

Article

Achieving Sustainable Development Goals Through Hybrid Energy Supply Systems in Mining: The Case of the Varvarinskoye Copper–Gold Deposit

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Abstract

Many companies in the mining industry include decarbonization of production among their key strategic goals as part of their internal sustainability strategy. This need is driven by a number of factors: stricter regulation in the area of carbon footprint (introduction of carbon taxes, emissions quotas, reporting requirements); sustained growth in demand for electricity and rising market prices; economic feasibility—the need to optimize operating costs and improve energy efficiency. This study provides a comprehensive technical and economic justification for implementing a hybrid power supply system—combining a solar power plant (SPP) and a gas engine power plant (GPP)—at Solidcore Resources' Varvarinsky hub in Kazakhstan. The methodology includes modeling the energy balance of the real asset (156.9 GWh of annual energy consumption), calculating the output of a 22.6 MW SPP based on local GHI/PR/η parameters, forming and determining the adaptability coefficient K_a (proportion of PV in total monthly electricity generation), conducting an economic assessment (NPV, payback period, sensitivity), and inventorying CO₂ emissions under Scope 1–2. The SPP provides approximately 41.3 GWh of electricity generation per year, with an average annual $K_a = 0.263$; the 40 MW installed capacity of the gas piston power plant covers the residual demand, forming a stable daily and seasonal balance. The project demonstrates a positive NPV (After Tax) = USD 23.65 million with an estimated payback period of 10 years, while the cost of energy in extraction and processing is reduced by almost three times, and the total reduction in CO₂ emissions will be 51%. Thus, hybridization of energy supply systems is a practical compromise between reliability and decarbonization. Determining the adaptability coefficient K_a allows the flexibility of the system to be taken into account, shows how effectively the new energy system uses renewable energy sources, and can be used to optimize the operation of the energy system to achieve the company's internal sustainable development goals.

Keywords: sustainable development; hybrid energy systems; mineral resource management; responsible mining; economic efficiency; solar power plant (SPP); gas engine power plant (GPP); copper–gold deposit; decarbonization



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1. Introduction

Mining companies are among the most energy-intensive industrial enterprises and face growing pressure to improve economic efficiency while simultaneously improving

environmental performance [1,2]. At the same time, the global energy system is undergoing structural changes; low-emission sources continue to expand, but growing demand for electricity and the inertia of outdated assets mean that fossil fuels will continue to play a critical role in ensuring system adequacy in the near term [3,4].

Figure 1 shows the projected dynamics of global primary energy supply under two scenarios: “Current Trajectory” and “Below 2°”. Renewable energy sources, including solar, wind, bio and geothermal, will increase more than two-and-a-half to three-and-a-half times by 2050, gradually replacing coal and oil in the global energy balance. Despite this rapid growth, fossil fuels, especially natural gas, will retain a significant proportion; gas demand in the baseline scenario will increase by about 20% and will only decline in the event of accelerated decarbonization. Overall, oil will remain the dominant energy source until the middle of the century, while renewable energy sources and gas will provide about a quarter of total primary energy by 2050. Against this backdrop, energy supply strategies for mining facilities that combine cost control, operational reliability and measurable decarbonization are becoming increasingly strategic [5–7]. Hybrid on-site systems, particularly those that combine photovoltaic (PV) generation with gas engine power plant (GPP), offer a pragmatic approach to reducing purchased electricity, hedging tariff volatility and achieving sustainability goals without compromising production continuity [8,9].

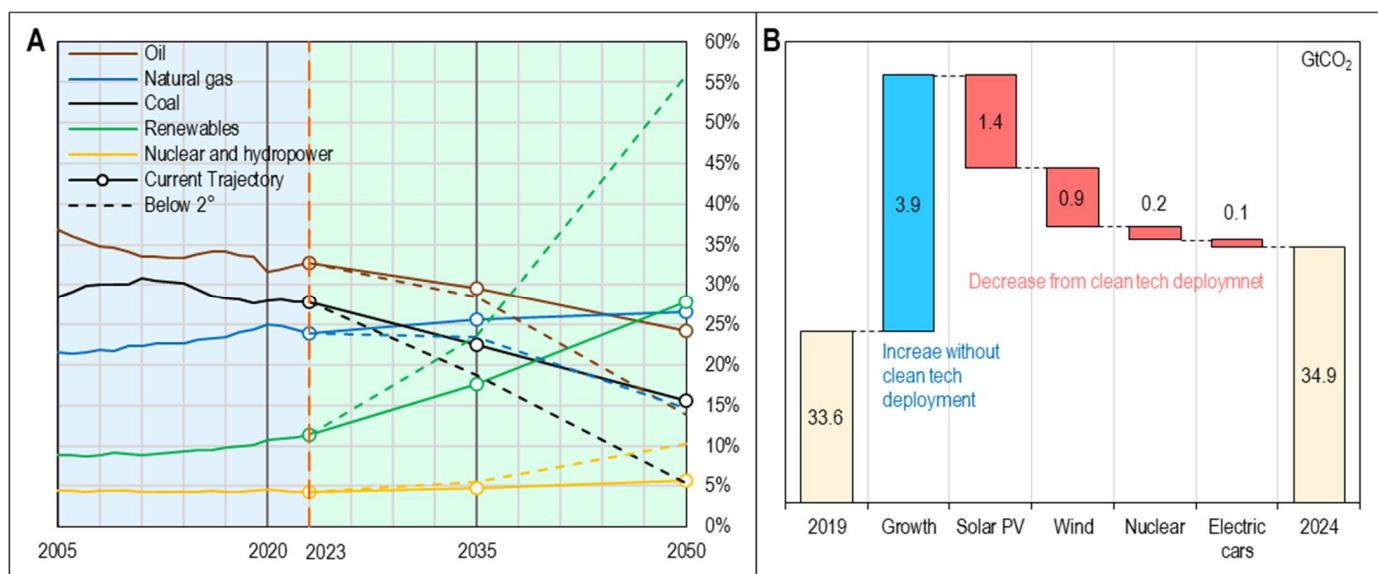


Figure 1. (A)—Primary energy pathways in the two scenarios [10]. (B)—Change in CO₂ emissions from fuel combustion and avoided emissions from deployment of selected clean technologies [11].

Recent studies on industrial energy efficiency highlight the dual effect of modern low-carbon technologies; in addition to direct energy savings and reduced operating costs, companies often reap the associated benefits of innovation and labor market gains, which are consistent with sustainable development goals [12–14]. In the literature on the energy sector, global assessments indicate that achieving deep decarbonization by mid-century will require both large-scale use of renewable energy sources and accelerated efficiency improvements and digitalized logistics enhance competitiveness while maintaining grid stability and affordability for energy-intensive industries, including mining [15–17].

At the same time, a number of contradictions and discrepancies in hypotheses complicate the situation. First, “clean” technologies are not resource-neutral; the supply chains for wind, solar energy and electric vehicles are material-intensive and depend, among other things, on copper and rare earth elements (REEs) [18–20]. The risks of concentration are not trivial—processing and component manufacturing are geographically clustered, creating

strategic vulnerabilities for energy transitions that depend on the mining industry [21,22]. Second, the environmental impact of renewable energy sources throughout their life cycle remains a subject of debate; land use, plant material balance, end-of-life management, and hazardous waste treatment can negate some of the gains in operational emissions if not properly regulated [23,24]. These contradictions motivate technical and economic projects that deliver clear sustainability benefits and withstand shocks in the supply chain, politics and the market.

Levelized cost of electricity (LCOE) estimates for industrial photovoltaic installations in Asia have fallen to competitive levels ($\approx \$0.044/\text{kWh}$), but project viability depends on specific irradiation, performance coefficients, discount rates, and integration costs [25]. In contrast, in many mining regions, retail or wholesale electricity prices remain several times higher, strengthening the economic case for on-site power generation, subject to capital investment and the necessary financing conditions [26,27]. Some methodologies also note potential biases in mainstream LCOE reports and the need to compare them with local market data and actual operating performance [28]. Finally, investment frictions—high upfront costs, high technological risk and policy uncertainty—can hinder adoption, so government incentives and carbon pricing schemes are often drivers that facilitate the financing of green projects in the extractive industry [29,30].

Occupational safety is also part of the economic calculation of a mine's capacity [31,32]. Photovoltaic installations are associated with specific electrical and fire hazards that require engineering protection, monitoring and operating protocols, as there are risks associated with ignition, noise and vibration at the gas processing plant, which are regulated by certified maintenance regimes and emergency procedures [33–35]. Integrating these factors into the project assessment brings the economics of hybrid energy into line with ESG requirements common to modern mineral resource management [36,37].

The aim of this study is to develop and apply a decision-oriented model to justify the feasibility of using hybrid energy supply systems based on a combination of solar power stations and gas engine power plant (GPP) at mining enterprises to achieve sustainable development goals. To achieve this goal, a number of tasks need to be solved:

- Modeling the energy balance of a real mining asset.
- Quantitative assessment of technical and economic indicators (NPV, IRR, payback period) and risk (sensitivity to key variables).
- Assessment of associated environmental and social impacts.

To account for seasonal variability in resources and the complementarity of dispatch services, this study introduces the adaptive energy system coefficient (K_a), the ratio of photovoltaic energy generation to the total capacity of hybrid systems over a given period.

2. Materials and Methods

2.1. Geographical Overview and Production Indicators

The Varvarinskoye field is a center for gold and copper mining and processing in the Kostanay region in northwestern Kazakhstan (Figure 2). The field is located approximately 130 km southwest of the Kostanay city, approximately 35 km from Taranovka and approximately 4 km from the border with Russia. The site is accessible by paved roads; there is a railway connection between Tobol (65 km) and Bataly (15 km). Solidcore Resources, Astana, Kazakhstan (formerly Polymetal International) has been operating this asset since 2009 as a regional processing center. In 2015, a dedicated 13 km railway line was commissioned to speed up ore logistics. As of 1 January 2025, reserves stood at 17.6 million tons at 0.8 g/t gold (473,000 ounces of gold equivalent) [38].

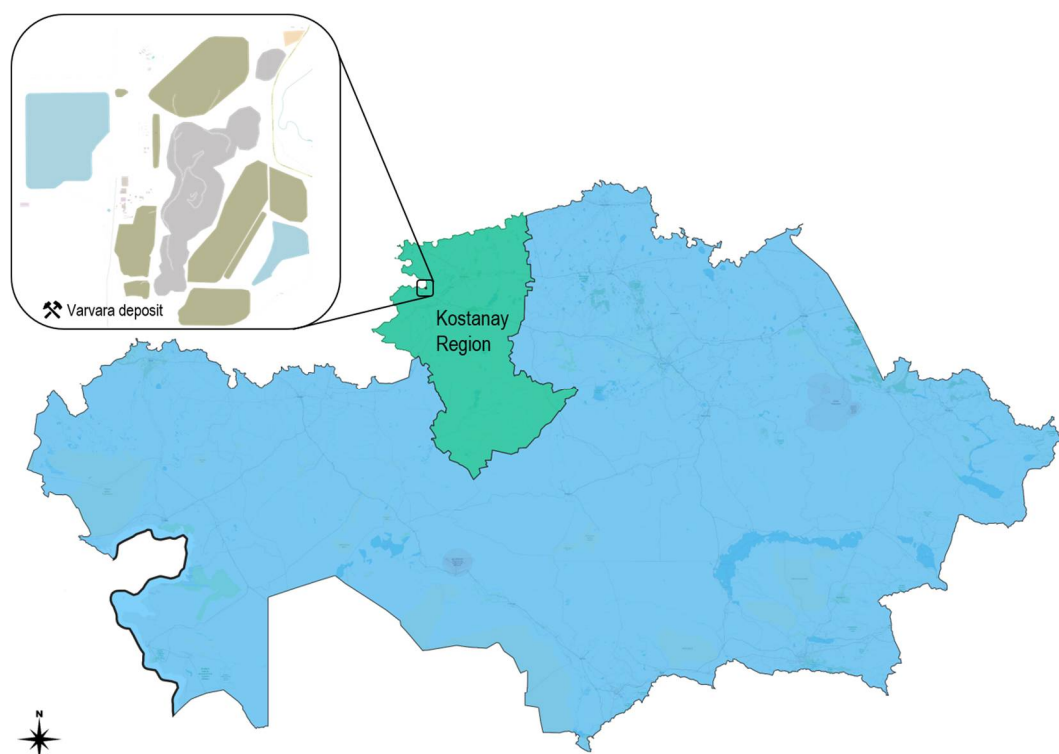


Figure 2. Geographical location of Varvarinskoye field. Adapted from [38] using QGIS Desktop 3.34.0.

2.2. Energy Balance

The annual electricity demand at the Varvarinsky field is 156.9 GWh. Most of the electricity is consumed by the gold extraction plant (GEP), as well as the mine, auxiliary manufactory, transport and technological facilities, and the field camp. The structure of planned electricity consumption by field sites is shown in Table 1.

Table 1. Planned indicators of electricity consumption.

	Electricity, GWh	Processing, Extraction, t (m ³)	Flow Rate, kWh/t (m ³)
Gold-Processing plant	137.34	3,746,633	36.7
Mining Site	4.05	1,517,940	2.7
Auxiliary production	5.08		
Section of quarry and technological transport	1.09		
Shift settlement	3.07		
Own needs and losses	6.23		
Total for the company	156.87		

Source: company data.

Currently, power supply is carried out mainly due to purchased electricity from the grid, the wave structure of the energy balance of the field can be viewed in Figure 3.

Thus, nowadays, the energy supply of Varvarinsky is mainly provided by purchased electricity. To meet the strategic goal of the company's sustainable development and increase energy efficiency, a hybrid energy supply system is being designed based on a combination of a solar power plant (SES) and a gas engine power plant (GPP).

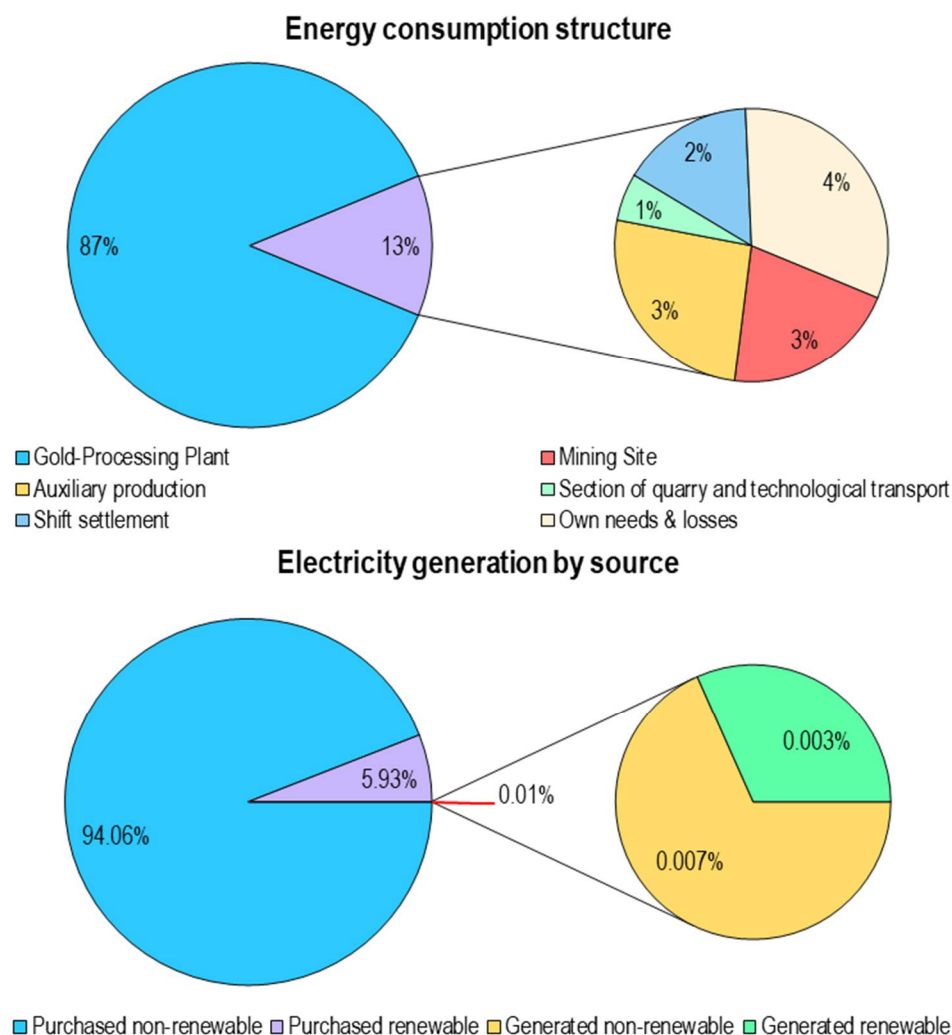


Figure 3. Energy consumption and production structure. Source: company data.

2.3. Hybrid Energy Supply Project

In order to meet the company's strategic goal (and, more broadly, the national goal of carbon neutrality by 2060) and improve energy efficiency (achieving cost reduction and decarbonization of production processes), the company is developing a hybrid power supply system consisting of a 22.6 MW photovoltaic plant using high-efficiency HJT modules (Unigreen Energy) and a gas engine power plant (GPP) with a capacity of up to 40 MW, designed as a controllable supplement to the photovoltaic power plant.

Currently, heterojunction technology (HJT) ranks among the world's most efficient photovoltaic solutions, ensuring stable performance parameters that guarantee product quality.

When choosing solar panel technology for the Varvarinskoye copper and gold deposit located near the village of Kostanay, several key factors must be taken into account:

- Kazakhstan's climate, characterized by hot summers and cold winters, necessitates solar panels with a low temperature coefficient of power to maintain efficiency across extreme temperature ranges.
- Gold mining sites typically experience high levels of dust and airborne particulates. This requires photovoltaic technology with minimal initial degradation to ensure long-term performance stability in polluted environments.
- High panel efficiency is critical, making solutions with the highest possible conversion rates the preferred choice.

Based on these criteria, HJT and IBC (interdigitated back contact) technologies emerge as the most suitable options. These technologies offer:

- optimal performance during sunny days;
- thermal stability at high temperatures;
- reliable long-term operation under challenging conditions.

A comparative analysis of solar panel technologies and environmental parameters are provided in Appendix A (Table A1, Table A2).

For the construction of the plant, gas piston engines from the Finnish company Wärtsilä [39] will be used, based on technology that allows generating the full capacity of the power plant with an unstable volume of gas fuel supply. The advantages of a gas piston power plant include its high efficiency, since the efficiency of a GPP can reach 40–45%, and with cogeneration 90%, and the station starts and stops quickly. GPPs are more environmentally friendly than coal-fired ones, and biogas, hydrogen, and synthesis gas (a mixture of carbon monoxide and hydrogen) can be used. In addition, the possibility of cogeneration allows efficient use of the generated heat and reduces heating costs.

A conceptual diagram of the hybrid power supply system project for the Varvarinsky field is shown in Figure 4.

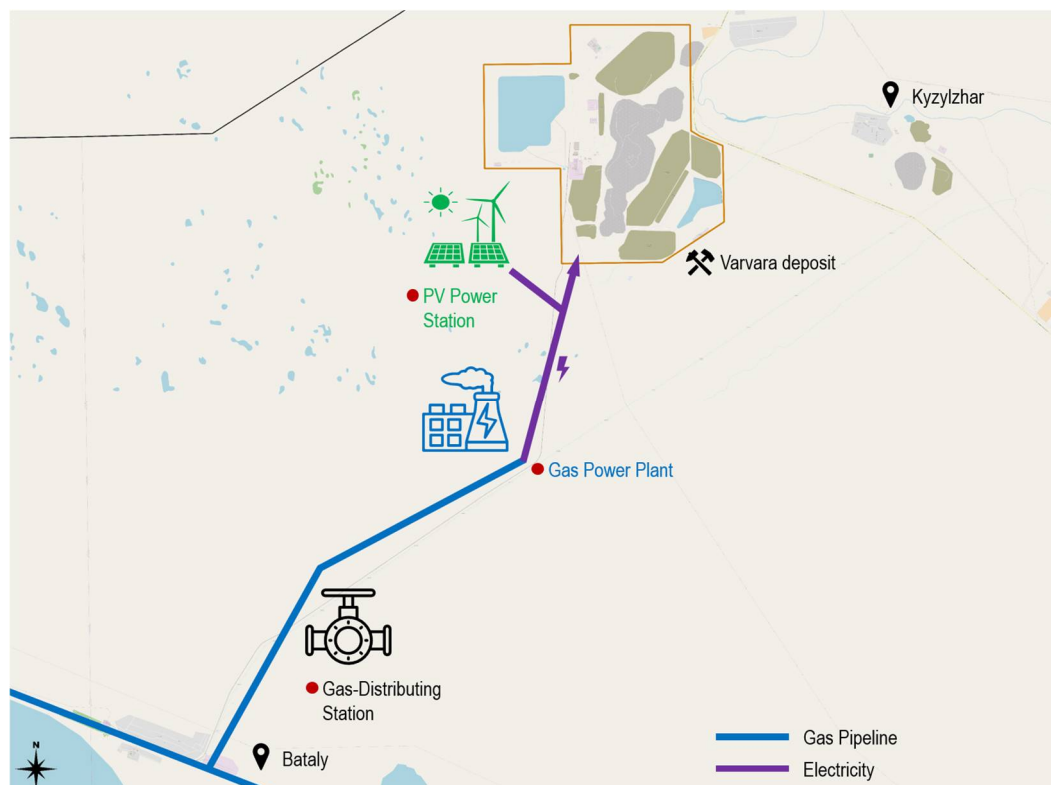


Figure 4. Conceptual scheme of the hybrid power supply system project. Compiled using QGIS Desktop 3.34.0.

The photovoltaic power plant is scheduled to be commissioned in 2025, and the GPP in 2025–2026. The site layout includes a gas distribution station (GDS) and branches from the national trunk line near the village of Bataly [40,41].

2.4. Methodology for Calculating Electricity Generation: Adaptability Coefficient

Figure 5 shows the number of cloudy and sunny days per month in the Kostanay city, plus the average daily number of hours of sunshine [42].

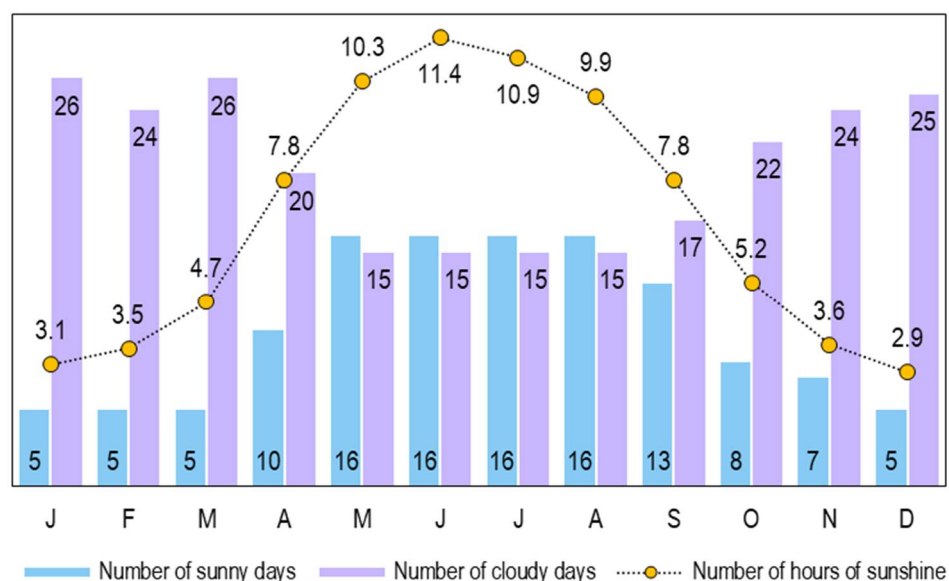


Figure 5. Number of sunny, cloudy days and insolation in Kostanay. Adapted from [42].

The average solar insolation in the city of Kostanay is 6.76 h per day; consequently, the enterprise will operate on purchased electricity for 17.24 h.

An approximate distribution of the SPP and GPP capacities over a 24 h period is presented in Figure 6. The chart is constructed as an approximation, based on the average insolation value of 6.76 h, and it demonstrates the mechanism of combined power generation by the two power plants. The SPP operates at its peak capacity of 22.6 MW during daylight hours. The GPP is activated at night and during periods of insufficient solar power generation, providing backup for the SPP during the night, morning, and evening hours by gradually ramping its output up and down.

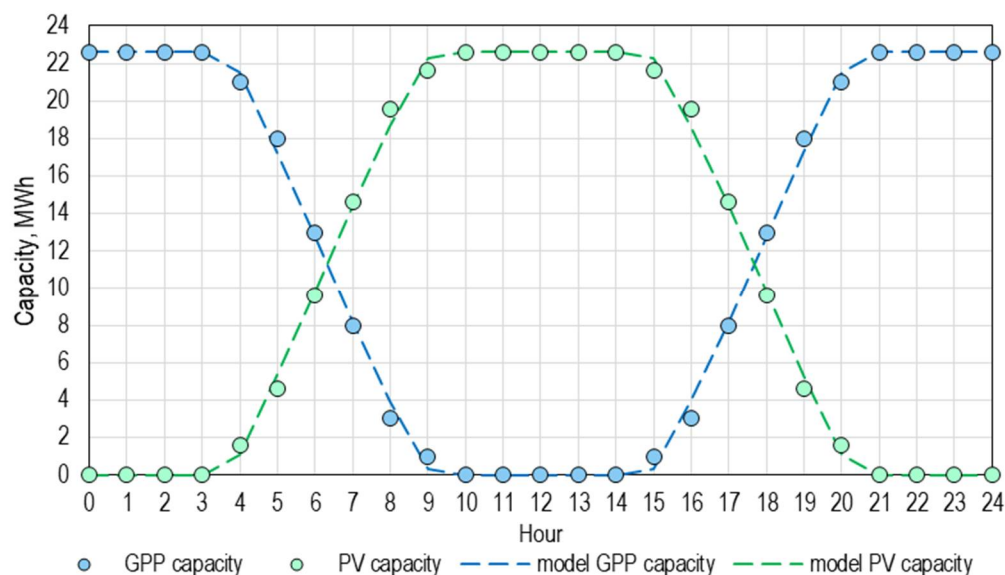


Figure 6. Distribution of PV and GPP capacities during the day.

The nature of the SPP (solar power plant) power output variation is close to a half sine wave (from dawn to dusk). Assuming a fixed rated capacity and symmetric irradiance conditions around solar noon, the SPP power output can be approximated by a sinusoidal

function with lower clipping (no generation at night) and upper saturation at the rated capacity. The relationship can be described by Formula (1):

$$\begin{cases} \text{Capacity}_{PV}(t) = \min[P_{\max}, \max(0, b + a \cdot \sin(\frac{2\pi}{24} \cdot (t - t_0)))], \\ \text{Capacity}_{GPP}(t) = P_{\max} - \text{Capacity}_{PV}(t). \end{cases} \quad (1)$$

where t is the hour of the day; $P_{\max}$ is the rated (maximum) PV capacity, $P_{\max} = 22.6$ MWh; a is the sinusoidal amplitude ($a = 17.5355$); t_0 represents the phase shift corresponding to sunrise time ($t_0 = 6$); b is a vertical offset accounting for the daytime plateau ($b = 9.8668$).

This model captures the main physical characteristics of PV generation: zero output at night, smooth ramp-up after sunrise, a possible flat-top around midday due to capacity saturation, and symmetric ramp-down toward sunset. The total monthly sunshine duration is calculated as the product of the number of sunny days per month and the average daily sunshine hours obtained from Figure 5. The total number of sunshine hours per year in the city of Kostanay is 997.2.

However, the power plant also operates on cloudy days, albeit at a lower capacity. For example, during sunny hours, the panel operates at 80–100% capacity, while on cloudy days it operates at 10–40%. To account for this factor, it is necessary to use the concept of full-load hours or effective hours H_{eff} , which indicates the amount of time required for a power plant to produce a given amount of energy if it were operating at full capacity (i.e., if the output were uniform) [43]:

$$H_{eff} = \frac{E}{P} \quad (2)$$

where H_{eff} is the full-load hours, h/year; E is the actual annual output of the SPP, kWh/m²; P is the installed capacity per 1 m², kWh/m², calculated using Formula (3):

where p is the rated capacity of a single panel, kWh; s is the area of a single panel, m².

The actual annual output of the SPP, kWh/m²/year [44]:

$$E = GHI \cdot \eta_{PV} \cdot PR, \quad (3)$$

where GHI is the global horizontal irradiance, kWh/m²/year; η_{PV} —panel efficiency, dimensionless; PR —performance ratio, dimensionless.

According to the Global Solar Atlas, the GHI for Kostanay is 1500 kWh/m²/year [45]. The efficiency of heterojunction bifacial photovoltaic modules from Unigreen Energy is 22%, and the rated capacity is 570 W per panel with an area of 2.63 m² [46]. The PR is a coefficient that indicates the total system losses, accounting for losses in inverters, cables, and transformers, as well as shading, soiling, panel heating, and the difference between standard factory test conditions and actual weather. For HJT panels, $PR = 0.8 - 0.82$ [47].

The number of panels, based on the maximum capacity, is determined by Formula (4):

$$N = \frac{P_{\max}}{p}. \quad (4)$$

The total area of the SPP panels is calculated as

$$S_{PV} = 1.5 \cdot N \cdot s, \quad (5)$$

where 1.5 is the coefficient accounting for the presence of inverters, access ways, and other infrastructure.

The actual annual output of the SPP, GWh, is

$$E_{PV} = 10^{-6} \cdot E \cdot S \quad (6)$$

The GPP will operate to prevent a drop in power generation and to cover the enterprise's remaining electricity demand. The calculation of the GPP output is presented in Formula (7):

$$E_{GPP} = Q - E_{PV}, \quad (7)$$

where Q is the annual electricity demand, GWh.

The annual gas volume required for the GPP operation:

$$V = \frac{E_{GPP}}{10^{-6} \cdot LHV \cdot \eta_{GPP}}, \quad (8)$$

where LHV is the lower heating value of the fuel, kWh/m³; η_{GPP} is the efficiency of the gas piston power plant, dimensionless.

The GPP efficiency is an indicator that shows what portion of the fuel energy is converted into electrical energy, and what portion is lost as heat, noise, etc. The GPP efficiency is assumed to be 40%, as gas piston power plants typically have an efficiency ranging from 35% to 45%. The calorific value of natural gas is 33.08 MJ/m³ or, equivalently, 9.19 kWh/m³, measured under standard conditions.

The introduction of an energy system adaptability coefficient (K_a) is proposed. This coefficient accounts for how the system responds to seasonal variations, as the solar power plant operates more in the summer, while the gas piston power plant operates more in the winter.

Energy system adaptability is its ability to withstand external factors while maintaining normal operation. The primary external factors implied are climatic conditions, as the number of sunshine hours varies monthly. In the process of energy system adaptation, the outputs of the two power plants—the gas piston and the solar—are adjusted based on the actual output of the SPP, thereby ensuring the constant generation of the required amount of electricity.

This coefficient allows for accounting of the system's flexibility. It indicates how effectively the new energy system utilizes renewable energy sources (the SPP) compared to the capacity of the GPP, which runs on purchased gas. By calculating this coefficient, the enterprise can assess the extent to which it can rely on solar energy and how the share of gas in power generation changes. This indicator is dynamic, as it is calculated on a monthly basis; its value will vary depending on the natural and climatic conditions during the period. The calculation of the coefficient is presented by Formula (9):

$$K_a(t) = \frac{E_{PV}(t)}{E_{GPP}(t) + E_{PV}(t)}, \quad (9)$$

where t is the period under consideration (from 1 to 12 months).

The coefficient values can range from 0 to 1. If $K_a = 1$, the system operates entirely on solar energy, and reserve capacities are not used. However, this situation is unlikely, as the power plant will not cover the entire electricity demand in winter or on cloudy days. If $K_a = 0.5$, half of the energy is generated by the SPP and the other half by the GPP. If $K_a = 0$, all energy is generated by the GPP, and the SPP is not operating. This situation may occur during prolonged periods of cloudy weather.

The average annual energy system adaptability coefficient represents the share of electricity generated by the solar power plant. The calculation of the average annual energy system adaptability coefficient is presented in Formula (10):

$$\overline{K_a} = \frac{\sum_{t=1}^{12} K_a(t)}{12}. \quad (10)$$

The coefficient can be used to optimize the energy system's operation. That is, if the coefficient is low, the enterprise is highly dependent on gas, and it is necessary, for example, to implement batteries for storing energy from the SPP. This would help maintain the required level of power generation, aligning with the company's goals of replacing fossil fuels with renewable energy (Solidcore Resources aims to achieve a 30% share of renewable energy in the company's total energy consumption by 2030, and a 7% share for the Varvarinskoye field). If the coefficient is high, the GPP capacity can be reduced. Furthermore, the coefficient demonstrates resilience to seasonal fluctuations, meaning it is possible to track the system's efficiency across different months and identify periods when gas costs will be higher.

2.5. Economic Model

2.5.1. Macroparameters and Fiscal Terms

The electricity cost for the Varvarinskoye deposit, located in the Kostanay Region (northwest Kazakhstan), was USD 0.23 per kWh in 2023, according to Solidcore Resources.

The marginal price in tenge per thousand cubic meters, excluding value-added tax and the US dollar exchange rate in tenge, is presented in Table 2.

Table 2. Marginal Gas Price Excluding VAT and Exchange Rate.

Date	Gas Price, KZT/1000 m ³ [48]	Exchange Rate, KZT/USD [49]	Gas Price, USD/1000 m ³
1 July 2023–30 June 2024	22,387	456.5	49.0
1 July 2024–30 June 2025	25,521	505.1	50.5
1 July 2025–30 June 2026	33,379	473.0 *	70.6
1 July 2026–30 June 2027	36,478	473.0 *	77.1
1 July 2027–30 June 2028	58,365	473.0 *	123.4

* Average value for the preceding 3 years (1 July 2022–1 June 2025).

The discount rate is taken as the WACC value, calculated using the formula

$$WACC = \omega_E \cdot K_E + \omega_D \cdot K_D \cdot (1 - T), \quad (11)$$

where ω_E , ω_D are the share of equity and the share of debt capital, respectively; K_D is the effective cost of debt; T is the corporate income tax rate in Kazakhstan; K_E is the cost of equity, calculated using the CAPM model,

$$K_E = R_f + \beta \cdot ERP_{Kaz}, \quad (12)$$

where R_f is the risk-free rate (yield on 10-year government bonds, 17%); β is the beta coefficient; ERP_{Kaz} is the country risk premium for Kazakhstan.

According to the Tax Code of the Republic of Kazakhstan, the corporate income tax rate for legal entities is 20% [50]. The profit is the economic effect, equal to the difference in profit before and after the project.

The property tax rate in Kazakhstan is 1.5% [51].

2.5.2. Capital and Operating Expenditures

Capital investments for the entire project are presented in Figure 7. All facilities are currently at the pre-FEED (Front-End Engineering Design) stage [38].

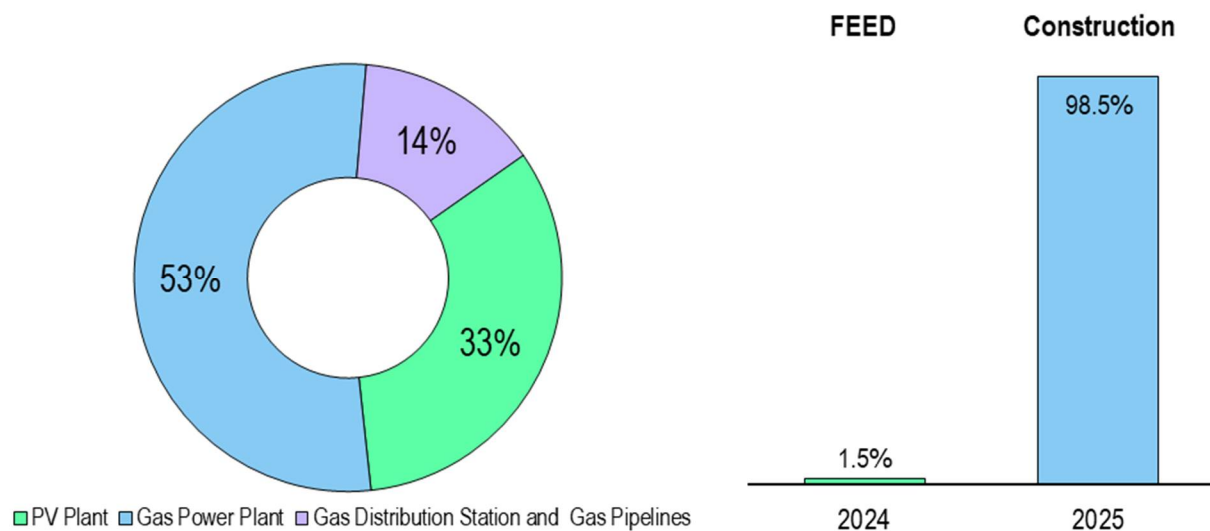


Figure 7. Structure of CAPEX of the Project.

The operating costs for the SPP are assumed to be equal to the LCOE (Levelized Cost of Energy) as the average estimated cost of producing 1 kWh of electricity over the entire life cycle of the power plant [25,52,53].

The operating costs for the GPP include labor costs, social contributions, maintenance, materials and spare parts, administrative expenses, equipment insurance, other expenses (environmental fees, metrological studies, audits), and depreciation calculated using the straight-line method (Figure 8).

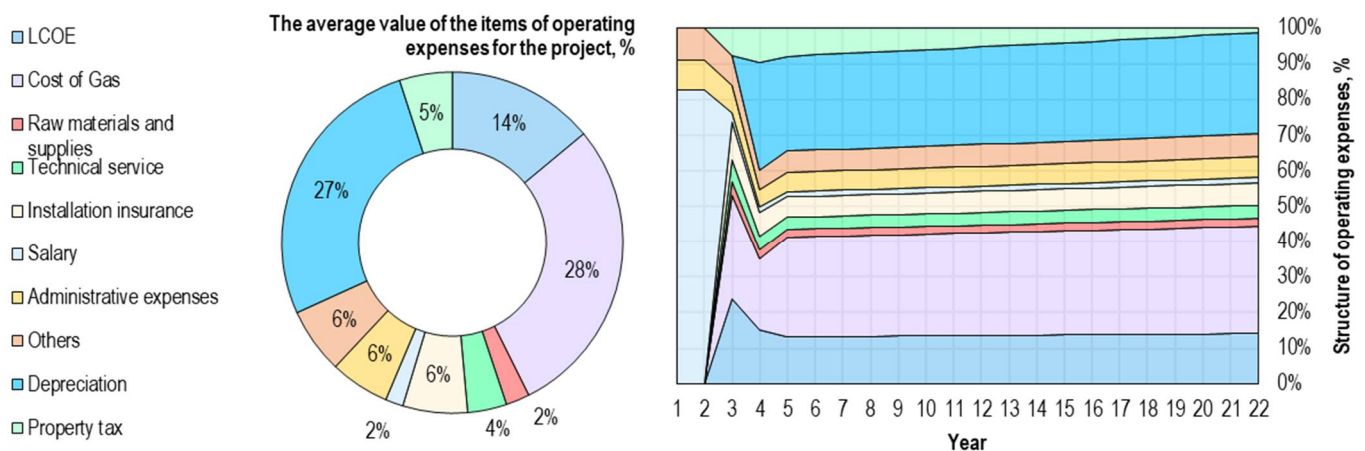


Figure 8. Structure of OPEX of the Project.

The economic effect of the project to switch to hybrid power supply can be assessed using Formula (13):

$$E_{econ} = Q \cdot \text{Price}_{energy} - LCOE - 10^{-3} \cdot V \cdot \text{Price}_{gas} - C_{GPP} - D - \text{Tax}_{property}, \quad (13)$$

where E_{econ} is the economic effect, USDM; Price_{energy} is the price of purchased electricity, \$/kWh; Price_{gas} is the gas price for the GPP, \$/1000 m³; C_{GPP} is the GPP operating costs, USDM; D is the depreciation of fixed assets, USDM; $\text{Tax}_{property}$ is the property tax, USDM.

Then, the net profit can be estimated as

$$NP = \begin{cases} E_{econ}, & \text{if } E_{econ} < 0 \\ E_{econ} \cdot (1 - T), & \text{otherwise} \end{cases} \quad (14)$$

The project's net present value after corporate income tax, in USDM, is calculated as

$$NPV_{\text{After Tax}} = \sum_{i=0}^N \frac{NP_i - CAPEX_i + D_i}{(1 + WACC)^i}. \quad (15)$$

3. Results

3.1. Adaptability Coefficient and Energy Balance

After implementing the hybrid power supply system, the annual output of the SPP with an installed capacity of 22.6 MW and the given parameters GHI, PR, and η provides approximately 41.3 GWh of electricity; the remaining part of the annual demand is covered by the GPP according to Equation (7). Monthly values of $Ka(t)$ demonstrate pronounced seasonality (summer peaks and winter minima), reflecting the complementarity of the SPP and GPP (Figure 9).

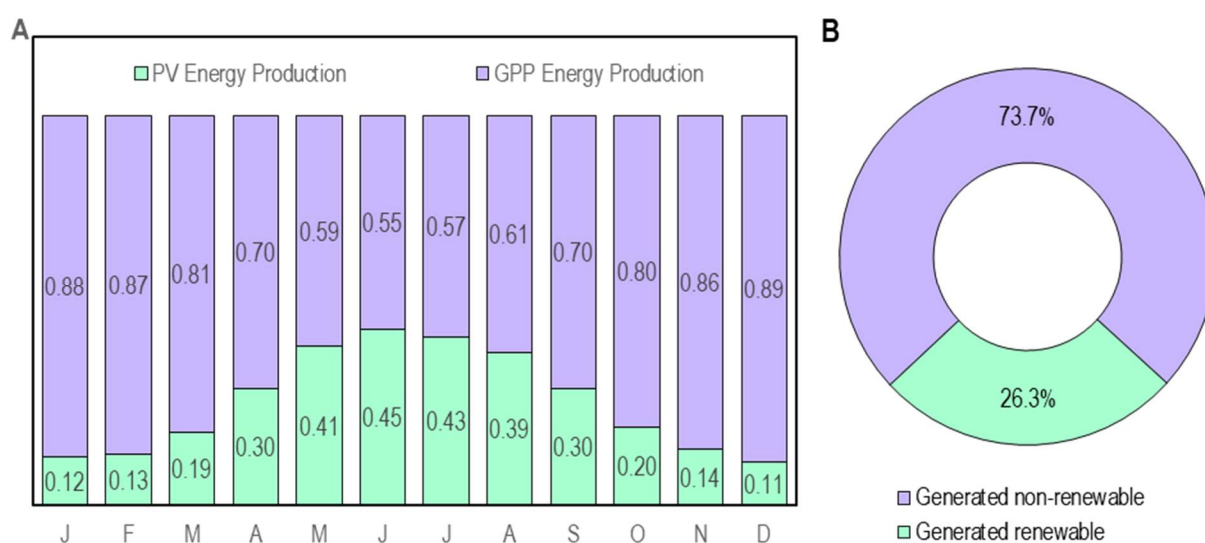


Figure 9. (A) is the energy balance after the project implementation. (B) is the coefficient of adaptability by month.

The average annual adaptability coefficient is 0.263, i.e., the SPP contributes 26.3% to the total output of the hybrid system (Figure 9). This confirms the validity of the system “adaptability” concept; as solar resource availability increases, the SPP share grows, while the GPP automatically performs a balancing role without energy curtailment to the grid or load.

From a strategic standpoint, the achieved SPP contribution of 26.3% significantly exceeds the group's minimum renewable electricity target of 7%, thereby providing a substantial margin for compliance under conservative solar resource assumptions. Moreover, the scalability of the proposed hybrid system allows for future capacity expansion or integration with additional low-carbon technologies, further improving resilience to regulatory, market, and fuel price uncertainties. Collectively, these results confirm that the hybrid SPP–GPP system represents a technically robust and economically viable pathway for increasing the share of on-site renewable electricity generation while maintaining supply security.

3.2. Economic Effect and Sensitivity Analysis

The project achieves payback within 10 years, reaching an NPV after tax of USD23.65 million (NPV before tax = USD49.78 million) (Figure 10). Sensitivity analysis was performed for four parameters: CAPEX, OPEX, Energy Price, and LCOE. The

Energy Price exhibits the highest elasticity—a 1% change in Energy Price leads to a 6.72% change in NPV. CAPEX changes have a smaller effect (4.31%), while LCOE impacts the project minimally (0.41%).

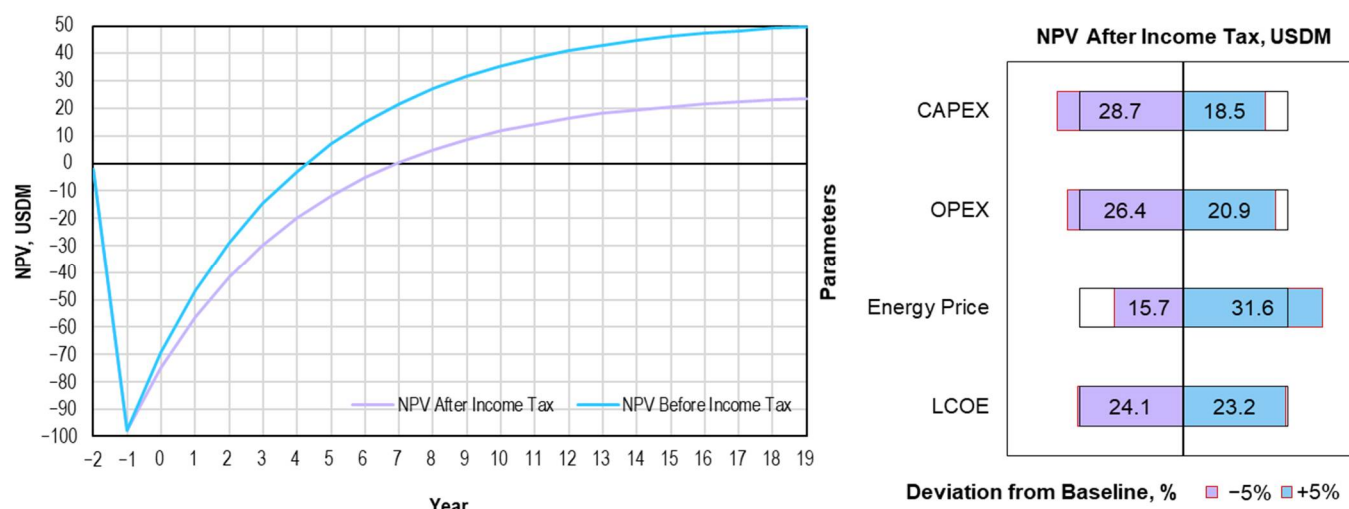


Figure 10. NPV of the project and sensitivity analysis.

The reduction in production costs is reflected in extraction and processing as follows:

- The energy consumption rate for mining 1 m³ of ore (Table 1, Figure 3) is 2.7 kWh. Before the project, the energy cost of mining 1 m³ of ore was 2.7 kWh/m³ × 0.23 US\$/kWh = 0.61 US\$/m³, while after the project it will be 2.7 kWh/m³ × 0.083 US\$/kWh = 0.22 US\$/m³. In other words, energy-related mining costs decrease almost threefold.
- The energy consumption rate for processing 1 ton of ore (Table 1, Figure 3) is 36.7 kWh. Before the project, the energy cost of processing 1 ton of ore was 36.7 kWh/t × 0.23 US\$/kWh = 8.44 US\$/t, and after the project, it will be 36.7 kWh/t × 0.083 US\$/kWh = 3.03 US\$/t. Thus, energy-related processing costs decrease nearly 2.5 times.

3.3. Environmental and Social Effect, Government Revenue

Considering corporate and national decarbonization targets, the environmental efficiency of the project regarding CO₂ emissions should be evaluated.

With the implementation of the SPP and GPP, Scope 2 emissions (indirect) are expected to decrease significantly, as the company will no longer purchase electricity in the same volumes. Scope 1 emissions (direct), i.e., from on-site fuel combustion (gas, diesel at the facility, fuel for machinery), are expected to increase because the GPP emits CO₂ during natural gas combustion.

Therefore, it is necessary to calculate CO₂ emissions from the GPP while accounting for the portion of electricity supplied by the SPP, which avoids CO₂ emissions.

CO₂ emissions from natural gas combustion are calculated using Equation (16),

$$Q_i^{CO_2} = V_i^{gas} \cdot k, \quad (16)$$

where i is the current period, and k is the coefficient representing the amount of CO₂ emitted per 1000 m³ of gas, $k = 1.87$ t CO₂/1000 m³.

Thus, the annual CO₂ emissions will amount to 70.4 kt CO₂ (Scope 1—68.9 kt CO₂, Scope 2—1.44 kt CO₂). CO₂ emissions before and after the project are presented in Figure 11.

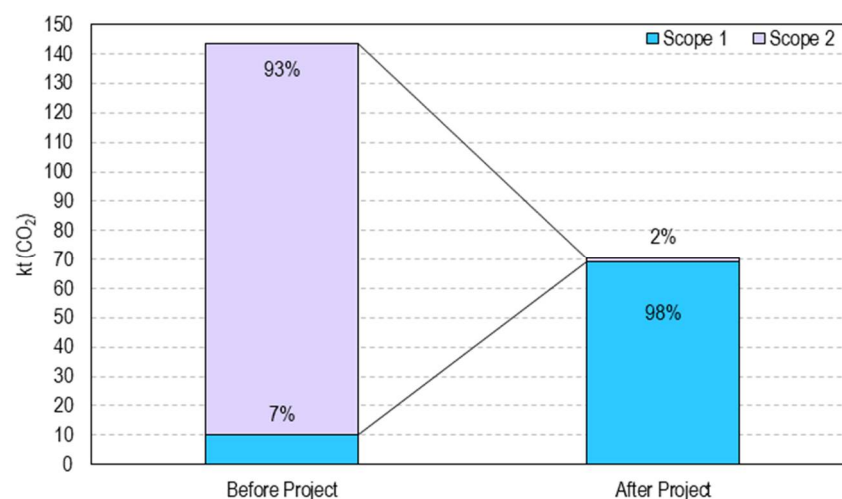


Figure 11. Data on CO₂ emissions before and after the project.

Baseline CO₂ emissions at Varvarinskoye field: 143.6 kt CO₂ (Scope 1—10.3 kt CO₂; Scope 2—133.3 kt CO₂). A hybrid energy system will cut CO₂ emissions by 73.2 kt CO₂. Scope 1 emissions are the sum of pre-project and post-project values since transportation emissions remain at the facility. Indirect emissions decrease by 99%, with 1% assumed for any necessary electricity purchases. Overall, the project allows a 51% reduction in CO₂ emissions, contributing to the company Solidcore Resources' goal, stated in the integrated report, to increase the share of renewables in total electricity production and reduce CO₂ emissions by 2030.

In addition to the base case without carbon revenue, two alternative scenarios were considered, incorporating potential income from the sale of avoided CO₂ emissions at carbon prices of 1 USD/t and 10 USD/t, respectively.

The results indicate that, at a carbon price of 1 USD/t, the NPV after income tax increases by approximately 0.32 million USD compared to the case without carbon credit revenues (USDM 23.65 and USDM 23.97). Under a higher carbon price assumption of 10 USD/t, reflecting potential future carbon market developments or the application of shadow carbon pricing, the NPV increases by approximately 3.22 million USD (USDM 23.65 and USDM 26.87).

These findings demonstrate that the project's economic performance is moderately sensitive to low carbon-price levels and highly sensitive to higher carbon-pricing scenarios, thereby enhancing the forward-looking robustness of the economic assessment under evolving emissions trading and climate policy frameworks.

Additionally, the project can be evaluated in terms of broader environmental impact beyond greenhouse gas emissions. A comparative table of SPP, GPP, and thermal power plants (TPP) regarding key environmental parameters is provided in Appendix A. TPPs serve as the baseline, as in Kazakhstan, the majority (70%) of electricity is generated by coal-fired TPPs, and there are no nuclear power plants [54]. Among the considered energy sources, SPP demonstrates the lowest environmental impact; it produces no pollutant emissions, has low noise levels, minimal water consumption, and generates no operational waste. The GPP has moderate environmental impact—emissions exist but are several times lower than those of a TPP, which is the least environmentally friendly option.

As part of the investigation, a preliminary evaluation was performed on the feasibility of deploying energy storage systems (ESS) with a capacity of 90.4 MWh—sufficient to provide 2–4 h of operation at 22.6 MW. The assessment examined three distinct battery technologies: LiFePO₄ (lithium-iron-phosphate); AGM and GEL (lead-acid); LTO

(lithium-titanate). According to preliminary estimates, the system cost will range from USD 10.4 million to USD 40.2 million, representing 12.1–50.5% of the total project cost.

The project also creates 15 additional jobs. The budgetary efficiency (discounted government revenue), including corporate income tax, property tax, social contributions, and personal income tax, is estimated at USD 31.1 million.

3.4. Scenario Analysis of the Hybrid Power Supply System Integration Project for the Varvarinsky Field

In light of the multifaceted determinants influencing the performance metrics of the project aimed at integrating hybrid power solutions into the energy supply infrastructure of the Varvarinsky field, a comprehensive scenario analysis was undertaken. This analysis systematically evaluated three distinct trajectories for project development and adaptation over the implementation horizon.

The analytical framework comprises the following scenarios:

Scenario 0: Baseline (Reference) Scenario. Serving as the counterfactual benchmark, this scenario assumes continuation of the existing energy supply configuration without the introduction of either carbon pricing or energy storage systems. It provides a foundation for comparative assessment, enabling quantification of incremental benefits and costs associated with the alternative scenarios.

Scenario 1: Introduction of an Emissions Trading System (ETS) in the Republic of Kazakhstan. Effective from 2026, this scenario envisages the institutionalization of a carbon market mechanism. It incorporates a progressive escalation in the price of CO₂ emission allowances, from USD 1 per ton in 2026 to USD 5 per ton by 2030. The design reflects a policy-driven approach to internalize the environmental costs of fossil-fuel-based energy generation.

Scenario 2: Enhancement of System Adaptability via Battery Energy Storage Deployment. This scenario focuses on technological modernization through the integration of an energy storage system; the ESS is specified with a nominal power capacity of 22.6 MW, intended to augment grid flexibility, mitigate intermittency of renewable sources, and optimize load management. The primary objective is to increase the system's resilience and operational efficiency through energy time-shifting and ancillary services.

Scenario 3: Synergistic Integration of Carbon Regulation and Energy Storage. This composite scenario combines the regulatory framework of Scenario 1 with the technological intervention of Scenario 2. It accounts for both the adoption of carbon pricing mechanisms in Kazakhstan and the capital investment required for ESS deployment. The scenario aims to capture potential synergies between regulatory compliance and infrastructure modernization, potentially yielding enhanced economic and environmental outcomes.

The results of the scenario modeling are presented in Figure 12 and Table 3.

The analysis reveals that, under the first scenario, the net present value (NPV) increases by nearly 5%—reaching USD 24.8 million—due to the additional revenue from carbon quota sales.

In the second scenario, the deployment of an energy storage system (ESS) requires a minimum investment of USD 10.4 million. This substantial upfront cost leads to a notable decline in project efficiency, reducing the net present value (NPV) to USD 13.2 million—a 44% decrease. Despite this financial impact, the additional investment yields significant technical benefits:

- The system's adaptability coefficient increases to 30% or higher;
- During optimal periods, renewable energy sources can contribute up to 50% of total energy generation;
- CO₂ emissions are reduced by 11.8%, from 70.4 kt CO₂ to 62.04 kt CO₂.

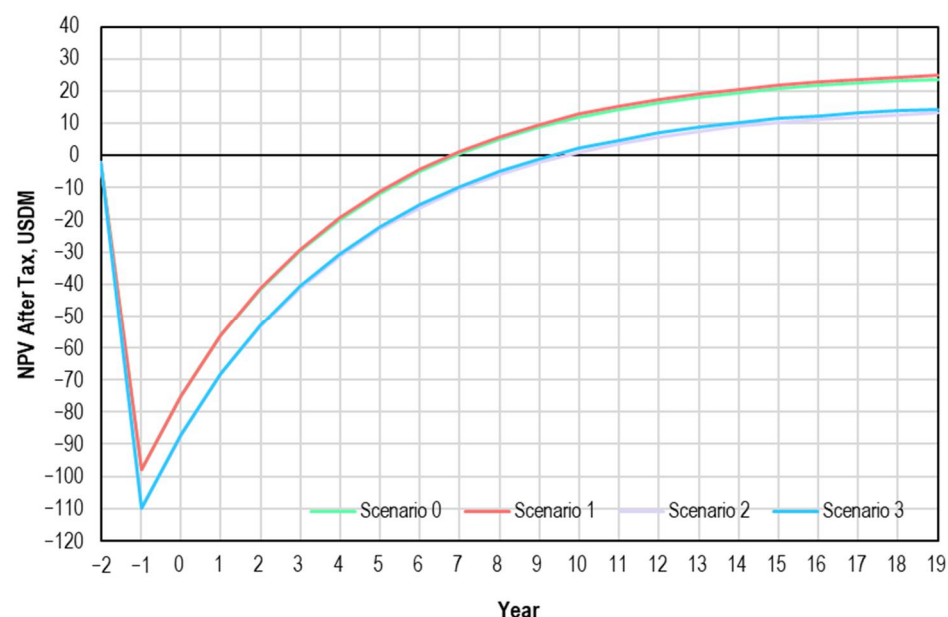


Figure 12. NPV changes depending on the scenario.

Table 3. Comparative Summary of Key Metrics.

Description	CAPEX, USDM	Total OPEX, USDM	NPV After Tax, USDM	DPP, Years	DPI	CO ₂ Emissions, kt per Year	Adaptability Coefficient
Scenario 0—Base Case	79.7	260.1	23.6	9.9	1.24	70.4	0.26
Scenario 1—Carbon Pricing Regime	79.7	260.1	24.8	9.8	1.25	70.4	0.26
Scenario 2—Energy Storage System Deployment	90.1	263.1	13.2	12.7	1.12	62.04	0.34
Scenario 3—Combined Carbon Pricing + ESS Deployment	90.1	263.1	14.4	12.3	1.13	62.04	0.34

These outcomes highlight the trade-off between economic performance and technical/environmental gains.

Scenario 3 demonstrates a notable enhancement in system reliability and achieves a 12% reduction in emissions. However, these improvements come at a financial cost: the project's net present value (NPV) declines to USD 14.4 million, representing a 38.9% decrease from the baseline.

This structured scenario approach facilitates a robust evaluation of project viability under varying regulatory, technological, and economic conditions, thereby supporting evidence-based decision-making for sustainable energy transition.

4. Discussion

The results align with studies on the feasibility of integrating renewables into energy supply for remote and energy-intensive mining assets [5,15]: hybridization ensures competitive electricity costs while maintaining reliability.

From a sustainable development perspective, the results confirm the dual role of the mining sector: it is both a major energy consumer and a key actor in decarbonization through the adoption of clean technologies and optimization of energy supply modes [55,56]. The SPP contribution in the hybrid scheme (26.3%) demonstrates that

“clean” generation can be economically significant even with moderate solar resources if the system is designed for adaptability and technological complementarity. This is particularly important given that rapid growth in renewables does not fully eliminate the need for dispatchable capacity in the medium term (Figure 1A), and avoided emissions depend on the pace and scale of technology deployment (Figure 1B) [57].

Kazakhstan operates an Emissions Trading System (ETS)—a market mechanism where the government sets quotas, i.e., limits on greenhouse gas emissions for enterprises [58]. If a company reduces emissions, remaining quotas can be sold; if the limit is exceeded, additional quotas must be purchased from other participants or at auction. The system covers enterprises emitting more than 20,000 t CO₂/year [59]. Currently, the domestic CO₂ price in Kazakhstan is \$1/t [60]. The system incentivizes emission reduction and renewable energy investment, and it prevents losses from EU carbon border taxes—CBAM (Carbon Border Adjustment Mechanism) [61]. CBAM will be fully applied starting in 2026. Thanks to the ETS in Kazakhstan, CBAM duties are avoided. While gold and copper are currently outside CBAM regulation, in the event of an expanded product list, quota systems will prevent additional taxes.

According to the national carbon quota plan under the Order of the Minister of Ecology and Natural Resources of RK dated 30.01.2024 № 16-Θ, the number of carbon quota units for the metallurgical industry in 2025 is 29,661,879 t CO₂ (30,383,809 t in 2024) [62]. These quotas are allocated free of charge based on benchmarking principles per the Order of the Minister of Ecology, Geology and Natural Resources of the Republic of Kazakhstan dated 19 July 2021 No. 260.

ETS in Kazakhstan covers 43% of national GHG emissions and applies only to 200 large companies with emissions above 20,000 t CO₂/year. However, the government proposed reducing quotas by 5% annually from 2026, increasing business pressure. Data on quotas allocated to Solidcore are unavailable; however, project implementation and a 51% emissions reduction will minimize the burden from quota reductions.

Given the relatively low cost of natural gas for a gas piston station, the main rationale for deploying additional ESS is not the economic performance of the project, but to increase the flexibility of the adaptability of the hybrid energy supply system and increase electricity generation without using natural resources. Such additional investments inevitably affect the key performance indicators of the project: reducing the NPV of the project and increasing the payback period. It is worth noting that the exact cost of energy storage systems for a solar power plant depends on many factors: the type of batteries, required capacity, climatic conditions, manufacturer, installation region, and other parameters. Accurate results require additional calculations.

5. Conclusions

This study proposes and tests a methodology for the techno-economic assessment of a hybrid power supply system based on SPP and GPP for mining enterprises. The Solidcore Resources Varvarinsky hub (Kazakhstan) served as a case study, demonstrating that:

- The hybrid energy system ensures a stable energy balance, eliminating power shortages. The solar energy system (SES) demonstrates an average annual contribution of 26.3%, as measured by the coefficient of adaptability. This figure accounts for pronounced seasonal variations and significantly exceeds the group’s minimum renewable electricity target of 7% established for the field in the company’s development plans.
- There is a significant reduction in energy costs for ore extraction: from USD 0.61/m³ to USD 0.22/m³. Energy-related processing costs also decrease substantially, falling from US\$ 8.44/t to USD 3.03/t.

- Taking local pricing and financial parameters into account, the project exhibits a positive net present value (NPV, after tax) of USD 23.65 million and a reasonable discounted payback period of 10 years. However, capital expenditures (CAPEX) and energy purchase prices remain the primary risk factors.
- The implementation of a hybrid energy system at the Varvarinskoye field will reduce CO₂ emissions by 73.2 thousand tons, resulting in a 51% decrease from the baseline level of 143.6 thousand tons to 70.4 thousand tons of CO₂. This achievement aligns with Solidcore Resources' sustainable development strategy, which prioritizes the reduction in greenhouse gas emissions and the integration of renewable energy sources.
- In addition to the baseline scenario (excluding carbon revenue), two alternative scenarios were evaluated. They include potential revenue from the sale of prevented carbon emissions, assuming carbon prices of USD 1/t and USD 10/t, respectively. The analysis shows that the net profit of the project after deduction of income tax increases by about USD 0.32–3.22 million compared to the scenario excluding income from carbon credits. This forecast takes into account the potential development of carbon markets in the future and the application of shadow pricing for carbon emissions. These considerations enhance the long-term reliability of economic assessment, especially in light of developing emissions trading systems and climate policy frameworks.
- The project achieves notable social benefits 15 new jobs are created. From a fiscal perspective, the discounted government revenue—encompassing corporate income tax, property tax, social contributions, and personal income tax—is estimated at USD 31.1 million.
- An increase in the project's capital expenditures by 12% to 50%—required for deploying energy storage systems (ESS) with a capacity of 90.4 MWh—enables the system's adaptability coefficient to rise to 30% or higher. Under optimal conditions, renewable energy sources can contribute up to 50% of total energy production. However, such additional investments have a direct impact on key project performance indicators; they reduce the NPV of the project and increase the payback period.
- In the context of the continuing role of fossil fuels in the energy mix (Figure 1A), hybridization is a practical compromise between reliability and decarbonization, relevant for mining assets in regions with moderate solar resources.

The collective results confirm that the hybrid solar photovoltaic (SPP)–gas power plant (GPP) system constitutes a technically robust and economically viable solution for increasing the share of on-site renewable electricity generation while preserving supply security. The practical significance lies in the fact that the proposed K_n indicator and associated methodology enable transparent calibration of renewable shares, identification of seasonal “bottlenecks,” and management of GPP/SPP capacities. Further work should consider hourly optimization, module degradation over lifetime, and the impact of carbon pricing on the integrated project economics.

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Abbreviations

The following abbreviations are used in this manuscript:

CAPEX	Capital Expenditures
CBAM	Carbon Border Adjustment Mechanism
ESG	Environmental, Social and Governance
ETS	Emissions Trading System
GDS	Gas Distributing Station
GHI	Global Horizontal Irradiation
GPP	Gas engine power plant
GRP	Gas Refinery Plant
IRR	Internal Rate on Return
LCOE	Levelized Cost of Energy
NPV	Net Present Value
OPEX	Operational Expenditures
PV	Photovoltaic
REE	Rare Earth Elements
RES	Renewable Energy Sources
SPP	Solar power plant
TPP	Thermal Power Plant

Appendix A

Table A1. Comparison of solar panel technologies.

	HJT	PERC	IBC	TOPCon
Description	Heterojunction—solar panels with a heterojunction structure. It is based on a combination of crystalline silicon with amorphous silicon.	Passivated Emitter Rear Contact was the main technology (standard) in 2015–2022, based on the manufacture of solar cells using the technology of passivated emitters and the back surface from a single crystal of the <i>p</i> -type.	Interdigitated Back Contact—Panels with contacts on the back side, without contacts on the front side	Tunnel Oxide Passive Contact is the most advanced technology for an <i>n</i> -type solar cell.

Table A1. Cont.

	HJT	PERC	IBC	TOPCon
Technology	The crystalline elements are coated with additional thin-film layers of amorphous silicon on each side, which form heterojunctions in addition to the main transition in the crystalline element (different types of transitions convert different parts of the sunlight spectrum into electricity, which leads to an increase in overall efficiency)	The dielectric layer on the back of the PERC solar cell reflects the light that passes through the solar element back into the cell and allows for the generation of more free electrons (backside passivity effect)	Solar elements create a grid of 30 or more conductors that connect to the back of the solar cell, the front surface of the cell is completely free, thereby improving efficiency (unlike conventional elements with visible current-carrying busbars and a current-carrying grid)	Tunnel oxide and passivated contact technology for increased efficiency
Efficiency	- 22–23% for cells based on conventional solar cells with plug-in busbars - up to 26.5% (due to the combination of heterostructure with IBC technologies for forming current terminals)	>20% (conventional silicon solar cells of the <i>p</i> -type with an efficiency of 17–19%)	21.7–22.6%	>22%
Advantages	- High-quality hydrogenated proprietary amorphous silicon, which provides passivation (transition to a non-active state) of defects on the front and back surfaces of silicon wafers - High efficiency and low-light performance - Low degradation	Affordable cost (0.2–0.25 dollars per peak watt), good price–performance ratio	- The most mechanically durable, as the rear contact surface creates additional rigidity and support for the silicon element - High efficiency	- The ultra-thin layer reduces recombination losses in the junction, which leads to current losses.
Degradation in the first year of operation	1–2%	2–3%	1–2%	1–2%
Annual degradation	0.3–0.5%	0.5–0.8%	0.3–0.5%	0.3–0.5%

Table A2. Comparison of SPP, GPP, and TPP by Environmental Parameters. Adapted from [63,64].

Parameter	SPP	GPP	TPP
CO ₂ emissions	None	1.87 t CO ₂ per 1000 m ³ of gas	2.7–2.8 t CO ₂ per ton of coal
Noise impact	45 dB at 150 m	70–80 dB at 1 m (can be reduced by sound proofing)	85–100 dB near turbines and boilers
NO emissions (mg/m ³)	0	0.4 mg/m ³	250–450 mg/m ³
SO ₂ emissions (mg/m ³)	0	5 mg/m ³	100–300 mg/m ³
CO emissions (mg/m ³)	0	<0.05 mg/m ³	100–300 mg/m ³
Soot and dust (mg/m ³)	0	0.15 mg/m ³	up to 300 mg/m ³

Table A2. Cont.

Parameter	SPP	GPP	TPP
Acrolein (mg/m ³)	0	0.03 mg/m ³	0.05–0.1 mg/m ³
Exhaust temperature, C	None	400–500	400–600
Water consumption (m ³ /MWh)	Only for panel cleaning	0.5–1 m ³ for cooling and technical needs	1.7–2.5 m ³ for steam system and ash handing
Waste	None	Used oil and filters	Ash (100–200 kg/MWh), slags, gypsum from desulfurization
Fire hazard	Low (in case of malfunction)	Moderate (in case of gas or oil leakage)	High (due to coal dust and fuel oil)
Recycling and disposal	Aluminum, glass, silicon are recycled	Oils and filters recycled according to sanitary regulations	Most ash goes to landfills, only a small portion is processed
Biological impact	Low	Located in industrial zones	Quarries, ash dumps, water and soil pollution

References

1. Tian, L.; Wang, Q. Improving Mineral Mining Enterprises Environmental Performance through Corporate Social Responsibility Practices in China: Implications for Minerals Policymaking. *Resour. Policy* **2024**, *88*, 104442. [\[CrossRef\]](#)
2. Adomako, S.; Tran, M.D. Sustainable environmental strategy, firm competitiveness, and financial performance: Evidence from the mining industry. *Resour. Policy* **2022**, *75*, 102515. [\[CrossRef\]](#)
3. Kabeyi, M.J.B.; Olanrewaju, O.A. Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply. *Front. Energy Res.* **2022**, *9*, 743114. [\[CrossRef\]](#)
4. Litvinenko, V. The Role of Hydrocarbons in the Global Energy Agenda: The Focus on Liquefied Natural Gas. *Resources* **2020**, *9*, 59. [\[CrossRef\]](#)
5. Ampah, J.D.; Jin, C.; Agyekum, E.B.; Afrane, S.; Geng, Z.; Adun, H.; Yusuf, A.A.; Liu, H.; Bamisile, O. Performance Analysis and Socio-Enviro-Economic Feasibility Study of a New Hybrid Energy System-Based Decarbonization Approach for Coal Mine Sites. *Sci. Total Environ.* **2023**, *854*, 158820. [\[CrossRef\]](#)
6. Marinina, O.; Kirsanova, N.; Nevskaya, M. Circular Economy Models in Industry: Developing a Conceptual Framework. *Energies* **2022**, *15*, 9376. [\[CrossRef\]](#)
7. Nevskaya, M.; Shabalova, A.; Nikolaichuk, L.; Kirsanova, N. Development of a Quantitative Assessment Algorithm for Operational Risks in Mining Engineering. *Resources* **2025**, *14*, 53. [\[CrossRef\]](#)
8. Victoria, M.; Haegel, N.; Peters, I.M.; Sinton, R.; Jäger-Waldau, A.; del Cañizo, C.; Breyer, C.; Stocks, M.; Blakers, A.; Kaizuka, I.; et al. Solar Photovoltaics Is Ready to Power a Sustainable Future. *Joule* **2021**, *5*, 1041–1056. [\[CrossRef\]](#)
9. Hosenuzzaman, M.; Rahim, N.A.; Selvaraj, J.; Hasanuzzaman, M.; Malek, A.B.M.A.; Nahar, A. Global Prospects, Progress, Policies, and Environmental Impact of Solar Photovoltaic Power Generation. *Renew. Sustain. Energy Rev.* **2015**, *41*, 284–297. [\[CrossRef\]](#)
10. BP Energy Outlook: 2025 Edition. Available online: <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2025.pdf> (accessed on 25 October 2025).
11. IEA Global Energy Review 2025. Available online: <https://www.iea.org/reports/global-energy-review-2025> (accessed on 25 October 2025).
12. Dmitrieva, D.; Chanysheva, A.; Solovyova, V. A Conceptual Model for the Sustainable Development of the Arctic's Mineral Resources Considering Current Global Trends: Future Scenarios, Key Actors, and Recommendations. *Resources* **2023**, *12*, 63. [\[CrossRef\]](#)
13. Cherepovitsyn, A.; Mekerova, I.; Nevolin, A. Analysis of the Palladium Market: A Strategic Aspect of Sustainable Development. *Mining* **2025**, *5*, 39. [\[CrossRef\]](#)
14. Kruk, M.N.; Perdomo Millán, A.; Torres Batista, Y. Evaluation of the Efficiency of Implementation of the Sustainable Development Program at Nickel-Cobalt Ore Mining Enterprises. *Sustainability* **2025**, *17*, 9441. [\[CrossRef\]](#)
15. Kronja, J.; Galić, I. Integration of Renewable Energy Sources to Achieve Sustainability and Resilience of Mines in Remote Areas. *Mining* **2025**, *5*, 51. [\[CrossRef\]](#)
16. Cherepovitsyn, A.; Stroykov, G.; Nevolin, A. Efficiency of Low-Carbon Technologies Implementation at Non-Ferrous Metallurgy Enterprises under the Conditions of Carbon-Regulation Development in Russia. *Sustainability* **2023**, *15*, 16640. [\[CrossRef\]](#)

17. Bratskikh, D.S.; Romasheva, N. A Comprehensive Approach to Assessing the Efficiency and Sustainability of Oil Supply Chains Under Digital Transformation. *SOCAR Proc.* **2025**, 214–225. Available online: https://proceedings.socar.az/uploads/pdf/115/214_225_OGP20250401142.pdf. (accessed on 25 October 2025).
18. Golroudbary, S.R.; Makarava, I.; Kraslawski, A.; Repo, E. Global Environmental Cost of Using Rare Earth Elements in Green Energy Technologies. *Sci. Total Environ.* **2022**, 832, 155022. [CrossRef] [PubMed]
19. Cherepovitsyn, A.E.; Dorozhkina, I.P.; Solov'eva, V.M. Forecasts of Rare-Earth Elements Consumption in Russia: Basic and Emerging Industries. *Stud. Russ. Econ. Dev.* **2024**, 35, 688–696. [CrossRef]
20. Ilyushin, Y.V.; Boronko, E.A. Analysis of Energy Sustainability and Problems of Technological Process of Primary Aluminum Production. *Energies* **2025**, 18, 2194. [CrossRef]
21. Krane, J.; Idel, R. More Transitions, Less Risk: How Renewable Energy Reduces Risks from Mining, Trade and Political Dependence. *Energy Res. Soc. Sci.* **2021**, 82, 102311. [CrossRef]
22. Klebanov, A.F.; Bondarenko, A.V.; Zhukovsky, Y.L.; Klebanov, D.A. Establishing Remote Control Centers of a Mining Operation: Strategic Prerequisites and Implementation Stages. *Min. Ind. J. Gorn. Promishlennost* **2024**, 174–183. [CrossRef]
23. Sahoo, M.; Sethi, N. The Intermittent Effects of Renewable Energy on Ecological Footprint: Evidence from Developing Countries. *Environ. Sci. Pollut. Res.* **2021**, 28, 56401–56417. [CrossRef]
24. Shabani, Z.D.; Tsvetkov, P. Do Social Capital Spillovers Affect CO₂ Emissions? *J. Clean. Prod.* **2025**, 522, 146288. [CrossRef]
25. Global Average Solar LCOE Stood at \$0.044/KWh in 2023, Says IRENA. Available online: <https://www.pv-magazine.com/2024/09/27/global-average-solar-lcoe-stood-at-0-044-kwh-in-2023-says-irena/> (accessed on 25 October 2025).
26. Glachant, J.-M. New Business Models in the Electricity Sector. In *Handbook on Electricity Markets*; Edward Elgar Publishing: Cheltenham, UK, 2021.
27. Tsvetkov, P.; Fedoseev, S. Analysis of Project Organization Specifics in Small-Scale LNG Production. *J. Min. Inst.* **2021**, 246, 678–686. [CrossRef]
28. Aldersey-Williams, J.; Broadbent, I.D.; Strachan, P.A. Better Estimates of LCOE from Audited Accounts—A New Methodology with Examples from United Kingdom Offshore Wind and CCGT. *Energy Policy* **2019**, 128, 25–35. [CrossRef]
29. Park, H.; Kim, J.D. Transition towards Green Banking: Role of Financial Regulators and Financial Institutions. *Asian J. Sustain. Soc. Responsib.* **2020**, 5, 5. [CrossRef]
30. Galevskiy, S.; Ponomarenko, T.; Tsiglianu, P. The Impact of Self-Sufficiency in Basic Raw Materials of Metallurgical Companies on Required Return and Capitalization: The Case of Russia. *J. Risk Financ. Manag.* **2025**, 18, 318. [CrossRef]
31. Cano, Y.; Quispe, G.; Chavez, H.; Mamani-Macedo, N.; Raymundo-Ibañez, C.; Dominguez, F. Occupational Health and Safety Management Model for Mining Contracts. In *Human Interaction, Emerging Technologies and Future Applications II, Proceedings of the 2nd International Conference on Human Interaction and Emerging Technologies: Future Applications (IHET-AI 2020), Lausanne, Switzerland, 23–25 April 2020*; Springer: Cham, Switzerland, 2020; pp. 486–492.
32. Gendler, S.; Prokhorova, E. Risk-Based Methodology for Determining Priority Directions for Improving Occupational Safety in the Mining Industry of the Arctic Zone. *Resources* **2021**, 10, 20. [CrossRef]
33. Vaverková, M.D.; Winkler, J.; Uldrijan, D.; Ogrodnik, P.; Vespalcová, T.; Aleksiejuk-Gawron, J.; Adamcová, D.; Koda, E. Fire Hazard Associated with Different Types of Photovoltaic Power Plants: Effect of Vegetation Management. *Renew. Sustain. Energy Rev.* **2022**, 162, 112491. [CrossRef]
34. Falvo, M.C.; Capparella, S. Safety Issues in PV Systems: Design Choices for a Secure Fault Detection and for Preventing Fire Risk. *Case Stud. Fire Saf.* **2015**, 3, 1–16. [CrossRef]
35. Belsky, A.A.; Glukhanich, D.Y.; Carrizosa, M.J.; Starshaia, V.V. Analysis of Specifications of Solar Photovoltaic Panels. *Renew. Sustain. Energy Rev.* **2022**, 159, 112239. [CrossRef]
36. Zatonatska, T.; Soboliev, O.; Artyukhov, A.; Zatonatskiy, D.; Balan, V.; Wołowicz, T.; Woźniak, D. Sustainable Energy Investments: ESG-Centric Evaluation and Planning of Energy Projects. *Energies* **2025**, 18, 1942. [CrossRef]
37. Blinova, E.; Ponomarenko, T.; Knysh, V. Analyzing the Concept of Corporate Sustainability in the Context of Sustainable Business Development in the Mining Sector with Elements of Circular Economy. *Sustainability* **2022**, 14, 8163. [CrossRef]
38. Solidcore Resources. Varvara Hub. Available online: <https://www.solidcore-resources.com/en/assets/where-we-operate/varvara/> (accessed on 25 October 2025).
39. Wärtsilä. Engine Power Plant Solutions. Available online: <https://www.wartsila.com/energy/engine-power-plant-solutions> (accessed on 18 November 2025).
40. 1150-500-220-110 Kv Electric Grid Diagram of the UES of the Republic of Kazakhstan. Available online: <https://storage.energybase.ru/source/876/4CQftnpfHzIHCzUhE6Qga8GjYeE6TGcT.pdf> (accessed on 27 October 2025). (In Russian)
41. QAZAQGAZ; AIMAQ; JSC. Capacity and Gasification Scheme. Available online: <https://www.aimaq.kz/en/capacity-and-gasification-scheme/> (accessed on 27 October 2025).
42. Weather in Kostanay by Month. Available online: <http://kazakhstan.pogoda360.ru/448741/avg/> (accessed on 27 October 2025). (In Russian)

43. Xu, R.; Song, Z.; Tang, Q.; Yu, Z. The Cost and Marketability of Renewable Energy after Power Market Reform in China: A Review. *J. Clean. Prod.* **2018**, *204*, 409–424. [CrossRef]
44. Li, H.; Xu, Y.; Adhikari, S.; Rizy, D.T.; Li, F.; Irminger, P. Real and Reactive Power Control of a Three-Phase Single-Stage PV System and PV Voltage Stability. In *2012 IEEE Power and Energy Society General Meeting*; IEEE: Piscataway, NJ, USA, 2012; pp. 1–8.
45. The World Bank. Validation Report for Global Solar Radiation Model. Available online: <https://documents1.worldbank.org/curated/en/507341592893487792/pdf/Global-Solar-Atlas-2-0-Validation-Report.pdf> (accessed on 27 October 2025).
46. Heterojunction Bifacial Photovoltaic Modules. Available online: https://unigreen-energy.com/upload/iblock/d75/07kc1jg45r18lhbweb5k7mhv4338fd89/HJT_144H-MBB-M10-540_570-RUS.pdf (accessed on 27 October 2025). (In Russian)
47. Calculating the Performance of Solar Panels. Available online: <https://solarsoul.net/raschet-solnechnoj-batarei/> (accessed on 27 October 2025). (In Russian)
48. Order of the Minister of Energy of the Republic of Kazakhstan Dated May 21, 2025 No. 216-n/a. Available online: <https://zakon.uchet.kz/rus/docs/G25JVM00216> (accessed on 30 October 2025). (In Russian)
49. USD/KZT-US Dollar Kazakh Tenge. Available online: <https://www.investing.com/currencies/usd-kzt> (accessed on 31 October 2025).
50. Kazakhstan. Corporate-Taxes on Corporate Income. Available online: <https://taxsummaries.pwc.com/kazakhstan/corporate/taxes-on-corporate-income> (accessed on 31 October 2025).
51. Basic Taxes for Companies in Kazakhstan in 2025. Available online: <https://www.garant.ru/1c-wiseadvice/guide/nalogooblozhenie-v-kazakhstane/> (accessed on 31 October 2025). (In Russian)
52. Lazard's Levelized Cost of Energy+ (LCOE+). Available online: <https://www.lazard.com/research-insights/levelized-cost-of-energyplus-lcoeplus/> (accessed on 31 October 2025).
53. IRENA. *Renewable Power Generation Costs in 2021*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2022.
54. Kazakhstan Electric Power Industry Key Factors. Available online: <https://www.kegoc.kz/en/electric-power/elektroenergetika-kazakhstana/> (accessed on 7 November 2025).
55. Wesseling, J.H.; Lechtenböhmer, S.; Åhman, M.; Nilsson, L.J.; Worrell, E.; Coenen, L. The Transition of Energy Intensive Processing Industries towards Deep Decarbonization: Characteristics and Implications for Future Research. *Renew. Sustain. Energy Rev.* **2017**, *79*, 1303–1313. [CrossRef]
56. Tian, X.; An, C.; Chen, Z. The Role of Clean Energy in Achieving Decarbonization of Electricity Generation, Transportation, and Heating Sectors by 2050: A Meta-Analysis Review. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113404. [CrossRef]
57. Pavel, T.; Polina, S.; Liubov, N. The Research of the Impact of Energy Efficiency on Mitigating Greenhouse Gas Emissions at the National Level. *Energy Convers. Manag.* **2024**, *314*, 118671. [CrossRef]
58. Howie, P.; Gupta, S.; Park, H.; Akmetov, D. Evaluating policy success of emissions trading schemes in emerging economies: Comparing the experiences of Korea and Kazakhstan. *Clim. Policy* **2020**, *20*, 577–592. [CrossRef]
59. Emissions Trading System. Available online: <https://recycle.kz/en/parnikovye-gazy> (accessed on 2 November 2025).
60. How Can Kazakhstan Improve Its Carbon Regulation System? AIFC Report. Available online: <https://aifc.kz/news/how-can-kazakhstan-improve-its-carbon-regulation-system/> (accessed on 2 November 2025).
61. Erdogdu, E. The Carbon Border Adjustment Mechanism: Opportunities and Challenges for Non-EU Countries. *WIREs Energy Environ.* **2025**, *14*, e70000. [CrossRef]
62. On the Approval of the National Carbon Quota Plan. Available online: <https://adilet.zan.kz/rus/docs/V2200028798> (accessed on 2 November 2025). (In Russian)
63. Nussey, B. How Much CO₂ and Pollution Comes from Burning Coal? Available online: <https://www.freeingenergy.com/how-much-co2-and-other-pollutants-come-from-burning-coal/> (accessed on 7 November 2025).
64. Gas Piston Installations (GPIs). Available online: <https://manbw.ru/analitics/gpu.html> (accessed on 7 November 2025). (In Russian)

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