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# Integrating Renewable Energy into Railway Systems: a Path to Sustainable Transportation – A Review

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Integrating renewable energy sources into railway systems presents a promising solution to mitigate rising $CO_2$ emissions, growing energy demands, and environmental degradation. This paper reviews the potential of incorporating renewable energy technologies such as solar, wind, bioenergy, and kinetic energy recovery into railway infrastructure. By employing intelligent multi-agent systems to manage rail microgrids, the study demonstrates significant enhancements in energy efficiency, operational cost reduction, and system reliability. Strategic deployment of these energy solutions has shown a potential reduction in energy consumption by up to 30 %. This paper underscores the importance of advanced energy storage and management systems to address the variability of renewable sources, ensuring a stable and consistent energy supply. These findings highlight the critical role of smart grid technologies and AI-driven energy management in advancing the sustainability of railway operations and contributing to global sustainable development objectives.

## 1. Introduction

The global challenges of rising $CO_2$ emissions, increasing energy demands, and environmental degradation require immediate action, particularly in the transportation sector (Bridge et al., 2013). Railways, as a major component of transportation infrastructure, consume significant energy, which makes finding sustainable energy solutions critical (Loorbach and Rotmans, 2010). Developing renewable energy sources such as solar, wind, bioenergy, and kinetic energy recovery has become essential in supporting a sustainable energy transition for railways (Chen et al., 2022). Additionally, the specific characteristics of materials like crushed stone aggregates used in railway construction have been shown to influence both the durability and sustainability of the infrastructure (Ezsias et al., 2024). Solar energy has gained popularity due to its scalability and declining costs (Singh et al., 2022). Wind energy is also being explored as a reliable source, particularly in areas with high wind potential (Nazir, 2019). Bioenergy is emerging as a valuable alternative, as it utilizes waste products and supports a circular economy (Doci et al., 2015).

Integrating renewable energy into railway systems has been the subject of various studies. For instance, Liu et al. (2018) demonstrated the technical and economic benefits of integrating photovoltaic (PV) systems into railway infrastructure. Nazir (2019) analyzed the potential of wind energy for railways, showing its capacity to reduce dependency on traditional power grids. Aguado et al. (2016) proposed hybrid energy storage systems (HESS) to ensure a stable energy supply in railways by combining renewable energy sources. Regenerative braking systems have also been highlighted as an effective method for improving energy efficiency and reducing operational expenses in high-speed trains (Fischer and Kocsis Szurke, 2023).

However, several challenges still exist in fully integrating renewable energy into railway systems. The variability of renewable energy sources, such as solar and wind, demands more efficient energy storage solutions (Park and Salkuti, 2019). Additionally, intelligent energy management systems are necessary to optimize energy distribution and ensure the reliability of rail networks (Ye et al., 2024).

This paper addresses these challenges by submitting a novel strategy for managing railway microgrids using an intelligent multi-agent system. The system is designed to optimize energy distribution, reduce operational expenses, and enhance the reliability of railway operations (Aguado et al., 2016). By strategically deploying renewable energy technologies, such as solar panels and wind turbines, alongside advanced energy storage

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solutions, this research seeks to overcome the current limitations in the field and contribute to developing more sustainable railway operations (Kuznetsov et al., 2024).

## 2. Methods

Integrating renewable energy sources (RES) into railway systems is a complex challenge that involves carefully considering various technologies and their interaction. This section overviews the critical methodologies and approaches used in incorporating RES into railways, focusing on solar, wind, and regenerative braking technologies. By bringing together these different approaches, this review aims to highlight best practices and identify areas where further research is needed.

### 2.1 Solar energy in railways

Solar power is a leading option for making railways more sustainable due to its scalability, decreasing costs, and improving photovoltaic (PV) efficiency. For instance, Chen et al. (2022) examined how existing high-speed railway infrastructures can be utilized for photovoltaic electricity generation, offering significant economic and environmental benefits. This review examines how solar energy has been incorporated into railway infrastructure, including the strategic placement of PV panels along railway lines and using grid-connected systems with energy storage. These systems' performance, cost-effectiveness, and environmental impact are critically analyzed (Nazir, 2019).

### 2.2 Wind energy along rail corridors

Wind energy is another promising solution, particularly in areas with strong wind resources. Placing wind turbines along railway corridors can provide a steady, renewable power source. Kuznetsov et al. (2024) explored various setups for wind turbines near railway lines, showing they can significantly contribute to the energy supply. This review looks at the effectiveness of these setups, considering factors like wind availability, turbine efficiency, and how well wind energy can be integrated into existing railway power systems.

### 2.3 Regenerative braking systems

Regenerative braking systems, which capture the kinetic energy generated during train braking and convert it into electricity, offer a significant opportunity to improve railway energy efficiency. Fischer and Kocsis Szurke (2023) detailed the latest advancements in these systems, mainly how they work with hybrid energy storage solutions. Recent research has further highlighted the role of regenerative braking systems in advancing sustainability efforts, particularly in reducing the carbon footprint of railway operations (Ezsias et al., 2023). The degradation of frog rails due to crossing wear significantly contributes to rolling contact fatigue, ultimately reducing the lifespan and operational efficiency of railway infrastructure, as highlighted by Kou et al. (2024). This review examines methods for optimizing regenerative braking, including how much energy can be recaptured, the design of storage systems, and the potential for reducing overall energy consumption in railway operations (Ehsani et al., 2018).

### 2.4 Challenges of hybrid electric energy storage systems

Integrating Hybrid Electric Energy Storage Systems (HEESS), which combine ultracapacitors and batteries, presents significant challenges. Ultracapacitors are great for handling quick bursts of power, while batteries are better for storing more significant amounts of energy over time (Ye et al., 2024). This review explores how to balance these systems' performance, cost, and lifespan, highlighting the importance of advanced energy management strategies that can take advantage of the strengths of each technology while minimizing their weaknesses (Li et al., 2015).

### 2.5 Managing the variability of renewable energy

One of the greatest challenges with using solar and wind energy on railways is their natural variability. This section reviews the advanced energy storage solutions and smart energy management systems being developed to tackle these issues. Park and Salkuti (2019) analyzed recent improvements in battery technology, such as solid-state batteries that offer higher energy density and less degradation, and how these can be applied to railway systems. The review also considers the logistical and financial challenges of retrofitting existing railway infrastructure to incorporate these technologies (Volkov et al., 2020).

### 2.6 Comprehensive analysis and synthesis of approaches

The current review combines the different methodologies discussed, providing a comprehensive look at the current state of research on integrating RES into railway systems. By comparing various approaches, this section identifies critical areas where more research is needed, especially optimizing energy storage, developing intelligent energy management systems, and integrating hybrid technologies. It also highlights successful case studies and best practices that can guide future efforts in this field (Nazir, 2019).

## 3. Case study

Integrating renewable energy sources into railway systems is a compelling example of how transportation infrastructure can contribute to sustainability goals. A notable case is the Swiss Federal Railways (SBB), which has made significant strides in reducing greenhouse gas emissions by adopting renewable energy (Deutsche Bahn, 2023). SBB's approach is particularly innovative due to its reliance on hydroelectric power, which supplies over 90 % of the railway's electricity needs, drastically reducing its dependence on external electricity sources (Suter et al., 2002).

SBB's commitment to sustainability extends beyond its use of hydroelectric power. The company is actively procuring green electricity from certified suppliers, ensuring its operations are efficient and environmentally responsible. Despite the substantial initial costs and technical challenges of integrating renewable energy into existing infrastructure, SBB has shown that these can yield long-term benefits (van Baal and Finger, 2020).

SBB has seen significant reductions in its carbon footprint and operational costs, enhancing its environmental performance and public image (Hagedoorn et al., 2021). The company secured the necessary funding to implement technological upgrades, overcoming financial and logistical hurdles associated with the transition to renewable energy (Hagedoorn et al., 2021). SBB's forward-thinking approach aligns with Switzerland's Energy Strategy 2050, recognizing that the upfront costs of renewable energy infrastructure are offset by long-term savings (van Baal and Finger, 2020).

SBB's experience offers valuable lessons for other railway networks around the world. SBB has positioned itself as a leader in the energy transition within the transportation sector by focusing on energy efficiency, electrification, and the integration of renewable energy sources. The company's success underscores the importance of strategic planning, investment in sustainable technologies, and the willingness to embrace innovative energy management approaches (Wagemans et al., 2019). This case study highlights the potential of renewable energy in reducing the environmental footprint of railways while illustrating broader economic and societal benefits (Sovacool and Dworkin, 2015).

## 4. Results

Railway systems rely heavily on electricity, traditionally sourced from power lines, to ensure efficient operations. However, generating electricity on demand poses significant challenges, including high costs for both power plants and rail operators. Consequently, there is growing interest in exploring renewable energy sources, such as solar power and advanced storage solutions, to meet the energy demands of railways (Davies et al., 2017).

Recent research highlights the potential benefits of integrating renewable energy technologies within rail microgrids. While the use of renewable energy in train operations has garnered considerable attention, there remains a paucity of research on the comprehensive management of rail microgrids. Efficient scheduling and operational optimization are crucial in enhancing the overall efficiency of energy systems – a principle that holds particular relevance in densely populated urban areas and megacities (Saukenova et al., 2022).

Introducing an intelligent energy management system represents a significant advancement in incorporating renewable energy into railway infrastructure. Using an intelligent multi-agent system, this energy management framework efficiently oversees rail microgrids and integrates renewable energy technologies, such as solar panels and wind turbines (Aguado et al., 2016). This system is designed to be adaptable across various types of catenaries and trains, accommodating diverse voltage and frequency requirements. Insights gained from the system's design process underscore the potential for more effective utilization of renewable energy within rail operations.

In remote and isolated communities, the strategic placement of power generation devices enhances infrastructure resilience, particularly during natural disasters. These placements increase energy availability and reduce the cost of energy purchases for eco-conscious citizens. Excess energy can be stored and redistributed through blockchain-based systems, providing stability to the grid during emergencies. This approach facilitates rapid energy distribution to aid disaster recovery efforts (Sovacool and Dworkin, 2015).

The transition to a sustainable society necessitates the widespread adoption of eco-friendly technologies. This includes the installation of solar panels or wind turbines at the household level, supplemented by battery-based energy storage systems. Photovoltaic (PV) panels, particularly when integrated into agri-solar farms, offer dual benefits by reducing energy costs while supporting agricultural productivity. This approach minimizes the carbon footprint without compromising the agricultural environment.

In remote agricultural regions, natural gas derived from cow manure can be harnessed to power gas turbines, promoting sustainable agricultural practices and energy conservation. These communities can leverage micro-smart grids that incorporate renewable energy sources and natural gas storage to meet their energy needs efficiently throughout the year. By strategically deploying wind turbines and solar panels, these micro-smart grids can optimize power output and effectively manage energy storage, meeting the energy demands of remote areas (Li et al., 2015).

## 5. Discussion

The financial analysis of integrating renewable energy sources into railway systems reveals significant opportunities and challenges. A comprehensive study by Nazir (2019) on the Cairo-Alexandria railway line illustrates the cost-benefit dynamics of railway electrification. The study identifies substantial initial investments, with catenary costs ranging from 800,000 to 2,000,000 $/km. Despite these high upfront costs, the long-term benefits, such as reduced operational expenses and lower greenhouse gas emissions, justify these investments (Hagedoorn et al., 2021). The findings underscore the importance of evaluating the initial financial outlays and the long-term advantages of electrification projects (Nazir, 2019).

In the Netherlands, the HEAVENN initiative exemplifies the practical benefits of renewable hydrogen as a sustainable alternative to diesel-powered trains on non-electrified railway lines. With a total investment of 2.8 billion EUR, including 90 million EUR dedicated specifically to hydrogen infrastructure and applications, the project has demonstrated substantial long-term savings. These savings are realized through lower operational costs and a significant reduction in greenhouse gas emissions, highlighting the economic viability of renewable hydrogen in railway systems (Hagedoorn et al., 2021).

Solar power integration also presents a promising opportunity for the railway sector. High-speed electric railways have substantial energy requirements, often necessitating dedicated power plants. Installing grid-connected PV solar plants with battery storage along rail networks can enhance grid connectivity and increase energy self-sufficiency. For instance, the installation of a 330 MW PV solar plant with battery storage along the Mumbai-Ahmedabad high-speed rail link, although incurring an initial cost of 1.67 M$/MW, is projected to yield long-term savings of approximately 58 M$/y after a payback period of 11 y (Nazir, 2019). This case demonstrates that despite the high initial investment, the long-term benefits – such as reduced energy tariffs and maintenance costs – make such projects economically sound (Nazir, 2019).

Integrating renewable energy into railway systems is a pivotal step toward achieving global sustainability goals. This transition reduces reliance on fossil fuels and offers substantial long-term financial and environmental benefits. Effective management and informed policy development are critical to realizing these benefits (International Energy Agency, 2022). Active participation from governments and public institutions is essential to facilitate this shift to renewable energy sources (Sovacool and Dworkin, 2015). Establishing efficient governance frameworks is vital to gaining public acceptance and ensuring successful implementation (Kalkbrenner and Roosen, 2016).

Collaboration has proven vital in successfully executing renewable energy projects within the railway sector, particularly in countries with rigid planning frameworks. Emphasizing alternative policies and community education is crucial. Stakeholder cooperation – encompassing government agencies, railway companies, energy providers, and environmental organizations – is necessary to develop effective policies and strategies (Sovacool and Dworkin, 2015). This collaboration is instrumental in integrating renewable energy sources into railway infrastructure and addressing potential challenges (Sovacool and Dworkin, 2015).

For example, South Africa's transition from coal to renewable electricity in railways demonstrates the effectiveness of a 'collaborative visioning' approach. Similarly, collaboration among the government, Deutsche Bahn, and renewable energy companies in Germany has led to successful solar and wind-powered train projects. Japan's Shinkansen network also exemplifies the benefits of cooperation among government bodies, railway companies, energy providers, and technology firms in implementing solutions like regenerative braking and solar panels (Japan Transport Research Institute, 2022).

Modernizing railway infrastructure with renewable energy is essential for sustainable transportation (Kuchak et al., 2020). Policymaking should be grounded in the specific requirements of the task and should involve on-the-ground decision-making (Kuchak et al., 2021). Internal microgrids can enhance energy efficiency and facilitate energy sharing within railway systems. Railway stations can function as energy distribution hubs and local hydrogen production facilities can meet regional energy needs. Integrating small-scale hydroelectric, micro-CHP, and geothermal plants along railway routes can effectively meet energy demands (Tian et al., 2022).

In remote locations, using wind and solar energy, complemented by advanced storage systems, can significantly enhance sustainability. These energy sources provide a reliable and renewable power supply, helping to reduce dependence on fossil fuels and mitigate environmental impacts (Li et al., 2015). However, the current energy infrastructure challenges reducing carbon emissions and transitioning to cleaner sources. Innovative approaches and business models are essential to maximizing the potential of renewable energy in railways (Geels and Schot, 2007). Implementing intelligent policies will be crucial in overcoming these obstacles and seamlessly integrating renewable energy into railway systems, contributing to environmental preservation while optimizing the efficiency of train operations (Geels and Schot, 2007).

## 6. Conclusions

The transition to renewable energy in railway systems is no longer optional; it is a necessity driven by the urgent need to reduce $CO_2$ emissions, meet rising energy demands, and mitigate environmental degradation (Borras and Edler, 2014). With their significant energy requirements, railways benefit greatly from renewable sources like solar, wind, bioenergy, and kinetic energy recovery, which offer sustainable and efficient alternatives (Kuznetsov et al., 2024). This paper emphasizes that integrating renewable energy reduces environmental impact and enhances the overall sustainability of rail networks (Nazir, 2019).

A key takeaway is the potential of intelligent multi-agent systems to manage railway microgrids, increasing energy efficiency and lowering operational expenses (Aguado et al., 2016). Deploying hybrid energy systems that combine various renewable sources and energy storage technologies ensures a stable and consistent power supply while reducing reliance on traditional energy grids (Liu et al., 2018). For example, high-efficiency solar panels and strategically placed wind turbines offer an effective means to achieve energy self-sufficiency and long-term financial savings (Chen et al., 2022).

Smart grid technologies and AI-driven energy management systems are crucial in optimizing energy distribution within railway operations, dynamically managing energy flow to maximize efficiency (Park and Salkuti, 2019). Artificial intelligence (AI) plays a pivotal role in optimizing energy management systems for railways, improving operational efficiency and reducing costs (Ficzere, 2023). Such systems provide the flexibility needed to accommodate varying energy demands across different railway components (Liu et al., 2018). Advanced energy storage solutions, such as batteries and ultracapacitors, further help to mitigate the variability of renewable energy sources like solar and wind (Ye et al., 2024).

For this transition to be successful, robust policy frameworks and regulatory support are essential to promote investment in renewable energy infrastructure and ensure alignment with environmental goals (Doci et al., 2015). Collaboration among stakeholders – railway operators, government agencies, energy providers, and environmental groups – is also critical for overcoming financial and logistical barriers (Wagemans et al., 2019). Future research should prioritize the development of hybrid energy systems and evaluate new financial models that support the large-scale integration of renewable energy in rail transport (Li et al., 2015). Drawing insights from successful case studies, such as the Swiss Federal Railways' use of hydroelectric power, will be vital in replicating these outcomes in other regions (Deutsche Bahn, 2023). Ultimately, the shift to renewable energy in railways will help meet global climate goals and create economic opportunities by reducing operational expenses and fostering green jobs (Geels and Schot, 2007).

In conclusion, adopting renewable energy in railway systems requires coordinated efforts across sectors, supported by sound policies and strategic planning (Wagemans et al., 2019). By embracing innovative technologies and collaboration, railways can significantly contribute to global sustainability goals while improving efficiency and reducing environmental impact (Deutsche Bahn, 2023). The path forward is clear: renewable energy is essential for the future of rail transportation and the planet (International Energy Agency, 2022).

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