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Optimization of Electrical Energy Management in Hu'u Mining Operations Using a Smart Grid Approach to Support Sustainable Development in Dompu

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Abstrak

Penelitian ini bertujuan untuk mengoptimalkan manajemen energi listrik pada kegiatan pertambangan di Hu'u, Kabupaten Dompu, melalui penerapan pendekatan smart grid guna mendukung pembangunan berkelanjutan. Penelitian menggunakan metode kuantitatif dengan menganalisis sistem energi eksisting, profil beban, serta pola konsumsi energi, kemudian dilanjutkan dengan simulasi menggunakan model energi hibrida yang mengintegrasikan generator diesel, sistem fotovoltaik surya (PLTS), dan penyimpanan energi. Kerangka smart grid yang diusulkan mengadopsi teknologi Internet of Things (IoT), pemantauan real-time, serta algoritma optimasi untuk meningkatkan efisiensi dan keandalan sistem. Hasil penelitian menunjukkan bahwa penerapan smart grid mampu menurunkan konsumsi bahan bakar, biaya operasional, serta emisi gas rumah kaca secara signifikan, sekaligus meningkatkan efisiensi energi dan stabilitas sistem. Analisis ekonomi menunjukkan bahwa sistem ini layak secara finansial dengan periode pengembalian investasi yang baik, sementara evaluasi lingkungan menunjukkan kontribusi terhadap pengurangan emisi dan pengelolaan sumber daya yang berkelanjutan. Selain itu, integrasi energi terbarukan dan sistem kendali cerdas meningkatkan ketahanan operasional pertambangan di daerah terpencil. Penelitian ini menyimpulkan bahwa manajemen energi berbasis smart grid merupakan solusi efektif dan berkelanjutan bagi kegiatan pertambangan di Dompu serta dapat menjadi referensi untuk wilayah lain.

Keywords :

Smart Grid; Energy Management; Mining Operations; Renewable Energy; Sustainable Development

Abstract

This study aims to optimize electrical energy management in Hu'u mining operations, Dompu Regency, through the implementation of a smart grid approach to support sustainable development. The research adopts a quantitative method by analyzing existing energy systems, load profiles, and energy consumption patterns, followed by simulation using hybrid energy models integrating diesel generators, solar photovoltaic (PV) systems, and energy storage. The proposed smart grid framework incorporates Internet of Things (IoT)-based monitoring, real-time data acquisition, and optimization algorithms to improve system efficiency and reliability. The results indicate that the smart grid approach significantly reduces fuel consumption, operational costs, and greenhouse gas emissions while enhancing energy efficiency and system stability. Economic analysis shows that the system is financially feasible with a favorable payback period, while environmental evaluation confirms its contribution to emission reduction and sustainable resource management. Furthermore, the integration of renewable energy and intelligent control systems strengthens the resilience of mining operations in remote areas. This study concludes that smart grid-based energy management provides an effective and sustainable solution for mining operations in Dompu and can serve as a reference for similar projects in other regions.

INTRODUCTION

The global mining industry is undergoing a significant transformation driven by the need to improve energy efficiency and reduce environmental impacts. As energy consumption constitutes a major operational cost in mining activities, the optimization of electrical energy management has become a critical area of research and practice (Meliani et al 2013). In developing regions, including Indonesia, the integration of advanced energy systems is essential to ensure sustainable resource utilization while maintaining economic competitiveness. In the context of Indonesia's regional development, mining plays a strategic role in supporting economic growth, particularly in resource-rich areas such as Dompu Regency. The Hu'u mining project represents a substantial opportunity to enhance local economic development; however, it also introduces challenges related to energy demand, environmental sustainability, and infrastructure resilience.

Electrical energy is a fundamental component of mining operations, powering processes such as drilling, hauling, crushing, and mineral processing. The high and fluctuating energy demand of these activities necessitates an efficient and reliable energy management system. Without proper optimization, excessive energy consumption can lead to increased operational costs and environmental degradation.

Traditional energy systems used in mining operations often rely heavily on fossil fuels, particularly diesel generators. While these systems provide reliability, they contribute significantly to greenhouse gas emissions and environmental pollution. This reliance poses a challenge in aligning mining practices with sustainable development goals.

Smart grid technology has significantly improved the efficiency and reliability of electrical energy systems through real-time monitoring and automated control (Amin, S.M. et al 2005; Miceli, 2013; Rathor et al., 2020). Furthermore, integrating renewable energy into smart grids can reduce greenhouse gas emissions while enhancing system sustainability (El Maghraoui et al., 2022; Kumar et al., 2025). In mining operations, smart grid implementation supports predictive maintenance, demand-side management, and hybrid energy integration, resulting in lower operational costs and improved environmental performance (Barra et al., 2023; Cioara et al., 2020; Shen et al., 2020). These findings are consistent with recent studies emphasizing the importance of intelligent energy management in achieving sustainable mining practices (Syahputra et al., 2025).

Moreover, smart grid systems enable predictive maintenance and fault detection, reducing downtime and improving operational reliability. This is especially important in remote mining areas where infrastructure limitations can hinder rapid response to system failures. The application of Internet of Things (IoT) technologies further enhances smart grid functionality by providing real-time data acquisition from various components of the energy system. Sensors and monitoring devices can track energy consumption, equipment performance, and environmental conditions. Data-driven decision-making is a key advantage of smart grid implementation. By analyzing energy consumption patterns, operators can identify inefficiencies and implement targeted strategies to optimize energy use (Ahleyani et al., 2025). In addition to technical benefits, optimized energy management contributes to cost savings, which can improve the economic viability of mining projects. Reduced fuel consumption and increased efficiency translate into lower operational expenses.

Environmental considerations are also central to energy optimization efforts. Reducing emissions and minimizing ecological disruption are critical for maintaining environmental integrity in mining areas such as Hu'u. Social acceptance of mining projects is increasingly influenced by their environmental performance. Communities in Dompu are likely to support mining activities that demonstrate a commitment to sustainability and responsible resource management. Government policies and regulations in Indonesia are progressively encouraging the adoption of clean energy and sustainable practices. Compliance with these policies is essential for the long-term operation of mining projects. Despite the potential benefits, the implementation of smart grid systems in mining operations faces several challenges, including high initial investment costs, technical complexity, and the need for skilled human resources.

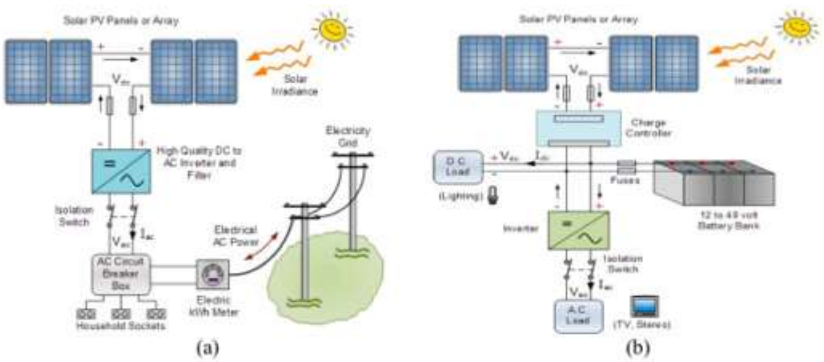
Therefore, a comprehensive study is required to evaluate the feasibility and effectiveness of smart grid-based energy management in the Hu'u mining project. Such research should consider technical, economic, and environmental aspects. This study aims to analyze the optimization of electrical energy management in Hu'u mining operations through the application of smart grid technology. The research focuses on improving energy efficiency, integrating renewable energy, and reducing environmental impacts. Furthermore, the study seeks to provide a framework for sustainable energy management that can be applied to other mining regions in Indonesia. The findings are expected to contribute to the broader discourse on sustainable mining practices. Ultimately, the optimization of electrical energy management using a smart grid approach represents a strategic pathway toward achieving sustainable development in Dompu. By aligning technological innovation with environmental and economic objectives, mining operations can become more resilient, efficient, and socially responsible.

Literature Review

Electrical energy management has emerged as a critical field of study within industrial systems, particularly in energy-intensive sectors such as mining. The literature highlights that effective energy management not only reduces operational costs but also improves system reliability and environmental performance. Scholars have emphasized the need for integrated approaches that combine technological innovation with strategic planning. Early studies on energy management in mining primarily focused on conventional methods, including load scheduling and fuel efficiency improvements. These approaches were largely limited to optimizing diesel generator performance and minimizing energy losses within isolated systems. While beneficial, such methods lacked the flexibility and intelligence required for modern, complex mining operations. With the advancement of digital technologies, the concept of smart energy management has gained prominence. Researchers have introduced frameworks that incorporate automation, real-time monitoring, and advanced analytics to improve decision-making processes. These developments have paved the way for the adoption of smart grid systems in industrial applications. Smart grid technology is widely defined as an intelligent electricity network that uses digital communication tools to monitor and manage energy flows. According to existing literature, smart grids enhance system efficiency by enabling bidirectional communication between energy producers and consumers. This capability is essential for dynamic load balancing and demand-side management.

Several studies have demonstrated the effectiveness of smart grids in reducing energy consumption and improving operational efficiency. For instance, the implementation of automated demand response systems allows for the adjustment of energy usage during peak periods, thereby minimizing energy costs and reducing strain on the power system. In the context of mining, smart grid applications are still developing but show significant potential (EL Maghraoui, A.L. et al 2022). Research indicates that mining operations can benefit from real-time energy monitoring, predictive maintenance, and optimized load distribution. These features are particularly valuable in remote mining sites where energy resources are limited. The integration of renewable energy into mining operations has been extensively discussed in recent literature. Solar photovoltaic (PV) systems, wind energy, and hybrid configurations are commonly proposed as alternatives to fossil fuel-based systems (Barra, L. X. et al. 2023). These solutions contribute to reducing greenhouse gas emissions and enhancing sustainability. Hybrid energy systems, which combine renewable sources with conventional generators, are considered a practical approach for mining operations. Studies suggest that hybrid systems can improve energy reliability while lowering fuel consumption. The optimization of such systems often involves advanced algorithms and simulation tools.

Figure 1. On-grid and Off-grid PLTS Configuration System



Energy storage technologies also play a crucial role in smart grid implementation. Batteries and other storage systems help balance supply and demand by storing excess energy and releasing it when needed. This capability is particularly important for integrating intermittent renewable energy sources. The use of Internet of Things (IoT) technologies has significantly enhanced energy management systems. IoT devices enable continuous data collection from various components of the energy network, providing valuable insights into system performance. This data-driven approach supports more accurate forecasting and efficient resource allocation. Big data analytics and machine learning have further advanced the capabilities of smart energy systems. Researchers have developed predictive models that can anticipate energy demand, detect anomalies, and optimize system operations. These tools contribute to improved efficiency and reduced operational risks. In addition to technological advancements, the literature emphasizes the importance of policy and regulatory frameworks. Government initiatives promoting renewable energy and energy efficiency have accelerated the adoption of smart grid technologies (Cioara, T. P. et al 2020). Compliance with these regulations is essential for sustainable industrial development.

Environmental impact assessment is another key area of focus in the literature. Studies have shown that optimized energy management can significantly reduce emissions, air pollution, and ecological disturbances associated with mining activities. This aligns with global efforts to combat climate change. Social aspects of energy management are also gaining attention. Community acceptance of mining projects is influenced by environmental performance and corporate responsibility. Transparent energy practices and sustainable initiatives can improve stakeholder trust and support. Economic analysis is frequently used to evaluate the feasibility of smart grid implementation. Although initial investment costs can be high, long-term benefits such as reduced fuel expenses and improved efficiency often justify the investment. Cost-benefit analysis is therefore a common approach in related studies. Several case studies from different regions have demonstrated successful implementation of smart energy systems in mining. These studies provide practical insights into system design, operational challenges, and performance outcomes. Lessons learned from these cases can inform future projects.

Despite the progress, the literature identifies several challenges in adopting smart grid technologies. These include technical complexity, lack of infrastructure, and limited human resource capacity. Addressing these barriers is crucial for successful implementation. Research gaps remain in the application of smart grid systems in specific local contexts, such as Dompu. Most existing studies focus on developed regions, leaving a need for research tailored to the conditions of developing areas with unique geographical and socio-economic characteristics (Putri, G.H. et al 2025). Furthermore, interdisciplinary approaches are increasingly recommended in the literature. Combining expertise from electrical engineering, environmental science, and economics can lead to more comprehensive and effective energy management solutions (Norgate, T. et al 2010). Overall, the literature supports the potential of smart grid-based energy management as a sustainable solution for mining operations. However, further research is needed to adapt these technologies to local conditions and to develop practical frameworks for implementation in regions like Hu'u, Dompu.

METHODS

This study adopts a quantitative research approach to evaluate the optimization of electrical energy management in Hu'u mining operations using a smart grid framework. The methodology is designed to integrate technical analysis, system modeling, and performance evaluation to ensure a comprehensive assessment of the proposed approach (Ramdhan, D. Et al 2025). The research is conducted in the Hu'u mining area located in Dompu Regency, Indonesia. This site is selected due to its strategic importance in regional development and its high energy demand associated with mining activities. The geographical and operational characteristics of the site are considered in the analysis. The research begins with a preliminary assessment of the existing energy system used in the mining operations (Sakhnini, J.K. et al 2020). This includes identifying the current energy sources, load profiles, energy consumption patterns, and system constraints. Data are collected from operational records, field observations, and relevant stakeholders. A detailed load analysis is performed to understand the temporal variation of electricity demand in the mining process. The load profile is categorized into different operational stages, such as extraction, processing, and supporting facilities. This classification helps in identifying peak demand periods and potential areas for optimization.

The study incorporates both primary and secondary data sources. Primary data are obtained through direct measurements, interviews with technical personnel, and on-site observations (Ranjiv A.A Sihombing et al 2025). Secondary data are collected from previous studies, government reports, and technical documentation related to mining and energy systems. To support the analysis, simulation tools are utilized to model the energy system. Software such as MATLAB, HOMER Pro, or similar platforms is employed to simulate different energy scenarios and evaluate system performance under varying conditions. The proposed smart grid framework is designed to integrate conventional energy sources with renewable energy systems (Kumar, A.S. et al 2025). Solar photovoltaic (PV) systems are considered as the primary renewable source due to the high solar potential in the Dompu region. A hybrid energy system model is developed, combining diesel generators with solar PV and, where applicable, energy storage systems. The configuration aims to reduce reliance on fossil fuels while maintaining system reliability.

The smart grid architecture includes components such as smart meters, sensors, communication networks, and a centralized control system. These components enable real-time monitoring and control of energy flows within the mining operation. Internet of Things (IoT) technology is incorporated to facilitate data acquisition from various system components (Fakhara, A.H. et al 2023). Sensors are deployed to measure parameters such as voltage, current, power consumption, and environmental conditions. Data collected from IoT devices are processed and analyzed using data analytics techniques. This analysis helps in identifying inefficiencies, predicting energy demand, and optimizing system performance. An optimization algorithm is applied to determine the most efficient energy management strategy. Techniques such as linear programming, genetic algorithms, or other optimization methods are used to minimize energy costs and emissions while meeting operational requirements.

The performance of the proposed system is evaluated based on several key indicators, including energy efficiency, cost savings, reliability, and environmental impact (Shen, H.L. et al 2020). These indicators provide a comprehensive measure of system effectiveness. A comparative analysis is conducted between the existing energy system and the proposed smart grid-based system. This comparison highlights the improvements achieved through optimization and identifies potential trade-offs (Syahputra, F.G. et al 2025). Environmental impact assessment is carried out to evaluate the reduction in greenhouse gas emissions and other pollutants. Standard emission factors are used to estimate the environmental benefits of the optimized system. Economic feasibility analysis is also performed to assess the financial viability of the proposed system. This includes calculating metrics such as net present value (NPV), internal rate of return (IRR), and payback period (Rathor, S.K. et al 2020).

Sensitivity analysis is conducted to examine the impact of key variables, such as fuel prices, solar irradiance, and load demand, on system performance (Shen, H.L. et al 2020). This analysis helps in understanding the robustness of the proposed solution. Validation of the simulation results is performed by comparing them with real-world data and established benchmarks. This step ensures the accuracy and reliability of the findings. The research methodology also considers potential implementation challenges, including technical limitations, infrastructure requirements, and human resource capacity. Strategies to address these challenges are discussed. Overall, this methodology provides a systematic approach to evaluating smart grid-based energy management in mining operations. It integrates technical, economic, and environmental analyses to support sustainable development in the Hu'u mining area of Dompu.

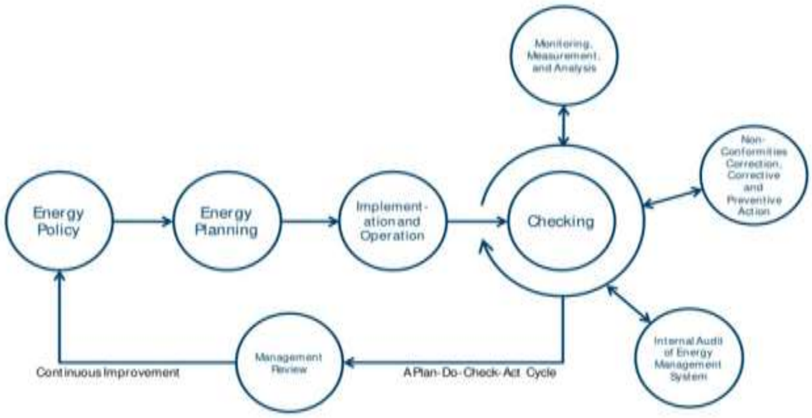
RESULT AND DISCUSSION

The results of this study demonstrate that the existing electrical energy system in Hu'u mining operations is heavily dependent on diesel generators, leading to high fuel consumption and operational costs. Baseline analysis indicates that energy demand fluctuates significantly throughout the day, with peak loads occurring during mineral processing activities. Load profile analysis reveals that inefficient load distribution contributes to energy losses and increased system stress. Peak demand periods are not effectively managed, resulting in excessive reliance on diesel-based generation. This condition highlights the need for a more adaptive and intelligent energy management system. Simulation of the proposed smart grid-based system shows a substantial improvement in load balancing. Through real-time monitoring and automated control, the system is able to distribute energy more efficiently across different operational units. This leads to a reduction in peak load pressure. Integration of solar photovoltaic (PV) systems significantly contributes to the overall energy supply. Simulation results indicate that solar energy can supply a considerable portion of daytime electricity demand, reducing the operational burden on diesel generators.

Hybrid energy system, combining diesel generators and solar PV, demonstrates enhanced reliability compared to the conventional system. The presence of multiple energy sources ensures continuity of supply, even under variable environmental conditions. Inclusion of energy storage systems further improves system performance by stabilizing energy supply. Excess solar energy generated during peak sunlight hours is stored and utilized during periods of low generation or high demand. Implementation of Internet of Things (IoT)-based monitoring enables real-time data acquisition, which enhances operational transparency. Operators are able to track energy consumption patterns and system performance with greater accuracy. Data analytics applied to the collected information reveals key inefficiencies in the existing system. For example, certain equipment was found to consume excessive energy due to outdated operational practices, which can now be corrected through optimized scheduling.

Optimization algorithm applied in this study successfully minimizes total energy cost while maintaining system reliability. The results show a significant reduction in fuel consumption, which directly impacts operational expenditure. From an economic perspective, the proposed system demonstrates promising financial benefits. The reduction in diesel fuel usage leads to lower operational costs, and the initial investment in renewable energy infrastructure is offset over time. Economic analysis indicates a favorable payback period, suggesting that the smart grid implementation is financially viable. Key indicators such as net present value (NPV) and internal rate of return (IRR) support the feasibility of the investment. Environmental analysis shows a notable decrease in greenhouse gas emissions due to reduced reliance on fossil fuels. This aligns with global sus tainability goals and national policies promoting clean energy.

Figure 2. Main Elements of an Energy Management System



Reduction in emissions also contributes to improved air quality in the surrounding environment. This is particularly important for maintaining ecological balance and protecting community health in the Dompu region. Smart grid system enhances operational reliability by enabling predictive maintenance. Potential system failures can be identified in advance, reducing downtime and maintenance costs. Results also highlight the importance of integrating advanced communication systems within the energy network. Reliable data transmission is essential for effective smart grid operation and decision-making. Despite the positive outcomes, the study identifies several challenges in implementation. High initial investment costs and the need for skilled personnel remain significant barriers to adoption.

Sensitivity analysis reveals that system performance is influenced by external factors such as fuel prices and solar irradiance. However, the proposed system remains robust under varying conditions, demonstrating its adaptability. Findings suggest that policy support and regulatory incentives are crucial for encouraging the adoption of smart grid technologies in mining operations. Government involvement can accelerate the transition toward sustainable energy systems. Discussion emphasizes that the successful implementation of smart grid-based energy management requires a multidisciplinary approach. Collaboration between engineers, policymakers, and industry stakeholders is essential. Overall, the results confirm that optimizing electrical energy management through a smart grid approach can significantly improve efficiency, reduce environmental impact, and support sustainable development in Hu'u mining operations in Dompu.

CONCLUSION

This study concludes that the optimization of electrical energy management in Hu'u mining operations is both necessary and feasible to address the increasing energy demand and environmental challenges associated with mining activities in Dompu. The reliance on conventional diesel-based systems has proven to be inefficient, costly, and environmentally unsustainable. Implementation of a smart grid approach provides a transformative solution by enabling real-time monitoring, automated control, and intelligent decision-making. These capabilities significantly enhance the efficiency and reliability of the energy system within mining operations. Integration of renewable energy, particularly solar photovoltaic systems, plays a crucial role in reducing dependence on fossil fuels. The study demonstrates that the hybridization of energy sources can create a more balanced and sustainable energy mix. Incorporation of energy storage systems further strengthens system stability by ensuring a continuous power supply during fluctuations in energy generation and demand. This contributes to improved operational resilience in remote mining areas.

Application of Internet of Things (IoT) technology and data analytics enhances the overall performance of the smart grid system. Real-time data acquisition and analysis allow for the identification of inefficiencies and the implementation of targeted optimization strategies. From an economic perspective, the optimized energy management system offers significant cost savings through reduced fuel consumption and improved operational efficiency. The financial analysis indicates that the initial investment can be justified by long-term economic benefits. Environmentally, the proposed system contributes to a substantial reduction in greenhouse gas emissions and environmental degradation. This supports broader sustainability goals and aligns with national and global efforts to promote clean energy. Despite these advantages, the study acknowledges the challenges associated with smart grid implementation, including high capital costs, technical complexity, and the need for skilled human resources. Addressing these challenges is essential for successful deployment.

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