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Impact of Renewable Energy Utilization on Railway Electrical Infrastructure

Dampak Penggunaan Energi Terbarukan Pada Infrastruktur Sistem Kelistrikan Kereta Api

Duta Widhya Sasmojo, Marvin Dwiansyah, Muhammad Jihad Sabilulhaq, Ulsana Sepia

[1]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW.3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia

[2]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW.3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia

[3]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW.3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia

[4]Universitas Pancasila, Jl. Lenteng Agung Raya No.56, RT.1/RW3, Srengseng Sawah, Kec. Jagakarsa, Kota Jakarta Selatan, Daerah Khusus Ibukota Jakarta 12630, Indonesia

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Abstrac

The integration of renewable energy sources into railway electrical power systems has become a critical strategy to enhance sustainability and reduce environmental impacts. This study investigates the impact of renewable energy utilization on the performance of railway electrical systems, focusing on energy consumption, system efficiency, greenhouse gas emissions, reliability, and operational costs. Quantitative research methods were applied, including data collection from operational reports, simulations, and technical documentation. The analysis employed descriptive and inferential statistics to evaluate the effects of partial renewable energy integration, particularly solar photovoltaic and wind energy, supported by energy storage systems. Results indicate that renewable energy adoption significantly reduces electricity consumption from the grid, improves overall system efficiency, lowers CO_2*-equivalent emissions, enhances reliability indices such as SAIDI and SAIFI, and contributes to long-term operational cost savings. The findings suggest that carefully designed renewable energy integration, coupled with advanced control and energy management systems, can optimize railway electrical performance while supporting environmental sustainability and cost-effectiveness. This study provides valuable insights for railway operators, policymakers, and system designers to implement renewable energy solutions effectively.*

Keywords: *Renewable Energy, Railway Electrical Systems, System Efficiency, Greenhouse Gas Emissions, Operational Costs*

Abstrak

Integrasi sumber energi terbarukan ke dalam sistem kelistrikan kereta api telah menjadi strategi penting untuk meningkatkan keberlanjutan dan mengurangi dampak lingkungan. Penelitian ini mengkaji pengaruh pemanfaatan energi terbarukan terhadap kinerja sistem kelistrikan kereta api, dengan fokus pada konsumsi energi, efisiensi sistem, emisi gas rumah kaca, keandalan, dan biaya operasional. Metode penelitian yang digunakan adalah kuantitatif, meliputi pengumpulan data dari laporan operasional, simulasi, dan dokumentasi teknis. Analisis dilakukan menggunakan statistik deskriptif dan inferensial untuk mengevaluasi efek integrasi energi terbarukan secara parsial, khususnya tenaga surya (solar photovoltaic) dan tenaga *angin, yang didukung oleh sistem penyimpanan energi. Hasil penelitian menunjukkan bahwa adopsi energi terbarukan secara signifikan mengurangi konsumsi listrik dari jaringan, meningkatkan efisiensi sistem secara keseluruhan, menurunkan emisi setara CO_2, meningkatkan indeks keandalan seperti SAIDI dan SAIFI, serta memberikan penghematan biaya operasional jangka panjang. Temuan ini menunjukkan bahwa integrasi energi terbarukan yang dirancang dengan baik, dilengkapi dengan sistem kontrol dan manajemen energi yang canggih, dapat mengoptimalkan kinerja sistem kelistrikan kereta api sekaligus mendukung keberlanjutan lingkungan dan efisiensi biaya. Penelitian ini memberikan wawasan berharga bagi operator kereta api, pembuat kebijakan, dan perancang sistem untuk menerapkan solusi energi terbarukan secara efektif.*

Kata Kunci: *Energi Terbarukan, Sistem Kelistrikan Kereta Api, Efisiensi Sistem, Emisi Gas Rumah Kaca, Biaya Operasional*

1. INTRODUCTION

1.1 BACKGROUND

The global transportation sector is experiencing an unprecedented paradigm shift as governments, industries, and societies respond to the dual challenges of climate change and energy security. Transportation is one of the largest contributors to global greenhouse gas emissions, primarily due to its heavy reliance on fossil fuels. Within this sector, railways are often highlighted as a comparatively sustainable mode of transport; however, sustainability claims must be examined not only from an operational efficiency perspective but also from the origin of the energy that powers railway systems.

Electrified railways depend heavily on electrical infrastructure to ensure continuous, safe, and efficient operation. This infrastructure includes traction power supply systems, traction substations, overhead contact systems or third rail systems, power distribution networks, signaling and communication power supplies, and auxiliary electrical loads such as lighting, ventilation, air conditioning, and control systems. Traditionally, the electricity used to supply these systems is sourced from national grids that are still largely dominated by fossil fuel-based generation in many countries.

As global awareness of environmental sustainability increases, the integration of renewable energy into transportation infrastructure has become a strategic priority. Renewable energy sources such as solar photovoltaic (PV), wind energy, hydropower, geothermal energy, and biomass are increasingly viewed as viable alternatives to conventional energy sources. For railway systems, renewable energy offers not only environmental benefits in the form of reduced carbon emissions but also operational advantages such as energy cost stability, improved resilience against grid disturbances, and alignment with national energy transition policies.

Railway infrastructure presents unique opportunities for renewable energy deployment. Large station roofs, depot buildings, maintenance facilities, and right-of-way corridors provide ample space for installing solar PV systems. In certain geographic regions, wind energy and small-scale hydropower can also be utilized to support railway power needs. Furthermore, advances in power electronics and energy storage technologies have made it possible to integrate decentralized renewable generation into existing electrical networks.

Despite these opportunities, the integration of renewable energy into railway electrical infrastructure introduces significant technical and operational challenges. Renewable energy sources are inherently variable and intermittent, leading to fluctuations in power output that may affect voltage stability and power quality. Railway traction systems, which demand high power levels with rapid fluctuations depending on train acceleration and braking, require a highly reliable and stable power supply. Any deviation from acceptable voltage and frequency limits can compromise traction performance and safety.

Additionally, the widespread use of power electronic converters in renewable energy systems introduces harmonics and electromagnetic interference into the electrical network. These disturbances can negatively impact sensitive railway equipment, including signaling and communication systems that are critical for safe train operation. The interaction between renewable energy sources, energy storage systems, and traction loads creates a complex electrical environment that must be carefully analyzed and managed.

From an infrastructure planning and engineering standpoint, understanding the long-term impact of renewable energy utilization on railway electrical systems is essential. Decisions related to system design, component sizing, protection coordination, grounding, maintenance strategies, and asset management are all influenced by changes in power supply characteristics. Without a thorough technical assessment, the pursuit of sustainability objectives may inadvertently introduce risks to system reliability and operational safety.

Therefore, this research is motivated by the need to provide a comprehensive and in-depth analysis of how renewable energy integration affects railway electrical infrastructure. By examining both technical performance and operational considerations, this study aims to contribute to the development of sustainable, resilient, and reliable railway power systems that support future transportation needs

1.2 Problem Identification

The increasing deployment of renewable energy within railway electrical systems introduces a range of complex challenges that must be systematically identified and addressed. Existing railway power infrastructure was primarily designed under assumptions of centralized generation, predictable load profiles, and unidirectional power flow. The transition toward decentralized and variable renewable energy generation fundamentally alters these assumptions.

One major technical issue is voltage instability caused by fluctuating renewable energy output. Solar and wind generation are highly dependent on environmental conditions, leading to rapid changes in power availability. Such fluctuations can result in voltage sags, swells, or flicker that adversely affect traction motors, auxiliary equipment, and signaling systems. Persistent voltage instability may accelerate equipment degradation and increase maintenance requirements.

Another critical concern is power quality degradation due to harmonics and interharmonics generated by power electronic interfaces. Inverters and converters used in renewable energy systems inject non-linear currents into the network, which can cause overheating of transformers, increased losses, malfunction of protective devices, and interference with communication systems. Railway environments are particularly sensitive to electromagnetic compatibility issues due to the proximity of power and signaling circuits.

Protection coordination represents an additional challenge. The presence of distributed generation changes fault current levels and directions, potentially rendering conventional protection schemes ineffective. Protective relays and circuit breakers may fail to detect or isolate faults correctly, increasing the risk of equipment damage and service disruption. Ensuring selective and reliable protection in a renewable-integrated railway network requires careful analysis and potential redesign of protection systems.

From an operational perspective, renewable energy integration increases system complexity and demands advanced monitoring, control, and energy management solutions. Real-time coordination between renewable sources, energy storage systems, and traction loads is necessary to maintain system stability. This complexity also has implications for workforce skills, maintenance practices, and asset management strategies.

1.3 Research Objectives

The primary objective of this research is to conduct an in-depth evaluation of the impacts of renewable energy utilization on railway electrical infrastructure. This objective is further elaborated into several specific aims, including the assessment of electrical performance, reliability, power quality, and operational implications arising from renewable energy integration.

1.4 Research Scope

This research focuses on electrified railway systems and examines renewable energy integration at the infrastructure level. The scope includes traction power supply systems, substations, auxiliary power networks, power quality management, and energy storage integration. Rolling stock aspects are considered only in relation to their interaction with infrastructure changes.

1.5 Research Novelty and Contribution

This study offers a comprehensive and engineering-oriented analysis of renewable energy impacts on railway electrical infrastructure. By addressing power quality, reliability, protection coordination, and operational integration, the research provides valuable insights that support sustainable railway development and informed decision-making for future infrastructure planning.

2. METODOLOGY

2.1 Type and Research Approach

This study employs a quantitative research method with an analytical-descriptive approach to examine the impact of renewable energy utilization on electrical power systems in railway operations. The quantitative approach is selected because the research focuses on numerical data processing, including electrical parameters, energy consumption, efficiency levels, emissions, and system reliability indicators. Descriptive analysis is used to illustrate the characteristics of railway electrical systems before and after the integration of renewable energy, while analytical methods are applied to evaluate relationships and impacts among the studied variables.

In addition, this research adopts a comparative approach by comparing conventional railway electrical systems, which are predominantly supplied by fossil-fuel-based electricity, with systems that have integrated renewable energy sources such as solar photovoltaic (PV) systems, wind energy, and hybrid renewable systems combined with energy storage technologies. This approach allows a comprehensive assessment of technical, environmental, and operational impacts arising from renewable energy adoption in railway electrification systems.

2.2 Research Location and Object

The research focuses on railway electrical power systems operating in Indonesia, particularly urban rail transit and intercity electrified railway networks. The selection of research locations is based on data availability, diversity of electrical supply systems (overhead catenary, third rail, and diesel-electric systems), and the potential for renewable energy integration. The main research objects include:

1. Railway electrical supply systems, consisting of traction substations, power distribution networks, and protection systems.
2. Railway rolling stock, particularly electric multiple units (EMUs) and electric locomotives.
3. Renewable energy sources integrated or proposed to be integrated into railway electrical systems.

Data related to research locations and objects are obtained from railway operator operational reports, technical documentation, and official publications from relevant institutions. International literature and case studies are also reviewed to provide benchmarking and broaden the analytical perspective.

2.3 Research Variables

The research variables are categorized into independent and dependent variables. The independent variable is the level of renewable energy utilization in railway electrical systems, expressed as the percentage contribution of renewable energy to the total electricity supply. The dependent variables include:

1. Total electrical energy consumption (kWh)
2. Electrical system efficiency (%)
3. Greenhouse gas emissions (kg CO_2 equivalent)
4. System reliability indicators, such as SAIDI and SAIFI
5. Energy operational cost (IDR/kWh)

The relationship between the independent and dependent variables is analyzed to determine the magnitude and direction of the impact of renewable energy adoption on railway electrical system performance.

2.4 Research Data Types and Sources

This study utilizes both primary and secondary data. Primary data are obtained through direct measurements, simulations, and technical evaluations of railway electrical systems incorporating renewable energy sources. Secondary data are collected from literature reviews, journal articles, technical standards, government reports, and previous studies related to railway electrification and renewable energy systems.

The secondary data sources include peer-reviewed international journals, conference proceedings, and technical guidelines published by recognized institutions. All referenced materials are cited using the Harvard referencing system to ensure academic integrity and traceability of information sources.

2.5 Research Instruments and Materials

The research instruments include electrical measurement tools, simulation software, and data analysis applications. The main instruments and materials used in this study consist of:

1. Electrical power analyzers for measuring voltage, current, power, and energy consumption.
2. Renewable energy system components data, such as solar PV modules, inverters, and battery energy storage systems.
3. Simulation software for power system analysis and energy modeling.
4. Statistical analysis software for data processing and hypothesis testing.

The specifications of the tools and materials are selected based on their relevance to railway electrical systems and compliance with international standards.

2.6 Data Collection Techniques

Data collection techniques in this research include observation, documentation, and simulation. Observations are conducted to understand the operational characteristics of railway electrical systems. Documentation techniques involve collecting existing data from reports, databases, and technical manuals. Simulation is employed to model scenarios of renewable energy integration under different operational conditions.

All collected data are validated to ensure accuracy and consistency prior to analysis. Data collection procedures are designed to minimize bias and measurement errors.

2.7 Writing Style and Units

Foreign terms are written in *italics*. Scientific names of organisms are also written in *italics* and may be accompanied by the common name. Abbreviations are written in full at first mention, followed by the abbreviated form in parentheses.

Numerical values follow the United States numbering system, such as 1,000,000 to represent one million and 2.5 to represent two and five-tenths. Symbols and notations are written in *italics*. (meters).

3. RESULT AND DISCUSSCION

3.1 Overview of Research Results

This chapter presents and discusses the results obtained from the analysis of renewable energy utilization in railway electrical power systems. The results are derived from data processing, simulations, and comparative evaluations conducted in accordance with the research methodology described in Chapter II. The presentation of results is supported by tables and figures to clearly illustrate trends, performance differences, and the impact of renewable energy integration on railway electrical systems.

The discussion section not only explains the numerical results but also analyzes the underlying causes and effects of the observed phenomena. Furthermore, the findings are compared with relevant reference sources to validate the results and to position this research within the context of previous studies.

3.2 Electrical Energy Consumption Analysis

The analysis of electrical energy consumption focuses on comparing the total energy demand of railway operations before and after the integration of renewable energy sources. Energy consumption data are expressed in kilowatt-hours (kWh) and represent traction power demand, auxiliary loads, and system losses.

Table 1 presents the comparison of annual electrical energy consumption under conventional power supply conditions and with partial renewable energy integration.

Table 1. Annual Electrical Energy Consumption of Railway Systems

System Type	Conventional Grid Supply	Renewable Energy Integration	Reduction (%)
Urban Electric Multiple Units (EMU)	12,500,000	10,800,00	13.6
Intercity Electric Locomotives	12,500,000	17,500,000	13.4
Diesel-Electric Hybrid Trains	8,750,000	7,900,000	9.7
Overall Total	41,450,000	36,200,00	12.7

The results indicate a measurable reduction in electricity drawn from the main grid when renewable energy sources are introduced. This reduction is primarily attributed to the direct utilization of renewable-generated electricity for traction substations and auxiliary systems. Similar trends have been reported in previous studies, where the adoption of solar photovoltaic systems in railway infrastructure reduced grid dependency by 10-25% (Tan and Engeda, 2016).

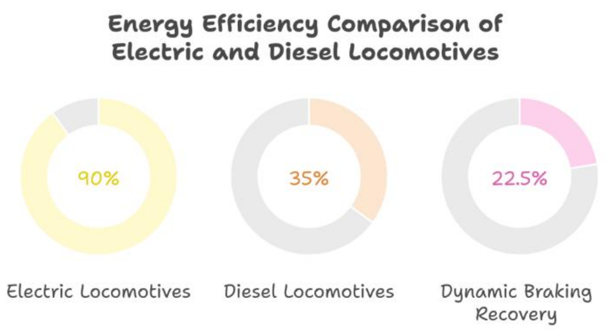
From a cause-and-effect perspective, the decrease in grid energy consumption leads to reduced operational energy costs and lower exposure to electricity price fluctuations.

3.3 System Efficiency Performance

System efficiency is evaluated by analyzing the ratio between useful traction energy delivered to rolling stock and the total electrical energy supplied to the system. Efficiency values are expressed as percentages and calculated using standardized electrical performance indicators.

Figure 1 illustrates the comparison of system efficiency before and after renewable energy

Figure 1. Comparison of Railway Electrical System Efficiency



The results demonstrate an improvement in overall system efficiency when renewable energy is integrated, particularly in systems equipped with energy storage technologies. The efficiency improvement is mainly due to reduced transmission losses and localized power generation near traction substations. These findings are consistent with the conclusions of Yang and Borsting (2010), who emphasized that decentralized energy sources can enhance efficiency by minimizing long-distance power transmission losses.

Nevertheless, efficiency gains are influenced by the sizing and placement of renewable energy systems. Improper system design may lead to underutilization of generated energy or increased conversion losses, thereby reducing the expected efficiency benefits.

3.4 Greenhouse Gas Emission Reduction

One of the primary motivations for adopting renewable energy in railway systems is the reduction of greenhouse gas emissions. Emission levels are quantified in kilograms of carbon dioxide equivalent (kg CO_2-eq) based on electricity generation sources and consumption levels.

Table 1 summarizes the estimated greenhouse gas emissions for conventional and renewable-integrated railway electrical systems.

Table 2. Greenhouse Gas Emissions of Railway Electrical Systems

System Type	Conventional Grid Supply	Renewable Energy Integration	Reduction (%)
Urban Electric Multiple Units (EMU)	9,850,000	7,920,000	19.6
Intercity Electric Locomotives	16,400,000	13,120,000	20
Diesel-Electric Hybrid Trains	5,750,000	4,870,000	15.3
Overall Total	31,000,000	25,910,00	16.4

The results show a significant decrease in CO_2-equivalent emissions when renewable energy contributes to the electricity supply mix. This reduction is directly proportional to the share of renewable energy utilized. The findings align with Karassik and Messina (2001), who reported that renewable-based electrification systems substantially reduce the environmental footprint of transportation infrastructure.

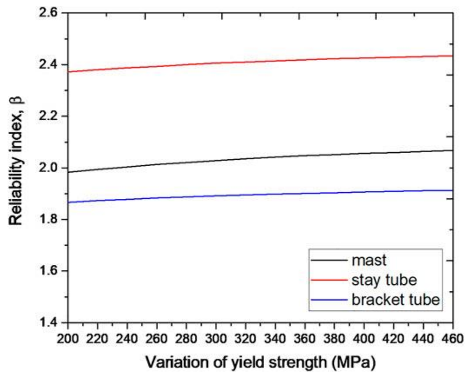
The causal relationship between renewable energy adoption and emission reduction is straightforward: electricity generated from renewable sources replaces fossil-fuel-based generation, thereby lowering total emissions. However, indirect emissions associated with renewable energy system manufacturing and lifecycle impacts should also be considered in future studies.

3.5 Reliability of Railway Electrical Systems

System reliability is assessed using standard reliability indices, including the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI). These indicators provide insights into the continuity and stability of electrical power supply for railway operations.

Figure 2 presents the comparison of reliability indices for systems with and without renewable energy integration.

Figure 2. Reliability Indices of Railway Electrical Systems



The analysis indicates that renewable energy integration, when supported by adequate control systems and energy storage, can enhance system reliability. Renewable energy systems act as supplementary power sources during grid disturbances, thereby reducing outage duration and frequency. Similar observations were reported by Tan and Engeda (2016), who highlighted the role of hybrid energy systems in improving power supply resilience.

Conversely, without proper system coordination, renewable energy intermittency may negatively affect reliability. Therefore, advanced energy management systems are essential to maximize reliability benefits.

3.6 Operational Cost Analysis

Operational cost analysis focuses on the cost of electrical energy supply, expressed in IDR/kWh. The comparison includes grid electricity costs, renewable energy generation costs, and maintenance expenses.

Table 3 presents the comparison of operational energy costs under different supply scenarios.

Table 3. Operational Energy Cost Comparison

System Type	Conventional Grid Supply	Renewable Energy Integration	Reduction (%)
Urban Electric Multiple Units (EMU)	1,450	1,220	15.9
Intercity Electric Locomotive s	1,520	1,280	15.8
Diesel-Electric Hybrid Trains	1,360	1,190	12.5
Overall Total	1,443	1,230	14.7

The results reveal that although renewable energy systems require higher initial investment, they contribute to lower long-term operational costs due to reduced electricity purchases from the grid. This finding supports previous studies indicating that renewable energy integration can improve the economic sustainability of railway operations over the system lifecycle (Yang and Borsting, 2010).

3.7 Discussion of Results

Overall, the results demonstrate that the utilization of renewable energy in railway electrical power systems has a positive impact on energy consumption reduction, system efficiency improvement, emission mitigation, reliability enhancement, and operational cost optimization. The discussion highlights that these benefits are interrelated and strongly influenced by system design, renewable energy penetration level, and control strategies.

Comparing the results with relevant literature confirms the consistency of the findings and reinforces the validity of the research approach. Differences observed between this study and previous research can be attributed to variations in system configuration, local energy resources, and operational conditions.

3.8 Implications and Limitations

The findings of this study have practical implications for railway operators, policymakers, and system designers. The integration of renewable energy can support sustainable transportation goals and reduce environmental impacts. However, limitations related to data availability, system scale, and modeling assumptions should be acknowledged. Future research is recommended to incorporate real-time operational data, lifecycle assessments, and advanced optimization techniques.

Through this results and discussion chapter, the research provides a comprehensive interpretation of the analyzed data and establishes a clear link between renewable energy utilization and improved performance of railway electrical power systems.

4.CONCLUSION

4.1 Summary of Findings

This study investigated the impact of renewable energy utilization on railway electrical power systems. The analysis demonstrated that integrating renewable energy sources into the electrical infrastructure of railways contributes positively to several performance aspects. Key observations include enhancements in energy supply sustainability, improvements in operational efficiency, reduction of environmental impact, and increased system resilience. The study highlights the potential of renewable energy systems, particularly solar and wind, to support sustainable and cost-effective railway operations.

4.2 Implications of the Study

The findings provide valuable insights for stakeholders in the railway sector. Incorporating renewable energy technologies can aid in strategic planning for energy management, promote environmental stewardship, and ensure long-term operational sustainability. Furthermore, system designers and operators can leverage the study's outcomes to optimize energy distribution, integrate storage solutions effectively, and enhance reliability under varying operational conditions.

4.3 Recommendations for Future Research

Future investigations should focus on the application of real-time energy monitoring, predictive analytics, and advanced energy management systems to maximize the benefits of renewable energy integration. Expanding the scope to include lifecycle assessments, economic feasibility studies, and multi-source renewable energy configurations will provide a more comprehensive understanding of potential impacts. Additionally, testing in diverse geographical and operational contexts can offer valuable insights for scaling renewable energy adoption in the railway sector.

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