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Research article

Integration of renewable energy at coal mining enterprises: problems and prospects

Fedor S. NEPSHA[1,2]✉, **Kirill A. VARNAVSKIY**[1], **Vyacheslav A. VORONIN**[1], **Ilya S. ZASLAVSKIY**[1], **Andrey S. LIVEN**[1]

[1] *T.F.Gorbachev Kuzbass State Technical University, Kemerovo, Russia*

[2] *National University of Oil and Gas "Gubkin University", Moscow, Russia*

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Abstract. This article addresses the issue of developing renewable energy in coal mining enterprises in the Russian Federation. The study presents a methodology for assessing the technical and economic efficiency of introducing renewable energy sources based on simulation modeling. An analysis of the potential of solar and wind energy for coal mining regions in Russia is conducted. The authors use a custom software developed by them to simulate the power supply system for various scenarios of renewable energy integration, including solar generation, wind generation, solar generation with energy storage, wind generation together with solar generation. Based on the example of the Rostov region, a feasibility study of the considered options is presented. Additionally, the research includes a sensitivity analysis of the investment project in the conditions of uncertainty in the development of Russian renewable energy. The research findings indicate that even in market conditions with CO_2 emission quotas and prices at the level of the Sakhalin experiment, renewable energy in coal mining enterprises in Russia remains unattractive and requires additional support.

Keywords: energy efficiency; renewable energy; distributed generation; decarbonization of coal mines; simulation modeling

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Introduction. In accordance with the ratified Kyoto Protocol to the United Nations Framework Convention on Climate Change, the Paris Agreement, as well as the agreements adopted at the Climate Change Conference in Glasgow (2021) and Sharm el-Sheikh (2022), the Russian Federation took on commitments to reduce the carbon footprint by decarbonizing the economy [1]. Many countries are actively introducing carbon payments, declaring a complete phase-out of fossil energy resources, including coal, and setting the goal of achieving carbon neutrality in the period 2045-2060 [2]. Despite this, the coal industry continues to play a significant role in the global energy sector. As of 2021[1], coal provided about 27 % of global energy consumption (10.9 % in Russia), and the electric power industry accounted for 36.7 % of coal consumption in the world (17.3 % in Russia). The share of coal use is especially high in Asian countries: China – 62.93 %, India – 74.17 %, Indonesia – 61.46 %. According to EIA and IEA analytical reports, coal will retain a significant role in the power industry until 2050. Thus, despite the active lobbying for measures to decarbonize the economy and the constant increase in the use of renewable energy sources (RES), the coal industry remains an important component of the global energy balance.

[1] Ritchie H., Roser M., Rosado P. Energy. URL: https://ourworldindata.org/energy (accessed 14.04.2023).

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However, the implementation of the economy decarbonization strategy is not the only challenge for the Russian coal industry. Unprecedented sanctions pressure, reorientation to new sales markets in the countries of Southeast Asia and the Indian Ocean, increase in the logistics chain and transportation costs, export price volatility are also serious external shocks for the Russian coal industry [3]. Of particular importance is the increase in the competitiveness of Russian coal companies through the introduction of modern technologies such as IoT (Internet of Things) and Big Data, as well as the energy efficiency of power supply to coal enterprises [4]. The introduction by coal companies of highly efficient technologies, including digital ones, in the processes of coal mining and processing is provided for by the Program for the Development of the Russian Coal Industry for the period up to 2035. Large investments are also aimed at creating a set of technologies that increase the efficiency of coal mining and coal processing[2].

One of the ways to reduce the carbon footprint of Russia without harming the coal industry is to "green" the internal power consumption of coal mines through the introduction of the distributed generation. Studies [5, 6] noted the possibility of reducing the cost of purchasing electricity from the power grid and the volume of carbon dioxide emissions by coal mines when using their own generation on coal mine methane. The relevance and necessity of RES in the conditions of enterprises of the mineral resource complex (MRC) is substantiated in the work [7]. The article [8] considers the possibilities of integrating distributed generation based on RES for MRC enterprises, gives a positive assessment of the use of RES to provide electricity and heat supply. The work [9] is devoted to the study of the effectiveness of the use of hybrid energy systems based on solar, wind and diesel power plants, as well as the replacement of diesel transport with hydrogen for coal mines in Northern China. A high potential for reducing CO_2 emissions and reducing diesel fuel consumption was noted. The study [10] evaluated the effectiveness of the introduction of cogeneration on coal mine methane and noted a significant dependence of the investment attractiveness of the project on tariffs for CO_2 emissions. There are a number of projects on the use of RES at MRC enterprises: the introduction of mobile solar power plants by SunShift (Australia) at coal mines[3], 36 MW hybrid solar power plant at a gold mine in southwestern Mali[4], mining dump trucks with electric motors and the subsequent development of electric transport charging infrastructure as one of the business diversification options.

The studies mentioned above suggest that incorporating renewable energy into the power supply systems of MRC enterprises has the potential to reduce their carbon footprint, lower coal mining costs by reducing energy expenses, increase reliability, minimize financial losses from power outages, and create new high-tech employment opportunities.

The problem statement. The use of RES in industrial enterprises was considered by many scientists. The paper [11] considers the possibility of achieving energy independence of industrial enterprises through the use of RES. It is noted that the introduction of renewable energy sources (RES) in power utilities may present certain challenges, such as potential increases in electricity prices, complexities in managing power systems, and a reduction in reliability. Simultaneously, the study concluded that there are promising opportunities for utilizing renewable energy sources as decentralized energy sources within the power supply systems of industrial enterprises. This approach involves energy sources exclusively for the enterprise's consumers, without the possibility of transferring power to the grid. In the study [12], a system for managing energy flexibility in industrial enterprises

[2] The Order of the Government of the Russian Federation N 1144-r dated 11.05.2022 "On approval of the comprehensive scientific and technical program of the full innovation cycle "Development and implementation of a set of technologies in the areas of exploration and production of solid minerals, ensuring industrial safety, bioremediation, creating new products of deep processing from coal raw materials while consistently reducing the environmental impact on the environment and risks to the life of the population".

[3] SunSHIFT Global Fleet of Modular Moveable Megawatt Scale Solar Assets. URL: https://www.climatefinancelab.org/ideas/ sunshift-global-fleet-of-modular-moveable-megawatt-scale-solar-assets/ (accessed 20.06.2023).

[4] Takouleu J.M. MALI: Reuniwatt to buid weather forecasting system for Fekola solar hybrid power plant. URL: https://www.afrik21.africa/en/mali-reuniwatt-to-buid-weather-forecasting-system-for-fekola-solar-hybrid-power-plant/ (accessed 11.03.2023).

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is proposed. The findings indicate that the RES integration in industrial enterprises can have a positive impact on the development of the energy flexibility market. In the paper [13] the conclusion that there is a high potential for renewable sources in the territory of the Russian Federation was made based on an assessment of solar activity and wind speed data in different regions. It notes a mismatch between the periods of maximum solar radiation and wind speed for several regions in Russia throughout the day. Considering this, it is recommended to use hybrid solar-wind power plants to minimize the installed generation capacity in microgrids. Similar conclusions were made by foreign researchers in [14], who considered the application of a hybrid power plant (solar-wind power plant). This option has resulted in a reduction in electricity costs from $5,300,000 to $2,400,000 per year and the generation of additional income from selling electricity to the grid, amounting to $1,300,000 per year. As a result, the project has an estimated payback period of approximately six years.

Researchers from Tsinghua University [15] are studying the problem of selecting the optimal combination of solar generation, wind generation, and biogas generation for rural electrification. This research examines numerous grid development options involving different combinations of renewable energy generation. The most feasible approach is a hybrid system whereby the village's grid can operate both in parallel with and independently from the external grid. The study emphasizes the favorable impact of distributed energy resources on the environment and social factors.

As a solution to improve the reliability of power supply of the oil sector, the paper [16] considers the use of wind-diesel power plants for power supply of submersible electric motors of electric centrifugal pumps in oil wells. The article [17] considers the introduction of a cogeneration plant at oil production facilities with the possibility of additional power generation with a low demand for heat. Such a system could be promising in coal mines utilizing methane as the primary energy source.

In [18], Chinese researchers presented a hybrid power supply system, including wind and solar generating sources, as well as a pumped storage power plant (PSPP). PSPP acts as a backup power source on windless days and periods of increased cloud cover, ensuring the stability of the power supply system. It is proposed to use spent underground mine workings of coal mines in the Ningxia Hui Autonomous Region of China as reservoirs for water storage. A similar approach has been proposed by Spanish scientists [19] for the spent coal mines in the Asturian coal basin in Spain. Hydrodynamic models are presented that reflect the movement of mine water flows. It is noted that the absence of such models hinders the implementation of projects for the creation of PSPP in underground workings due to the impossibility of assessing their effectiveness. In the research [20], the same researchers analyze the technical and economic feasibility of using mine water from flooded coal mines to provide thermal and electrical energy to consumers located in nearby areas. The developed economic model shows that the performance of such a power supply system depends on many factors, but with proper development of implementation options, it can be very effective and will optimize consumers' power supply costs, as well as reduce carbon dioxide emissions into the environment.

The article [21] considers the problem of determining the optimal location of a PSPP in underground workings using the example of the Chinese province of Shanxi. The study is based on a multi-criteria decision-making method, four assessment criteria are given, and a number of quantitative indicators for real examples are presented. The necessity of improving the method by introducing additional assessment criteria is noted.

Another study on the problem of the optimal location of PSPP in the underground workings of closed mines, conducted by European scientists, is presented in [22]. A mathematical model is proposed to estimate the impact of hydrogeological factors, rock chemical composition, and other variables when selecting an appropriate location for an underground PSPP.

The article [23] shows the analysis of the current state and trends in usage of RES by Australian mining enterprises. The study highlights the factors that encourage mining enterprises to adopt RES, as well as the challenges that hinder their widespread implementation. However, the article notes that

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due to inadequate scientific and technical research on RES implementation in MRC enterprises, only approximately 7 % of Australian mining enterprises currently utilize RES.

The research [24] is devoted to the study of the possibilities of optimizing energy consumption using RES on the example of Zimbabwean mines. It is shown that the use of traditional methods for improving energy efficiency (optimization of the operating mode, increasing the power factor, etc.) without RES is the best option in terms of economic efficiency. Nevertheless, RES can prove to be beneficial in developing mechanisms for their own payback.

The article [25] proposes the developed multicriteria algorithm for the operation of the dispatch center of an integrated energy system that uses coal mine methane, mine water, etc. as primary energy sources. The algorithm has been tested in a coal mine and allows solving a wide range of problems from optimizing energy consumption and increasing the reliability of energy supply to reducing greenhouse gas emissions.

The study [26] presents the model of an integrated power supply system for a coal mine including energy storage devices and RES. Using this model and real data from one of the coal mines in Western China, the algorithm for two-stage optimization of the power supply system in the conditions of uncertainty was worked out. The algorithm application results in optimal loading of power equipment, enhancing the energy efficiency and reliability of the coal mine power supply system.

Researchers from the University of Virginia in [27] proposed the concept of using spent oil and gas wells, as well as spent underground workings of coal mines as compressed air accumulators, which can be used to stabilize the operation of nearby wind farms on windless days. The complexity of the implementation of such projects is noted, but at the same time, it points at a significant socio-economic effect from the development of infrastructure, the creation of new jobs, as well as an impetus in the development of mining science in the direction of finding and substantiating alternative approaches to the operation of mine workings.

The article [28] investigates the possibility of using low-potential heat sources typical for coal industry enterprises. A schematic diagram of the complex processing of mine waters with the production of thermal energy, drinking and technical water (suitable, for example, for the agro-industrial complex) is presented. According to the authors, the use of the proposed scheme will improve the reliability of heat supply to industrial and domestic consumers, as well as reduce the negative impact of the coal industry on the environment.

The paper [29] presents a thematic study on the possibilities of utilizing underground workings of coal mines as PSPP, compressed air energy storage systems, and geothermal energy sources. It is noted that the energy potential of underground excavations amounts to approximately 197 GW·h/year, with a significant reduction in CO_2 emissions.

In the article [30], the results of utilizing mine water from a flooded copper mine in the state of Michigan, USA, as a source of thermal energy for nearby consumers, are presented. The study concludes that the proposed solutions exhibit high efficiency. Additionally, the research indicates that the knowledge gained from implementing these technologies can be applied not only in the USA but also in other mining regions worldwide.

The topic of the optimal use of mine water as an energy source in the conditions of the closed mine Markham Colliery (Great Britain) is presented in [31], where the chemical composition of mine water is studied, measures are proposed to improve the efficiency of power equipment, as well as to increase its service life.

The article [32] is devoted to the study of the control algorithm for an electrical engineering complex, including a wind power plant, batteries, and a diesel generator. The study emphasizes that incorporating climatic factors and energy consumption forecast data for the upcoming day into the control algorithm enhances the efficiency of the power supply system. The findings are pertinent in analyzing models of power supply systems with RES for domestic MRC enterprises since the climatic conditions in Russia's mineral deposit regions can vary significantly.

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Despite a considerable amount of research on RES implementation in industrial enterprises, the effectiveness of RES in coal mining enterprises in the Russian Federation remains inadequately explored. Further study is necessary to assess the feasibility of introducing RES during the construction and modernization stages of these enterprises. The assessment of renewable generation efficiency and its integration into coal mine power supply systems is conducted using a custom computer program developed in Python programming language, along with specialized libraries such as pvlib and windpowerlib.

Methodology. There are several foreign software available for simulating hybrid power supply systems, including HOMER, iHOGA, PVsyst, SAM, RETScreen Expert, EnergyPlan, and many others [33]. The most efficient and convenient tool is HOMER PRO, which surpasses other available options with similar functionality [34]. However, HOMER PRO does not consider the special features of the Russian electricity and capacity market. Therefore, there is a need to develop domestic software that could account for these features and subsequently be used for preliminary testing and developing control systems for distributed energy facilities. The authors have developed a computer program that performs following functions:

• forming a profile of RES generation using location data while taking into account seasonality and installed capacity;

• forming an annual balance for a hybrid power supply system using optimal control algorithms;

• creation of a financial and economic model that allows assessing the sensitivity of an investment project and the risks of its implementation.

It is worth noting that foreign software has the potential to address these issues. However, challenges arise when it comes to implementing the financial and economic model in the context of the Russian electricity market. Furthermore, the optimization algorithms used are not sufficiently described to enable their integration within an actual control system. According to the authors of the software, in order to select the optimal equipment composition, the hybrid power supply system and its automated control system should be interconnected using common control algorithms. This will ensure a high degree of certainty that the results obtained during the equipment optimization process correspond to the actual operating experience of the control system.

Simulation model structure. Figure 1 provides a diagram of the power supply system model for the mining enterprise, which takes into account the integration of renewable energy sources. This model comprises the following components:

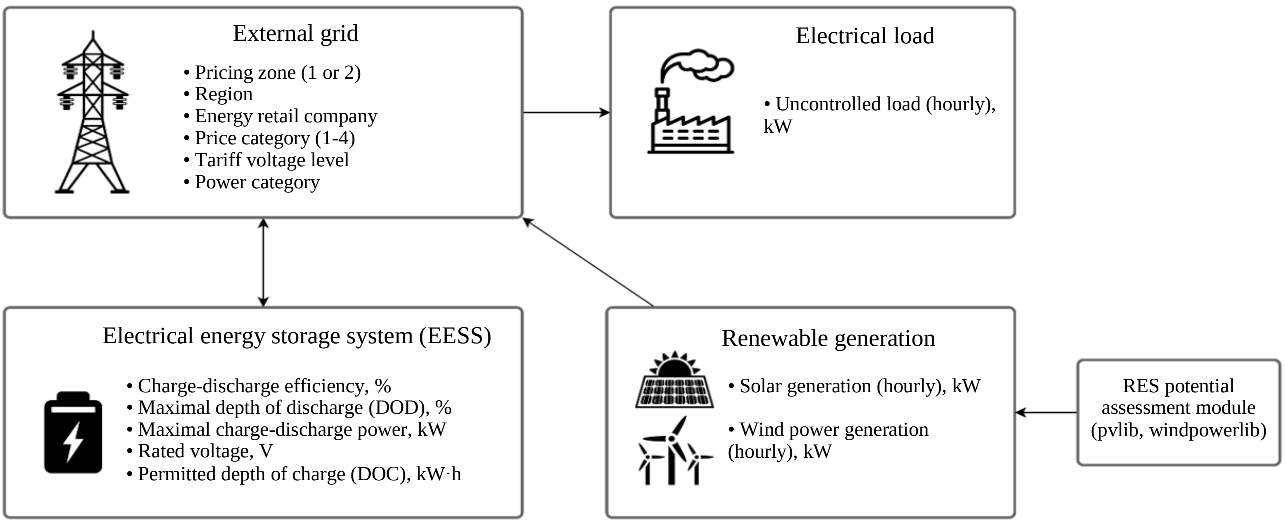

Fig.1. Block scheme of the simulation model for a hybrid power supply system

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• external grid the parameters of which are determined by the region of connection of the mining enterprise, as well as the contract for the sale of electrical energy and the contract for services for the transmission of electrical energy. In some cases, small enterprises may only need to sign one energy supply contract with an energy retail company;

• electrical load represented by mining equipment and the own needs of distributed energy facilities. The simulation model uses the load profile of a Kuzbass coal mine to set the consumption profile, which is assumed to be similar to the load schedule for coal mines in other regions due to their round-the-clock mode of operation;

• RES generation comprises a wind power plant (WPP) and/or a photovoltaic power plant (PVP). The generation profile is first generated using the pvlib and windpowerlib libraries and then used in the calculations to generate the annual profiles of wind and solar generation;

• electric energy storage system (EESS) is represented by the accumulation (storage) and power conversion subsystems.

Algorithm for feasibility study of the RES integration at the mining enterprise is shown in Fig.2 and includes the following steps:

• Setting a location. The coordinates of the object in question are entered, which are used in the formation of requests to external services.

• Loading data from external services. Data requests are generated for meteorological parameters (solar insolation, air temperature, atmospheric pressure, wind speed) using the NASA POWER API.

• Setting the power consumption profile. The power consumption profiles of mining equipment are entered.

• Setting the parameters of the generation equipment. The parameters of the main equipment of the hybrid energy complex are being entered: PVP, WPP, EESS.

• Formation of the RES generation profile. It is carried out based on data on the location of the object and the specified parameters for the nominal capacities of the PVP, WPP, and EESS. To calculate the generation profiles of solar and wind power plants, the pvlib and windpowerlib python libraries are used, which allow considering the main characteristics of photovoltaic panels with inverters and the parameters of wind turbines.

• Simulation modeling and balance calculation involve calculating the power balances, which include power consumption profiles from the external grid using the obtained RES generation profiles and a given electrical load profile. In the presence of EESS, its optimal management is ensured to reduce power consumption during peak load hours and absorb excess RES generation.

• NPV and LCOE calculation. To assess the energy efficiency of the considered hybrid power supply system, the net present value (NPV) and the levelized cost of electricity (LCOE) are calculated:

$$\mathrm{NPV} = \sum_{n=1}^{N} \frac{CF_n}{(1+i)^n} - \mathrm{CAPEX}, \tag{1}$$

where CF_n – cash flow for the n-th tear; CAPEX – capital expenditures; N – duration of the project, years; i – discount rate, which is taken at a level of 7.5 %

In terms of income, the economic model considers the savings achieved by reducing the amount of electricity purchased from the grid, as well as penalties for indirect carbon dioxide emissions into the atmosphere. In terms of expenses, the model considers capital investments in the purchase of equipment and operating expenses, including regular maintenance.

To evaluate the profitability of RES generation, the present value of electricity is calculated. This represents the cost of producing one kilowatt-hour of electricity throughout the entire life cycle of the project:

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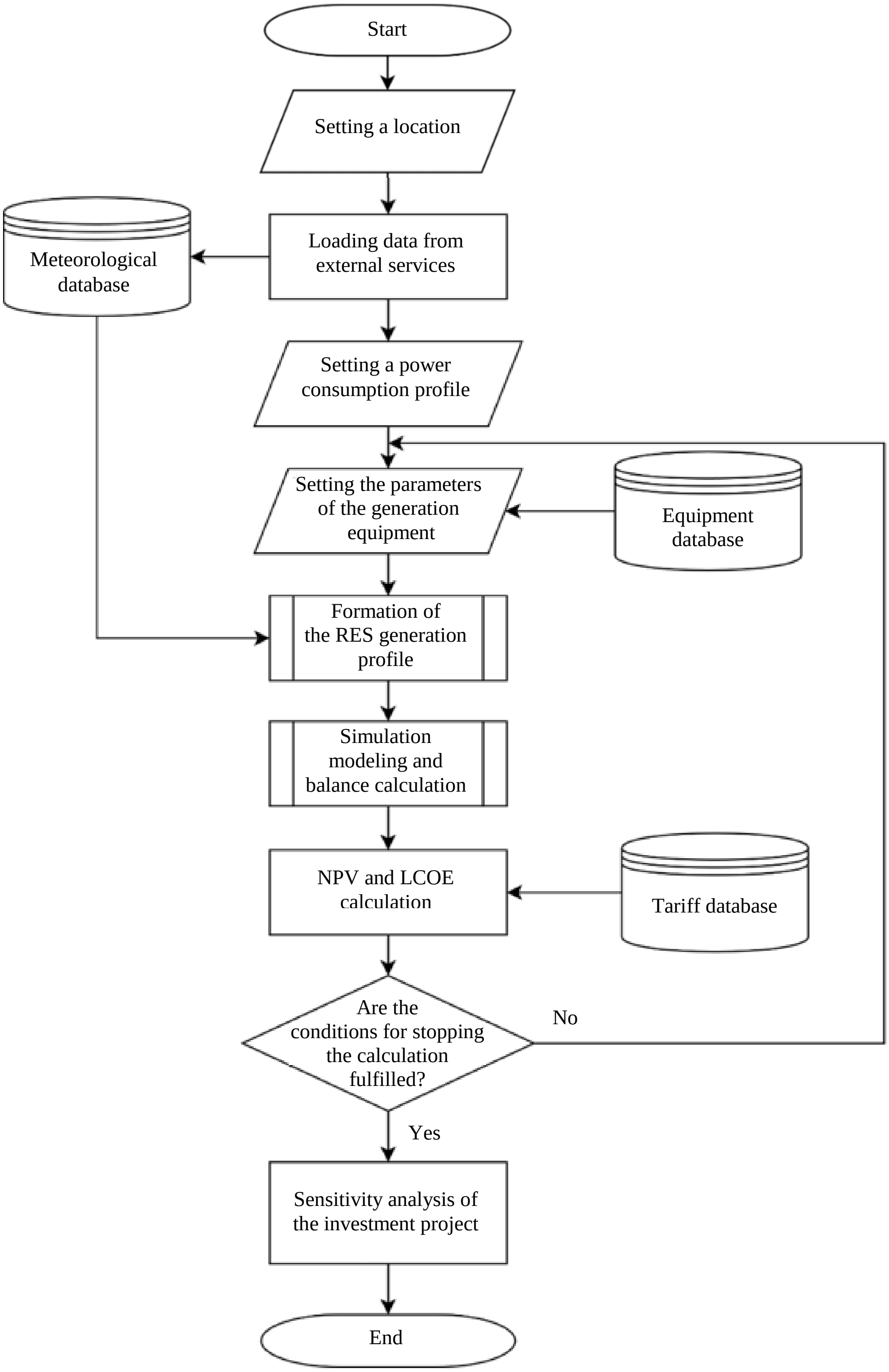

Fig.2. Algorithm for feasibility study of the RES integration at the mining enterprise

$$\mathrm{LCOE} = \frac{\mathrm{EUAC}}{E_{\mathrm{gen}}}, \tag{2}$$

where EUAC – equivalent uniform annual cost taking into account discount rate, mln rub./year; E_{gen} – power generation per year, GW·h.

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Equivalent uniform annual cost taking into account discounting, is determined by the formula

$$\text{EUAC} = \text{NPC}\frac{i(1+i)^N}{(1+i)^N - 1}, \quad (3)$$

where NPC – net present cost, mln rub.,

$$\text{NPC} = \sum_{t=0}^{N} \frac{\text{OPEX}_n}{(1+i)^n} + \text{CAPEX}, \quad (4)$$

OPEX_n – operational expenditures in *n*-th year, mln rub.

The reduction in indirect carbon footprint for the year is calculated by the formula (3):

$$\text{CO}_{2\,\text{reduct}} = 1000 EF_{\text{CO}_2,\,\text{year}} E_{\text{gen}}, \quad (5)$$

where $EF_{\text{CO}_2,\,\text{year}}$ – carbon dioxide emission factor CO_2, tonn/MW·h, accepted according to the site of JSC “ATS”[5].

As a condition for stopping the calculation, the condition for maximizing NPV is taken:

$$\max \text{NPV}(P_{\text{PVP}}, P_{\text{WPP}}, P_{\text{EESS}}) \text{ while} \begin{cases} 0 \le P_{\text{PVP}} \le P_{\text{PVPmax}}; \\ 0 \le P_{\text{WPP}} \le P_{\text{WPPmax}}; \\ 0 \le P_{\text{EESS}} \le P_{\text{EESSmax}}, \end{cases} \quad (6)$$

where P_{PVP}, P_{WPP}, P_{EESS} – installed capacities of the PVP, WPP, and EESS, MW; P_{PVPmax}, P_{WPPmax}, P_{EESSmax} – maximum values of the installed capacity of the PVP, WPP, and EESS which limit the search area for the optimal solution, MW.

In addition to economic effects, social effects were also calculated. According to the article [35], the potential of PVP to create new jobs is $0.27549 \cdot 10^{-7}$ kW·h/year.

• The sensitivity of the investment project was analyzed by determining the payback period sensitivity to changes in the unit cost of the installed capacity of PVP, WPP, and EESS, the discount rate, and the cost of electric energy and capacity. The developed computer program can be used to select the optimal RES generation configuration at other industrial enterprises.

Results and discussion. The research focuses on the power supply system of a coal mine. A time series of hourly power consumption measurements for the year 2020, obtained from a coal mine in the Kemerovo region, was utilized to model electricity consumption. This dataset spans a one-year time period and includes 8,784 measurements. The analysis proceeds under the assumption that such a time series accurately characterizes the profiles of electricity consumption of coal mining enterprises in Russia and undergoes minor changes when evaluating the economic effectiveness of the proposed solutions. The considered mine operates round-the-clock, with an average annual consumption of 8.51 MW. The annual and daily load profiles are shown in Fig.3. According to Fig.3, *a*, it can be observed that the consumption peaks of the coal mine mostly occur in the period after noon, around 20:00 local time. Hourly consumption values during this period can range from 2.6 to 17 MW. There is noticeable cyclicality in the technological process of the coal mine. The most demanding hours are 3-4 am, 12 pm, and 5 pm. The identified intervals of maximum load partially coincide with the peak load hours for wholesale and retail markets, as well as the peak load hour in the respective region of the Russian Federation. According to Fig.3, *b* the mine load has the lowest value during the summer months and the highest consumption during the autumn and spring periods. Seasonal

[5] Carbon dioxide emission factor for the first pricing zone of the UES of Russia (from JSC “ATS” website). URL: https://www.atsenergo.ru/results/CO2 (accessed 05.08.2022). For calculations, the actual value of the CO_2 emission factor for 2022 was used, which is 0.348 tonn/MW·h.

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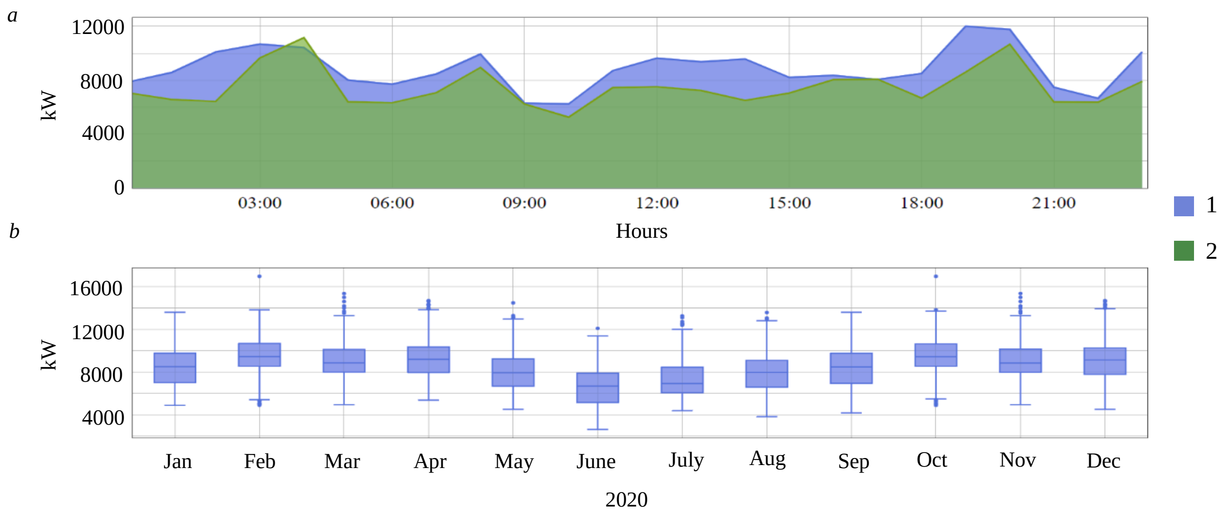

Fig.3. Load patterns of the considered coal mine: *a* – daily profile; *b* – annual profile
1 – winter; 2 – summer

variations in the coal mine consumption amount to approximately 25 %. Further examination of the effectiveness of renewable energy integration is carried out for the main coal mining regions in the Russian Federation.

The annual average values of parameters characterizing the renewable energy potential in coal mining regions are presented in Table 1. The data in Table 1 indicate that the Rostov region has the highest solar energy potential, with the total solar insolation being approximately 25-30 % higher than in the other considered regions. It is worth noting that the highest solar activity is recorded in June, while the lowest is in December. The insolation clearness index varies across the regions, ranging from 0.55 p.u. during the winter months to 0.72 p.u. in the spring period.

Table 1

Average annual values of parameters by region

Parameters	Rostov region	Republic Sakha	Kemerovo region	Sakhalin region	Zabaikalsky krai	Primorsky krai	Krasnoyarsk krai	Komi Republic	Republic of Khakassia
Daily global horizontal irradiance (GHI), kW·h/m^2	3.85	2.98	3.01	3.09	3.36	3.62	2.66	2.29	3.31
Insolation clearness index, p.u.	0.66	0.66	0.66	0.69	0.72	0.7	0.66	0.61	0.68
Wind speed, m/s	6.80	3.66	5.57	5.26	4.89	4.54	5.52	4.76	5.25

Wind speed values were obtained from the NASA[6] database for a surface height of 50 m. In the considered territories the value of average wind speed during the year varies from 3 to 9 m/s. The highest wind energy potential is in Rostov region with an average annual wind speed of 6.8 m/s, while the lowest is in Sakha Republic with a value of 3.66 m/s, which is 54 % lower. The highest wind speed is observed in winter and spring months.

The most attractive region for the introduction of WPP and PV power plants is Rostov region, which has the greatest potential for wind and solar energy. Further, the installation of RES-based generation only in Rostov region as the most attractive region in terms of RES potential is considered.

Simulation modeling and calculation of balances are carried out. Structural schemes are presented in Fig.4. Specific values of capital and operating costs adopted for simulation modeling were determined as a result of the analysis of the Order of the Ministry of Energy of Russia[7] and are presented in Table 2.

[6] NASA Prediction of Worldwide Energy Resources. URL: https://power.larc.nasa.gov/data-access-viewer/ (accessed 01.03.2023).

[7] The Order of the Ministry of Energy of Russia N 146 dated 28.02.2022 "On approval of the scheme and program for the development of the unified energy system of Russia for 2022-2028".

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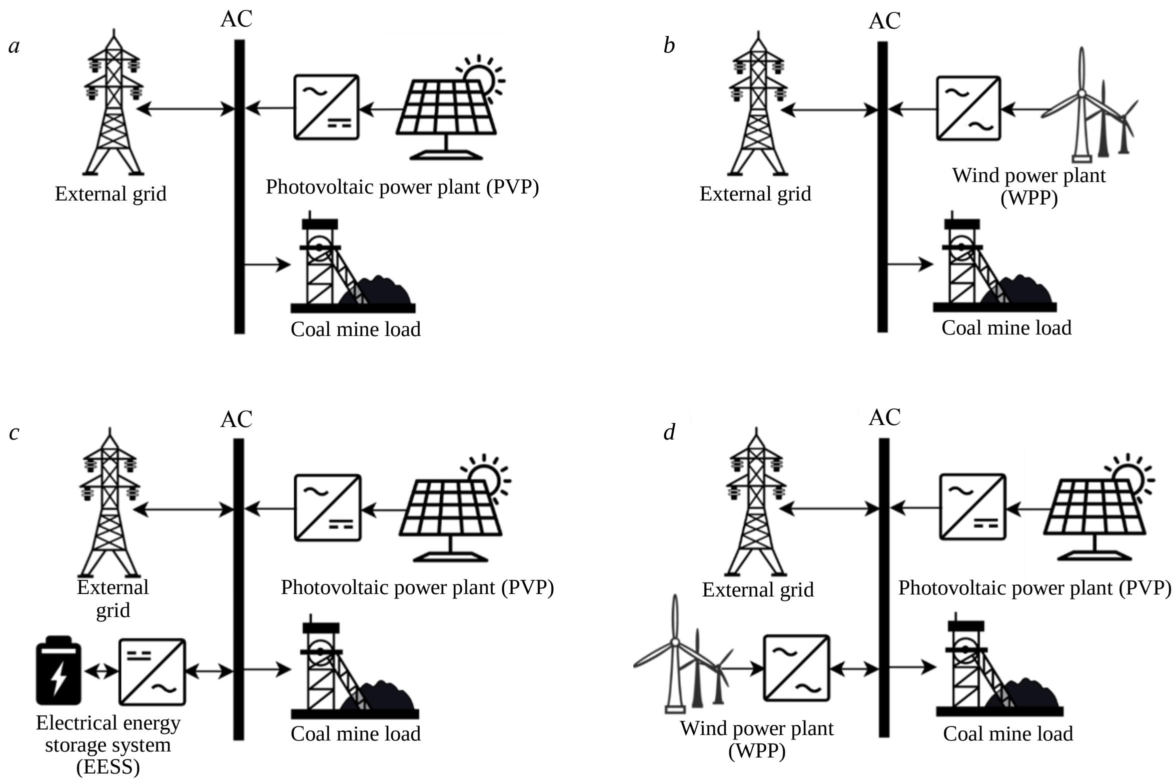

Fig.4. Considered variants of the hybrid energy system: *a* – solar generation; *b* – wind generation; *c* – solar generation and EESS; *d* – solar generation and wind generation

Table 2

Specific values of capital and operating costs

Component of hybrid energy system	PVP	WPP	EESS
CAPEX[8]	800 $/kW/ 61850 rub./kW	2000 $/kW/ 154650 rub./kW	800 $/kW·h/ 61850 rub./kW
OPEX for the year	23 $/kW/ 1778 rub./kW	100 $/kW/ 7732 rub./kW	12 $/kW/ 928 rub./kW

To select the installed capacity of solar panels, we used the method of coordinate descent [36] – a gradual decrease in the installed capacity of PVP, starting from a value equal to the peak consumption of the coal mine under consideration. At the same time, the library pvlib was used to select the required number of solar panels and inverters. The criterion for optimization was the net discounted income for 10 years (6). In the process of searching for the optimal configuration, it was found that the optimal installed capacity of PVP plant for the Rostov region is 8 MW (51040 polycrystalline solar panels ET-P660255WWAC from ET Solar Industry with a capacity of 255 W and a size of 1640×992 mm) with an area of 15 hectares. Figure 5 shows the energy balance graph of the coal mine during the period of maximum solar generation. The selection of the installed capacity of WPP was performed in the same way. The optimal option was the installation of one E-53/800 wind turbine with a total installed capacity of 0.8 MW. In the case of EESS and PVP plant implementation, the value of installed capacity of PVP plant determined in the first scenario was taken as the initial capacity for PVP plant. In this case, the accumulator was used for price arbitrage and absorption of excess solar generation during peak hours of solar activity with the purpose of further discharge during peak load hours. Figure 6 shows a graph of the EESS operation. The data in the figure shows that he storage device is charged during the solar maximum hours, the discharge takes in the hour with

[8] The exchange rate used in the calculations is 77.32 rub./dol.

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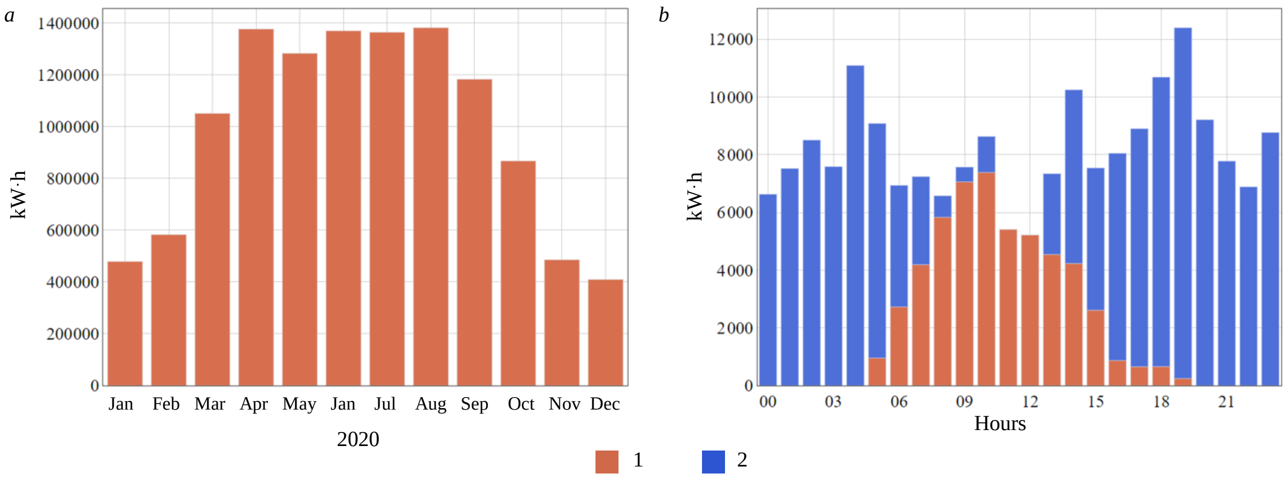

Fig.5. Seasonal (*a*) and daily (*b*) profile of solar generation with an installed capacity of 8 MW in the Rostov region
1 – solar generation; 2 – consumption from the external network

the sign of peak hour to get additional effect. Table 3 shows the comparison of the considered options. The LCOE value ranges from 0.07 to 0.1 $/ kW·h (from 5.41 to 7.73 rub./ kW·h), which is higher than the world level, which is 0.048 $/kW·h according to IRENA[9] in 2021. The analyzed alternatives do not yield a return on investment within the 20-year study period, primarily due to the low cost of electricity and nominal penalties for CO_2 emissions (16 rub. per 1 ton of CO_2).

The sensitivity analysis of the investment project is given for the considered case for the implementation of EESS and PVP in the Rostov region. Since the greatest impact on the NPC has the unit cost of PVP and EESS, and the income values depend on the cost of CO_2 emission quotas and electricity tariffs, the parameters and values presented in Table 4 were taken for calculations.

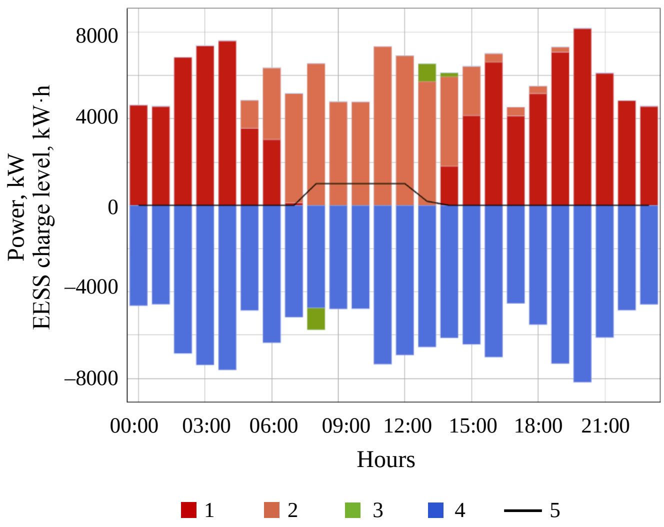

Fig.6. Daily operation profile of a hybrid PSS with WPP of an installed capacity of 9 MW and an EESS with a nominal energy capacity of 1 MW·h
1 – consumption from the external grid;
2 – solar generation; 3 – EESS; 4 – load; 5 – EESS charge level

Table 3

Comparison of RES implementation options for Rostov region

Parameter	PVP 8 MW	WPP 0.8 MW	PVP 9 MW + + EESS 1 MW·h	PVP 8 MW + + WPP 0.8 MW
Electrical energy production, GW·h	11.82	2.42	13.32	14.18
Share of RES, %	18.84	3.35	21.71	23.47
NPC, million rub.	639.56	187.48	790.52	827.04
NPV for 20 years, million rub.	–14.35	–61.21	–85.69	–78.8
LCOE, rub./kW·h/$/kW·h	5.11/0.066	7.32/0.093	5.60/0.071	5.51/0.07
CO_2 emissions, kt	22.97	26.41	22.46	22.11
CO_2 emissions reduction, kt	4.33	0.89	4.88	5.19
Employment creation (for the project lifespan)	9.77	2.00	11.01	11.72

[9] Renewable Power Generation Costs in 2021. URL: https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021 (accessed 01.04.2023).

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Table 4

Researched parameters in the sensitivity analysis of the investment project

Parameter	Value	Researched effect
PVP unit cost ratio, p.u.	0.3-1.3	NPC, LCOE
EESS unit cost ratio, p.u.	0.3-1.3	NPC, LCOE
Electrical power and energy tariffs, p.u.	1-5	NPV, DPP
CO_2 emissions quotas, $/t/rub./t	0-100/0-7732	NPV, DPP

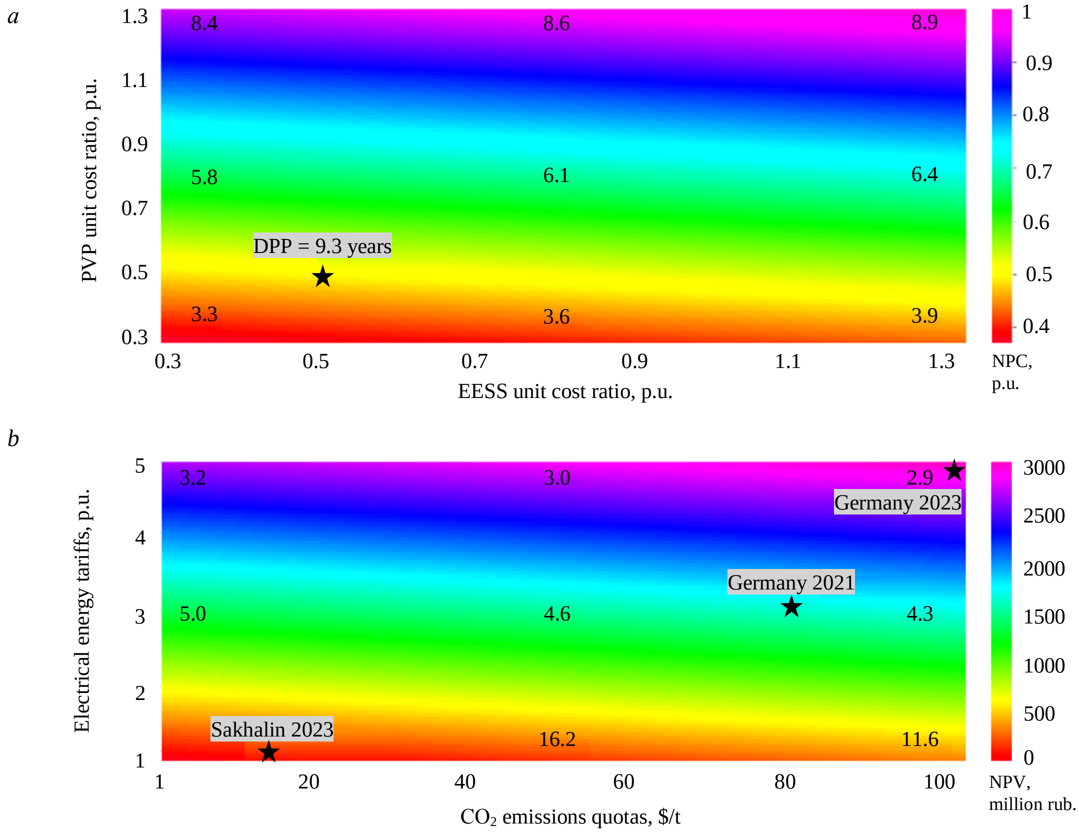

Fig.7. Sensitivity analysis of investment project results: *a* – PVP and EESS unit cost ratio impact on NPC and LCOE (LCOE values is shown on top of the figure); *b* – CO_2 emissions quotas (NPC – const) and electrical power and energy tariffs impact on NPV and DPP (DPP values is shown on top of the figure)

According to calculations, the unit cost of RES and EESS has decreased significantly over the past 10 years. Figure 7, *a* shows the effect of changing capital costs and LCOE in relation to current conditions.

The data in Fig.7, *a* show that the LCOE and NPC values can be reduced by up to 50 % if the unit costs of PVP and EESS are reduced by 70 %. It should be noted that in the Russian Federation the unit cost of renewable energy generation is 2-4 times higher than the world average, which creates significant barriers to the implementation of such projects. However, even a two-fold reduction in prices will reduce the payback period only to 9 years.

The cost of electricity and the cost of quotas impact on emissions is shown in Fig.7, *b*.

According to Fig.7, *b*, with an increase in the cost of emission quotas to the European level (80-100 $/t CO_2/6186-7732 rub./t CO_2), the level of investment attractiveness of the project (DPP) remains insufficient (≈11 years). In the case of setting the cost of quotas for CO_2 emissions equal to the values in the Sakhalin experiment (1000 rub. ≈ 12.8 $/t CO_2) of limiting greenhouse gas

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emissions[10], the payback period is reduced to only 18 years, which also remains unacceptable. It should be noted that tariffs for electric energy and power have the greatest impact on the payback period of such projects. Project does not pay off with the current tariff values. With electricity tariffs at the level of prices for industrial consumers in Germany in 2021[11] (0.21 \$/kW·h/16.24 rub./kW·h), the payback period is reduced to 4.5 years. With the current electricity price level (0.4 \$/kW·h/30.93 rub./kW·h in 2023), conditions are becoming even more favorable in Germany, which is helping to accelerate the development of renewable energy. In Russia, such conditions have not been created at the moment, and a renewable energy sources capacity delivery agreements is not designed to support industrial consumers. Thus, even in the context of the creation of a market for CO_2 emissions quotas and pricing at the level of the Sakhalin experiment, renewable energy at enterprises of the mineral resource complex in Russia remains unattractive and requires additional support.

Conclusions. Global goals to achieve carbon neutrality create new challenges for Russian enterprises of mineral resource complex. At the same time, additional problems arise that increase social tension, in particular, the reduction of jobs employed at coal mining enterprises, and, as a result, active depopulation and a decrease in the standard of living of single-industry towns. One of the options for solving the above problems is the introduction of RES. To evaluate the feasibility of this approach, the authors analyzed the RES potential of nine coal-mining regions of Russia and selected the Rostov region for further investigation. To assess the prospects for the introduction of renewable energy sources, the author's computer program was used, which allows modeling electric power balances when implementing RES generation. In further studies, it is planned to perform a feasibility study on the creation of a hydrogen cluster based on the infrastructure of a coal mine.

The presented study is important from the perspective of the climate agenda and achieving carbon neutrality in the Russian Federation by 2060. It shows that in the conditions of the Russian electricity and capacity market, even if a market for CO_2 emissions is created, additional funding will be required for projects to introduce RES at enterprises of MRC to ensure their payback. Thus, according to the authors' opinion, it is advisable to develop measures of state support for the decarbonization of enterprises of mineral resource complex to stimulate projects for their "greening".

The effectiveness of RES implementation also depends on the daily electrical load profile. In cases where power consumption and generation peaks do not align (and grid output restrictions exist), EESS are necessary to correct the RES generation profile and prevent the limitation of generated power. This requirement increases investments in the hybrid energy complex and extends its payback period. However, in the considered case of the implementation of a hybrid energy complex at a 24/7 operation enterprise, the entire potential of solar generation is utilized as there is no reduction in power consumption during peak solar activity hours.

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Authors**: Fedor S. Nepsha,** *Candidate of Engineering Sciences, Senior Researcher, Associate Professor, nepshafs@kuzstu.ru, https://orcid.org/0000-0002-7468-2548* (*T.F.Gorbachev Kuzbass State Technical University, Kemerovo, Russia*; *National University of Oil and Gas* "*Gubkin University*", *Moscow, Russia*), **Kirill A. Varnavskiy,** *Doctor of Philosophy, Head of Laboratory, https://orcid.org/0000-0001-7116-8765* (*T.F.Gorbachev Kuzbass State Technical University, Kemerovo, Russia*), **Vyacheslav A. Voronin,** *Candidate of Engineering Sciences, Senior Researcher, https://orcid.org/0000-0002-7242-9100* (*T.F.Gorbachev Kuzbass State Technical University, Kemerovo, Russia*), **Ilya S. Zaslavskiy,** *Technician, https://orcid.org/0000-0001-9226-6022* (*T.F.Gorbachev Kuzbass State Technical University, Kemerovo, Russia*), **Andrey S. Liven,** *Technician, https://orcid.org/0000-0001-9138-6858* (*T.F.Gorbachev Kuzbass State Technical University, Kemerovo, Russia*).

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