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*Case report*

# Assessment of the implications of energy-efficient technologies on the environmental sustainability of rail operation

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**Abstract:** Railway transportation is a significant contributor to Green House Gas (G.H.G.) emissions in the transportation sector. To mitigate this impact, it is crucial to adopt energy-efficient technology solutions. Improving the energy efficiency of railways can significantly reduce their environmental footprint. We employ a case study methodology to evaluate how energy-efficient technologies such as regenerative braking and lightweight materials affect the sustainability of railway operations. The research assesses the amount of energy used, emissions produced and overall effectiveness of these innovations on railway systems. The findings provide valuable insights into enhancing sustainability in rail transport and inform further research and policy initiatives to advance energy efficiency in the transportation industry. By embracing these technologies, we can potentially reduce the environmental impact of railways while supporting more equitable and sustainable transportation systems that align with global emission reduction goals and U.N. Sustainable Development Goals 2030.

**Keywords:** environmental sustainability; carbon emission; transportation; railways; sustainable development; energy efficiency

## 1. Introduction

Global carbon dioxide emissions mainly cause climate change. Climate change and environmental deterioration cannot be ignored in the name of economic progress. Many countries pursue the UN SDG 2030 Agenda directly or indirectly through their sectoral and other policies. Mainly, nations have implemented initiatives to increase the resilience of their economies. Circular economies and low-carbon economies are becoming more popular. According to the United Nations' 2019 Sustainable Development Goals Report, 77% of the direct economic losses of approximately 3 trillion US dollars generated by disasters from 1998 to 2017 were attributable to climate-related disasters worldwide [1]. A resource-saving and environmentally friendly society must focus on the transportation sector, which uses resources and consumes energy. Rail transportation has long been lauded as an energy-efficient mode of moving people and goods, offering environmental benefits compared to road and air alternatives. However, railways still consume much energy, and improving their energy efficiency is vital for decreasing their environmental impact.

Fossil fuel combustion produces greenhouse gases that play a significant role in climate change by being released into the atmosphere. As the world grapples with the urgency of addressing climate change and reducing carbon emissions, the role of rail operations in sustainable transportation becomes even more crucial. Transportation systems' energy efficiency must be increased to combat climate change since the transportation industry contributes significantly to these emissions. The integration of energy-efficient technologies within rail systems emerges as a key strategy to enhance the environmental sustainability of this mode of transport.

According to a study, a 1% increase in a railroad's operational mileage results in a 1.114% reduction in CO2 emissions. In other words, long-term railway expansion can lower CO2 emissions [2]. Regarding railway freight, [3] found that intermodal road-rail operations might reduce emissions by as much as 77.4% and reduce air pollution. High-speed rail (HSR) has a favorable effect on local air quality. The SDGs, a series of 17 goals agreed upon by the United Nations in 2015 to promote sustainable development globally, depend heavily on energy efficiency. Energy is a significant factor in economic development, and increasing energy efficiency can lower energy prices, boost energy security and support economic growth. Energy efficiency can also help to achieve SDGs, including Goal 7: Inexpensive and clean energy, which aims to guarantee that everyone has access to affordable, dependable and contemporary energy services. By fostering sustainable transportation networks and minimising the environmental effect of metropolitan areas, improving energy efficiency can also support other SDGs, such as Goal 11: Sustainable Cities and Communities. Increasing energy efficiency by lowering greenhouse gas emissions and encouraging more sustainable energy use can further support Goal 13: Climate Action.

Increasing global energy efficiency is essential for combating climate change and accomplishing the SDGs. Energy efficiency can help create a more equal and sustainable future for everyone by encouraging more sustainable energy consumption and lowering greenhouse gas emissions. People, cultures, cities, nations and continents are all connected by transportation. It serves as one of the vital pillars of contemporary societies and economies, enabling global trade and the exploration of new areas by visitors and producers of goods. In addition to ensuring access to critical public services such as education and health, transportation networks also improve quality of life. Connecting people to transportation promotes economic growth in rural areas by generating jobs and distributing income. However, there is a drawback to our present transportation system. The transportation industry has a significant detrimental influence on the environment and human health. A quarter of the EU's total greenhouse gas (GHG) emissions are attributed to transportation, contributing to habitat fragmentation, noise and air pollution. The global energy crisis and climate change risk have brought the opportunity and difficulties of using sustainable energy into sharp focus [4,5].

Passenger and freight rail in Europe virtually stagnated between 2000 and 2018, dropping by 1 and 3 percentage points, respectively. Despite the country's efforts to enhance rail spending, freight and passenger shares in India fell by ten percentage points. While freight increased its share by four percentage points in the United States, passenger transportation remained minor. China and Australia are two major exceptions. During the nearly two-decade period in China, transportation increased by 23 percentage points, while freight decreased by 11 percentage points. The opposite is true in Australia, where freight increased by 17 percentage points while passenger rail usage remained low [6]. Within the framework of global climate change, the issue of greenhouse gas emissions has assumed a progressively grave nature. The steel sector significantly contributes to annual CO2 emissions, therefore establishing itself as a prominent contributor to climate change. Numerous nations are devoting significant attention to the implementation of emission reduction technology within the steel industry. Consequently, a discernible trend has emerged, emphasising the reform and innovative transformations of steel enterprises [7].

Today, the majority of rail networks are found in India, the People's Republic of China, Japan, Europe, North America and the Russian Federation, while metro and light rail networks are found in the majority of the world's major cities. Over 90% of all passenger movements on conventional rail occur in these nations and regions, with India leading the way at 39%, the People's Republic of China ("China") coming in second at 27%, Japan coming in third at 11% and the European Union coming in ninth at 9% [8]. Creating low-carbon mobility is one of the most effective ways to reduce CO2 emissions, as the transport industry is responsible for 14% of greenhouse gas emissions. High-speed rail (HSR) is an example of "green transportation" because it uses less energy than flying or driving a car [9,10]. The goal of environmentally friendly railway construction innovations is to lessen the effects of rail traffic. One of the most popular topics in energy economics is the study of energy efficiency. However, little research has provided a distinct and consistent quantitative measure of energy efficiency.

The hindrance of innovation assistance in the building industry has impeded advancements in energy efficiency. Consequently, challenges may arise in effectively translating breakthrough scientific and technological accomplishments into tangible production outcomes. Hence, it is imperative for national, provincial and municipal governments to expedite the establishment of a comprehensive industry-university-research integration system in order to facilitate the swift conversion of scientific research outcomes into tangible and quantifiable impacts [11]. Transportation is a significant contributor to global CO2 emissions. By understanding how energy-efficient technologies impact rail operations' environmental sustainability, stakeholders can make more informed decisions about future investments and policies. As technologies evolve, it is essential to continually assess their implications, ensuring that they deliver on their promise of increased efficiency and sustainability. Energy and/or environmental efficiency assessments in the transportation sector have recently drawn increasing attention. As a result, the sector is searching for fresh and novel approaches to assist in achieving its objectives for environmental sustainability. Energy-efficient technology can play a crucial role in accomplishing this objective, and we try to analyze its influence on railway operations and environmental sustainability. Rail transport is often seen as a more sustainable alternative to other modes. By thoroughly understanding its environmental implications, policymakers can better advocate for its expansion and adoption. Governments, investors and rail operators must understand the economic implications of energy-efficient technologies to ensure the financial sustainability of rail operations. Beyond just direct emissions reductions, a comprehensive understanding of both direct and indirect environmental implications is crucial to ensure that new technologies do not introduce new, unforeseen environmental challenges. Understanding the environmental impacts of energy-efficient rail technologies is vital for governments and organisations aiming to meet specific environmental goals or targets, such as those set out in international agreements or national policies. Considering their environmental and operational implications, assessing energy-efficient technologies in rail operations provides a comprehensive understanding that aids in policy formulation, strategic planning and further technological development.

The trend of replacing small ships with larger ones is resulting in the use of diverse ship fleets on various routes. However, the current mathematical models that tackle the primary strategic decisions in liner shipping often use the assumption that a uniform fleet of ships is deployed on a specific route. The study introduced a novel integrated optimisation model, referred to as the Tactical-Level Planning Decisions in Liner Shipping with Heterogeneous Ship Fleet and Environmental Considerations (TLP-HSF) model. This model comprehensively addresses the key tactical decisions in liner shipping, including the determination of service frequency, ship fleet deployment, optimization of ship sailing speed and design of ship schedules. Moreover, it enables the deployment of a heterogeneous ship fleet on each liner shipping route while taking into account the emissions generated throughout the entire liner shipping operations [12]. In the broader context of the transportation sector's impact on the environment, rail transport has stood out for its lower carbon footprint per unit of distance travelled. As governments and industries increasingly set ambitious climate targets, the rail industry is positioned to play a significant role in achieving these goals. However, the expansion of rail networks, increased traffic demands and evolving passenger expectations necessitate continuous efforts to innovate and reduce environmental impacts [13–15]. Energy-efficient technologies offer a promising avenue to enhance rail operations' environmental performance. These technologies encompass a spectrum of advancements, including regenerative braking systems, aerodynamic design improvements and energy-efficient propulsion systems [16,17].

The private sector's commitments have demonstrated a substantial reduction in deforestation from the year of commitment to 2019, with a statistically significant confidence level of 90%. In order to effectively uphold zero-deforestation promises, it is imperative to implement substantial changes in existing policies and practices. This entails bolstering law enforcement measures to effectively address illegal actions, enhancing transparency to facilitate the monitoring of progress and formulating strategic and executable strategies [18]. The use of energy-efficient technological advancements has been widely acknowledged as a highly effective strategy for mitigating energy consumption in buildings [19]. However, while individual studies have examined the benefits of these technologies, a comprehensive assessment of their combined implications on rail sustainability remains limited in the literature.

We seek to address this gap by conducting a comprehensive evaluation of the implications of energy-efficient technologies on the environmental sustainability of rail operations. By considering both quantitative measures, such as energy consumption reduction and emissions mitigation, and qualitative aspects, including stakeholder perspectives and economic viability, we aim to provide a holistic understanding of the potential impact of these technologies.

The remaining portion of the paper is divided into five sections after this introduction. The literature review is covered in Section 2, and Section 3 presents the research methodology. Section 4 introduces the results' analysis; Section 5 draws conclusions; Section 6 summarizes the study's findings and provides scope for further research.

## 2. Related works

Railway transportation is important in the global transportation system because it is a low-cost and ecologically beneficial means of transit for people and cargo. Rail transit, however, has major environmental consequences, including greenhouse gas emissions, air pollution and noise pollution. There is an increasing need to evaluate the environmental efficiency of railway transport and develop methods to encourage sustainable practices. Therefore, sustainable development has developed as a significant idea, emphasising the incorporation of environmental, social and economic issues into decision-making processes. Environmental, social and governance (ESG) standards are widely used in the investing business to assess the long-term performance of firms and industries, including the railway transportation sector.

### *2.1. Railway transportation, energy and environmental efficiency:*

According to China's national strategy, electrifying railways is critical to cutting carbon emissions and improving the country's transportation system's energy structure. In this article, we investigate China's potential for reducing carbon emissions through rail electrification and propose a model to calculate $CO2$ emissions under three different future scenarios. With the existing energy generation mix, railway electrification can cut carbon emissions by 8.9%. However, a maximum decrease in carbon emissions of 65.4% can be attained by utilising a generation mix similar to that of the UK [20]. The railway system in China has been effectively contributing to the enhancement of environmental quality. In order to effectively implement policies, it is imperative for local authorities to demonstrate support for urban public services, such as buses and metro systems, and strive to enhance the quality of public transport services. Concurrently, authorities may also propose innovative concepts for a collaborative economic model, such as the implementation of shared bicycles and automobiles, with the aim of diminishing reliance on privately-owned transportation [21].

High-speed rail (HSR) is a secure, quick, pleasant and environmentally friendly means of transportation that has drastically changed how people travel. However, its level of greenness and impact on the county's air quality needs more research. In southern Jing-Jin-Ji, HSR benefits the environment at least 4% more on the side closest to Beijing and Tianjin than on the opposite side. As a result of the magnitude, structural and technical benefits of HSR, the region's air quality has improved [22]. Environmental efficiency shows regional disparities, with the eastern region having the highest environmental efficiency and the western region having the lowest.

Additionally, we discovered a significant positive impact of railway transportation on higher environmental efficiency [23]. The China Railway Express (CRE) has influenced the environmental sustainability of important towns and cargo transportation between China and Europe. Environmental efficiency has increased dramatically because of CRE. Through the promotion of technological advancement and a decrease in the inflow of damaging foreign investment, the openness of CRE has enhanced environmental performance [24]. HSR has lower $CO2$ emissions during operation than road and air transportation, enabling reductions of 10 to 60% and 46 to 73%, respectively [25]. As a result, the railway's substitution effect reduces $CO_2$ emissions [26].

High-speed, practical, secure and comfortable HSR significantly reduces carbon emissions in Sanitary and Phytosanitary Measures (SPS) counties compared to traditional railways. The few SPS counties in China that are a part of the national HSR system benefit significantly in terms of the environment. The endogenous mediation mechanism demonstrates that the opening of a railway has a two-way impact on carbon emissions. In other words, while it directly lowers emissions, it also indirectly increases emissions due to the expansion of economic activity and population shifts. Establishing conventional trains and HSRs dramatically increases carbon emissions by significantly accelerating economic development in SPS counties [27].

Governments should enhance HSR technologies and broaden HSR networks to support environmentally friendly development. Building HSR aids in reducing $CO_2$ emissions [28]. In China, the transport sector, particularly the road and rail industries, contributes significantly to $CO_2$ emissions. The western region has the highest average energy-environmental efficacy in the railway industry, surpassing the central and eastern areas [29]. Rail transports 8% of the world's passengers and 7% of freight while accounting for only 2% of transport energy usage, and high-speed services over long distances provide an environmentally benign option for short-distance air travel by lowering emissions. Metros and light rail provide dependable, economical and rapid alternatives to city auto transit, decreasing congestion, local pollution and greenhouse gas emissions. High-speed rail offers a high-quality alternative to short-distance aircraft between large urban areas. Rail freight provides a low-emissions and low-cost connection in freight supply chains [8,30].

The utilization of battery-hydrogen hybrid locomotives should be regarded as the most optimal option for future locomotive technology. The utilization of hydrogen locomotives exhibits considerable potential as a viable substitute for conventional diesel-powered railway locomotives. Nevertheless, there exist specific technological obstacles that must be addressed in order to augment the overall efficacy and dependability of the system, hence advancing its feasibility for implementation within the railway industry [31].

The results emphasize the adverse effects of fossil fuels on $CO_2$ emissions in countries with high carbon output. Considering the results of the MARS analysis, policy recommendations such as decreasing the use of fossil sources, increasing energy efficiency and supporting renewable sources are proposed. Other measures, such as positioning $CO_2$ emissions as a macroprudential concern, managing $CO_2$ emissions at a high level of country management, and immediate participation in the Paris (Climate) Accord, are also conceivable [32]. The integration of energy-efficient technologies into rail operations has received considerable attention in recent years.

### *2.2. Sustainable development, environmental, social and governance (ESG) and railway transportation:*

Businesses heavily consider ESG (environmental, social and governance) issues when conducting business and making decisions. ESG is now a requirement for businesses to keep their social licence to operate and is no longer optional. Rails continue to be the foundation of a low-carbon public transportation system that will be carbon neutral by 2050, as recommended in Hong Kong's Climate Action Plan 2050, published by the HKSAR Government. By designating 2021 as the European Year of Rail, the European Commission hopes to increase connectivity within Europe and promote rail as a smart and environmentally friendly means of transportation [33]. The transport sector has a substantial role in the generation of greenhouse gas emissions. Hence, the proposed resolution to address this issue of environmental degradation is to implement measures that promote sustainability within the transportation sector. This would involve the adoption of environmentally friendly vehicles and the mitigation of harmful emissions in various countries [34].

Sustainable development, especially with health as the social pillar, is best supported by the rail transportation mode [35]. The rail/road option has been demonstrated to be significantly more environmentally benign than its deep-sea shipping counterpart regarding environmental and social performance. This is primarily because it uses electricity instead of the crude oil used by deep-sea shipping for propulsion. The rail/road alternative has also outperformed the other performance parameters, except for noise [36]. If steps are not taken to limit and manage GHGs, the increased use of fossil fuels will severely impact climate change. The utilization of more renewable energy sources and energy efficiency can assist in mitigating climate change and lowering the chances of catastrophic events for humans and other creatures. Since biomass is found everywhere in the world, it can be used to replace fossil fuels as a dependable and sustainable local energy source. Converting biomass into electricity is a sustainable technique to reduce environmental GHG emissions. The seventh and twelfth SDGs are related to biomass-to-energy technologies and their capacity to utilize waste's energy potential. The accomplishment of these two objectives will depend on these developments [37].

Biomass energy is essential since it is among the best sources for lowering CO2 emissions. Additionally, it is anticipated that since biomass offers new and effective ways of producing and using energy, it will have an adverse effect on carbon emissions. With the aid of biomass energy, the globe could effectively facilitate and promote economic growth and reinforce its environmental protections by changing the trend of energy production and usage [38]. The allocation of resources towards railway infrastructure has been effective in mitigating the ecological footprint and minimizing environmental harm within OECD countries. This positive outcome may be attributed to the utilization of clean technology, the cost-effectiveness of such investments and the advantageous scale at which railway systems operate [39].

Effective technology transfer improves the efficiency and long-term viability of standard-gauge railways. Additionally, the findings highlight areas for development that will ensure the effective transfer of rail technology, which would be valuable for advancing knowledge of technology transfer and providing a theoretical framework for technology innovation transfer processes [40]. Sustainable rail transportation is essential for economic development because it gives citizens access to markets, generates jobs and improves people's quality of life [41]. To lower overall energy consumption in the rail industry, it is essential to increase the efficiency of air conditioning units (ACUs), which account for 30% of the total operational energy consumption. The use of desiccant-coated heat exchanger (DCHE)-based technology in the rail industry can significantly contribute to the industry's decarbonisation and prepare rail transportation for a green transformation [42].

Clean energy, rail transportation, new materials and other green businesses are all supported by green finance. Green financing may reduce environmental pollution, which will boost economic growth. Additionally, it demonstrates how environmental management and economic development are both environmentally friendly activities in which every section of the nation engages. Regional and national development are both impacted by environmental governance[53]. The Digital Railway Project is a complete and open innovation based on integrating communication technologies into digital systems. It is regarded as a complicated organisational and technical system. The integrated shift from the technical plane to the digital economy is peculiar to this project's development at Russian Railways. Organizational, managerial and technological readiness are requirements for successfully implementing digital railroads. These requirements include projects for polygon energy efficiency, which are determined by the level of integrative management. The criteria for optimising operational work should consider not only the interests of Russian Railways, including process economics, the productivity of the locomotive fleet and dispatch personnel, but also customers' interests related to the cost, volume and timing of cargo delivery. This task can be accomplished by automating the management and planning of the transportation process's technical chains on a single intelligent platform [44].

To ease the transition to net zero emissions (NZE), railroads (passenger and freight) must be fully electrified. The demand for biofuels will drop significantly due to a radical shift towards electrification in most of the passenger and freight road and rail sectors and the use of hydrogen as a fuel for high payload heavy commercial vehicles [45]. When a train brakes, it produces electrical energy that could be recycled to reduce energy use. More emphasis should be paid to recycling, storing and managing regenerative energy to prevent problems with the direct and complete use of regenerative energy. The environmental control systems in trains and stations operate more efficiently. To save energy, adequate steps must be taken to control the lighting, temperature, ventilation, elevators and other mechanical and electrical equipment based on the dynamic density of passenger flows and their need for the environment [46]. Rail transportation offers significant advantages over other modes of transportation due to its relatively minimal negative influence on the environment and society and its great importance in capacity for people and freight transit [47].

Railways and waterways are commonly recognized as environmentally sustainable forms of transportation for goods, in contrast to other alternatives. Embracing these modes of transportation can significantly mitigate the ecological impact associated with cargo transit [48]. The literature has emphasized the significance of rail transportation in the global transportation system and the need to promote sustainable practices within the industry. The use of energy-efficient technology in rail operations has the potential to reduce environmental impacts. Nevertheless, their implementation must consider the effects on the long-term viability of rail transportation [49]. The use of ESG criteria in the railway transport sector has grown in recent years, allowing investors to assess the sustainability performance of firms and industries. However, challenges remain, such as the lack of defined ESG indicators and the scarcity of ESG data for the railway transportation sector. The research area that needs to be examined is railway transport's environmental operational efficiency, which provides ways to encourage sustainable practices.

The necessity for railway companies to embrace sustainable practices and address their environmental and social implications as a commercial concern was noted in this literature assessment. Incorporating ESG factors into decision-making processes and using energy-efficient technologies can assist firms in reducing their environmental footprint and improving their sustainability performance, boosting their reputation and financial success. The literature has stressed the necessity of encouraging sustainable practices in railway transport and the possibility for energy-efficient technologies and ESG standards to help accomplish the goals of energy efficiency, net zero emissions and environmental sustainability.

## 3. Research methods

We primarily focus on the environmental implications of energy-efficient train technology, including the potential benefits and challenges involved. The case study approach was used in the research, with Indian Railways serving as the case study. This technique would allow for a comprehensive evaluation of the environmental implications of the energy-efficient system used by Indian Railways. In the data collection process, secondary data sources were primarily used and were collected by reading relevant literature, such as academic publications, industry reports and policy documents.

The necessity for railway companies to embrace sustainable practices and address their environmental and social implications as a commercial concern was noted in a literature review covering energy emissions, sustainable environment, operational efficiency and sustainable development goals. The literature has stressed the necessity of encouraging sustainable practices in railway transport and the possibility for energy-efficient technologies and ESG standards to help accomplish the goals of energy efficiency, net zero emissions and environmental sustainability. The case study method enables thorough, in-depth examinations of complicated issues in real-world situations. Business, law and policy disciplines all appreciate the significance of the case study methodology [50]. A case study is an empirical research activity that investigates a particular contemporary occurrence or action in a constrained environment using flexible empirical data collected in various ways. It aims to conduct in-depth research on a specific instance, such as an individual, organization, establishment or society. Using case studies, it is feasible to pinpoint crucial elements, procedures and connections [51].

## 4. Results

The transportation sector generally contributes significantly to greenhouse gas (GHG) emissions and other environmental problems, and railway transportation is no exception. As a result, there is a growing need to evaluate the environmental sustainability of rail operations and devise methods to mitigate their impact. The adoption of energy-efficient technologies in train operations is one way to attain this goal. The Indian Railways case study allows us to analyse the effects of energy-efficient technologies on the environmental sustainability of rail operations in a specific setting. Our purpose of this research is to evaluate the environmental consequences of energy-efficient technologies in Indian railways and to identify measures to promote sustainable practices in the industry. This study's analysis and interpretation can provide insights into the possibilities for fostering sustainable practices in the rail transport sector, with policy and practice implications.

### *4.1. Indian railway: transitioning towards net zero carbon emissions:*

Indian Railways has a vision to "Promote a green environment and clean energy while making the Indian Railways a global leader in sustainable mass transport solutions". Indian Railways (IR) has one of the largest rail networks in the world, with 67,415 route kilometers. The I.R., which carries almost 23 million passengers daily and is the world's most extensive passenger transportation system, is vital to the country's growth. It also moves 1,225 million tonnes of freight annually over the length and breadth of the country, making it the fourth-largest freight transporter in the world.

India has committed to the United Nations Framework Convention on Climate Change to attain net zero emissions by 2070. Indian Railways wants to be a "net-zero carbon emitter" by 2030. The policy focused on five action points: energy-efficient equipment and appliances, a cloud-based data monitoring and management site, sustainable buildings, power quality and restoration and capacity building and awareness. It has set a target of electrifying all trains by December 2023, and non-renewable energy will be used predominantly to power the trains and terminals by 2030. The Indian

Railways' annual diesel consumption decreased from 3,066 million litres in 2018–19 to 1,092 million litres in 2020–21 (Source: Indian Railways). Mobility will be crucial as the Indian economy evolves, with the twin aims of sustainable development and economic prosperity [52,53]. An integrated strategy with resource efficiency at its core will be essential for IR to function as a low-carbon mass transportation system working for a green environment. The national transporter, which serves as the lifeblood of the nation, established the Environment Directorate at the Railway Board in January 2015 to coordinate all environmental management programmes across the Indian Railways. Since that time, the railroads have taken steps to organize their environmental management programmes. These initiatives include energy efficiency, renewable and alternative sources of energy, water conservation, reforestation, waste management and green certifications [52].

To make this happen, the budgetary support for the railway ministry for 2022–2023 has been boosted to more than US$ 16 billion, which is 28% higher than the previous year. These ambitious ambitions for Indian railways are costly financially, but they also have significant environmental impacts. The support of the Indian economy substantially affects climate change and greenhouse gas emissions (Indian Railways, 2023). According to UN Climate Change, the railway industry in India is responsible for 12% of greenhouse gas emissions [54]. Indian Railways has decided to switch to all solar power. Soon, railway coaches' lighting and fans will run on solar energy. This is a significant advance for India's market for renewable energy. Solar energy can save much money (roughly Rs 3 crore for each train over 25 years) by replacing diesel, which powers lights, fans and mobile charging stations.

### *4.2. Major strategic steps towards environmental sustainability*

By 2030, Indian Railways (IR) wants to achieve net-zero carbon emissions. The following actions were taken in this regard:

- IR has set a goal to electrify all railway tracks by 2030 to achieve "Net Zero" status as an organization.
- Indian Railways is working with numerous donor organisations and stakeholders to hasten the transition to a low-carbon future. It has a Memorandum of Understanding for cooperation on energy and sustainability under its Power Sector Reforms Programme with the Foreign, Commonwealth and Development Office (FCDO) of the United Kingdom.
- Complete electrification of the BG railway network.
- A total of 103 MW of wind power plants and approximately 142 MW of solar plants have been put into operation (until October 31, 2022).
- Locomotives, Electrical Multiple Unit (EMU) trains, Mainline Electric Multiple Unit (MEMU) trains, Kolkata Metro rakes and electric train sets all use regenerative braking in conjunction with a three-phase propulsion system.
- Reduce noise, air pollution and diesel consumption by converting end-on-generation (EOG) trains to (HOG) trains.
- All railway facilities, including stations, service buildings, housing and carriages, have light-emitting diode (LED) lighting to save electricity consumption.
- Railway properties are being planted with trees to boost carbon sinks.
- Green certifications have been completed for a number of industrial facilities, stations and other rail facilities. A number of railway stations have also undergone Environmental Management System (EMS) accreditation (ISO 14001).

- Building Dedicated freight corridors (DFCs) in the east and west
- Construction of waste-to-energy facilities.
- Up to 2030, water consumption efficiency will be increased by 20%.
- Planting trees to boost the carbon sink.
- Pollution prevention and waste management.
- Adopting best practices for managing resources and infrastructure to promote environmental sustainability in IR expansion in green buildings, industrial units and other institutions.
- An overhead equipment (OHE) cum battery-powered tower car for OHE inspection and maintenance was created by Eastern Railway (ER), the first of its kind on Indian Railways. Old MEMU coaches have been appropriately modified to meet various needs, including adding an overhead inspection boom, a bio-toilet, tool cupboards, a crew rest space and a roof-mounted catwalk.
- Indian Railways has wind energy installations across the country, including a 26 MW wind project in Rajasthan, a 56.4 MW plant in Maharashtra and 2 x 10.5 (totalling 21 MW) projects in Tamil Nadu (Indian Railway, 2021b; Press Information Bureau.

Government of India, Ministry of Railways, March 2021).

*4.3. Green certification from the state pollution control board since 2015:*

- Approximately 700 train stations have received accreditation for executing an Environmental Management System in accordance with ISO 14001.
- More than 545 stations have received the State Pollution Control Board's consent to operate (CTO).
- Green accreditation was achieved for 31 railway buildings (offices, training facilities, hospitals and schools), 32 stations and 55 workshops or PUs.

*4.4. Environmentally friendly bio-toilets by railways*

The installation of environmentally friendly bio-toilets in passenger coaches is one of several measures that Indian Railways has implemented to enhance the environmental sustainability of its operations. Anaerobic bacteria are used in biotools to cleanse human waste, and as a byproduct, water and methane gas are produced.

There are many advantages to installing bio-toilets in passenger coaches. First, it eliminates the necessity for open human waste disposal on track, which can cause environmental degradation and health risks. Treating human waste onboard also lowers water use and raises water quality. Methane gas, which can be used as an energy source for railway operations, is the final product.

The installation of bio-toilets has had positive social and economic effects and environmental benefits. Especially for long-distance travel, it has enhanced the cleanliness and sanitation of passenger coaches and decreased the health risks connected to the open discharge of human waste. By maintaining and servicing bio-toilets it has also given local communities economic opportunities.

For Indian Railways, installing bio-toilets in passenger coaches has been a major endeavor. Over 250,000 passenger coaches have bio-toilets established as of 2021, and they intend to put bio-toilets in every coach by 2023. The installation procedure includes adding bio-toilets to existing coaches or installing them in newly built coaches while they are being built. The anaerobic bacteria required to process human waste are present in a biodigester tank connected to the biotoilets. Cleaned water is poured onto the railway rails, and methane gas is captured and used as a fuel source for the train.

Some of the initiatives taken by the IRs include:

- Indian Railways (IR) has developed bio-toilets for passenger carriages in collaboration with the Defence Research and Development Organisation (DRDO).
- A total of 3,647 coaches had 9,587 bio-toilets installed as of March 2014. The task of fitting biotoilets in all passenger-carrying coaches operating on Indian railways has been successfully completed, with 2,58,990 biotoilets installed in approximately 73,110 coaches up to March 2021 [53,55].

Thus, following the "Swachh Bharat Mission," the direct discharge of human waste from trains has been stopped. In 2015, the Ministry of Railways began the "Swachh Rail, Swachh Bharat" campaign, intending to achieve major and long-term improvements in the cleanliness standards of trains and stations to improve the Indian passenger experience.

### *4.5. Transition to renewable energy sources*

The railroad intends to incorporate more renewable energy into its overall energy mix. The carrier has already installed rooftop solar panels in all railway facilities to achieve this goal. It has over 100 MW of rooftop and bare land solar panel installations, and it intends to set up over 20 GW of solar capacity by 2030. Railways unveiled the Bina Solar Power Project in February 2023, a pioneering solar facility that generates and delivers solar electricity directly at 25 kV Overhead Electrical Equipment to haul trains. The project was developed in collaboration with the Government-owned Bharat Heavy Electricals Ltd. (BHEL), and it directly powers the overhead rails that locomotives use for movement. By utilizing renewable energy sources, Indian Railways may significantly reduce its reliance on fossil fuels and lessen its carbon impact. Approximately 103 MW of wind power plants will be operational through October 2022.

To meet the anticipated demand needs of over 33 billion units by 2030, Indian Railways plans to build 20 GW of solar projects on undeveloped territory. To handle nontraction demands at railway stations, solar power plants with a 500 MW capacity will be installed on the roofs of railway structures. Additionally, the South-Central Railway Zone is implementing several energy-saving measures, such as using renewable energy. In the area, stations and service buildings will have solar panels installed. These excellent efforts to make the entire rail network sustainable will encourage other nations to take similar actions and help the environment.

**Table 1.** Major projects by railways.

| Project name | Location | Capacity (MW) | Year of Commissioning |
|---|---|---|---|
| Jodhpur Railway Station Solar Power Plant | Jodhpur, Rajasthan | 1 | 2016 |
| Guwahati Railway Station Solar Power Plant | Guwahati, Assam | 700 kW | 2017 |
| Katra Railway Station Solar Power Plant | Katra, Jammu and Kashmir | 1 | 2017 |
| New Delhi Railway Station Solar Power Plant | New Delhi | 2.6 | 2017 |
| Diwana Solar Plant | Jhajjar, Haryana | 10 | 2017 |
| Kochi Metro Rail Limited (KMRL) Solar Power Plant | Kochi, Kerala | 4.8 | 2018 |
| Kolkata Metro Rail Corporation (KMRC) Solar Power Plant | Kolkata, West Bengal | 2.4 | 2018 |
| Bhilai Railway Station Solar Power Plant | Bhilai, Chhattisgarh | 0.5 | 2019 |
| Bina Traction Substation Solar Power Plant | Bina, Madhya Pradesh | 1.7 | 2019 |
| Visakhapatnam Railway Station Solar Power Plant | Visakhapatnam, Andhra Pradesh | 0.5 | 2019 |
| Bina Railway Station Solar Power Plant | Bina, Madhya Pradesh | 1 | 2020 |
| Secunderabad Railway Station Solar Power Plant | Secunderabad, Telangana | 0.6 | 2020 |
| Raipur Railway Station Solar Power Plant | Raipur, Chhattisgarh | 0.6 | 2021 |

Source: Authors's compilation.

### *4.6. Reducing carbon emissions*

The transport industry must grow sustainably for the nation to meet its developmental goals, as it is and will continue to be a major enabler of progress. More than 25% of India's energy needs and more than half of its overall petroleum consumption are linked to transportation. Approximately 13% of all GHG emissions come from it. Given the relative efficiency advantage of rail-based transport, increasing the proportion of rail for both passenger (regional, suburban and urban) and freight transport is essential for improving the energy efficiency of the transport sector and lowering the nation's GHG emissions [52].

The transport sector is one of the core sectors with significant mitigation potential, and the government of India has set a target of 33% emissions intensity reduction as part of its Nationally Determined Contributions (NDCs). The Government of India decided that one of the most important methods for reducing transport emissions was to increase the share of Indian railways in freight transit from the current 35–36% to 45% by 2030. IR is establishing Dedicated Freight Corridors (DFCs) across the country. The first two corridors are currently being built. Over the next 30 years, this project's first phase is predicted to reduce emissions by 457 million tonnes of CO2. Railways should continue increasing their energy efficiency for diesel and electric traction to help the nation reduce its GHG emissions [52,55].

*4.7. Indian railway energy efficiency policy and action points for non-traction installations*

The IR has formulated an energy efficiency policy with an action plan comprising five action points (APs) for reducing energy use in nontraction installations. The policy broadly centres around five action points, i.e., sustainable buildings, cloud-based data monitoring and management portals, energy efficiency in equipment and appliances, power quality restoration, capacity building and awareness. Key features of the policy are as follows:

- Energy efficiency upgrades of existing stations and all other buildings. All existing buildings are to be made BEE Shunya or Shunya+ rating compliant.
- Adoption of Super ECBC for new buildings and station developments and ECBC (R) for all residential projects.
- Online monitoring and control of provision through a cloud-based, centralized web portal.
- Procurement of BEE 5-star rated appliances, adoption of low carbon cooling systems and other feasible energy conservation measures.
- Provisions for ensuring power quality across nontraction loads.
- Capacity building and awareness campaigns for energy efficiency.

Further details of various action points mentioned in the policy are attached as an annexure [56].

*4.8. Improvement in energy efficiency in the electrification of railways:*

The development of energy-efficient three-phase locomotive technology is expected to reduce annual carbon emissions by 500 tonnes. These locomotives have regenerative braking features, which allow them to generate electricity while braking and feed it back into the grid. Indian Railways have been progressively electrifying their rail routes to reduce the nation's dependence on imported petroleum-based energy and to enhance energy security for the country, as well as to make the railway system more eco-friendly and modernize it.

From the 388 route kilometres (RKMs) electrified route of the preindependence period, by March 2022, electrification on Indian Railways had been extended to 50,394 RKMs out of the total Broad Gauge (BG) rail network of 65,093 RKMs (68043 RKMs all gauge), including the Konkan Railway. This constitutes 77.41% of the total BG Railway Network, and 74.5% of freight traffic and 78.8% of passenger traffic are hauled on this electrified route. Indian Railways is rapidly progressing to accomplish Mission 100% Electrification and has become the world's most extensive green railway network. A total of 6,542 RKMs have been achieved in IR history between 2022 and 2023. The fuel cost for electric traction is merely 47% of the total traction fuel cost of Indian railways. IR has since electrified the diamond quadrilateral routes along with its diagonals, which connect the metro cities of Delhi, Mumbai, Kolkata and Chennai with progressive electrification and has planned to electrify the balance of BG rail routes expeditiously in mission mode [52,53]. The progress of electrification since independence is tabulated below.

**Table 2.** Year cumulative electrified (RKM) on IR.

| Year | Route Kilometres |
|---|---|
| 1951 | 388 |
| 1961 | 748 |
| 1971 | 3706 |
| 1981 | 5345 |
| 1991 | 9968 |
| 2001 | 14856 |
| 2011 | 19008 |
| 2019 | 34319 |
| 2020 | 39329 |
| 2021 | 44802 |
| 2022 | 50394 |
| 2023 | 56936 |

Source: India Railways Yearbook 2021-22 and PIB report dated 02 April 2023.

Regenerative braking technology is also a feature of the conventional electric locomotive WAG7, which BHEL Jhansi first produced in February 2019. First, Madhepura Electric Locomotive Pvt Ltd. (MELPL) has produced a 12000 HP WAG12 electric locomotive in India. Modern IGBT-based, three-phase, 12000 horsepower electric locomotive with a regenerative braking system that significantly reduces operating energy consumption. These powerful locomotives, which increase freight train loading capacity and average speed, will aid in clearing the congested tracks.

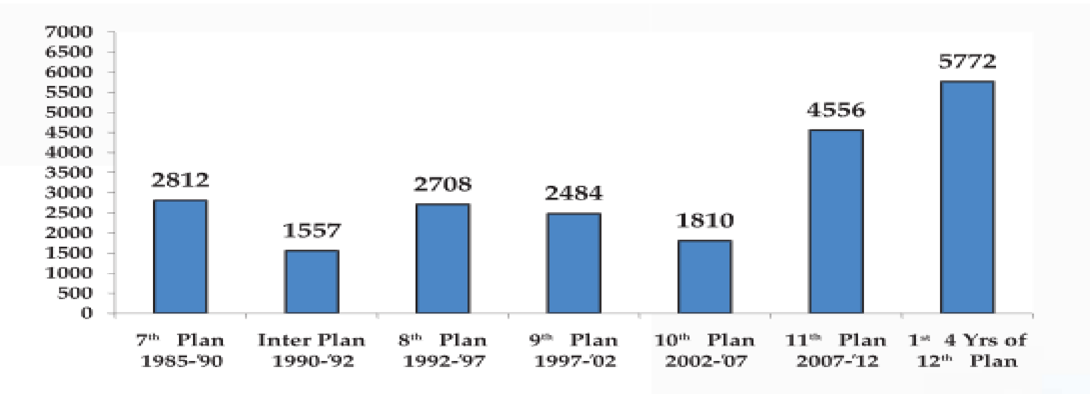


**Figure 1.** Indian Railways, Plan-wise Progress of Electrification.

The entire fleet strength of Indian Railways increased to 13,215 units in fiscal year 2022. While the number of diesel locomotives declined, the number of electric locomotives continued to rise. India's railway industry is one of the world's largest under single management.

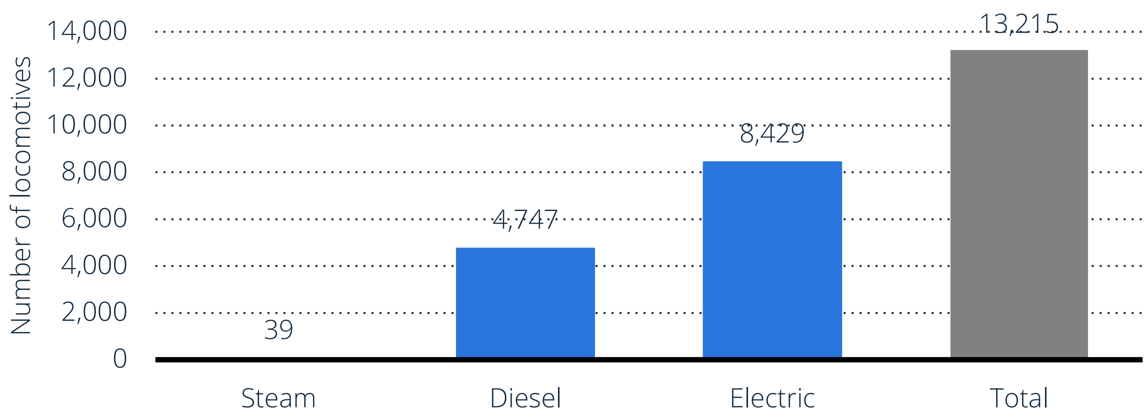


**Figure 2.** Number of locomotives in railway fleet in India FY 2022, by type. (Source(s): Ministry of Railways (India).

Some of the major initiatives are as follows:

- Ensure complete electrification of the broad gauge by December 2023. As of January 2021, 42,354 route kilometres had been electrified. The railways completed 1973 route kilometres of electrification in FY23, a 41% increase over the prior year.
- Installation of 1000 kVA hotel load converters to provide power for the lights, air conditioning and pantry cars of trains.
- Energy consumption speed monitoring (ESMON) systems are installed on all electric locomotives to track the efficiency of the locomotive pilots.
- Loco pilots are encouraged to make the most of the regenerative brakes on three-phase electric locomotives to lower the traction energy cost.
- The crew management system tracks each member's energy use and recovery throughout each trip.
- Optimization of energy demand through actions such as retrofitting locomotives with Head on Generation (HOG) systems, installing 100% LED lights and high-star appliances, conducting energy audits, implementing smart metres, converting diesel locomotives to electric locomotives, increasing the production of electric locomotives, using performance-based contracting for the manufacture of powerful locomotives and using energy-efficient rakes, among others.
- Indian Railways has completely switched to the construction of energy-efficient 3-phase electric locomotives with regenerative characteristics, which allow for the regeneration of electric energy while the train brakes and feeds regenerative energy back into the grid. Pilots of locomotives are routinely advised to turn off the blower and employ the regenerative feature if their yard detention is expected to last more than 15 minutes.
- In the event of multiple units, the trailing locomotives of a train carrying a light load are turned off to conserve energy. All electric locomotives are equipped with microprocessor-based energy metres that allow for regular energy usage monitoring.
- Under the MOU with CII, energy efficiency studies of all eight production units and 12 workshops were performed, leading to a 15% improvement in energy efficiency.
- The inauguration of the 'Make in India' semihigh-speed Vande Bharata Express trains was Indian Railways' most remarkable success story in 2020. The IR intends to introduce a number of other

world-class trains in the upcoming years, therefore improving the country's rail connectivity and eventually beginning to export trains.

- Switching to electrified routes with improved signalling is boosting the capacity of the train infrastructure. The European Train Control System (ETCS), which checks if the train's speed restriction is compatible with the permissible speed allowed by signalling, is being introduced as part of the signalling system's modernization to improve safety and punctuality.

By lowering its carbon footprint, Indian Railways, the fourth-largest railway system in the world, hopes to become a green transporter. In FY 2020, Indian Railways used approximately 18,410 million units of electricity for traction and 2,338 million units for nontraction loads. Indian Railways is committed to becoming a "net-zero" carbon emissions organization by 2030 and has made significant efforts to minimize its carbon footprint and fuel costs. The vast gauge network of the railway will be completely electrified, energy consumption will be reduced and renewable energy (RE) will be used to meet energy demand. Indian Railways presently has 220 Megawatts (MW) of renewable energy capacity, and they are planning to add another 3,450 MW [53]. The Indian Railway Ministry is trying to implement cutting-edge technology such as artificial intelligence (A.I.) and the Internet of Things (IoT) to monitor its greenhouse gas emissions.

Another path that IR has taken is to employ various sustainable construction strategies. The trash produced during tunnel construction, known as "tunnel muck," was used in the construction of the Udhampur-Srinagar-Baramulla Rail Link. This helps minimize carbon emissions by up to 80% and project expenses by 30%. Furthermore, railway stations are being outfitted with sustainable resource management systems. For example, the ECoR's Visakhapatnam railway station has adopted the green concept by implementing waste segregation, establishing and operating a 500 kiloliter per day sewage treatment plant for station and colony water, establishing solar panels to conserve power and installing 100% LED lighting. It received the highest platinum rating and the Indian Green Building Council's Green Railway Station Certification. Other IR methods include carbon capture and sequestration through tree planting. IR intends to offset emissions by planting trees as part of its plans to purchase carbon credits. It plans to plant 0.72 million saplings between 2021 and 2022 to create an additional 6.5 million tonnes of carbon dioxide sink by 2030. Furthermore, water conservation is achieved by mechanized cleaning of tracks and coaches using high-pressure jet cleaners, wet and dry vacuum cleaners, etc. This would reduce water waste and save time. Automatic coach washing plants have been constructed, and rainwater collection has been implemented. The central government has proposed manufacturing 35 hydrogen fuel-based trains in the Union Budget 2023–24, which is a significant step towards carbon neutrality. Furthermore, the National Rail Plan's Vision 2024 aims to reduce freight transit time by boosting freight train average speeds to 50 kilometres per hour for a greener and cheaper network [57]. India has formulated a strategic initiative to substitute its existing railway infrastructure, now managed by Indian Railways, with environmentally sustainable alternatives referred to as "green railways." The primary objective of this endeavor is to attain a state of net-zero carbon emissions by the year 2030.

### *4.9. International experience*

Railways play a crucial role in transportation systems in numerous Western countries. Several techniques have been implemented to enhance energy efficiency in railways, such as the regenerative braking technique, which is widely used in many railway systems. This technique stores the energy generated during braking and reuses it to power the train during acceleration, thus reducing energy consumption. In Germany, Deutsche Bahn implemented regenerative braking techniques in their railway system and used lightweight materials in train construction. Lightweight materials, such as aluminum alloys and composites, reduce the overall weight of the train, resulting in a lower energy requirement for train movement.

The use of energy-efficient lighting systems on railways is another strategy that many nations, including the United Kingdom and France, have adopted. Conventional lighting systems have been replaced with LEDs, significantly reducing energy consumption in trains. Additionally, many Western countries have implemented an energy management system that employs sensors and real-time data to optimize train operations, including the use of power and heating/cooling systems, to reduce energy consumption. High-speed rail systems also help save energy, using advanced aerodynamics and propulsion technologies to increase energy efficiency compared to conventional rail systems.

Indian Railways are expected to have an energy demand of approximately 8,200 Mega Watt (MW) in 2029-2030. It is estimated that approximately 30,000 MW of renewable energy capacity will be required by 2029-2030 to achieve net zero carbon emissions. As of February 2023, approximately 147 MW of solar power plants (both on rooftops and land) and approximately 103 MW of wind power plants were operational. Furthermore, approximately 2150 MW of renewable energy capacity has been committed. Moreover, IR intends to gradually meet its future energy requirements by acquiring renewable energy through various power procurement strategies. The railways have established a goal of producing 20 GW of solar energy by 2030 (PIB,2023). Indian Railways has solarized approximately 960 stations. Indian Railways' goal is to migrate to a "green mode of transportation" using solar energy to meet its traction power requirements. This is consistent with the Prime Minister's 2020 directive to solarize train stations and utilize unused railway land for renewable energy (RE) projects. According to news reports, approximately 142 megawatts of solar plants and 103 megawatts of wind power plants have been commissioned through October 31, 2022. In addition, Indian Railways is taking steps to enhance the usage of green fuels. It uses a 5% biofuel blend in traction diesel fuel [55]. Railways are also taking steps to minimize carbon emissions from goods trains, a major pollution source.

## 5. Conclusion and policy implications

Achieving sustainable development is a pressing challenge that the world faces today. The transportation of people and goods has significant environmental impacts, including noise pollution, pollutant emissions and land use. Civil society, regular people and decision-makers all now recognize the critical role that rail transportation plays in achieving sustainable development objectives while reducing the adverse effects of climate change. Indian railways play an important role in reducing the nation's carbon footprint as part of the government's objectives. To achieve this goal, it is essential to focus on reduced energy consumption and sustainability in railway operations to minimize environmental impact. Automated technologies can be employed in modern railway systems to track and monitor train activity while lowering carbon footprints associated with sophisticated rail equipment through innovations such as regenerative braking and lightweight construction materials that significantly reduce energy use and emissions. Railways can play a critical role in protecting our environment for future generations by ensuring minimal pollution release during transport activities. The research demonstrates the effectiveness of these technologies in promoting sustainable railway systems, providing valuable guidance for future research and policy initiatives aimed at enhancing energy efficiency within the transportation sector.

Indian Railways is one of the world's largest railway networks and contributes significantly to greenhouse gas emissions. However, the application of AI and the Internet of Things (IoT) can help minimize emissions from the railway sector. AI and IoT can be used to optimize railway operations in areas such as scheduling, maintenance and energy consumption. AI algorithms can predict train delays and recommend alternate routes, reducing the time trains spend idling and lowering fuel consumption and emissions. Similarly, IoT sensors can monitor train components and track conditions in real-time, allowing for preventive maintenance and reducing the need for emergency repairs, which can result in delays and emissions. Indian Railways has already incorporated AI and IoT technologies to improve its operations. For example, the "FOIS" (Freight Operations Information System) employs AI to optimize freight train operations and save transit time. Furthermore, the "IR-OneICT" initiative seeks to modernize railway infrastructure through IoT and other digital technologies, such as installing sensors for real-time monitoring of train movements and track conditions.

AI and IoT can help cut emissions from railway-related activities such as electricity usage and trash management, in addition to optimising railway operations. The use of AI and IoT can assist India Railways in lowering its greenhouse gas emissions by optimizing train operations, improving energy efficiency and reducing waste output. As India's rail network expands, adopting these technologies will be critical to making the railway sector more sustainable and ecologically benign. Indian Railways is making enormous efforts to decrease its carbon footprint and move towards a more sustainable or inclusive development. Progress has been made thus far, and it is envisaged that railways will continue to embrace more sustainable practices.

The findings of this study may have many ramifications for researchers, politicians and industry stakeholders. First, the study might emphasize how energy-saving innovations such as regenerative braking and lightweight materials can increase the sustainability and energy efficiency of railway operations. Policymakers could use this information to create and carry out initiatives that encourage the adoption of these technologies in railroad networks.

Second, the study might highlight conflicts between energy efficiency and other operational factors, such as upkeep and capital expenditures. Industry stakeholders could use this information to intelligently decide whether to implement energy-efficient solutions in their operations. Finally, the study may influence future investigations to enhance train system sustainability and energy efficiency.

## 6. Scope for future work

To better understand the possible effects of energy-efficient technologies on railway operations and environmental sustainability, future research in different settings and regions may employ the case study methodology used in this work as a model. The scope for future work in energy-efficient technologies within the realm of rail operations spans various dimensions. The potential transformation of train efficiencies is anticipated through the utilisation of new propulsion systems and the incorporation of artificial intelligence, which are both examples of technological developments. The optimisation of energy usage can be further enhanced by the implementation of infrastructure improvements, such as the integration of intelligent railway systems and the adoption of sustainable design principles. The process of policymaking can effectively provide incentives and establish stringent standards, ensuring widespread compliance throughout the business. In addition, a thorough examination of economic factors, assessments of the entire life cycle and comparisons on a worldwide scale can yield valuable information regarding optimal strategies and opportunities for enhancement. In order to achieve a comprehensive and lasting change in the rail sector, it is crucial to have a deep understanding of public views, foster intermodal synergies and provide the workforce with the necessary skills.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.


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## Conflict of interest

We would like to state that there is no conflict of interest.

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