources. In the cogeneration of coal with an installed boiler and a small steam turbine, a small CHP is used [24]. However, thermal storage with a storage capacity of 46 MWh is used.

In Scenario 3, a wind turbine with an installed capacity of 4 MW, a pump with an installed capacity of 1 MW, and biomass cogeneration with an installed boiler and a small steam turbine (small CHP) have been considered [25].

In Scenario 4, a small CHP plant is used for coal-fired cogeneration with a 12 MW boiler and a small steam turbine.

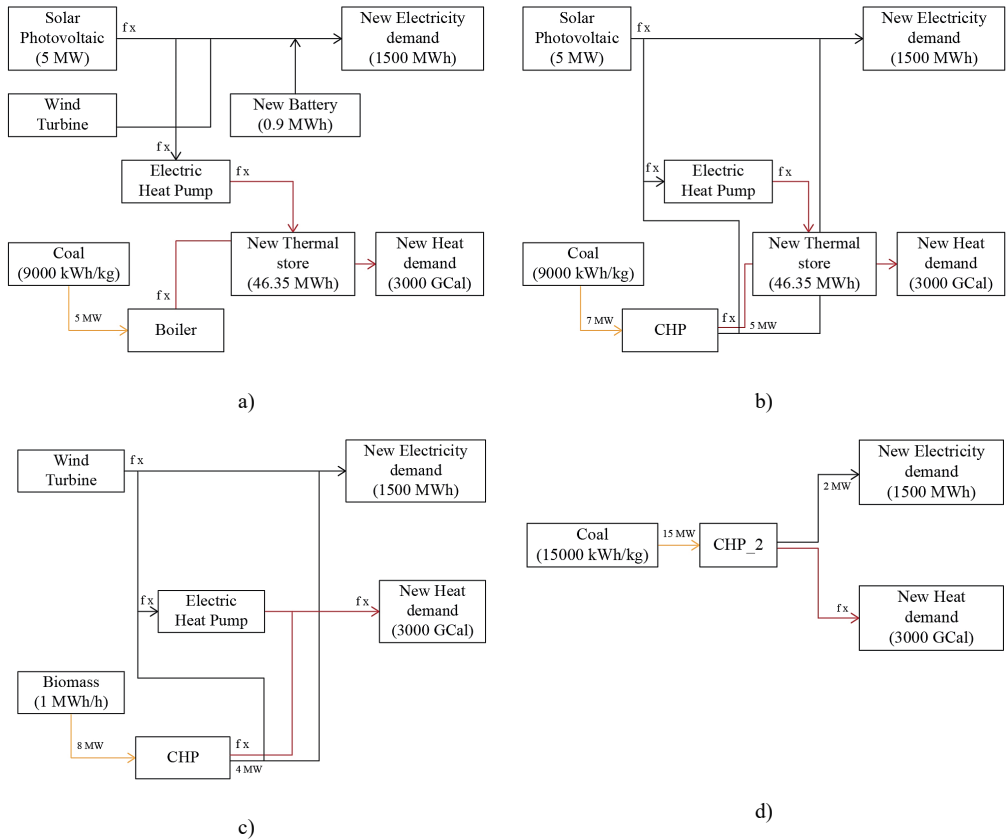


Fig. 2. Energy hub solutions in: a) Scenario 1; b) Scenario 2; c) Scenario 3; d) Scenario 4.

2.4. Input Data

The distribution of heat and power demand is modelled using two corresponding time series, each containing 8760 data values for each hour of the year. These series are calculated based on information received from the local district heating company and the transmission system operator. Data on environmental conditions, such as heat and solar energy, are obtained from a software database for the analysed location of Stepnoye village [16]. In the Kostanay region, the climate is sharply continental, mainly the weather is windy, and in

summer the peak of heat is in June and July. The average values of temperature, wind and solar energy can be seen in Fig. 3.

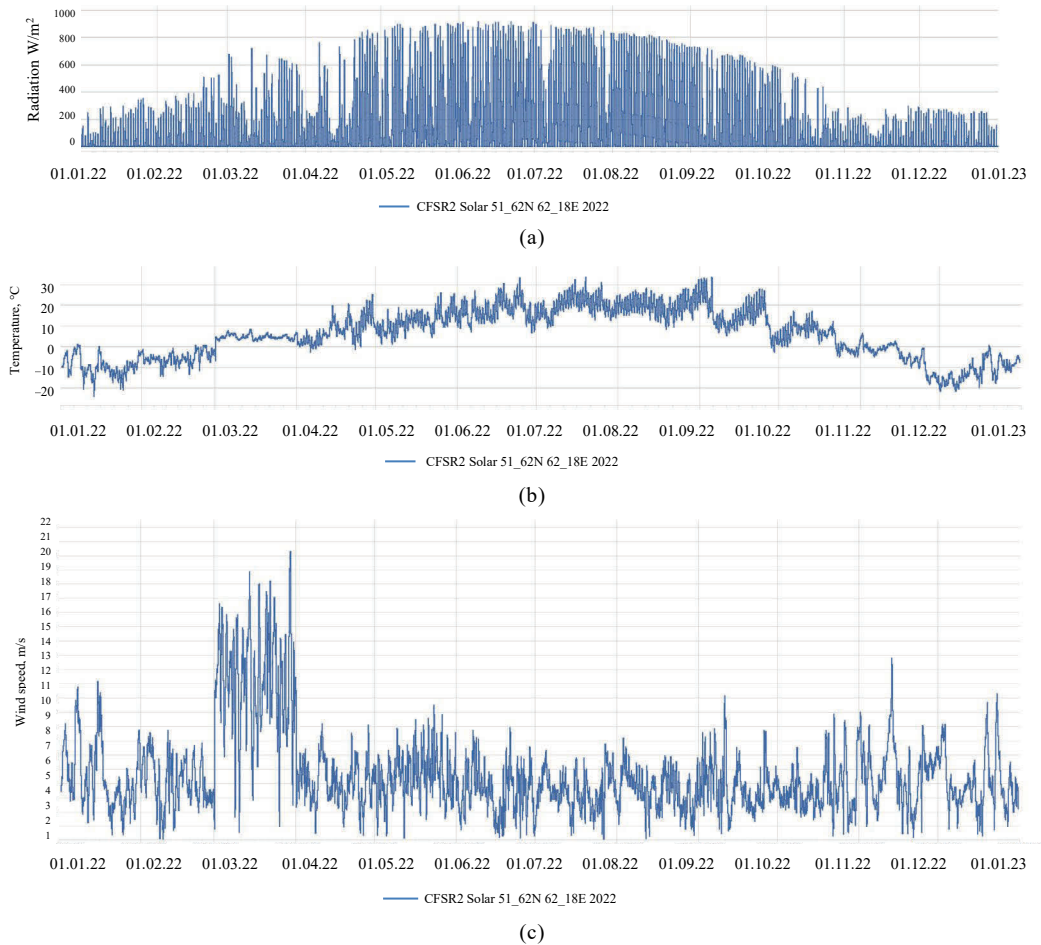


Fig. 3. Climatic conditions used in energy hub simulation: a) outdoor temperature; b) solar radiation and c) wind speed.

The outdoor temperature for the year varies from $-25\text{ }^{\circ}\text{C}$ to $+34\text{ }^{\circ}\text{C}$, on which the entire operation of the energy hub depends. The peak operation of the solar collector will be from mid-April to October with a total calculation of 6 months. The solar radiation in the summer period reaches up to 900 W/m^2 , which is good for the operation of the collector. The third graph shows the capacity for the whole year. On average, the power of a solar photovoltaic collector is 2500 kW. The wind speed (see Fig. 3(c)) in this area is on average 7–10 m/s per year, the highest speed reaches 20 m/s in March.

2.5. Investments, Taxes and Subsidies

Another important assumption includes economic parameters. Investment and maintenance costs are presented in EUR. The investment includes equipment, delivery and installation. The solar system offers a solar power plant with a storage capacity of 5000 kW for

2 600 000 EUR. Vestas wind turbine with a capacity of 2 MW for 1 200 000 EUR. The MKU 5 MW water-heating modular boiler plant with a capacity of 5 MW on a solid coal boiler plant for 300 000 EUR. A biomass boiler with a capacity of 8 MW costs 460 000 EUR. Maintenance costs include taxes, fuel, seasonal repairs, and salaries of employees [26].

The following types of investment preferences are searched for an investment priority project:

- tax preferences;
- corporate income tax;
- land tax;
- property tax;
- investment subsidy;
- state in-kind grants.

One of the most promising support schemes for sustainable development projects involves emissions trading and subsidies for measures that ensure the mitigation of the impact on climate change. Joint Implementation and Clean Development projects are still being implemented around the world, the integration of which into Energy Hub solutions could be a new challenge for foreign investors and the Kazakh government.

The amount of GHG emissions from Energy Hub sources depends on energy demand (Q , MWh/year), energy efficiency of energy production (n) and energy emission factor (R , tCO₂/MWh) [27]. It is calculated by the Equation (1).

$$GHG = \frac{R \cdot Q}{n}, \text{ tCO}_2/\text{year} \quad (1)$$

The specific investment for the reduction of one ton of GHG emissions (I , EUR/tCO₂) is calculated by the Equation (2) that considers capital investment (K , EUR) and GHG emission reductions (ΔGHG , tCO₂).

$$I = \frac{K}{\Delta GHG}, \text{ EUR/tCO}_2 \quad (2)$$

In addition, CO₂ trading costs show the economic benefits of the replacement of coal by renewable energy resources.

3. RESULTS

3.1. Comparison of Scenarios

In Scenario 1 (see Fig. 4), hourly electricity production of solar PV panels is around 0.16 MW. The hourly power production rates of wind turbine vary from 0.32 MW to 0.160 MW. The consumption of coal during the heating season varies from 16 kg/h to 98 kg/h.

According to Scenario 2 (see Fig. 5) the heat generation of a small CHP varies from 0.2 MW to 2 MW, and the production of a heat pump is 1.5 MW. Electricity production with a 0.64 MW solar collector, with a small CHP varies from 0.128 MW to 0.64 MW. Coal consumption during the heating season varies from 32 kg/h to 149 kg/h. The operation of the heat accumulator varies from 4 MWh/day to 46 MWh/day.



Fig. 4. Annual result for heat and power generation in Scenario 1.



Fig. 5. Annual result for heat and power generation in Scenario 2.



Fig. 6. Annual result for heat and power generation in Scenario 3.



Fig. 7. Annual result for heat and power generation in Scenario 4.

According to the results of three scenarios, heat generation with a heat pump varies from 0.06 MW to 0.828 MW, with a small CHP it varies from 0.128 to 0.342 MW. Electricity production with a wind turbine varies from 0.224 to 0.468 MW, with a small CHP it varies from 0.116 to 0.338 MW. Biomass production 0.15–0.65 MWh/day.

As the results of Scenario 4 show, the heat generation of a small CHP varies from 0.159 MW to 0.922 MW, the electricity generation of a small CHP – from 0.026 MW to 0.136 MW, but the electricity consumption is 0.171 MW. Coal consumption is from 42 kg/h to 70 kg/h.

TABLE 3. FINANCIAL AND TECHNICAL INDICATORS

Scenario	Equipment	Electricity generation, MWh/year	Heat generation, MWh/year	Capital investment, million EUR
1	Solar power plant with storage	1413	–	2.6
	Wind generator	1411	–	1.2
	Coal	–	342	0.5
	Total	2824	342	4.3
2	Solar thermal plant with storage	0	1576	2.6
	Coal	3955	403	0.7
	Total	3955	1979	3.3
3	Wind generator	4349	3778	2.3
	Biomass	720	1440	0.8
	Total	5069	5218	3.1
4	Coal	3000	6978	5.4
	Total	3000	6978	5.4

The financial and technical Table 3 contains all the necessary data of all scenarios from *EnergyPro* for GHG emission analysis – electricity generation and heat generation (MWh/year) as well as necessary investments. In the second scenario, a solar power plant and in the third scenario, a wind generator generates heat energy due to an electric heat pump (Figs. 4–7). In the second scenario, the electricity generation of a solar power plant shows 0, because the *EnergyPro* program always shows how to generate energy profitably and cheaply. In this case, operation of a modular boiler plant with the help of a small CHP is more beneficial and generates 3955 MWh/year.

3.2. Climate Neutrality Diagram

The climate neutrality chart is being developed to provide economic feasibility for GHG emission reductions to replace fossil energy resources with renewables. This is realized using a financial analysis of the techno economical results of *EnergyPro* scenarios.

The diagram (Fig. 8) is built on the principle of comparison and using Eq. (1) and Eq. (2). Two boundary curves have been selected: upper for fossil (Scenario 4) and lower for renewable (Scenario 3) energy, which characterizes the additional costs or benefits of the energy source depending on the GHG emission reduction policy (taxes and subsidies for the implementation of climate projects). In general scenarios A and B, the curves of all other scenarios will be placed between these two boundary curves, whereby the higher the RES, the more the overall energy source expenditure (“–“ income) decreases.

The added value of the chart is its use to predict the return on investment. Knowing the annual investment volume of the project, a straight line to the upper boundary curve is pulled. At its intersection, it can be determined how much the payment will be to the emissions trading system or what the necessary subsidies will be. By pulling the vertical straight from this intersection to the characteristic curve of any scenario, it is possible to identify the benefits (cost reductions or subsidies) of the reduction in GHG emissions. Thus, the chart provides an insight into the benefits or losses of the energy source moving towards climate neutrality.

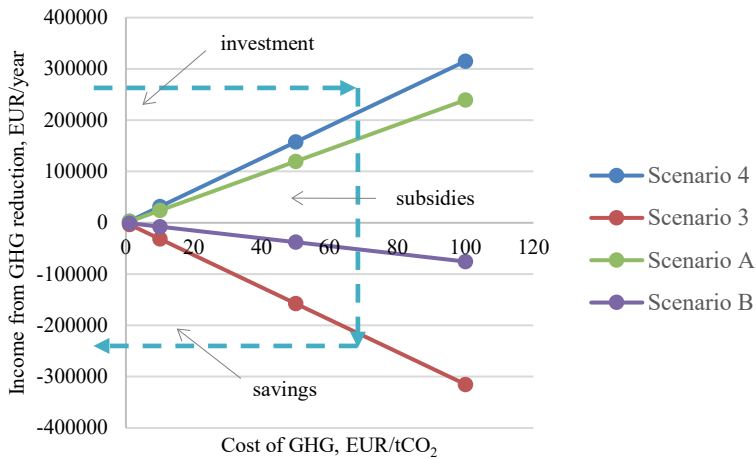


Fig. 8. Climate neutrality diagram.

4. CONCLUSION

The research analyses the potential to entirely phase out fossil fuels for energy supply in an agricultural complex engaged in the cultivation and production of a wide range of agricultural products. The *EnergyPro* software is used to evaluate the most optimal decarbonization solutions by considering various technologies merged in the energy hub: solar PV panels, wind turbines, heat pumps, biomass boilers and energy storage systems. The potential fossil-free solutions are evaluated from technical, economic, and environmental perspectives.

To sum up, the most promising and cost-effective option is scenario 3 with an integrated wind park, heat pump and biomass boiler. As the village of Stepnoye produces grains and other agricultural products, which indicates a significant amount of waste and residues produced, and therefore has significant amounts of available waste, especially concerning crops, manure and solid waste, bioenergy is a very stable source of energy production. In terms of climate, this region is sharply continental and windy, therefore the wind energy in this region has significant potential.

The simulation results show that the ambitious goal of creating a fully renewable energy system in Kazakhstan is achievable. By 2050, it is possible to develop renewable electricity and heat infrastructure, exceeding the country's Green Vision target of providing 50 % renewable energy for the same period. Consequently, a 100 % renewable energy system is likely to be viable in other parts of Eurasia and regions with similar climatic conditions [30].

In Kazakhstan local fossil fuels are available; therefore, there should be additional policy measures to motivate switching to RES. The analyses show that a CO₂ emission cost increase could be one of the solutions to increase the economic benefit of RES integration and the development of more complex energy hubs with several energy production units and storage systems.

The developed energy hub methodology can be further adapted and used for other sites with various energy consumers to analyse RES potential. Further research could focus on more detailed analyses of energy patterns including demand-side measures to align the RES production and energy demand. Additional analyses could be dedicated to policy measures promoting energy hub development such as electricity price variations or investment support policies.

ACKNOWLEDGEMENT

Research is carried out as part of the project AP14871978 «Highly efficient wind generator with the use of a multi-rotor system» of grant funding from the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

We are expressing gratitude to the EnergyPRO team in Denmark and personally Ext. Ass. Professor in Aalborg University PhD Anders N. Andersen.

REFERENCES

- [1] Haghjoo R., Choobchian S., Abbasi E. Unveiling energy security in agriculture through vital indicators extraction and insights. *Sci Rep* 2024;14(1):8626. <https://doi.org/10.1038/s41598-024-59273-3>
- [2] Peng X., Guan X., Zeng Y., Zhang J. Artificial Intelligence-Driven Multi-Energy Optimization: Promoting Green Transition of Rural Energy Planning and Sustainable Energy Economy. *Sustainability* 2024;16(10):4111. <https://doi.org/10.3390/su16104111>
- [3] Wei S., Yang Y., Xu Y. Regional development, agricultural industrial upgrading and carbon emissions: What is the role of fiscal expenditure? Evidence from Northeast China. *Economic Analysis and Policy* 2023;80:1858–1871. <https://doi.org/10.1016/j.eap.2023.11.016>
- [4] Paris B. *et al.* Energy use in open-field agriculture in the EU: A critical review recommending energy efficiency measures and renewable energy sources adoption. *Renewable and Sustainable Energy Reviews* 2022;158:112098. <https://doi.org/10.1016/j.rser.2022.112098>
- [5] Maradin D. Advantages and disadvantages of renewable energy sources utilization. *IJEPP* 2021;11(3):176–183. <https://doi.org/10.32479/ijepp.11027>
- [6] Hvelplund F. Policies for 100% Renewable Energy Systems. In *Im Hürdenlauf zur Energiewende* Brunnengräber A., Di Nucci M. R., Eds., Wiesbaden: Springer Fachmedien Wiesbaden, 2014:215–223. https://doi.org/10.1007/978-3-658-06788-5_14
- [7] Resch G. *et al.* Assessment of Policy Pathways for Reaching the EU Target of (At Least) 27% Renewable Energies by 2030, in *The European Dimension of Germany's Energy Transition*, Gawel E., Strunz S., Lehmann P., Purkus A., Eds., Cham: Springer International Publishing, 2019:45–65. https://doi.org/10.1007/978-3-030-03374-3_4
- [8] European Commission. REPowerEU: Affordable, Secure and Sustainable Energy for Europe. [Online]. [Accessed 18.12.2023]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en
- [9] Zhou S., Solomon B. D. Do renewable portfolio standards in the United States stunt renewable electricity development beyond mandatory targets? *Energy Policy* 2020;140:111377. <https://doi.org/10.1016/j.enpol.2020.111377>
- [10] Heredia-Fonseca R., Kumar S., Ghosh S., Thakur J., Bhattacharya A. Modeling a 100% renewable energy pathway in developing Countries: A case study of State of Goa, India. *Energy Conversion and Management* 2024;315:118800. <https://doi.org/10.1016/j.enconman.2024.118800>
- [11] Zhao C., Wang F. Economy-equity equilibrium based bi-level provincial renewable portfolio standard target allocation: Perspective from China. *Energy* 2024;290:130248. <https://doi.org/10.1016/j.energy.2024.130248>
- [12] Poullikkas A., Kourtis G., Hadjipaschalis I. A review of net metering mechanism for electricity renewable energy sources. *International Journal of Energy and Environment* 2013;4(6):975–1002.
- [13] Hasanov F. J., Mikayilov J. I., Mukhtarov S., Suleymanov E. Correction to: Does CO2 emissions–economic growth relationship reveal EKC in developing countries? Evidence from Kazakhstan. *Environ Sci Pollut Res* 2019;26(34):35282–35282. <https://doi.org/10.1007/s11356-019-06464-5>
- [14] Li L. *et al.* Enabling Renewable Energy Technologies in Harsh Climates with Ultra-Efficient Electro-Thermal Desnowing, Defrosting, and Deicing. *Adv Funct Materials* 2022;32(31):2201521. <https://doi.org/10.1002/adfm.202201521>
- [15] Zholdayakova S., Abuov Y., Zhakupov D., Suleimenova B., Kim A. Toward a Hydrogen Economy in Kazakhstan. Asian Development Bank Institute, Oct. 2022. <https://doi.org/10.56506/IWLU3832>
- [16] Alhassan H. The effect of agricultural total factor productivity on environmental degradation in sub-Saharan Africa. *Scientific African* 2021;12:e00740. <https://doi.org/10.1016/j.sciaf.2021.e00740>
- [17] The Government of the Republic of and Kazakhstan. Strategy for achieving carbon neutrality in the Republic of Kazakhstan by 2060 (in Kazakh). 2023:121. [Online]. [Accessed: 10.02.2024]. Available: <https://adilet.zan.kz/rus/docs/U2300000121>
- [18] Republic of Kazakhstan. Law on support for the use of renewable energy sources (in Kazakh). Jul. 04, 2009. [Online]. [Accessed: 10.02.2024]. Available: <https://adilet.zan.kz/rus/docs/Z090000165>
- [19] Victoria M., Zhu K., Brown T., Andresen G. B., Greiner M. Early decarbonisation of the European energy system pays off. *Nat Commun* 2020;11(1):6223. <https://doi.org/10.1038/s41467-020-20015-4>

-
- [20] Laktuka K., Pakere I., Kalnbalkite A., Zlaugotne B., Blumberga D. Renewable energy project implementation: Will the Baltic States catch up with the Nordic countries? *Utilities Policy* 2023;82:101577. <https://doi.org/10.1016/j.jup.2023.101577>
- [21] Kwon P. S., Østergaard P. A. Priority order in using biomass resources – Energy systems analyses of future scenarios for Denmark. *Energy* 2013;63:86–94. <https://doi.org/10.1016/j.energy.2013.10.005>
- [22] Gumber A., Zana R., Steffen B. A global analysis of renewable energy project commissioning timelines. *Applied Energy* 2024;358:122563. <https://doi.org/10.1016/j.apenergy.2023.122563>
- [23] Østergaard P. A., Andersen A. N. Variable taxes promoting district heating heat pump flexibility. *Energy* 2021;221:119839. <https://doi.org/10.1016/j.energy.2021.119839>
- [24] Wang H. *et al.* Heat-power peak shaving and wind power accommodation of combined heat and power plant with thermal energy storage and electric heat pump. *Energy Conversion and Management* 2023;297:117732. <https://doi.org/10.1016/j.enconman.2023.117732>
- [25] Østergaard P. A., Andersen A. N. Optimal heat storage in district energy plants with heat pumps and electrolyzers. *Energy* 2023;275:127423. <https://doi.org/10.1016/j.energy.2023.127423>
- [26] The Danish Energy Agency. Technology Data – Generation of Electricity and District heating. 2020.
- [27] European Commission. Directorate General for Energy, Directorate General for Climate Action., and European Commission. Directorate General for Mobility and Transport., EU reference scenario 2020: energy, transport and GHG emissions: trends to 2050. LU: Publications Office, 2021. [Online]. [Accessed 18.12.2023]. Available: <https://data.europa.eu/doi/10.2833/35750>