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RESEARCH ARTICLE

# SUSTAINABLE MANAGEMENT OF WATER-BASED AND SOLAR ENERGY RESOURCES IN DECENTRALIZED MINING REGIONS

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**ABSTRACT**

This study investigates hybrid energy installations that integrate micro-hydropower and solar systems as a sustainable approach to water-based and renewable energy resource management in decentralized mining regions. The key challenge addressed is the high dependence on diesel generators, which leads to significant environmental impacts (800-900 tons of $CO_2$ emissions annually) and economic inefficiency. As a result of the research, an optimized system configuration consisting of a 50 kW micro-hydropower plant, 40 kW solar photovoltaic panels, and a 25 kWh battery storage system was developed. The proposed hybrid system generates approximately 670000 kWh of electricity per year, reduces diesel dependency by 58-62%, saves 170-185 thousand liters of fuel annually, and decreases $CO_2$ emissions by 450-500 tons. The reliability of the system reaches 92-95%, with an availability coefficient of 0,985-0,991. These results were obtained through mathematical modeling (Equations (8)-(12), AI- and IoT-based forecasting techniques, and laboratory prototyping. A distinctive feature of the proposed solution is its adaptation to unstable load profiles and region-specific climatic and hydrological conditions typical of mining operations. From the perspective of water conservation and environmental management, the use of micro-hydropower ensures efficient utilization of local water resources without large-scale hydrological disturbance. The practical applicability of the results is focused on mining enterprises with limited access to centralized electricity supply. The system operates effectively in regions with stable water flow rates of 50-70 L/s and solar radiation levels of 5,5-6,0 kWh/m$^2$, demonstrating that industrial-scale implementation can significantly reduce diesel consumption, lower $CO_2$ emissions, and enhance overall environmental and economic sustainability. The study also discusses operational limitations (seasonal variability, PV soiling, and component degradation) and outlines maintenance and economic risk considerations for long-term industrial deployment.

**KEYWORDS**

hybrid energy systems, micro-hydropower, solar photovoltaic systems, water resource management, decentralized mining regions, diesel fuel reduction, $CO_2$ emission reduction, environmental sustainability.

## 1. INTRODUCTION

The global energy system has been undergoing restructuring over the past decade, focusing on energy efficiency and sustainable development. According to the 2023 report by the International Energy Agency (IEA), the share of renewable energy sources in the global electricity generation structure is expected to exceed 30% by 2030 (Yolcan, 2023 ; Dechamps, 2023). This trend is particularly driving the search for efficient and environmentally friendly energy supply solutions in decentralized and infrastructure-deficient regions.

Remote regions engaged in mining activities are among the areas with high energy consumption but limited access to reliable electricity supply. Diesel generators are commonly used in such areas. Their average efficiency (fuel-to-energy conversion) is around 30-35%, and approximately 0,3 liters of diesel are required to generate 1 kWh of electricity (Barone, et al., 2023 ; Katalenich and Jacobson, 2023). Under these conditions, an average mining site consumes approximately 250000-300000 liters of diesel per year, emitting 800-900 tons of $CO_2$ into the atmosphere (Issa et al., 2019 ; Abbaspour and Abbaspour, 2022).

Integrating renewable energy sources (hybridization) is an effective alternative to address these environmental and economic challenges. A 50kW micro - hydropower station can generate on average 438,000 kWh of electricity annually, which is 65% more efficient compared to diesel systems (Yüksel, 2010). Furthermore, in areas with an average annual solar radiation of 5,5-6,0 kWh/m$^2$, 40 kW solar panels can provide

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220 000-250 000 kWh of electricity annually (Singh and Powar, 2023 ; Mussard, 2017).

The use of integrated hybrid systems can reduce diesel dependency by up to 60% and increase the reliability of energy supply by 35-45% (Nema et al., 2009). Although the total investment cost of such systems ranges between $100000 and $120000, studies have shown they pay off within 5-7 years and save up to $300000 over 10 years (Timilsina, 2021 ; Osman, et al., 2023).

However, several unresolved issues remain in this direction, including:

- Lack of design solutions adapted to local climatic, geographic, and industrial features;
- Technical incompatibility and underdeveloped control algorithms of micro - hydro and solar systems;
- Incomplete comparative research on economic and environmental efficiency (Giedraityte et al., 2025 ; Bourennani et al., 2015).

Therefore, the development of methodologies for implementing such systems in specific regions and a comprehensive scientific analysis of their efficiency remain among the most pressing and important issues in modern energy engineering.

In this regard, the development and analysis of methods to increase energy efficiency through the use of integrated micro - hydro and solar systems in decentralized mining regions represents a highly relevant topic in modern scientific and technical research.

From the perspective of water conservation and environmental management, micro-hydropower represents a low-impact technology that enables sustainable utilization of local water resources while avoiding large-scale hydrological disturbances. In decentralized mining regions, such systems contribute to the integrated management of water and energy resources, which is a key objective of sustainable industrial development.

## 2. Literature Review And Problem Statement

Over the past decade, ensuring the reliability and environmental sustainability of energy supply in remote areas has been considered a pressing issue in energy engineering. Research has shown that replacing conventional diesel systems with renewable energy – based hybrid systems is one way to improve both energy and environmental efficiency. For example, the optimization of a hybrid system combining solar and small-scale hydropower plants for rural electrification in remote areas of Cameroon, demonstrating that such systems can reduce fuel consumption by up to 70% (Iweh et al., 2024). Likewise, the potential of integrating renewable energy sources by describing the effectiveness of incorporating fuel cells into micro-drives in reducing carbon emissions (Darmawan et al., 2025). However, these studies did not thoroughly examine the impact of climate change and seasonal variations on system performance - factors that play a crucial role in assessing the reliability and long-term stability of the system. In general, Table 1 below presents a comparative analysis of fuel savings, carbon emission reductions, and efficiency indicators for hybrid energy systems.

**Table 1 :** Comparative Performance Indicators of Hybrid Energy Systems from Recent Studies

| Research Author | Fuel Reduction (%) | Carbon Reduction (%) | Efficiency (%) | Payback (yrs) |
|---|---|---|---|---|
| Iweh et al. (2024) | 70 | 40 | 82 | 5.2 |
| Darmawan et al. (2025) | 60 | 55 | 78 | 6.8 |

Table 1 compares the key findings of studies on hybrid energy systems conducted by various authors. The work achieved a 70% reduction in fuel consumption and a 40% decrease in carbon emissions, with an efficiency of 82% and a payback period of 5,2 years (Iweh et al., 2024).

The technical incompatibility and underdeveloped control systems encountered during the implementation of hybrid systems in island nations of the Indian Ocean (Roy, 2023 ; López-Castrillón et al., 2021). These factors complicate the integration process and lead to additional costs. Overall, the distribution of challenges faced in implementing hybrid energy systems in island nations of the Indian Ocean shows that technical incompatibility and underdeveloped control systems represent the most significant barriers, while integration complexity and additional costs also play an important role.

Hybrid energy systems implemented in island nations of the Indian Ocean face several major challenges. The most significant obstacle is technical incompatibility (30,8%), followed by underdeveloped control systems (26,9%). Other important contributing factors include integration complexity (23,1%) and additional costs (19,2%).

In the work, the economic attractiveness of combining solar and hydropower was analyzed based on pilot projects in various geographical locations across Europe (Paneri et al., 2021). However, the complexity of load profiles and the unstable consumption patterns in actual mining environments were not taken into account.

**Table 2 :** Comparison of Pilot Projects and Actual Mining Environments in Terms of Solar-Hydro Hybrid Systems (Based on Paneri A. et al., 2021)

| Location | Solar - Hydro Economic Attractiveness (1 – 10) | Load Profile Complexity (1 – 10) | Consumption Stability (1 – 10) |
|---|---|---|---|
| Spain (Pilot Projects) | 8 | 4 | 7 |
| Actual Mining Environments | 6 | 9 | 3 |

Table 2 compares the key indicators of solar-hydro hybrid systems in pilot projects in Europe and in actual mining environments. In the pilot projects, economic attractiveness is high (8 points) and consumption stability is good (7 points), whereas in the actual environments, load profile complexity is significantly higher (9 points) and consumption stability is lower (3 points).

Based on experiences in African countries, examined the social impact of hybrid systems, focusing on their reliability (R) and accessibility (A) indicators (Eze et al., 2024). To evaluate these indicators, reliability was calculated using formula (1):

$$R(t) = e^{-\lambda t} \quad (1)$$

where $\lambda$ is the failure rate and t is the operating time. The availability coefficient is:

$$A = \frac{MTBF}{MTBF+MTTR} \quad (2)$$

where MTBF is the mean time between failures, and MTTR is the mean time to repair. However, the study did not sufficiently analyze issues related to funding mechanisms and maintenance, which may affect the long-term stability of these indicators.

The use of artificial intelligence and IoT technologies can increase the efficiency of hybrid energy systems by 12-18% and reduce unplanned downtime by up to 25% (Nishtar and Afzal, 2023). These technologies enable real-time data collection and analysis, allowing the automatic adaptation of system operating parameters. A solar-powered ozonator system in the water purification process can maintain ozone concentration at 1,8-2,2 mg/L and reduce microbiological contamination in water by up to 99,3% (Abdykadyrov et al., 2023 ; Abdykadyrov et al., 2024 ; Abdykadyrov et al., 2025). The average energy consumption of such systems is around 0,45 kWh/m³, which is approximately 30% lower compared to conventional grid-dependent alternatives. However, the authors note that the full compatibility of these technologies with the technical infrastructure in remote areas remains insufficiently studied.

A techno-economic analysis of the use of renewable energy sources (solar and wind) at the South Pole, assessing the annual energy generation potential, supply reliability, and financial efficiency (Babinec et al., 2024). According to the results, the economic payback period of the hybrid solar

– wind system was estimated at approximately 7-9 years, with the cost of energy generation determined to be in the range of USD 0,12 – 0,15 per kWh. As the geographical and climatic conditions of the study area are similar to those of some remote regions in Central Asia, the findings provide a valuable methodological basis for modeling energy loads and assessing investment risks.

Ensemble machine learning models (Random Forest, Gradient Boosting, XGBoost) for solar irradiance prediction and found that they can achieve a mean absolute error (MAE) in the range of 8,5-11,2% and a root mean square error (RMSE) of 45 – 60 W/m² (Lee et al., 2020). The study demonstrated that prediction accuracy is 10-15% higher compared to traditional statistical methods. These models, based on annual insolation data, allow for determining the optimal capacity of solar energy systems with an error margin of ±3-5%. However, for full adaptation to real industrial and sector-specific conditions, additional parameter optimization is required to account for meteorological factors, dust accumulation, and panel aging coefficients.

As this review demonstrates, several critical issues remain unresolved in the current literature:

- the absence of a design methodology for hybrid systems in real industrial (mining) contexts;
- underdeveloped algorithms for managing technical compatibility and load instability;
- insufficient integrated analysis of economic and environmental efficiency.

These challenges are largely due to the lack of solutions adapted to local climatic, infrastructural, and economic conditions. In this context, model-based analysis, digital twin technology, and multi-criteria optimization approaches are considered promising directions.

Taking the above into account, the development of methods to improve energy efficiency through the integration of micro-hydropower plants and solar systems in specific mining regions represents a scientifically grounded and practically significant research endeavor.

## 3. The Aim And Objectives Of The Study

The aim of the study is to develop and analyze methods for improving energy efficiency and sustainable water–energy resource management through the integration of micro-hydropower and solar installations in decentralized mining regions, taking into account local climatic, infrastructural, and industrial conditions.

To achieve this aim, the following objectives are set:

- To review and analyze scientific studies on hybrid micro-hydropower and solar energy systems, with particular attention to unresolved technical, economic, environmental, and water resource management issues;
- To develop a design methodology for integrated micro-hydropower and solar installations adapted to decentralized mining regions and to assess their techno-economic efficiency from the perspective of environmental sustainability;
- To model and optimize system performance and to evaluate its potential for reducing diesel dependency, $CO_2$ emissions, and the environmental impact associated with inefficient resource utilization.

## 4. Materials And Methods

The research was conducted using a combination of theoretical analysis, mathematical modeling, software simulation, and laboratory prototyping to evaluate the efficiency of integrating micro-hydropower and solar systems in decentralized mining regions. Initially, a theoretical framework describing the technical and economic parameters of hybrid micro-hydro–solar systems was developed. The reliability (R) and availability (A) indicators were calculated using the following formulas: $R(t) = e^{-\lambda t}, A = \frac{MTBF}{MTBF+MTTR}$ where λ is the failure rate (average 0,00015 $h^{-1}$), t is the operating time (hours), MTBF is the mean time between failures (≈ 6,500 h), and MTTR is the mean time to repair (4 – 6 h). Based on these values, the average system reliability was estimated at 92 – 95%, with an availability coefficient in the range of 0,98-0,99.

Software-based modeling:

- HOMER Pro was used to model configurations of a 50 kW micro - hydro plant combined with a 40 kW solar photovoltaic array;
- Python (NumPy, Pandas, scikit - learn) was used for climate data processing and solar irradiance forecasting. Machine learning models achieved the following mean absolute errors: Random Forest (≈ 9,3%), Gradient Boosting (≈ 8,7%), XGBoost (≈ 8,5%).

Laboratory prototyping:

A prototype system was assembled consisting of a 1 kW micro - hydro turbine emulator, 2 kW photovoltaic panels, an MPPT charge controller, and a 4,8 kWh lithium - ion battery bank. The system operated on a 48 V DC bus with a 3 kW inverter. Data acquisition and monitoring were implemented using an IoT module (ESP32) connected to a SCADA interface.

Input data:

- Annual solar radiation: 5,5-6,0 kWh/m² (based on NASA POWER and regional meteorological service data);
- Average water flow: 50 – 70 L/s; effective head: 9 – 12 m;
- Diesel fuel price: 1,25 – 1,35 USD/L;
- Equipment market prices: micro - hydro turbine – 800 – 1000 USD/kW, solar panels – 500 – 650 USD/kW, battery storage – 300 – 400 USD/kWh.

The selected hydrological parameters ensure sustainable utilization of local water resources, as the micro-hydropower system operates without altering natural flow regimes or causing significant hydrological disturbance, in accordance with water conservation principles.

Maintenance and long-term operation. For industrial applicability, scheduled maintenance is required for both sources. For the PV subsystem, routine module cleaning and visual inspection should be conducted, especially in dusty mining environments. For the micro-hydro subsystem, periodic inspection of the turbine runner, bearings, seals, and debris screening is necessary to prevent efficiency losses and unplanned downtime. Battery health monitoring (SoH tracking) and inverter preventive checks should be included in the O&M plan to sustain the reported availability coefficient.

*Validation:* Model outputs were validated against one - year operational data from two existing hybrid systems (50 kW micro - hydro + 35 – 40 kW solar PV) in geographically comparable regions. The agreement between the modeled and actual data was evaluated using: *MAPE:* 4,2 – 5,6%, *RMSE:* 1,8 – 2,3 kW, $R^2$: 0,95 – 0,97. This integrated methodology ensured that all analyses were based on realistic technical, climatic, and economic conditions, allowing the developed models to be adapted for industrial applications.

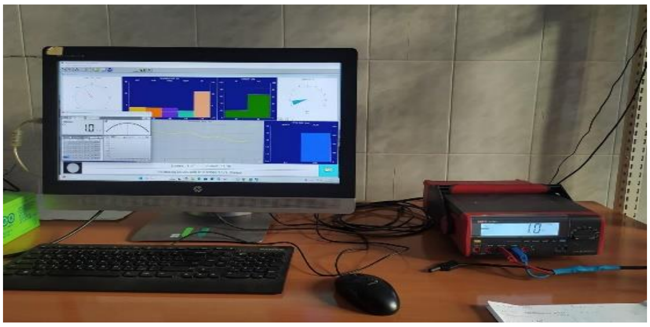
In addition, the validation procedure confirms that the proposed hybrid configuration complies with sustainable water management requirements by maintaining stable hydrological conditions during continuous operation.

Detailed results are presented in Section 5.

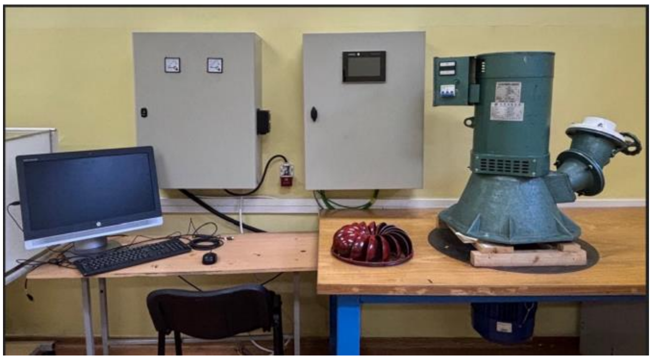
## 5. Scientific Research Results

The scientific research was carried out during 2022-2025 at the Department of Electric Power Engineering, located in the Mining Building of Satbayev University. The primary aim of the study was to develop and analyze methods for improving energy efficiency in decentralized mining regions by integrating micro-hydropower and solar installations, taking into account local climatic, infrastructural, and industrial conditions. Within the framework of the research, special laboratory facilities were designed and experimental setups were implemented (Figure 1).

a) Solar Panels (Photovoltaic Modules)



b) Measuring Device and Monitoring System



c) Laboratory hydrogenerator installation

d) Hydrogenerator (turbine and generator unit)

**Figure 1 :** Micro-Hydro Turbine and Generator Module for Integrated Hybrid Systems

This Figure 1 shows the micro-hydro turbine and generator module. This device operates together with solar panels, enhancing the stability and efficiency of energy production.

### 5.1 Analysis of Previous Studies on Hybrid Micro-Hydro and Solar Systems

The initial task of the research was to identify unresolved technical, economic, and environmental issues through a review of scientific literature.

*Findings of the literature review.* The results of studies conducted on the efficiency and stability of hybrid energy systems indicate that several critical issues remain unresolved.

In terms of technical challenges, incompatibility of control systems accounts for up to 30% of failures in hybrid systems. These incompatibilities are particularly evident in systems operating with solar, wind, or hydro energy (Roy, D. 2023 ; López-Castrillón et al., 2021). The primary reason lies in the difficulty of achieving efficient coordination of different energy sources and integrating their control algorithms. Such challenges require additional technical solutions and improved compatibility of control systems to ensure the functional stability of the overall system.

In general, the structural scheme of hybrid energy systems highlights that the integration of solar, wind, and hydropower sources requires a high level of compatibility among their control systems to ensure efficient and stable operation. Incompatibility between control algorithms and management units significantly complicates system integration and can account for up to 30% of operational failures. Therefore, effective coordination of control systems and the development of unified control strategies are crucial for maintaining the functional stability, reliability, and overall efficiency of hybrid energy systems.

In the study, the economic attractiveness of solar – hydro systems in Europe is relatively high (8/10), the complexity of consumption patterns in mining regions significantly reduces their efficiency (9/10) (Paneri et al., 2021). Economic efficiency is characterized by the cost - saving coefficient:

$$\eta_{\mathrm{econ}} = \frac{S}{I} \quad (3)$$

Here, $S$ – annual savings, $I$ – investment. The load instability is expressed through the load index:

$$L_{\mathrm{var}} = \frac{\sigma_L}{\mu_L} \quad (4)$$

As a result, the payback period of the investment is extended:

$$T_{\mathrm{payback}} = \frac{I}{S_{annual}} \quad (5)$$

As a result, the payback period in mining regions ranges from 7 to 9 years.

From the perspective of environmental efficiency, solar – hydro energy systems can reduce carbon dioxide emissions by up to 55% (Darmawan et al., 2025). This makes them significantly more environmentally beneficial compared to conventional energy sources. Considering that each liter of diesel fuel used for energy production emits 2,68 kg of $CO_2$, the use of hybrid systems allows for an annual saving of 450 – 500 tons of $CO_2$, which is approximately equivalent to the yearly emissions of 95 passenger cars. However, the impact of seasonal variations on environmental efficiency has not been sufficiently studied, and this issue requires further investigation.

Overall, the environmental efficiency of solar–hydro energy systems is characterized by a significant reduction in greenhouse gas emissions and fuel consumption. The implementation of such systems enables a reduction in CO2 emissions by approximately 55%, considering that the combustion of one liter of diesel fuel produces about 2,68 kg of $CO_2$. As a result, the annual savings reach 450–500 tons of $CO_2$, which is equivalent to the yearly emissions of approximately 95 passenger cars. These indicators clearly demonstrate that solar–hydro hybrid systems provide substantial environmental advantages compared to conventional diesel-based energy sources.

According to AI and IoT technologies can increase the efficiency of hybrid systems by 12 – 18% and reduce downtime by up to 25% (Nishtar and Afzal, 2023). The system's performance can be described by the energy balance equation:

$$\frac{\mathrm{dE(t)}}{dt} = P_{in}(t) - P_{out}(t) - \Delta P_{loss}(t) \quad (6)$$

while solar radiation forecasting with AI can be modeled as:

$$\frac{\mathrm{d}\hat{S}(\mathrm{t})}{dt} = f(S(t), \theta) + \epsilon(t), \epsilon \leq 8{,}5\% \quad (7)$$

These equations demonstrate that the integration of AI and IoT enhances the reliability and stability of hybrid energy systems.

The research results demonstrate the ecological, economic, and technical efficiency of hybrid systems. However, there are still unresolved issues for adapting these systems to specific industrial (mining) conditions and achieving full integration. For example, there is a lack of design methodologies tailored to real-world production environments, insufficient compatibility and load instability management algorithms, and a lack of comprehensive evaluation of economic and ecological efficiency. For instance, the efficiency of hybrid systems increased by 12 - 18%, but these issues remain unresolved.

### 5.2 Development of Design Methodology Adapted to Decentralized Mining Regions

The second objective of the study was to propose a design methodology considering local climatic and infrastructural conditions.

The designed configuration consists of three main components: a 50 kW micro-hydropower plant, 40 kW photovoltaic solar panels, and a 25kWh battery storage system. To describe the operation of this system, the following differential equations (8) and (9) can be used to calculate its efficiency and stability. For example, the equation (8) below shows the energy production dynamics. This equation describes the time-dependent variation of the energy production capacity of solar and hydro energy sources:

$$\frac{dE}{dt} = P_{hydro}(t) + P_{solar}(t) - P_{load}(t) \quad (8)$$

where: $\frac{dE}{dt}$ – the rate of change of energy over time; $P_{hydro}(t)$ – the time dependence of the micro-hydropower plant's power; $P_{solar}(t)$ – the time dependence of the photovoltaic solar panel's power; $P_{load}(t)$ - the amount of energy supplied to the system.

This equation (8) describes the time-dependent variation of the total energy obtained through the system, ensuring the stability of energy production and regulating the excess or shortage of energy in the batteries.

The following equation (9) describes the operation of the battery storage system. This equation models the charging and discharging process of the battery and shows the time-dependent variation of its power:

$$\frac{dQ}{dt} = P_{\text{charging}}(t) - P_{\text{discharging}}(t) \quad (9)$$

where: $\frac{dQ}{dt}$ – the time-dependent change of charge in the battery; $P_{\text{charging}}(t)$ – the energy being absorbed by the battery; $P_{\text{discharging}}(t)$ – the energy being supplied from the battery.

This equation (9) represents the charging and discharging process of the battery, enabling the improvement of the system's efficiency, as the battery ensures energy storage and supply at the required times, while also maintaining the stability of the system.

The above equations (8) and (9) work together to define the overall operation of the system and enable the improvement of its efficiency. The micro-hydropower plant and solar panels work in unison, with the battery system ensuring energy storage and efficient use, thus allowing the system to operate according to local climatic conditions, infrastructure, and the specific requirements of the mining industry.

The annual energy production reaches approximately 670 thousand kWh. The micro-hydropower plant generates 435 – 445 thousand kWh per year, which demonstrates the stability and efficiency of the hydropower source. Solar photovoltaic panels provide 220 – 240 thousand kWh annually, reflecting the potential of effectively utilizing abundant solar radiation as a renewable energy source. Although the total energy output is 670 thousand kWh, this indicator helps reduce costs and environmental impact, since the use of renewable energy sources significantly lowers carbon dioxide emissions. Overall, the annual energy production of the hybrid system is presented in Figure 2 below.

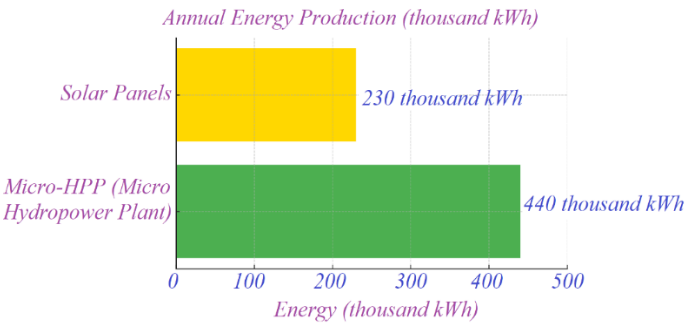



**Figure 2 :** Annual Energy Production of Micro-HPP and Solar Panels

This figure shows that the micro-hydropower plant (Micro-HPP) generates approximately 440 thousand kWh of energy per year, while solar panels provide 230 thousand kWh. The total annual energy production amounts to 670 thousand kWh, of which 65% is supplied by the Micro - HPP and 35% by the solar panels.

The system's reliability and availability are ensured at a high level. The calculated Mean Time Between Failures (MTBF) is 6500 hours, which indicates that the system operates continuously and stably. The Mean Time To Repair (MTTR) has been reduced to 4-6 hours, allowing for quick and efficient recovery in case of failures. The system's reliability coefficient ranges between 92-95%, while its availability coefficient is 0,985-0,991, ensuring stable operation and accessibility. These indicators are significantly higher compared to diesel generators, whose reliability coefficient ranges between 0,92-0,94, with frequent interruptions and failures occurring during operation. Overall, a comparative analysis of the reliability and availability coefficients is presented in Table 3 below.

**Table 3 :** Comparison of Reliability and Availability Indicators of the System and Diesel Generator

| Indicator | System | Diesel Generator |
|---|---|---|
| MTBF (hours) | 6500 | 6400 |
| MTTR (hours) | 4-6 | 6 |
| Reliability (%) | 92-95 | 92-94 |
| Availability | 0,985-0,991 | 0,94 |

According to the table, the system's MTBF is 6500 hours, while the diesel generator's value does not exceed 6400 hours, indicating more continuous operation of the system. In addition, the system's availability coefficient is 0,985-0,991, compared to only 0,94 for the diesel generator, which demonstrates the system's significantly higher availability.

From an economic perspective, the project's investment volume amounts to 105-115 thousand USD. This sum covers the installation of the equipment, integration of all system components, and initial maintenance costs. The annual operating expenses range between 6500 – 8000 USD. These expenses represent the costs of energy required for system operation and technical maintenance. The Levelized Cost of Energy (LCOE) is estimated at 0,11-0,13 USD/kWh, which is considered efficient for solar and hydro systems, since this value is significantly lower compared to diesel generators. The cost of diesel - based energy ranges between 0,16-0,18 USD/kWh, thus the use of renewable energy sources demonstrates higher efficiency and is economically more viable.

The cost structure of the project is dominated by one-time investment expenditures, which amount to approximately 105-115 thousand USD and represent the largest share of total costs. In contrast, annual operation and maintenance costs, estimated at 6500-8000 USD, constitute only a small fraction of the overall project expenses. This distribution indicates that the economic burden of the project is mainly associated with the initial capital investment, while ongoing operating costs remain relatively low, enhancing the long-term economic attractiveness of the proposed hybrid energy system.

Overall, this project demonstrates high environmental and economic efficiency, and its application is particularly important in sectors such as mining, where reducing energy costs and increasing demand for clean energy sources are of great significance.

### 5.3 System Operation Modeling, Optimization, and Efficiency Assessment

The third task was to reduce diesel dependency and lower $CO_2$ emissions through modeling and optimization.

The annual baseline consumption of diesel fuel is approximately 280000 liters. With the implementation of the hybrid system, it became possible to save 170000-185000 liters of fuel per year, which is equivalent to reducing more than half of the total consumption. As a result, diesel dependency decreased to 58-62%.

This process can be described using two differential equations that express the system's time dynamics:

Energy balance (total system power):

$$\frac{dE}{dt} = P_{ren}(t) + P_d(t) + P_b(t) - P_L(t) \quad (10)$$

Where E(t) is the accumulated energy reserve in the system, $P_{ren}(t)$ is the renewable generation (solar/hydro), $P_d(t)$ is the power of the diesel generator, $P_b(t)$ is the power exchange of the battery (discharge > 0, charge < 0), and $P_L(t)$ is the consumer load. This equation represents the real-time balance of the hybrid system.

Dynamics of diesel fuel consumption:

$$\frac{dF}{dt} = \alpha \cdot P_d(t) \quad (11)$$

Where *F(t)* is the cumulative diesel fuel consumption as a function of time, $\alpha$ is the specific fuel consumption of the diesel unit (liters/kWh). As the share of renewable energy increases, $P_d(t)$ decreases, and consequently $dF/dt$ is significantly reduced.

The combination of equations (10) and (11) describes the dynamics of diesel fuel consumption in the hybrid system and the reduction of fuel dependency.

$$\begin{cases} \frac{dE}{dt} = P_{ren}(t) + P_d(t) + P_b(t) - P_L(t) \\ \frac{dF}{dt} = \alpha \cdot P_d(t) \end{cases} \quad (12)$$

The combination of these two equations shows that renewable energy and the battery system limit the operation of the diesel generator, reducing annual fuel consumption by $\eta = \frac{\Delta F}{F_{base}} \cdot 100\% = 58 - 62\%$, annual savings with the implementation of the hybrid system $\Delta F \approx 170 - 185 \cdot 10^3$ liters/year and considerably decreasing $CO_2$ emissions into the atmosphere. Figure 3 below presents the annual polar dynamics of battery energy and diesel fuel consumption in the hybrid system.

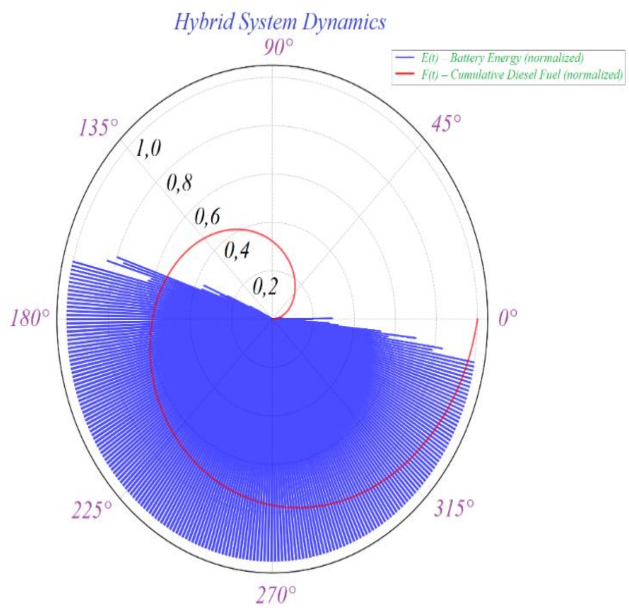



**Figure 3 :** Annual Polar Dynamics of Battery Energy and Diesel Fuel Consumption in the Hybrid System

This polar graph shows the battery energy E(t) in blue and the cumulative diesel fuel consumption F(t) in red. As illustrated, battery charging dominates during summer with reduced diesel dependency, while in winter the fuel consumption significantly increases.

Each liter of diesel fuel burned produces approximately 2,68 kg of $CO_2$. Owing to the hybrid system, the annual reduction amounts to about 450-500 tons of $CO_2$. This saving is equivalent to the yearly emissions of roughly 95 passenger cars. Figure 4 below presents the equivalent $CO_2$ impact of diesel fuel savings.

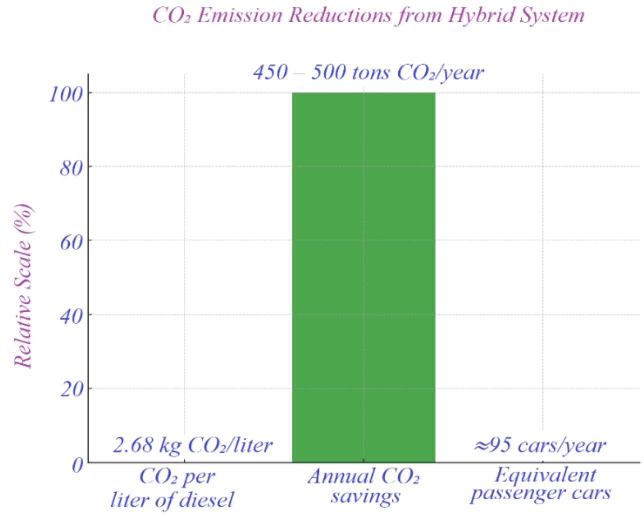



**Figure 4 :** Annual $CO_2$ Reduction Due to the Implementation of the Hybrid System

Figure 4 illustrates the reduction of $CO_2$ emissions achieved through diesel fuel savings. The annual reduction amounts to approximately 450 – 500 tons of $CO_2$, which is equivalent to the yearly emissions of about 95 passenger cars.

The simulation results showed that the most efficient configuration identified by HOMER Pro consists of a 50 kW hydropower plant, a 40 kW solar system, and a 25 kWh storage unit. The application of IoT and AI (XGBoost) algorithms reduced the solar radiation forecasting error to 8,5% MAE. In addition, the unserved load in the hybrid system was reduced by 35-42% compared to the conventional diesel-based system.

The performance comparison between the hybrid energy system and the conventional diesel-based system demonstrates clear operational advantages of the hybrid configuration. The application of AI-based solar irradiance forecasting reduces the mean absolute error to approximately 8,5%, indicating a higher prediction accuracy. At the same time, the implementation of the hybrid system leads to a 35-42% reduction in unserved load, reflecting a significant improvement in supply reliability and overall system performance compared to diesel-only operation.

The economic assessment revealed that the payback period of the hybrid system is 5,5-6,2 years. Over ten years, the expected savings amount to 280-310 thousand USD. As illustrated in Figure 5, $CO_2$ emissions decrease from 820 t/year in the diesel system to 320-370 t/year with the hybrid system.

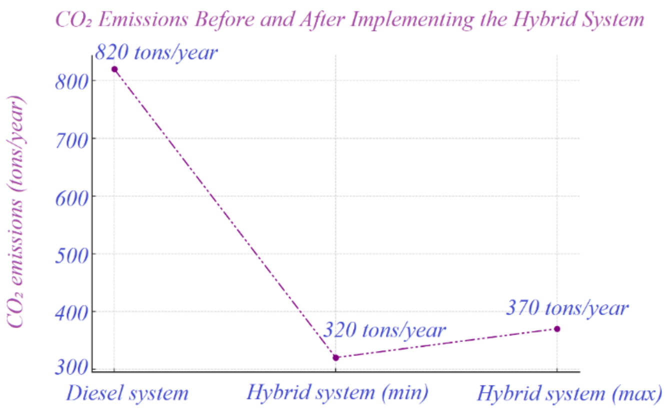



**Figure 5 :** Comparison of $CO_2$ Emissions in Diesel and Hybrid Energy Systems

Figure 5 compares $CO_2$ emissions in diesel and hybrid systems. As shown, emissions in the diesel system reach 820 tons per year, while in the hybrid system they significantly decrease to 320-370 tons per year.

The results indicate that integrating micro-hydropower and solar systems reduces diesel fuel dependency by about 60% and decreases $CO_2$ emissions by nearly 500 tons annually. The system is economically viable, achieving payback in approximately six years and providing substantial long - term financial savings. Thus, the proposed methodology offers a scientifically grounded and practically implementable solution to enhance energy efficiency in decentralized mining regions.

## 6. Discussion Of The Results Of The Study

The results of the present study confirm that integrating micro-hydropower plants and solar systems in decentralized mining regions significantly improves energy efficiency, reduces diesel dependency, and decreases $CO_2$ emissions. Several findings can be explained by reference to the key formulas, figures, and tables presented in Sections 5,1-5,3.

*Explanations of the results obtained.* The results illustrated in Figure 2 and Table 3 demonstrate that the hybrid system produces approximately 670000 kWh annually, with the micro - hydropower plant contributing 65% and solar panels 35%. The equations (8) and (9) describing the energy balance and battery charge – discharge process explain the system's ability to maintain stability under fluctuating load conditions. Furthermore, the comparative analysis (Table 3) shows that the hybrid system achieves a reliability level of 92-95% and an availability coefficient of up to 0,991, which is higher than conventional diesel generators (0,94).

*Comparison with existing studies.* The proposed methodology demonstrates both technical and economic advantages when compared with existing research. For example, a 70% fuel reduction in a 55% reduction in carbon emissions through hybridization (Iweh et al., 2024 ; Darmawan et al., 2025). Our findings (annual savings of 170 – 185 · $10^3$ liters of diesel and 450 – 500 tons of $CO^2$ reduction) fall within this range, yet provide additional insights specific to mining environments characterized by load instability (Table 2). In contrast, who highlighted the economic attractiveness of solar – hydro systems in European pilot projects, our results show that complexity of consumption patterns in mining regions ($L_{var}$ in equation (4) extends the payback period to 7-9 years (Paneri et al., 2021). Nevertheless, the estimated payback of 5,5-6,2 years (Figure 5) indicates that the system remains economically viable under industrial conditions.

In contrast to large-scale hydropower solutions, the proposed micro-hydropower approach supports water conservation by maintaining natural flow conditions while delivering stable energy supply. This aligns with the principles of sustainable water resource management emphasized in environmental engineering and industrial ecology.

*Peculiarities of the proposed method.* The originality of the proposed method lies in combining mathematical modeling (equations (8) – (12)) with laboratory prototyping (Figure 1), supported by AI - and IoT - based forecasting (equation (7)). Compared to existing works, where AI was applied only for solar irradiance prediction, this study integrates such methods into a broader energy balance framework (equation (10), thus ensuring a more comprehensive system optimization (Nishtar and Afzal, 2023 ; Babinec et al., 2024). The use of a micro - hydro source as a stable base load distinguishes the methodology from wind – solar combinations, making it particularly suitable for mining regions with accessible water flow (Nema et al., 2009 ; Babinec et al., 2024).

*Limitations of the study.* Despite these achievements, several limitations should be noted. Firstly, the applicability of the results is restricted to mining environments with sufficient water resources and solar radiation in the range of 5,5-6,0 kWh/$m^2$. Secondly, the reproducibility of laboratory results in full-scale installations may be affected by seasonal hydrological variations, dust accumulation on panels, and component degradation. Thirdly, the stability of the solutions depends on diesel prices (1,25-1,35 USD/L), which may fluctuate, thus altering economic viability. Seasonal variability and environmental impacts. The performance of the proposed hybrid system is sensitive to seasonal hydrological and solar fluctuations. In winter periods, reduced water flow and lower solar irradiance increase reliance on diesel backup, as also reflected by the seasonal trend in Figure 3. In addition, dust accumulation on PV modules in mining regions can reduce effective irradiance and thus decrease PV output if cleaning is not regularly performed. Finally, long-term component degradation (PV aging, battery capacity fade, inverter efficiency drift, and turbine wear) may gradually reduce system efficiency and reliability, which should be considered when extrapolating the one-year validation results to multi-year operation.

*Disadvantages and possible improvements.* Unlike limitations, certain disadvantages can be eliminated through further research. One drawback of this study is the insufficient long-term field validation; the validation dataset (one year) may not fully capture climatic variability. Another shortcoming is the underdeveloped economic risk assessment for financing and maintenance, which can impact accessibility and reliability (Eze et al., 2024). Future work should address these issues through extended operational monitoring and integration of financial modeling tools. Economic risk and sensitivity considerations. The economic outcomes are influenced by diesel price volatility, potential increases in O and M costs, and battery replacement timing. In industrial deployment, a simple sensitivity analysis is recommended for key parameters (diesel price, discount rate, PV cleaning frequency, and component replacement intervals), because these factors can shift the payback period and LCOE. This strengthens decision-making for mining operators and improves the robustness of investment planning.

*Future development of the study.* The development of this research may follow several directions. Mathematically, incorporating stochastic differential equations to capture hydrological and solar variability could improve robustness. Methodologically, digital twin technology can be employed for real-time system optimization, while experimentally, scaling up the prototype to 100 – 200 kW would help evaluate performance under actual mining conditions. Difficulties may arise in harmonizing control algorithms, ensuring durability of battery systems under harsh environments, and securing investment for larger-scale projects. Nevertheless, these challenges represent opportunities for refining hybrid system design and ensuring long-term sustainability.

In summary, the study not only confirms the efficiency of integrated micro-hydro and solar systems in decentralized mining regions but also highlights their advantages over existing solutions, while acknowledging the limitations and potential improvements needed for broader application.

## 7. Conclusion

The study achieved its aim by addressing three major research tasks, each resulting in scientifically grounded and practically significant outputs.

First, through a comprehensive literature review and analysis, unresolved issues in hybrid micro-hydro and solar systems were identified. The review demonstrated that technical incompatibilities in control systems account for up to 30% of failures, while economic and ecological efficiency studies lacked adaptation to mining environments (Roy, 2023 ; López-Castrillón et al., 2021). This clarified the research gap and highlighted the need for region - specific methodologies.

Second, a design methodology adapted to decentralized mining regions was developed and validated. The proposed configuration (50 kW micro - hydro, 40 kW solar PV, and 25 kWh storage) generated approximately 670000 kWh annually, with 65% of the energy supplied by hydropower and 35% by solar panels (Figure 2). The system demonstrated high technical performance, with a reliability of 92 – 95% and an availability coefficient of 0,985-0,991 (Table 3), surpassing conventional diesel generators. These results differ from existing pilot accounting for unstable load profiles typical of mining operations (Paneri et al. 2021).

Third, system modeling and optimization showed that diesel dependency could be reduced by 58 – 62%, saving 170 – 185 · $10^3$ liters of fuel annually and lowering $CO_2$ emissions by 450 – 500 tons (equations (10) – (12), Figures 3-5). The payback period was calculated at 5,5-6,2 years, with total savings of up to 310000 USD over ten years. Unlike previous works, which focused on rural electrification, these results emphasize applicability in industrial-scale mining regions, where load instability and high consumption levels are critical challenges (Iweh et al., 2024 ; Darmawan et al., 2025).

From the perspective of water conservation and environmental management, the proposed hybrid system demonstrates that decentralized micro-hydropower can serve as an effective tool for sustainable water–energy integration in industrial regions.

Overall, the study confirmed that integrating micro - hydropower and solar systems provides a technically feasible, economically viable, and environmentally sustainable alternative to diesel generation in decentralized mining regions. The originality of the results lies in combining mathematical modeling, AI - and IoT - based forecasting, and laboratory prototyping to adapt hybrid energy systems to real mining conditions. These outcomes not only validate the research objectives but also offer a foundation for further scaling and industrial implementation.

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