

Innovative solutions for improving energy efficiency in the mining industry

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Abstract

Purpose. To substantiate solutions for improving energy efficiency in the mining industry through the integration of renewable energy sources (RES), energy management systems (EMS), and hybrid energy technologies, considering their energy, environmental, and economic performance.

Methods. The study used theoretical analysis, comparative assessment, mathematical calculations, and data processing based on scientific publications and international reports. The main indicators of RES, EMS, and hybrid systems were compared using common energy, environmental, and economic parameters. Calculations were performed using Python with NumPy and Pandas libraries and SMATH Solver. Three scenarios were considered: conventional energy consumption, RES integration, and hybrid energy supply.

Findings. The results indicate that RES integration can reduce energy consumption by 10-30%, while hybrid systems provide a reduction of 15-35% and reported system-efficiency values of 70-90%. EMS can reduce energy consumption by 8-25%, peak loads by 10-30%, and CO₂ emissions by 6-20%. Total investment costs for RES projects were estimated at 57.5-156 million USD. For hybrid systems, the required investment ranges from USD 2.5 to 7.5 million, with annual savings of USD 0.5 to 1.2 million and a payback period of up to 10 years, whereas EMS require substantially lower capital investment and have a payback period of up to 6 years.

Originality. A comparative assessment of RES, EMS, and hybrid energy technologies was performed using a common set of energy, environmental, and economic indicators, which made it possible to identify differences in their efficiency, investment requirements, and implementation conditions.

Practical implications. The obtained results can be used to support the selection of energy-efficiency solutions for mining enterprises depending on production scale, investment capacity, infrastructure readiness, and expected energy savings.

Keywords: renewable energy sources; energy management systems; hybrid energy systems; energy efficiency; mining industry; CO₂ emissions; energy savings; economic efficiency

1. Introduction

1.1. Background and problem statement

Energy efficiency is currently an important issue worldwide, and the mining industry plays a significant role in this context due to its high energy demand. Global mining production accounts for about 10% of total energy consumption, with mineral processing and transportation being among the most energy-intensive processes [1], [2].

The growing scale and complexity of mining operations, increasing mechanization and electrification, and stricter environmental requirements make efficient energy use an increasingly important operational priority. Energy consumption directly affects production costs, technological stability, and the environmental performance of mining enterprises. There-

fore, improving energy efficiency should be considered as a system-wide task covering mineral extraction, processing, transportation, ventilation, pumping, and auxiliary operations. In practice, substantial improvements require not only the modernization of energy-intensive equipment but also better coordination of technological processes and energy supply.

Previous studies have considered different aspects of transport equipment and infrastructure, including locomotive-track interaction, freight-car dynamics, the operation of heavy-freight rolling stock, and the influence of railway vehicles on track structures [3]-[7]. Other research has focused on the performance and power transmission characteristics of vehicle transmissions, as well as on the optimization of transport routes and cyclic schedules [8]-[10]. Together, these studies show that improvements in transport efficiency

depend not only on the condition and reliability of individual vehicles, but also on drivetrain performance, infrastructure interaction, and the organization of transportation processes.

In 2021, the mining industry consumed approximately 5.5 billion MWh of energy worldwide, about 60% of which was used for mineral extraction and processing [11], [12]. Mining activities also contribute to carbon dioxide emissions, which increases the environmental pressure associated with mineral extraction and processing [13], [14]. The environmental consequences of mining also extend to post-mining and post-industrial landscapes, where the assessment of ecosystem services and the functioning of novel ecosystems can support more sustainable approaches to land redevelopment and environmental management [15]. In addition to energy consumption and emissions, environmental challenges in the mining sector include wastewater treatment, for which electrical-discharge technologies have also been investigated [16]–[18]. Complementary environmental approaches include ultraviolet-based methods for investigating and treating surface waters [19]. The main energy consumption and environmental impacts of the mining industry are summarized in Figure 1.

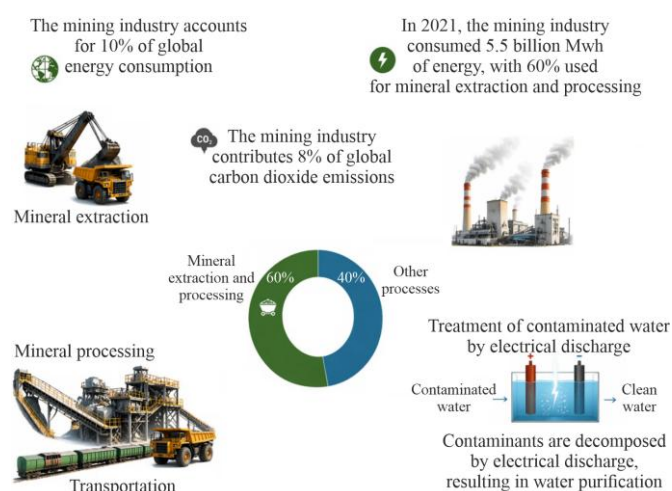


Figure 1. Energy consumption and environmental impact of the mining industry

Improving energy efficiency can also increase the economic performance of mining enterprises. A 10% reduction in energy consumption can lead to an average reduction of 3-5% in production costs. Therefore, the application of new energy management approaches and innovative technological solutions can provide significant economic benefits. One of the promising directions is the integration of renewable energy sources (RES). In 2020, renewable energy accounted for only about 2-3% of the energy used in the global mining industry, while available studies indicate the possibility of increasing this share to approximately 20%, with corresponding economic and environmental benefits [20]–[23].

In addition to renewable energy integration, improvements in the energy performance of mining and mineral-processing systems can be achieved through the modernization of technological equipment and the introduction of alternative energy-conversion and storage solutions. In-situ method of extraction been investigated as an approach for converting coal resources directly within the geological formation, including applications to steeply dipping coal seams [24], [25]. At the equipment level, the modernization of electrically driven

mining systems, including electromagnetic lifting installations, can contribute to more reliable operation of mine infrastructure [26]. Energy-storage technologies also represent an important component of modern energy systems, particularly where renewable generation is combined with variable loads. In this context, recent studies have focused on improving the electrochemical performance of supercapacitor electrode materials for advanced energy-storage applications [27]. These developments indicate that improving the energy performance of mining operations should involve not only changes in energy supply but also technological modernization, energy conversion, and energy-storage solutions.

Energy efficiency should also be considered within the broader framework of resource efficiency and environmental performance in mining and mineral-processing operations. Considerable attention has therefore been given to the recovery and reuse of technogenic materials, including ore-processing wastes, flotation tailings, metallurgical slags, and drilling wastes. Recent studies have investigated the utilization of industrial mineral wastes in composite materials [28], the separation and treatment of waste drilling muds [29], and the recovery of valuable components from ore and flotation tailings using bioleaching approaches [30], [31]. Other studies have considered the processing of copper-smelting slags [32] and the use of Kazakhstan ore-dressing wastes as secondary raw materials for the production of functional materials [33], [34]. Although these technologies are primarily aimed at material recovery and environmental protection, they reflect the wider transition toward more resource-efficient mining systems, in which energy consumption, waste generation, and secondary-resource utilization should be considered jointly.

Energy management systems (EMS) represent another approach to reducing energy consumption in mining operations. Previous studies report that the implementation of EMS can reduce energy costs by approximately 12% [35]–[38]. Similar approaches involving energy-saving measures and renewable energy technologies are also being developed in Kazakhstan [39]–[41]. The transition to green energy in Kazakhstan has also been considered at the national level, with particular attention to the challenges and possible solutions associated with the wider implementation of renewable energy technologies [42].

The reduction of environmental impacts is particularly relevant for the mining sector of Kazakhstan. In 2019, CO₂ emissions associated with the mining industry exceeded 80 million tons and accounted for about 10% of the country's total emissions [43]–[45]. Thus, improving energy efficiency is important not only for reducing operating costs but also for decreasing the environmental impact of mining operations. The importance of emission-reduction measures in Kazakhstan is also confirmed by studies of diesel road transport, where the use of exhaust-gas cleaning technologies has been considered for reducing harmful emissions and assessing CO₂ emissions [46]. Broader sustainability improvements in Kazakhstan's mining industry are also associated with the optimization of reverse supply chains and the recovery of value from mining waste, which can improve resource utilization and reduce environmental impacts [47].

Accordingly, the development and assessment of innovative energy-efficiency solutions remain relevant for the mining industry. Particular attention should be paid to the combined application of renewable energy sources, energy

management systems, and hybrid technologies, taking into account both their potential benefits and the economic and infrastructural limitations of their implementation.

1.2. Literature review

Improving energy efficiency in the mining industry has received considerable attention in recent years. The main research directions include the integration of renewable energy sources, optimization of technological processes, implementation of energy management systems, and development of hybrid energy solutions. Process-level optimization has also been used to determine rational energy-power parameters and reduce energy consumption in industrial material-processing operations [48]. At the same time, the large-scale application of these technologies remains constrained by economic, technical, and infrastructural factors. The main solutions and challenges associated with improving energy efficiency in the mining industry are summarized in Figure 2.



Figure 2. Solutions and challenges in improving energy efficiency in the mining industry

Table 1. Energy efficiency and CO₂ reduction in the mining industry

Research source	Energy efficiency improvement, %	Initial capital cost, million USD	Infrastructure renovation required, %	CO ₂ emissions reduction, %	Renewable energy capacity, GWh	Energy savings, GWh/year
Pouresmaeli et al. [50]	20-30	50-100	15-25	–	15002000	300400
Herrington [51]	15-25	60-120	20-30	10-15	12001800	250350

Table 2. Renewable energy integration in mining (key parameters)

Research source	Renewable energy used, MW	Energy savings cost, USD/MW	Additional labor challenges	Project completion time, years
Igogo et al. [52]	2000-2500	30000-40000	High	5-7
Li et al. [53]	2500-3000	35000-45000	Medium	4-6

The reliable operation and monitoring of electrical infrastructure are also important for energy-management applications in mining. Methods for determining insulation parameters in electrical networks have been developed specifically for mining enterprises [54], [55]. Energy management systems provide another approach to improving the efficiency of mining operations. Laayati et al. [56] developed a monitoring and forecasting system for peak energy loads in open-pit mining. Their results demonstrate the potential of real-time monitoring and forecasting to reduce energy consumption and peak loads. Laayati et al. [57] also emphasized the importance of energy metering, monitoring, and forecasting for mining enterprises. Nevertheless, the large-scale implemen-

Information and visualization tools can also support the assessment and monitoring of renewable energy resources. In Kazakhstan, approaches based on geographic information systems have been proposed for the visualization and monitoring of renewable energy potential [49].

Pouresmaeli et al. [50] showed that the integration of renewable energy sources combined with strategic planning can improve energy efficiency and support sustainable development in the mining industry. However, high initial capital costs and the need for infrastructure modernization remain major barriers to implementation. Herrington [51] also emphasized the role of renewable energy in reducing CO₂ emissions associated with mining activities, while noting the technical and economic difficulties related to large-scale deployment. The main indicators reported in these studies are compared in Table 1.

The reported improvement in energy efficiency ranges from 15 to 30%, while initial capital costs vary from 50 to 120 million USD. The estimated energy savings range from 250 to 400 GWh/year. These values indicate the considerable potential of renewable energy integration, but also demonstrate the substantial investment requirements associated with such projects.

Igogo et al. [52] reported that renewable energy integration in mining operations can reduce CO₂ emissions by up to 20%, although high capital requirements and infrastructure constraints remain important barriers. Li et al. [53] considered clean-energy development pathways for mining projects using big-data approaches and also identified financial and technical limitations affecting their practical implementation. Selected parameters reported in these studies are presented in Table 2.

According to the reported data, project implementation may require approximately 4-7 years, which confirms the need to consider not only energy performance but also economic and organizational factors.

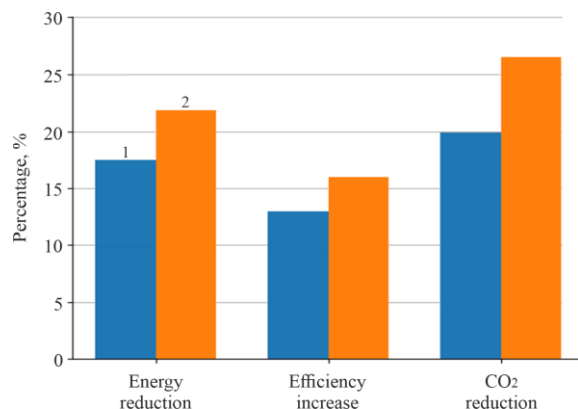
tation of such systems is still affected by financial constraints and infrastructure requirements. The main performance indicators reported in these studies are presented in Table 3.

According to Table 3, energy management systems can reduce energy consumption by 8-25%, peak loads by 10-30%, and CO₂ emissions by 6-20%. At the same time, implementation costs range from 30 to 200 thousand USD, while the estimated payback period varies from 2 to 6 years. Infrastructure complexity and financial constraints therefore remain important factors affecting the wider implementation of EMS. Anvari and Benndorf [58] reviewed recent developments in real-time mining and highlighted the importance of digital and real-time management systems for improving mining performance.

Table 3. Performance indicators and characteristics of energy management systems in mining

No.	Indicator	Laayati, et al., [56]	Laayati, et al., [57]
1	Energy consumption reduction, %	10-25	8-20
2	Peak load reduction, %	15-30	10-22
3	Prediction accuracy, %	85-95	80-90
4	Monitoring frequency, s	1-5	5-10
5	Data acquisition interval, min	1-15	5-30
6	Load balancing efficiency, %	12-28	8-18
7	Energy loss reduction, %	10-24	7-18
8	CO ₂ emission reduction, %	8-20	6-15
9	Equipment efficiency increase, %	10-22	8-16
10	Emergency downtime reduction, %	12-25	8-18
11	System implementation cost, thousand USD	50-200	30-120
12	Sensor share in system cost, %	20-35	15-30
13	Software share in system cost, %	15-25	10-20
14	Infrastructure cost share, %	30-45	25-40
15	Annual maintenance cost, %	5-12	4-10
16	Infrastructure complexity, points (1-10)	7-10	6-9
17	Financial constraint level, points (1-10)	8-10	7-9
18	Technical barrier level, points (1-10)	7-9	6-8
19	Payback period, years	2-5	3-6
20	Large-scale adoption potential, %	55-75	45-65

However, further assessment of their economic efficiency and scalability is still required. Dikgwatlhe et al. [59] analyzed the integration of clean energy technologies in mining and also identified challenges related to the assessment and large-scale implementation of energy-efficiency measures. A comparison of selected indicators reported in these studies is shown in Figure 3.

**Figure 3. Comparative analysis of energy efficiency metrics in the mining industry: 1 – Anvari & Benndorf [58]; 2 – Dikgwatlhe et al. [59]**

The comparison shows differences between the reported values of energy consumption reduction, efficiency improvement, and CO₂ reduction. These differences indicate that the effectiveness of energy-efficiency measures can vary depending on the technological solution and operating conditions.

Nepsha et al. [60] investigated renewable energy integration at coal-mining enterprises and showed that its implementation is affected by financial, technical, and economic constraints. Roemer et al. [61] reviewed energy consumption, decarbonization pathways, and renewable energy integration in the mining industry and confirmed the potential for substantial emission reduction. At the same time, they emphasized the need to overcome financial and technical barriers. Issa et al. [62], based on the Canadian mining industry, also high-

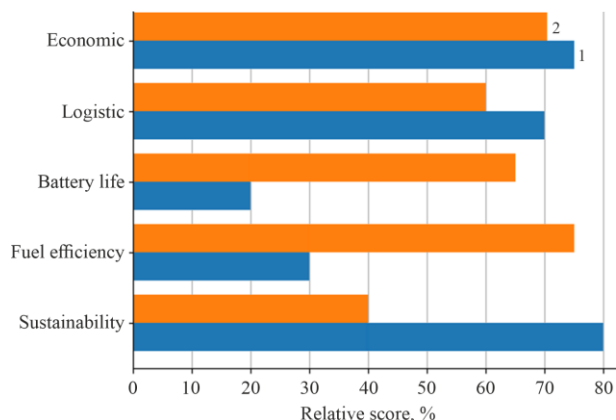
lighted the importance of economic and policy support for the implementation of renewable energy technologies. The main indicators reported in these studies are summarized in Table 4.

The data presented in Table 4 indicate that renewable energy integration may reduce energy consumption by 10-30% and CO₂ emissions by 12-40%. However, relatively high implementation costs and long payback periods remain important factors limiting the large-scale introduction of these technologies.

Table 4. Key indicators of renewable energy integration in the mining industry

No.	Indicator	Nepsha, et al., [60]	Roemer, et al., [61]	Issa et al., [62]
1	Energy consumption reduction, %	10-20	15-30	12-25
2	CO ₂ emissions reduction, %	12-22	20-40	18-35
3	Renewable integration level, %	20-35	25-50	30-55
4	Implementation cost, million USD	2.0-5.5	3.0-8.0	2.5-6.5
5	Payback period, years	4-8	5-10	4-9
6	Implementation rate, %	20-40	25-45	30-50
7	Government support level, %	30-50	40-65	50-75
8	Economic efficiency, %	15-30	20-35	18-32
9	Risk level, %	45-65	40-60	35-55
10	Infrastructure readiness, %	30-55	35-60	40-70

Hybrid energy systems represent another promising direction, particularly for remote mining operations. Kronja and Galić [63] examined the integration of renewable energy sources to improve the sustainability and resilience of remote mines and identified both economic and logistical challenges. Feng and Dong [64] considered energy management in large hybrid electric mining trucks, focusing on fuel economy and battery life. Selected parameters characterizing these approaches are compared in Figure 4.

**Figure 4. Multi-parameter assessment of energy management and integration in mining: 1 – Kronja & Galić [63]; 2 – Feng & Dong [64]**

Li et al. [65], [66] investigated energy management and optimization approaches for hydraulic hybrid mining trucks and demonstrated their potential to reduce energy consumption. However, high costs and scalability remain important limitations. Nkambule et al. [67] performed a techno-economic analysis of hybrid renewable energy systems for the South African mining industry and showed that such systems can improve energy efficiency, although their economic feasibility depends strongly on investment conditions. The main performance indicators reported in these studies are summarized in Table 5.

Table 5. Key performance indicators of hybrid energy systems in the mining industry

No.	Indicator	Li et al., [65], Li et al., [66]	Nkambule et al., [67]
1	Energy consumption reduction, %	15-30	20-35
2	Energy efficiency improvement, %	18-32	22-38
3	System efficiency, %	70-85	75-90
4	Implementation cost, million USD	2.5-6.0	3.0-7.5
5	Payback period, years	4-9	5-10
6	Scalability level, %	40-65	45-70
7	Technology adoption level, %	30-50	35-60
8	Economic efficiency, %	20-35	25-40
9	Risk level, %	40-60	35-55
10	Infrastructure readiness, %	35-60	40-65

According to Table 5, hybrid systems can reduce energy consumption by 15-35%, while the reported system efficiency ranges from 70 to 90%. Their implementation costs are estimated at 2.5-7.5 million USD, with a payback period of approximately 4-10 years. These values indicate considerable potential for improving energy performance, although investment costs and infrastructure readiness may limit large-scale implementation.

Kalantari et al. [68] proposed a hybrid renewable hydrogen-based energy solution for remote mines and showed its potential for improving energy accessibility and sustainability. However, the long-term feasibility and practical implementation of such systems require further investigation. Hydrogen-assisted combustion has also been investigated as an alternative approach for internal combustion engines, with experimental results indicating reductions in fuel consumption and exhaust emissions [69]. Overall, previous studies demonstrate the considerable potential of RES, EMS, and hybrid systems for reducing energy consumption and environmental impacts in mining. At the same time, these approaches are commonly considered separately, while their comparative energy, environmental, and economic characteristics vary considerably between studies. In addition, high initial costs, infrastructure limitations, scalability, and payback periods remain important barriers to their wider application. Therefore, a comparative assessment of these solutions using a common set of energy, environmental, and economic indicators is required to identify their potential applicability in mining operations [70].

1.3. Aim and objectives of the study

The aim of the study is to substantiate innovative solutions for improving energy efficiency in the mining industry through the integration of renewable energy sources, energy management systems, and hybrid technologies.

To achieve this aim, the following objectives are set:

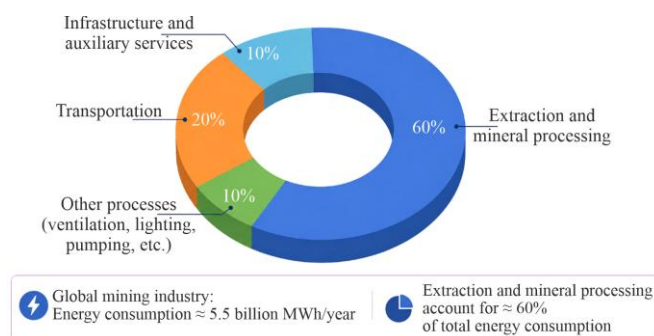
- to analyze the current level of energy consumption in the mining industry and assess modern technologies aimed at improving energy efficiency, including renewable energy sources and energy management systems;
- to evaluate the energy performance, economic feasibility, and practical applicability of renewable energy sources, energy management systems, and hybrid energy solutions in mining operations.

2. Materials and methods

This study used an integrated analytical approach to assess solutions for improving energy efficiency in the mining industry. The methodological framework included

theoretical analysis, comparative assessment, mathematical calculations, and data processing. The initial parameters were selected based on the scientific literature and international reports reviewed in the study.

As a baseline, the total annual energy consumption of the global mining industry was taken as approximately 5.5 billion MWh, of which about 60% is associated with mineral extraction and processing. The sectoral distribution of energy consumption used in the calculations is presented in Figure 5.

**Figure 5. Sectoral distribution of total energy consumption in the mining industry**

More than 30 scientific articles and international reports were considered to determine the ranges of the main parameters used in the comparative assessment. Based on the reviewed sources, the calculations considered an energy efficiency improvement of 10-30%, energy savings of 250-400 GWh/year, renewable energy values ranging from 120 to 3000 GWh, and a reduction in CO₂ emissions of 10-40%. In addition, the reported CO₂ emissions of the mining sector in Kazakhstan, exceeding 80 million tons, were considered as an environmental reference indicator.

The technological solutions considered in the study included renewable energy sources (RES), energy management systems (EMS), and hybrid energy systems. Their energy, environmental, and economic characteristics were compared using the parameter ranges obtained from the analyzed literature. Particular attention was paid to investment costs, infrastructure requirements, energy consumption reduction, CO₂ emission reduction, system efficiency, and payback period.

For renewable energy projects, the total investment cost was determined as the sum of the initial investment and infrastructure modernization costs:

$$C_{total} = C_{init} + C_{infra}, \quad (1)$$

where:

C_{total} – total investment cost;

C_{init} – initial investment cost, ranging from 50 to 120 million USD;

C_{infra} – infrastructure modernization cost.

According to the adopted assumptions, infrastructure modernization costs accounted for 15-30% of the initial investment. Therefore, Equation (2) can be expressed as:

$$C_{total} = C_{init} + (0.15 - 0.30)C_{init}. \quad (2)$$

This relationship was used to estimate the total capital requirements for renewable energy integration under different implementation conditions. The corresponding parameter ranges were derived from the literature reviewed in Section 1.2. The economic performance of hybrid energy systems and EMS was additionally evaluated using the simple payback period:

$$T_{\text{payback}} = \frac{C_{\text{system}}}{S_{\text{annual}}}, \quad (3)$$

where:

T_{payback} – payback period;
 C_{system} – total system cost;
 S_{annual} – annual economic saving.

The system cost was considered within the range of 2.5-7.5 million USD for hybrid systems and 30-200 thousand USD for energy management systems. Maintenance costs of approximately 4-12% per year were also taken into account when assessing economic performance.

To compare the performance of the considered energy-efficiency solutions, an integrated indicator was used. It combines the reduction in energy consumption, peak load, CO₂ emissions, and the improvement in equipment efficiency:

$$\eta_{\text{eff}} = a_1 \Delta E + a_2 \Delta P + a_3 \Delta \text{CO}_2 + a_4 \Delta \eta_{\text{eq}}, \quad (4)$$

where:

ΔE – reduction in energy consumption;
 ΔP – reduction in peak load;
 ΔCO_2 – reduction in carbon dioxide emissions;
 $\Delta \eta_{\text{eq}}$ – improvement in equipment efficiency;
 a_i – weighting coefficients reflecting the relative contribution of the considered indicators.

The ranges used for the comparative assessment were 8-25% for energy consumption reduction, 10-30% for peak load reduction, 6-20% for CO₂ emission reduction, and 8-22% for equipment efficiency improvement.

The operational performance of EMS was additionally characterized by prediction accuracy, data acquisition interval, and monitoring frequency:

$$Q = f(A_{\text{pred}}, T_{\text{data}}, f_{\text{mon}}), \quad (5)$$

where:

A_{pred} – prediction accuracy, ranging from 80 to 95%;
 T_{data} – data acquisition interval, ranging from 1 to 30 min;
 f_{mon} – monitoring interval, ranging from 1 to 10 s.

These parameters characterize the ability of the system to provide timely information for operational energy management.

The overall system performance was represented as:

$$\eta_{\text{sys}} = \eta_{\text{eff}} \cdot Q, \quad (6)$$

where:

η_{sys} – characterizes the combined energy and operational performance of the considered system.

This expression was used as a general comparative representation rather than as an independent physical efficiency coefficient. The calculations and comparative data processing were performed using Python with the NumPy and Pandas libraries, while the considered energy consumption scenarios were evaluated using SMATH Solver. To assess the stability of the obtained results, the main input parameters were varied within a range of 10-20%, and a sensitivity analysis was performed.

Three calculation scenarios were considered:

- a conventional energy consumption scenario representing the baseline conditions;
- a scenario with the integration of renewable energy sources, with the RES share increased up to 20%;
- a hybrid energy scenario combining conventional and renewable energy technologies.

For each scenario, energy savings, economic parameters, and environmental indicators were compared. The calculated values were also compared with the ranges reported in previous studies, including an energy efficiency improvement of 15-30% and a CO₂ emission reduction of 12-40%.

The study was based on analytical and comparative evaluation and did not include industrial-scale experiments. The considered project implementation period was 4-7 years, the estimated payback period ranged from 2 to 6 years for EMS and up to 4-10 years for hybrid systems, while the reported potential for large-scale implementation ranged from 55 to 75%. These assumptions were used to compare the technical and economic characteristics of the considered energy-efficiency solutions under a common analytical framework.

3. Results and discussion

3.1. Analysis of energy consumption levels and energy efficiency improvement technologies in mining

The analysis showed that the total annual energy consumption of the mining industry is approximately 5.5 billion MWh. About 3.3 billion MWh, or 60%, is associated with mineral extraction and processing, while the remaining 2.2 billion MWh is consumed by transportation, ventilation, and auxiliary operations. This distribution confirms that extraction and processing represent the main areas in which energy-efficiency measures can provide the greatest potential effect (Fig. 6).

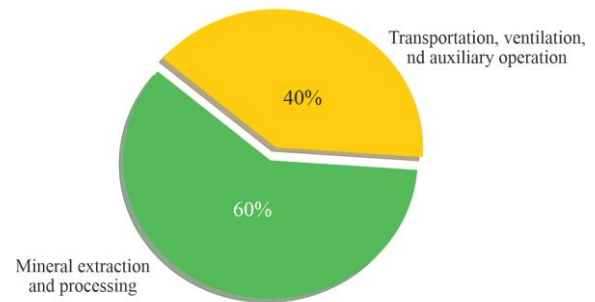


Figure 6. Share of energy consumption across processes in the mining industry

The scenario-based calculations indicate that the implementation of energy management systems can reduce energy consumption by 8-25%. Under the considered baseline conditions, total annual energy consumption decreases from 5.5 billion MWh to approximately 4.4-5.06 billion MWh, corresponding to energy savings of 0.44-1.1 billion MWh/year. Peak load reduction is estimated at 10-30%, while CO₂ emissions decrease from 80 million tons to approximately 64-75.2 million tons. In addition, equipment efficiency can increase by 8-22%. The ranges obtained for the main EMS indicators are presented in Figure 7.

The integration of renewable energy sources also demonstrates considerable potential. Increasing the RES share from approximately 2-3% to 20% corresponds to an increase in renewable energy use from about 110-165 million MWh to approximately 1.1 billion MWh. Within the adopted calculation assumptions, energy consumption can be reduced by 10-30%, corresponding to energy savings of 0.55-1.65 billion MWh/year. The estimated reduction in CO₂ emissions ranges from 12 to 40%.

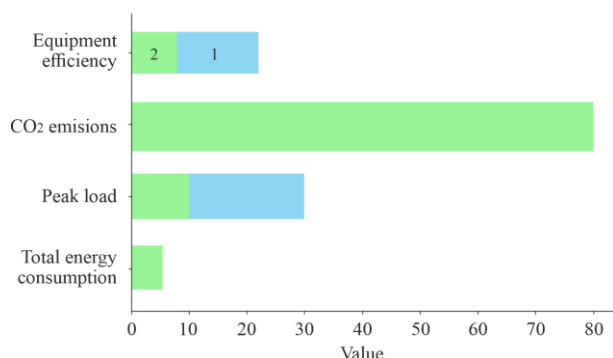


Figure 7. Comparison of energy management system results: 1 – upper range; 2 – lower range

At the same time, renewable energy integration requires substantial capital expenditure. The initial investment is estimated at 50-120 million USD, while infrastructure modernization costs range from approximately 7.5 to 36 million USD. Thus, the total economic effect of RES implementation depends not only on energy savings and emission reduction, but also on the required level of infrastructure renewal. The corresponding changes in energy, environmental, and investment indicators are presented in Figure 8.

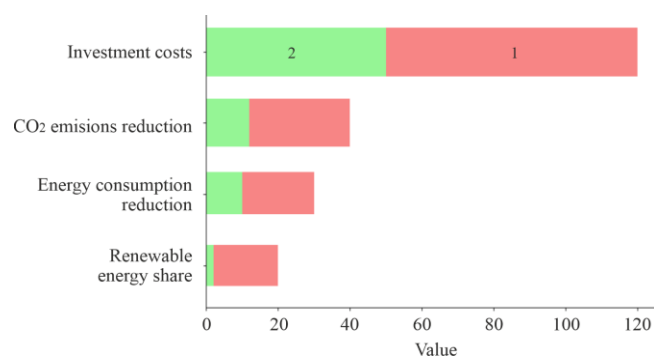


Figure 8. Changes in energy consumption, CO₂ emissions, and investment costs due to the integration of renewable energy sources: 1 – upper range; 2 – lower range

Hybrid energy systems showed the highest reported system-efficiency values among the considered solutions. Their system efficiency ranges from 70 to 90%, while the reduction in energy consumption is estimated at 15-35%. Under the adopted baseline conditions, this corresponds to annual energy savings of approximately 0.825-1.925 billion MWh. These results indicate that combining conventional and renewable energy sources with energy-management approaches can provide substantial energy and environmental benefits.

However, the wider implementation of such systems remains limited by investment costs and infrastructure complexity.

Overall, the obtained results indicate that EMS, RES, and hybrid technologies can all contribute to improving the energy performance of mining operations. Their effectiveness, however, differs depending on the technological configuration, implementation scale, and economic conditions.

3.2. Evaluation of the economic efficiency and practical application of the proposed solutions

The economic assessment showed that the total investment cost of renewable energy projects ranges from approximately 57.5 to 156 million USD. This includes initial investments of 50-120 million USD and infrastructure modernization costs of 7.5-36 million USD. The obtained values indicate that capital requirements remain one of the main limitations for the large-scale implementation of renewable energy technologies in mining. The main economic parameters of hybrid systems and energy management systems are presented in Table 6. For hybrid systems, the considered project cost ranges from 2.5 to 7.5 million USD, while annual savings range from approximately 0.5 to 1.2 million USD. The estimated payback period is 4-10 years. Energy consumption reduction is within the range of 8-25%, while peak-load reduction can reach 10-30%.

For energy management systems, the implementation cost ranges from approximately 30 to 200 thousand USD, while annual savings are estimated at 10-80 thousand USD. The corresponding payback period varies from 2 to 6 years. Compared with hybrid energy systems, EMS therefore require substantially lower initial capital expenditure, although their total energy effect is also more limited.

The efficiency and implementation characteristics of the considered systems are summarized in Table 7.

According to the obtained results, CO₂ emission reduction ranges from 6 to 20%, while equipment efficiency improvement reaches 8-22%. The integrated efficiency indicator considered in the calculations ranges from approximately 15 to 26%, while the values reported for individual hybrid energy systems can be considerably higher depending on the applied technological configuration. Infrastructure complexity is estimated at 6-10 points, risk level at 35-65%, and feasibility of implementation in remote areas at 45-75%.

The comparison also shows considerable differences between hybrid systems and EMS in terms of investment requirements. Hybrid systems are characterized by higher capital costs but can provide higher energy savings, while EMS are less expensive and can be implemented with a shorter payback period.

Table 6. Initial parameters of hybrid systems and energy management systems

System type	Project cost, million USD	Annual savings, million USD	Payback period, years	Energy consumption reduction, %	Peak load reduction, %
Hybrid systems	2.5-7.5	0.5-1.2	4-10	8-25	10-30
Energy management systems	0.03-0.20	0.01-0.08	2-6	–	–

Table 7. Efficiency and implementation parameters of hybrid systems and energy management systems

System type	CO ₂ emissions reduction, %	Equipment efficiency improvement, %	Overall efficiency, %	Implementation cost, million USD	Infrastructure complexity, points	Risk level, %	Remote-area implementation feasibility, %
Hybrid systems	6-20	8-22	15-26	0.03-7.5	6-10	35-65	45-75
Energy management systems	–	–	20-35	–	–	–	–

Therefore, the choice between these approaches should depend on the scale of the mining operation, available infrastructure, investment capacity, and the required level of energy-efficiency improvement.

The calculations were performed using Python and SMATH Solver, which made it possible to compare the main energy and economic parameters of the considered solutions under common assumptions. The results indicate that both hybrid systems and EMS can be practically applicable, although their implementation conditions differ significantly.

3.3. Discussion

The results obtained in this study generally confirm the conclusions reported in previous research on energy-efficiency improvement in the mining industry. The main considered directions – renewable energy sources, energy management systems, and hybrid technologies – demonstrate different levels of energy savings, environmental benefits, and economic feasibility.

The integration of renewable energy sources, which currently represents only a limited share of total energy use in mining, can provide a substantial contribution to reducing conventional energy demand and CO₂ emissions. Under the adopted assumptions, the increase in RES integration is associated with energy savings of 0.55-1.65 billion MWh/year and a reduction in CO₂ emissions of up to 40%. These results are generally consistent with the findings of Pouresmaeli et al. [50], who emphasized the potential role of renewable energy in increasing energy efficiency and supporting sustainable development in mining.

Similar conclusions were reported by Li et al. [53] and Roemer et al. [61], who showed that renewable energy integration can improve the energy and environmental performance of mining operations. At the same time, all these studies indicate that high investment requirements and infrastructure limitations remain major barriers to practical implementation. The present analysis provides similar results, with initial capital costs of 50-120 million USD and infrastructure modernization requirements of approximately 15-30%.

The results obtained for hybrid energy systems also agree with previous studies. Hybrid configurations combining renewable and conventional energy sources show system-efficiency values of approximately 70-90% and energy-consumption reductions of 15-35%. These results support the potential use of hybrid solutions, especially for remote mining operations where access to centralized energy infrastructure may be limited.

At the same time, the economic comparison shows that the implementation conditions differ considerably between the considered technologies. Hybrid systems require higher initial investment but can provide greater energy savings, while EMS generally have lower implementation costs and shorter payback periods. Therefore, no single technological solution can be considered universally optimal for all mining enterprises.

The study also has several limitations. First, the assessment is based mainly on literature-derived parameters and analytical calculations rather than on direct industrial experiments. As a result, the obtained values represent estimated ranges and may vary depending on mine type, production scale, local energy prices, technological readiness, and infrastructure conditions.

Second, the calculations assume relatively favorable implementation conditions for RES, EMS, and hybrid systems. In real mining operations, environmental conditions, regulatory requirements, equipment availability, and local infrastructure may significantly affect both technical and economic performance.

Another limitation is related to the scalability of the proposed approaches. The effectiveness of hybrid systems and renewable energy integration may differ between small, medium, and large mining enterprises. Therefore, the obtained results should be considered as a comparative analytical assessment rather than as fixed values applicable to all mining operations.

Further research should focus on the experimental validation of the considered approaches using real operating data from mining enterprises. Pilot projects and real-time monitoring could provide more accurate estimates of energy savings, emission reduction, investment efficiency, and payback periods.

Future studies may also consider the integration of hydrogen-based energy technologies, as proposed by Kalantari et al. [68], as well as predictive energy-management approaches based on machine-learning methods. Such developments could improve the adaptability and operational efficiency of energy systems under changing mining conditions. Future studies may also consider predictive energy-management approaches based on machine-learning methods and broader AI-supported management frameworks for sustainable digital transformation [71].

Overall, the results indicate that improving energy efficiency in the mining industry requires an integrated approach combining technological, economic, and environmental considerations. Renewable energy sources, EMS, and hybrid systems all demonstrate considerable potential, but their practical implementation depends on investment capacity, infrastructure readiness, and operating conditions.

4. Conclusions

The analysis showed that the mining industry is characterized by high energy consumption, with approximately 60% of total energy use associated with mineral extraction and processing. The considered energy-efficiency solutions demonstrate different levels of potential improvement. The integration of renewable energy sources is associated with an energy consumption reduction of 10-30%, while hybrid energy systems can provide a reduction of 15-35% and reported system-efficiency values of 70-90%. Energy management systems can reduce energy consumption by 8-25%, peak loads by 10-30%, and CO₂ emissions by 6-20%. These results indicate that RES, EMS, and hybrid technologies can all contribute to improving the energy and environmental performance of mining operations.

The economic assessment showed considerable differences between the considered solutions. Renewable energy projects require the highest capital investment, with total costs ranging from approximately 57.5 to 156 million USD when infrastructure modernization is included. Hybrid systems require investments of approximately 2.5-7.5 million USD and can provide annual savings of 0.5-1.2 million USD, with a payback period of 4-10 years. Energy management systems require substantially lower investment, approximately 30-200 thousand USD, with an estimated payback period

of 2-6 years. Thus, the practical choice of a particular solution should depend on the scale of the mining operation, investment capacity, infrastructure readiness, and required level of energy-efficiency improvement.

The comparative assessment indicates that no single technological solution can be considered universally optimal for all mining enterprises. Renewable energy sources provide substantial environmental benefits but require significant capital expenditure; EMS are characterized by lower implementation costs and shorter payback periods; and hybrid systems provide comparatively high energy-performance indicators but require more complex infrastructure. Therefore, improving energy efficiency in the mining industry should be based on a combined assessment of energy, environmental, and economic factors.

The obtained results should be considered within the limitations of the study, which is based mainly on literature-derived parameters and analytical calculations rather than direct industrial experiments. Further research should therefore focus on validating the considered solutions using operating data from mining enterprises and pilot-scale implementation under different technological and economic conditions.

Author contributions

Conceptualization: KZ, RK, MM; Data curation: SA, NS; Formal analysis: KZ, II; Funding acquisition: OK; Investigation: SA, MM; Methodology: RK; Project administration: II; Resources: OK; Software: OK; Validation: NS; Visualization: NS; Writing - original draft: SA, OK, MM; Writing - review & editing: KZ, RK, NS, II. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Інноваційні рішення для підвищення енергоефективності в гірничодобувній промисловості

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Мета. Обґрунтувати рішення щодо підвищення енергоефективності гірничодобувної промисловості шляхом інтеграції відновлюваних джерел енергії (ВДЕ), систем енергоменеджменту (СЕМ) і гібридних енергетичних технологій з урахуванням їх енергетичної, екологічної та економічної ефективності.

Методика. У дослідженні використано теоретичний аналіз, порівняльне оцінювання, математичні розрахунки та обробку даних на основі наукових публікацій і міжнародних звітів. Основні показники ВДЕ, СЕМ і гібридних систем порівнювали за спільними енергетичними, екологічними та економічними критеріями. Розрахунки виконано з використанням Python із бібліотеками NumPy і Pandas, а також SMath Solver. Розглянуто три сценарії: традиційне енергоспоживання, інтеграцію ВДЕ та використання гібридних енергетичних систем.

Результати. Встановлено, що інтеграція ВДЕ може забезпечити зниження енергоспоживання на 10-30%, тоді як гібридні системи дають змогу зменшити його на 15-35%, а їх системна ефективність становить 70-90%. Використання СЕМ дає змогу скоротити енергоспоживання на 8-25%, пікові навантаження – на 10-30%, а викиди CO₂ – на 6-20%. Загальні інвестиційні витрати для проєктів із ВДЕ оцінено в 57.5-156 млн дол. США. Для гібридних систем необхідні інвестиції в межах 2.5-7.5 млн дол. США при щорічній економії 0.5-1.2 млн дол. США та строку окупності до 10 років, тоді як СЕМ потребують значно менших капіталовкладень і мають строк окупності до 6 років.

Наукова новизна. Виконано порівняльне оцінювання ВДЕ, СЕМ і гібридних енергетичних технологій за єдиним комплексом енергетичних, екологічних та економічних показників, що дало змогу визначити відмінності в їх ефективності, інвестиційних потребах і умовах практичного впровадження.

Практична значимість. Отримані результати можуть бути використані для обґрунтування вибору енергоефективних рішень для гірничих підприємств з урахуванням масштабу виробництва, інвестиційних можливостей, готовності інфраструктури та очікуваного рівня енергозбереження.

Ключові слова: відновлювані джерела енергії; системи енергоменеджменту; гібридні енергетичні системи; енергоефективність; гірничодобувна промисловість; викиди CO₂; енергозбереження; економічна ефективність

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