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Riding the Green Rails: Revolutionising Indian Railways with Renewable Energy

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Abstract

The document focuses on the green initiatives of Indian Railways (IR) to transform into a more sustainable and environment friendly mode of transportation by incorporating renewable energy sources (RES) into its electrification processes. The paper emphasises IR's commitment to achieving Net-Zero Carbon Emissions by 2030 and its strategy to integrate RES, such as solar and wind energy, to power railway electrification. It explores the challenges and potential solutions related to achieving this green initiative, including the use of hybrid microgrids or round-the-clock (RTC) power supply and the adoption of energy-efficient measures in rolling stock design and operations. The document also highlights the importance of collaborative efforts from various stakeholders, to successfully achieve IR's goal of becoming an environmentally sustainable rail transport system by 2030. The paper provides a comprehensive overview of IR's initiatives to reduce carbon emissions and embrace sustainable practices, emphasising the potential of renewable energy sources to transform the railway network into a cleaner, greener, and environmentally sustainable mode of transportation. It underscores the significance of these efforts in reducing carbon emissions, promoting energy efficiency, and contributing to India's broader environmental goals of sustainable development with self-reliance.

Keywords: Indian Railways; Electrification; Renewable Energy; Carbon Emissions; Sustainability / decarbonisation of Indian Railways.

1. Introduction

Indian Railways, with 17 zones and 70 divisions has the 4th largest global network, & provides a vital link across India. It unifies the nation, connecting cultural heritage with a self-reliant future. Urban development and societal cohesion in India rely significantly on nearby railway access.

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The evolution of Indian Railways, from steam engines to high horse powered WAG-12 (*Broad Gauge Locomotive for carrying freight, having 12000HP*), exemplified by the semi-high speed Vande Bharat trains, demonstrates its technological advancements & commitment to growth. Noteworthy feats like the Chenab Bridge & Pamban Bridge highlight its engineering excellence & by providing concessionary travel to the devotees during the Maha Kumbh, it upholds the spiritual baton for the country also. Despite transporting almost 2% of Indian population every day, Indian Railways is steadfast to pioneer modern innovations for safe, efficient, and eco-friendly transport services.

The dependence of IR on fossil fuels to date is quite extensive & if continued, it may have long-term ramifications on public health, economic & ecological sustainability. This substantial carbon footprint of IR is mainly due to its extensive round-the-clock operations of approx. sixty thousand passenger coaches & 3,00,000 wagons (approx.), ever-growing infrastructural constructions (Road Over Bridges, Road Under Bridges, Office complexes, etc.), limited but significant usage of diesel locomotives, electricity consumption by both traction (*Over Head Electricals*) & non-traction (buildings, offices, stations, sheds etc.) activities, and other maintenance activities. As IR is one of the largest users of power in India, its decarbonisation is now a priority, as it would aid in the reduction of carbon emissions of the nation at large [20]. As per the latest figures, IR accounts for approx. 4% of carbon emissions among all modes of transportation [28]. Given the magnitude of its business dimensions along with its inherent Complex Adaptive Systems, IR is pioneering towards a green footprint on the environment and has thereby pledged an ambitious target of achieving Net Zero Carbon Emissions by 2030 [10].

IR is one of the most energy-efficient modes of transportation and already has a considerably smaller carbon footprint than roadways & airways. Indian Railways is the torchbearer to the Nationally Determined Contributions (NDC*) targets of the Government of India in reducing its greenhouse gas (GHG) emissions by 35% [28].

IR is committed to holistically achieve carbon neutrality through the green transformation of its tractive power, and its energy sources & through procurement/manufacturing of energy efficient Rolling stock. It has almost achieved electrification of its Broad Gauge (BG) track, which forms approx. 95% of its entire Route Km, amounting to 60,000 km approx. [7]. With the policy of phasing out diesel engines, induction of high Horsepower (HHP) 3-phase Electric locos (for both freight & passenger traffic), procuring/ manufacturing modern design energy efficient wagons & aerodynamically designed coaches/trainsets, IR is heavily investing in energy-efficient, green, and clean technology [18].

*(*The NDC targets were first set during the United Nations Climate Change Conference held in Paris in 2015.)*

To achieve the niche carbon mitigation strategy and environmentally sustainable development, IR is opting for clean energy options like RES such as solar, wind, RTC power, along with expansion in Hydrogen Fuel Cell (HFC). In the existing scenarios, an approx. 3,500 MW of power is consumed by IR to fuel its traction requirements, which is expected to rise to 7,500-8,000 MW approx., by 2030 [18]. Thus, for IR to become self-reliant in energy security by 2030, it needs sizeable RES installations through integrated analysis & advanced infrastructure planning.

IR, with its mission mode policy initiatives in tandem with the commitment of the Government of India at COP-28 of UNFCC, is taking keen and concerted steps of migrating from fossil fuel to becoming the torchbearer in the transportation industry in India and abroad and evolve as the largest green rail network in the world [21].

Through this research paper, we would learn & understand about the potential RES that can be integrated into railway electrification to achieve environmentally sustainable rail transportation by 2030. We would also assess the extent of Indian Railway's endeavours to reduce its carbon footprint by integrating renewable energy into the electrification of IR and the potential roadblocks that may deter its dedicated journey. Along with the above, we will also discuss the probable solutions that may reinforce the Indian railway's carbon neutral aspirations. Moreover, we would understand the concept of Hybrid Microgrids or RTC power supply (*in IR parlance*) & its significance in achieving sustainable development goals for IR in & our nation at large. This paper would also dwell into the advances made by IR in HFC and its prospects in upholding the determined ideology of IR in achieving Net zero by 2030.

Through this integrated quantitative & qualitative analysis (conducted as part of the review), we would appraise the impact of adopting the renewable energy mode in railway electrification and, thereby, the reduction in carbon emissions, increased efficiency in performance & overall ecological preservation. Further, the paper also discusses the policy & regulatory measures which can be prescribed to incentivise & accelerate this transition to reduce IR's carbon footprint & evolve as the sustainable rail transport solution for India. Further, this paper dives into effective implementation of such policies & means to enforce them to become a carbon-neutral & ecologically sustainable sector.

The document is structured into eight distinct parts. The first part introduces the potential measures IR being considered by IR to ensure a sustainable future by investing into renewable energy. The second part consists of a comprehensive review of all the relevant literature and research works related to the study. The third part consists of the research questions. The fourth part focuses on the methodology and data collection processes. The fifth examines the carbon mitigation strategies of IR, including a thorough analysis of the green transformation initiatives within IR, with a tabulation of some of the successful global initiatives. The sixth part discusses the challenges and constraints that may impact the proposed initiatives of IR. The seventh part presents clear policy recommendations, and the eighth part concludes with a discussion on the potential for future scalability and the long-term vision for IR's sustainable development.

2. Literature Review

a) Awareness and Urgent Need for Climate Action in Transportation

Awareness has been generated by the International Conference on Climate Change w.r.t. reduction & alleviating the ever rise of Green House Gases (GHGs), which is mainly augmented by the transportation sector. This paper highlighted the core thought that there is an urgent requirement to address the climate change problem through various low-carbon alternatives. The paper further discusses about mitigation and adaptation strategies which may aid in curbing carbon emissions & throws valuable insights into enhancing the share of renewable energy sources in railway electrification, which has also been gradually adopted by IR and discussed by the author of the current paper as well, which would enable IR to combat the increasing emissions. The paper also dwells on alternative fuels, but practically, they are not very effective in reducing the carbon footprint of Indian Railways. Furthermore, a lot of other green initiatives undertaken by IR have been discussed, but they may not be the real means to achieve the desirable end of reducing GHG (Green House Gas) emissions from rail transport and seem superficial [28].

This work professes an imperative shift towards an energy revolution, with low-carbon technologies playing a pivotal role, as without a significant change, CO_2 emissions are expected to surge by 2050, leading to economic, environmental, and social issues. Immediate action has been insisted upon. Otherwise, fossil fuel demand would exacerbate energy supply-security concerns. The paper also signifies that the current energy consumption and supply patterns are unsustainable and require a sustainable approach encompassing energy-efficient technology, renewable reproach, and other advanced transport solutions to reduce GHG emissions. An imperative need to develop a technology roadmap to expedite the adoption of transformative technologies, guiding governments, industry, and financial institutions toward informed decisions, has also been underscored. Further, the awareness & urgent need for hydrogen and fuel cell technologies to aid in climate change mitigation and energy security across various sectors, including transport and power generation sectors, has been pointed out. Continued government support through R&D funding as essential for advancing hydrogen generation has also been emphasised [35].

b) Electrification and Renewable Energy Strategies for Decarbonization

Another literature on Climate Policy Initiatives deliberates the necessity of electrification by decarbonisation efforts; since an electrified rail network can more readily shift to clean energy options like solar and wind power. It emphasises the shift towards clean energy options, such as solar and wind power, and discusses the potential for renewables to generate a significant portion of power for Indian Railways. The exploration of cost-effective maintenance and life cycle benefits of renewable sources are also featured, along with the proposed strategies for decarbonising the railways. Various pathways are provided as options by the authors [20] to help decarbonise IR keeping in view the future trends of demand of freight traffic and supply side of energy usage, which seem feasible and are being designed by IR as part of its carbon mitigation strategy.

This paper introduces a novel approach to harnessing clean energy from a moving train, capitalising on wind, solar, and the conversion of human waste. Unlike traditional wind power, the paper discusses the unique train-generated wind method, utilising the vacuum created by the train's movement to produce electricity. Solar energy is proposed to be harnessed by integrating solar cells into the train's roof, optimising space usage. Lastly, it also discusses transformation of human waste to power fuel cells. The paper emphasises the importance of renewable energy, waste-to-energy conversion, and the use of solar panels and wind turbines. It highlights the need for energy conservation and the development of new energy sources. The concept of trains' self-generating electricity is both innovative and sustainable, offering a promising alternative to traditional energy production [31].

c) Advantages of Clean Energy Fuels and Future Outlook

There is a significant increase in freight traffic demand, leading to higher oil usage and air pollution. This is so because transport development has strong correlations with the development of society and carbon emissions. The points brought out by the authors are very pertinent and need urgent answers. The paper convinces the reader of the pressing need to transform our policies so that our transportation segment becomes carbon-neutral. The paper's approach is to highlight the dual objective of the transportation sector, which is to achieve sustainable development and carbon mitigation, which can be achieved through advanced technologies. However, the paper does not show the pathway to achieve this mammoth-sized objective, and that too in a short span of 6-10 years [14].

Additionally, the benefits of clean energy fuels like solar, wind, and geothermal sources are explored, along with insights on studies and experiments showcasing the benefits of green energy sources in railway electrification, such as job creation, better quality of life, less air pollution, etc. The paper gives insights into practical studies and cases in various countries like Italy & India, & the saving of diesel and CO_2 emissions. This paper gave me an understanding that once favourable models of green energy sources are proliferated in IR as the primary source of electricity, IR will become the self-generating, self-sustaining, economically favourable, and excellent model of electrification in transportation in the world [4].

The paper by authors [24] also touches upon the future projections and transformative potential of renewable energy solutions in railways, offering a glimpse of a greener and more sustainable railway systems, which could be a watershed for Railway transportation across the world. This paper is very insightful and a must-read for policymakers; planning to weave renewable energy solutions into the Railways' operations, as this paper provides perspectives of both sides of the coin, i.e., both its advantages and disadvantages. Moreover, it also dwells into the aspects of how to harness these advantages to achieve an environmentally sustainable Railway system.

d) A step towards Hydrogen Trains

As Indian Railways progresses on its path towards a carbon-neutral future, global advancements in hydrogen-powered trains may offer valuable lessons for IR. The growing international momentum behind hydrogen rail solutions; especially in countries like Germany, the UK, and China could educate India, for charting its own journey towards cleaner & more sustainable rail operations. This paper provides a comprehensive overview of the global hydrogen train landscape, offering key takeaways for Indian policymakers and industry stakeholders [6].

One of the strongest aspects of the paper is its wide-ranging international analysis. For instance, insights from Germany's Alstom's Coradia iLint experience demonstrates how hydrogen trains perform in real-world conditions [6]. These insights are directly relevant as India is also considering similar pilots, especially on non-electrified, hilly routes or in regions where electrification is economically unfeasible. While the paper discusses the technology and its environmental benefits, it lacks any mention towards cost-related aspects. For India, cost is one of the key decision-making factors. How would hydrogen train compare financially to diesel or electric alternatives & what would be the capital and operational costs for establishing the hydrogen production, storage, and refueling infrastructure across even a single corridor need clear answers.

Despite some shortcomings, the paper serves as a valuable introduction to hydrogen rail technology and highlights its global progress. It is well-structured, informative, and balanced in its analysis. The major take-away for IR shall be the build on its foundation with region-specific research, cost modelling etc and formulate road maps for self- sustaining pilot projects tailored to our unique operational environment.

Mare J. Prins in her research investigates the social and institutional acceptance of hydrogen-powered trains, with a focus on the Dutch and broader European context. The paper highlights that while hydrogen fuel technology is maturing—evidenced by successful rollouts like Alstom's Coradia iLint operating in Germany since 2018-public trust and regulatory readiness are just as vital as technical innovation for broader adoption [32].

Prins explores key concerns raised by stakeholders in the Netherlands, such as safety aspects involved in handling hydrogen, reliability of its supply chains, and the importance of government involvement in infrastructure funding. Her findings show that the transition to green hydrogen in transport requires not only engineering solutions but also coordinated policy frameworks and public engagement.

This perspective is particularly relevant in the Indian context, where Indian Railways operates over 67,000 route km, and there still exists remote & mountainous terrains which non-electrified & might hugely benefit from the use of green hydrogen technology. While prototypes being developed by Indian Railways are in early stages, public awareness, trust, and policy support remain critical for scaling such efforts. Prins' work reminds us that successful implementation in India must address both technological feasibility and the human side of clean energy adoption.

Hydrogen technology is a symbol of innovation and progress & stand poised to be the transformative breakthrough for IR towards its journey for a greener & more sustainable railway network, especially when seamlessly woven into our renewable energy vision and infrastructure aspirations.

3. Research questions

The Main research question:

What is the proposed action plan devised/adopted by Indian Railways to achieve net-zero carbon emissions by 2030?

Sub-Research Questions:

1) How is Indian Railways planning to integrate renewable energy sources into its electrification processes?

2) What are the challenges and potential solutions related to Indian Railways' green initiatives?

3) What are the ongoing and proposed policies designed to facilitate the attainment of the stated target of environmentally sustainable rail transport through electrification using renewable energy sources within the Indian Railways system?

4. Methodology & Data

The study is based primarily on secondary sources of data. Multiple papers, journals, manuals, and newspaper articles have been consulted to gather the information required for this study. The main source for the data and figures has been taken from the Annual Reports of IR on Environment Sustainability on Net Zero Goals, along with IR's websites.

Additionally, to understand the ongoing policies in IR, to boost Renewable energy & to study future to augment the percentage of Renewable energy in railway electrification, senior/retired officers from IR have been consulted. Quantitative Data (facts/ figures, etc.) such as current prerequisites and future infrastructural/ technological infusions required have been studied and accumulated from multiple sources, such as the relevant papers, journals, etc., and incorporated in this concerned document to analyse the main topic of the research paper. Further, data has been accumulated from various secondary sources and incorporated to ascertain the electrification dynamics in IR through various Renewable energy sources.

Primarily, the methodology has been to explore the extent to which Indian Railways is making progress towards its target by analyzing all the current data and planned programs, both in quantitative & qualitative manners, to gauge their effectiveness in achieving its goal of becoming carbon neutral mode of transportation by 2030.

Apart from the above, the paper also discusses the shortcomings in the intended plan and methodologies, & steady renewable approach formulated to overcome them through deeper policy interventions at the ministerial level & public institutions.

5. Policy Assessment for transforming Rail Transportation towards a Path of Green and Sustainable Future

5.1. Carbon Mitigation strategy of IR: - A detailed analysis

Since independence, upgradation of Railway infrastructure has promoted socio- economic growth in India & fosters holistic development of the nation towards a modern society. However, to combat pollution caused by carbon emissions, innovative solutions need to be formulated & implemented. For IR to be a world-class railway network, it is required to provide a world-class travel experience, following stringent safety norms & at the same time, ensuring carbon neutrality.

To achieve decarbonisation of IR, & accomplish Net zero Emissions, IR has formulated a comprehensive strategic plan as under [16]:

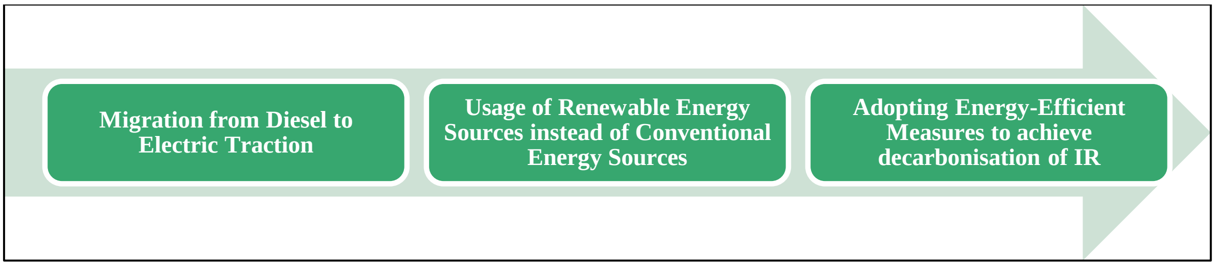

Figure 1: Strategic Plan of IR to achieve Net zero by 2030.

5.1.1. Migration from Diesel to Electric Traction: Green transformation of tractive Power

The mass transporter of the country, IR has a great opportunity to grow and successfully meet the aspirations of its citizens in both the freight and passenger segments by implementing a well-designed mission of 100% electrification policy. This migration would be a game-changer for the country, as this master plan would outshine the high-carbon path that other railway networks have previously followed.

IR is spread over 67,000 Route Km, of which more than 65,000 Route Kms are Broad Gauge (BG). As a primary condition to become a green railway, IR has majorly electrified its BG (90% approx.) by Dec'23 [7] & marching strong towards completing its entire network. Electrification of the tractive power is an efficacious approach, as it is energy efficient & emits lower GHGs than running on diesel locos on High-Speed Diesel (HSD). Not just the air quality but the entire ecosystem improves with the use of electrical power over diesel traction for railway operations. With the introduction of trainsets in IR in 2019, designed with a composite integrated system using Train Control Management system (TCMS), drawing power from Head on generation (HOG) based technology; the dependence of passenger traffic on diesel locomotives has substantially reduced & is expected to become negligible with their proliferation. The upgradation of rolling stock from Integral Coach Factory (ICF) passenger coaches to Linke Hofmann Busch (LHB) coaches to trainsets, which run only on electrified routes, is a giant leap by IR towards providing sustainable & energy efficient rolling stock, which promotes cleaner energy.

However, despite electrification initiatives, the usage of HSD for track machines, generators, and the remainder diesel locos for shunting, breakdown activities, etc., have consumed approx. 11.75 Lakh KL of HSD in 2020-21, emitting the whole range of GHGs [18].

Thus, to achieve complete carbon neutrality & sustainable environmental management, the power plants feeding the electric traction sub-stations, supplying electrical power to Over Head Electricals (OHE), would have to be replaced with RES instead of fossil fuel-fired plants.

5.1.2. Usage of Renewable Energy Sources instead of Conventional Energy Sources

Globally, economies are working towards tapping RES with the main objective of reducing carbon emissions. As per a generic definition of renewable sources, these are energy sources derived from inexhaustible natural resources like sunlight & wind, and while extracting power from these sources, they do not emit greenhouse gases.

To honor its commitment to the Net zero goals, IR plans to source its 100% power requirement from RES & have only 10% of its requirement as a backup from conventional energy Sources. This substantial use of RES would have a positive impact on ecology as well as on the users through cleaner air & better quality of life.

For an organisation which is more than 150 years old, having a widespread & diverse gamut of activities consuming electricity. Thus, clean energy options like solar and wind could have a huge relevance in IR. RES is not only effective in producing usable units of energy, but every unit produced is also carbon neutral. A SWOT analysis is also presented in the paper to appreciate the advantages of Renewable Energy Sources over their conventional counterparts & how to strategise to overcome their weaknesses. Further, the below mentioned SWOT analysis also presents the opportunities that lie ahead with the usage of Renewable energy sources & the perceivable threats which would require mitigation through collaborative efforts & integrated policy interventions.

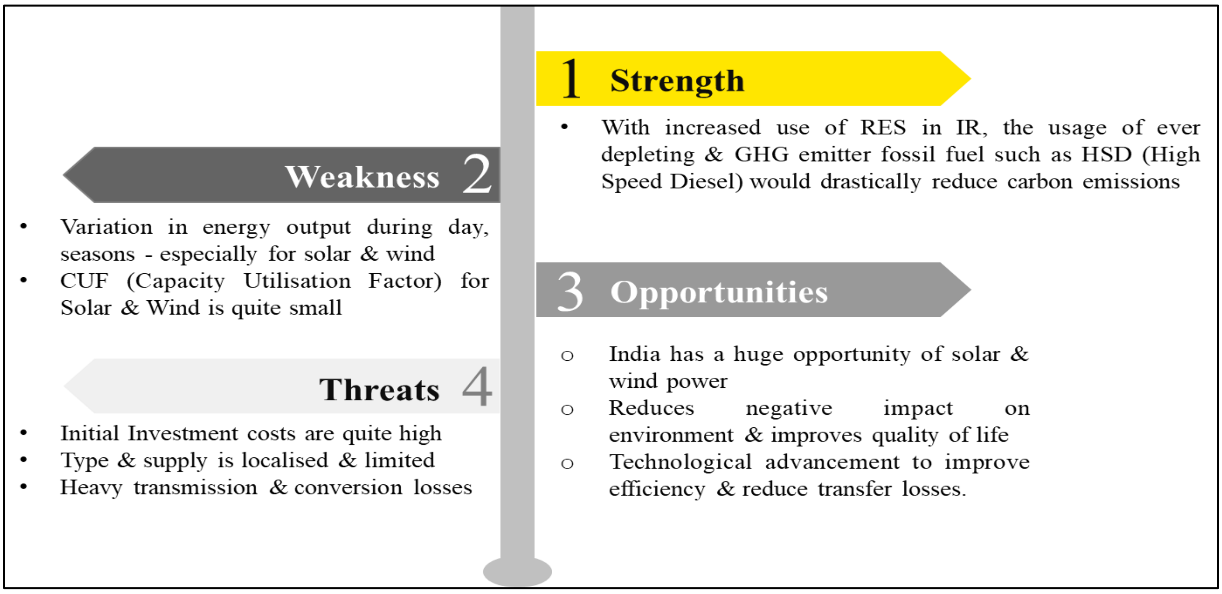

Figure 2: SWOT Analysis of Renewable Sources in IR

5.1.2.1. Types of RES which can/are being used by IR Electrification to mitigate the Carbon crisis

a) ***Solar Energy***

To have a positive ecological footprint of Railways & their ancillary activities, including electrification of its infrastructure, such as platforms, sheds, office buildings, etc., Solar Energy is one of the most promising & best available options for IR, among other renewable energy sources. In a country where a high percentage of its geographical area lies within the Tropic of Cancer & Equator, the incidence of sunlight is quite good compared to its other neighbouring nations. This huge Solar potential is the driver to attain RE-powered electrification for IR [5].

In the current scenario, the dynamic energy requirement of IR is approx. 3500 MW p.a., and solar's contribution to providing this quantum of power is still developing. It is pertinent to understand that solar energy has a Capacity utilisation factor (CUF) of only 20%, i.e., with every 100 MW installed, the output is only 20 MW or one-fifth of the installed capacity [18].

As per data, approx. 200 MW of Solar power has been commissioned in IR (in energy terms) [18], as per the given break up as under:

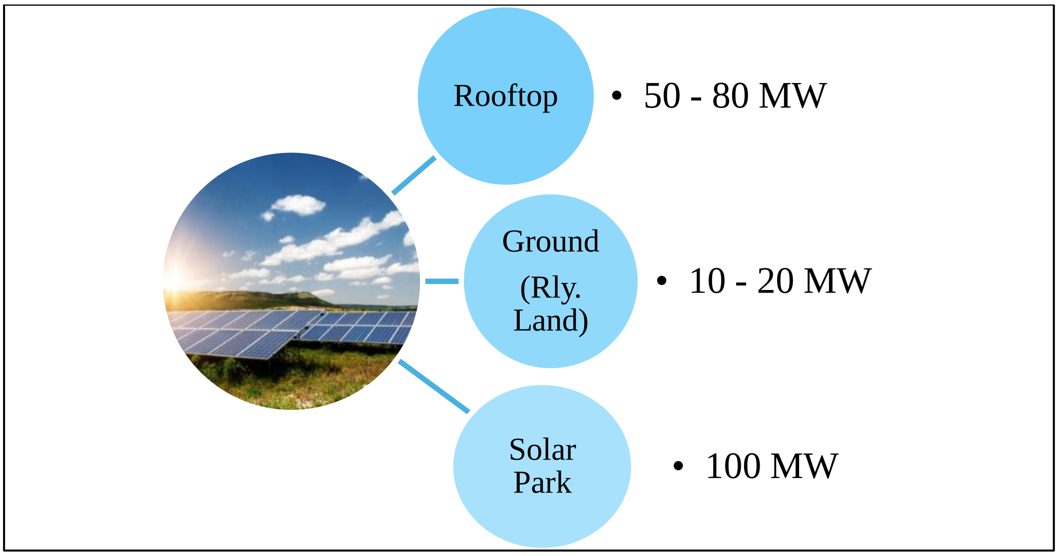

Figure 3: Solar Energy Supplied to IR, in energy terms

Further, to address its need for non-traction electricity, IR has been steadily mounting solar panels on the roofs of its numerous stations and service buildings. Some initiatives by IR are elaborated as under: -

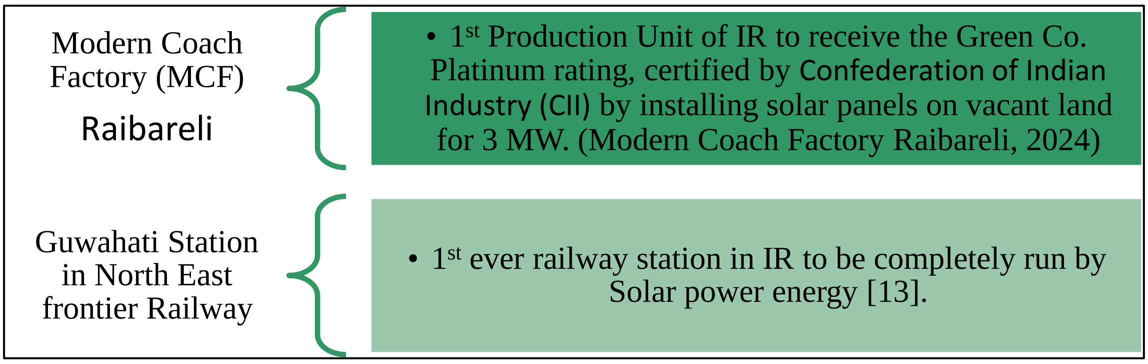

Figure 4: Green initiatives by IR

In fact, solar panels have been installed on the rooftops of over 1000 stations, and approx. 2500 more stations, including service buildings, are under the planning stage. To proliferate the use of Solar power, IR has also planned to gainfully utilise its vacant lands running across tracks (measuring approx. 50,000 hectares) for powering railway tractive activities.

Solar energy has distinctive benefits viz-viz its other renewable energy cousins, such as wind or hydropower. For instance, it can be easily installed on the tops of IR buildings, platforms, parcel sheds, etc, or along the rail tracks or even between two railway tracks (at a given inclination); it does not have rotatory parts, like wind or hydro turbines [24]. However, as discussed earlier, the CUF of solar energy is only 20% & as its scattered installation could be a hindrance in its maintenance & may also lead to transmission/conversion losses etc.

IR is already under planning stage to invest in ambitious Solar farm projects to extract higher energy outputs. These Solar farms, for instance, the Rewa Ultra Mega Solar farm, have various advantages over the scattered/piecemeal installation of Solar Photovoltaic panels [34].This enables an effortless integration (along with upkeep) with the Railway substation grid in a far less tedious manner. Moreover, due to the availability of vast pockets of agri/wastelands, these solar farms can be installed in rural areas as well, giving a source of livelihood to the native inhabitants.

b) Wind Power

Apart from Solar, IR has also invested in wind power, wherein a Power Purchase agreement has been signed in 2023 for wind power amounting to 50 MW, with a CUF of 25%. With the ever-expanding prospects of rail transport, the demand for installation of Wind capacity is also increasing.

Further, being the 4th in the world in terms of the production of Wind power, especially due to its peninsular geography (i.e., the long cost line), the future of wind generative power in India, on both on-shore & off-shore, is very promising. IR has already achieved 50%. of its target of approx. 200MW, as 100 MW of wind-powered power plants have already been put into service under wind energy [13]. A detailed break-up of the installed capacity of wind power by IR is as under:

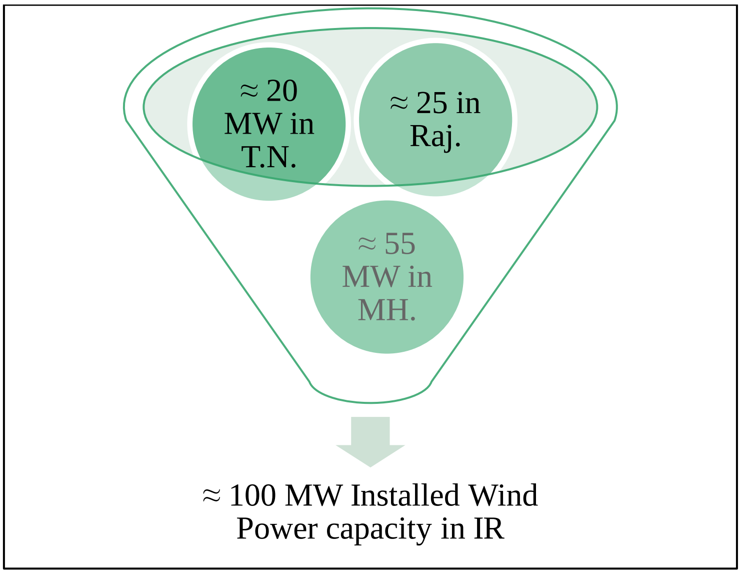

Figure 5: Break-up of the installed capacity of wind power by IR

The railway land across the tracks (especially in coastal areas) can be effectively used to harness the wind power & transmit it through centralised cable networks, which when connected to the substations; can be utilised to power the railway establishments including station buildings. However, as the percentage fluctuations are high & generation of power is erratic, investments in wind power have not been very substantial in IR.

c) ***RTC power***

Before moving any further with provisioning of electrification of IR through RE sources, it is prudent to appreciate that IR's tractive demands are generally flat, i.e. its daily or yearly requirements have minor/nil variations. Such an arrangement can only be achieved if the power supply is round the clock, i.e., without any peaks or troughs. These RTC power systems (also known as Hybrid Micro Grids in technical parlance) are intricately designed power sources where both renewable & conventional sources are integrated to provide clean energy to the end user in an effective & efficient manner.

The RTC power systems were introduced in IR in 2022 and have mainly 3 essential components:

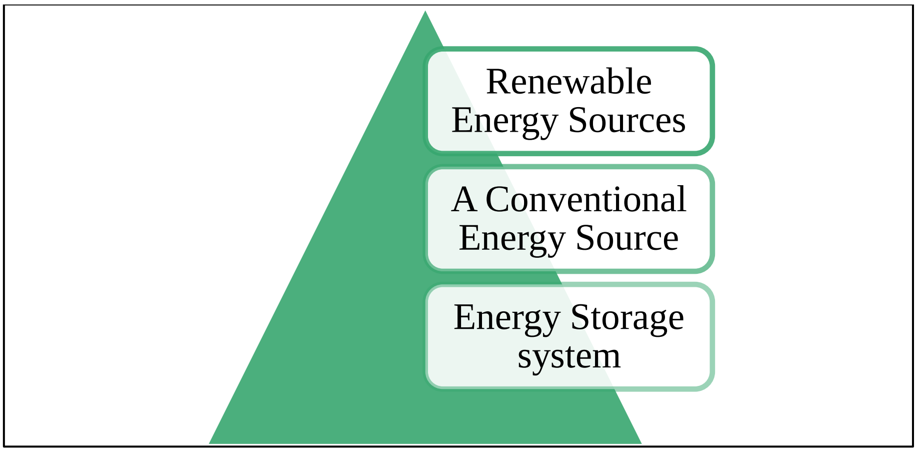

Figure 6: The Constituents of RTC

The cocktail mix of the various RE sources largely depends on the availability of RES at that location, be it solar, wind, hydro, etc. The conventional sources are weaved with the RE sources to cater to any emergency that falls out of the RE sources or when demand exceeds the power supply capacity by RE Sources.

The 3rd and one of the most crucial elements of the RTC is the Energy Storage system, which stores up the excess energy generated by the RES when the supply is more than the demand, for instance, storing solar energy during peak summer seasons or wind energy during monsoon seasons, etc. This Storage system acts as a key player in the RTC power system by providing an un-interrupted clean power to railway tractive or non-tractive activities, even when the power supply through RES is not generating sufficient energy, such as during cold winter months or seasons with no winds [24].

IR has already invested in RE power through RTC for 1000MW, for which the power flow is expected to commence by end of 2025. Another 1500 MW is under the planning stage. IR, being committed to the Net Zero Goals, has already planned to expand the RTC installations up to 7 times approx. extensively by 2026-27 so that all the plants are operational by 2029-2030, generating nothing but clean, carbon-free fuel with nil or minimal carbon emissions [18].

RTC power supply is the new age engineering marvel, which, when utilised gainfully, is the perfect harbinger to boost the ecological sustainability of IR. RTC power supply system beautifully addresses the intermittent and unpredictable nature of RE power, i.e. solar, wind, etc. Further, it fully aids in utilising the transmission corridor & most importantly, weaves the already available RE & Storage power into a mesh, designed to provide maximum output. The Energy demand of IR (both non-tractive & tractive activities) is expected to be above 8000 MW by 2029-30, & out of this, approx. 7500 MW is expected to be powered by Renewable energy sources & the rest (about 700 MW approx.) is expected to be extracted from the ongoing Power purchase agreement from IR's partly owned thermal plant.

Following the current planning & initiatives being undertaken by IR, a trend analysis has been generated to depict the reduction in the usage of conventional sources of energy & the gradual increase in the percentage share of renewable sources over the years, shown as under:

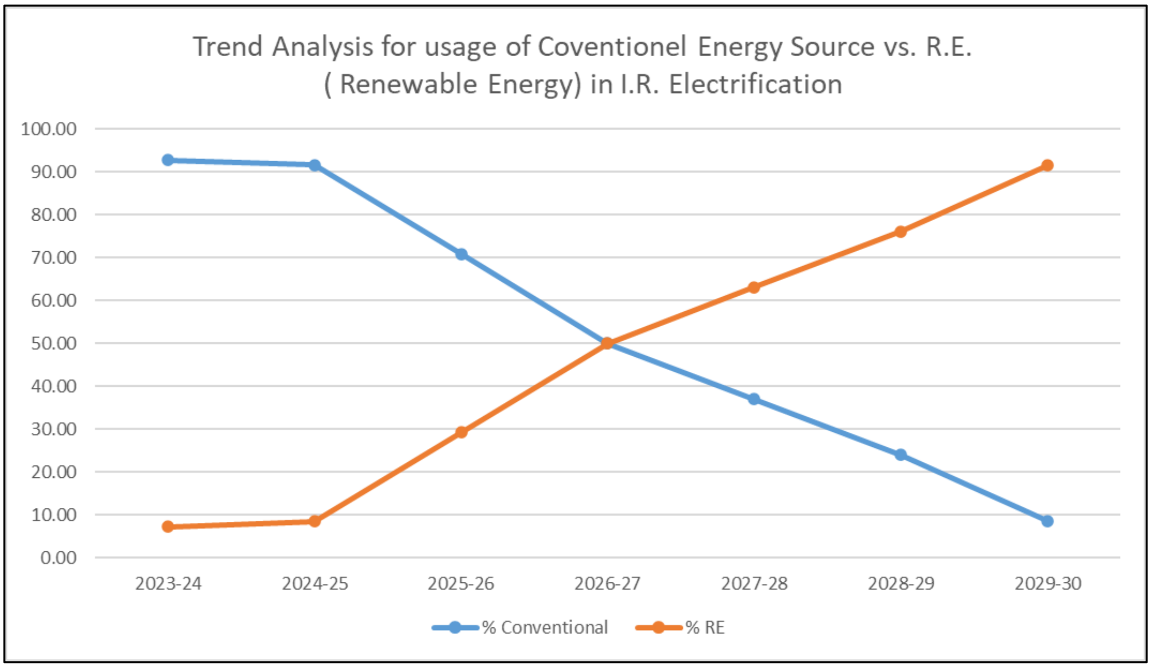

Figure 7: Trend Analysis in IR electrification,

Source - [18]

5.1.2.2. Successful Global Energy Initiatives

To appreciate the feasibility of renewable energy sources, examples of established world railways have been incorporated in the table below. These railways have outstandingly integrated the various types of renewable energy sources in their railway operations for both traction and non-tractive activities & demonstrate the feasibility of adopting these renewable energy initiatives. The types of Renewable energy are being used range from Solar to Geo-thermal & Hydro to Electric Hydrogen.

Table I: Examples of Integration of Renewable Energy by World Railways,

S.No.	Country	Type of Operations	Type of Renewable Energy	In Service Since
1	Japan	Passenger trains & stations	Solar, Geo-thermal, Hydro, Wind	2022
2	Netherlands	Passenger trains	Wind	2017
3	Germany	Non - tractive activities	Solar	2021
4	France	Passenger trains	Hydrogen	2021
5	Sweden	Tractive	Hydropower	Early 20th Century
6	Switzerland	Tractive	Hydropower	-

Source – [36,11], [8 &27].

Apart from above examples, Poland is also accelerating its transition from fossil fuel to low carbon emitting technologies & promoting development of RES such as wind & solar energy. Poland is expected to achieve 50% of its requirement by 2050 [36].

Further, Austria serves as an example of a country where trains are powered entirely by renewable energy. The traction electricity is primarily sourced from hydropower, supplemented by solar energy. This renewable energy is fed directly into the railway overhead lines, minimizing the need for additional electrical infrastructure. Additionally, some trains are directly powered by wind energy, which significantly reduces energy losses [36].

5.1.3. Adopting Energy-Efficient Measures to achieve decarbonisation of IR

For IR to become a carbon-neutral transporter by 2030 is a mammoth task & thus, single point solution of adopting Railway electrification through RES and RTC power supply, though essential, would not be sufficient. This is so because with current economic development, improved power supply, & inclusive growth, the demand for rail is ever growing.

Thus, it is imperative for policymakers to appreciate the fact that IR would need a multi-pronged strategy to become Net zero. IR has already realized this standpoint and committed to be an energy-efficient transport carrier by using state of the art design & fuel-efficient Rolling stock.

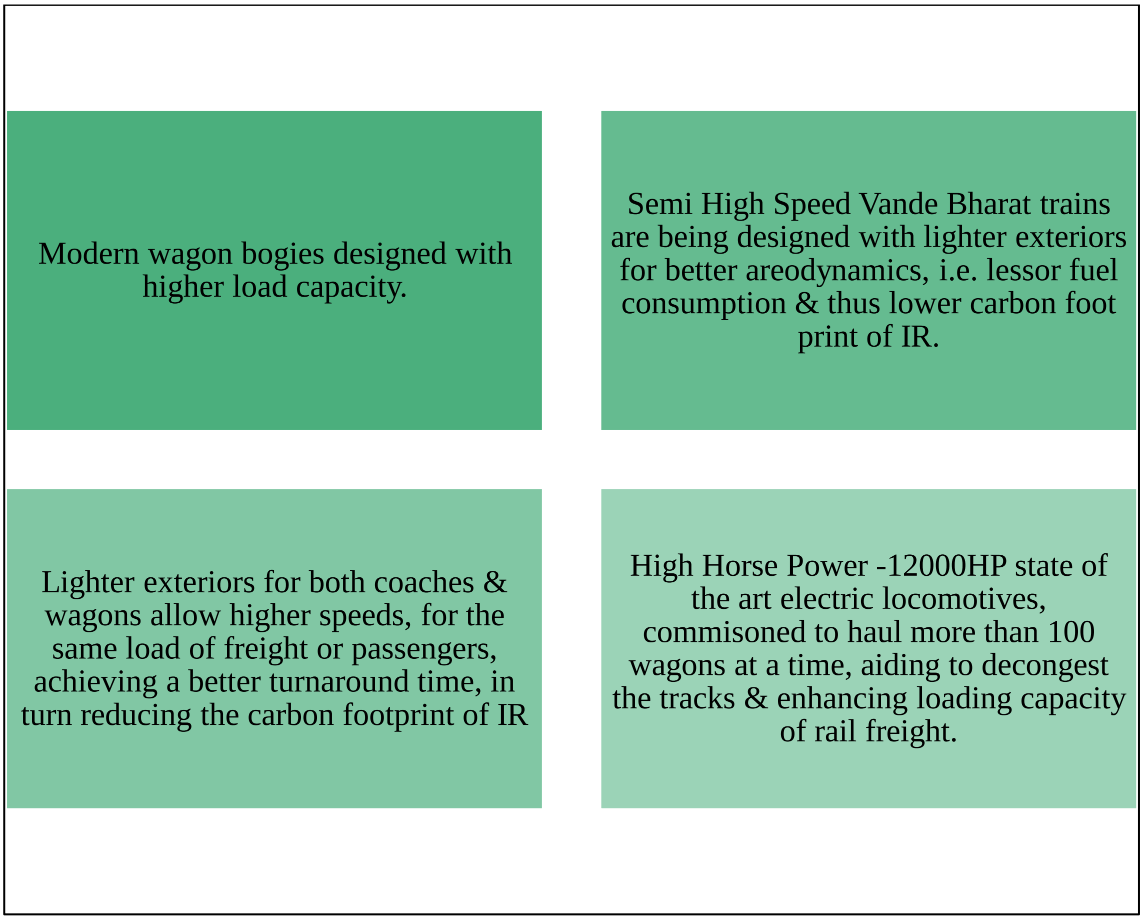

Figure 8: Examples of Fuel-efficient Modern Design Initiatives by IR

Additionally, IR has not only shifted from Diesel to electric locomotives but also dedicatedly working on the energy-efficient HOG (Head on Generation) technology, especially for its LHB coaches [26], by converting the 25KV of power from the OHE to the 750 Volts of power to the coaches, with the help of a converter. By using this HOG technology, electricity for the coaches is directed from the overhead wires, majorly reducing transmission losses. This power is then distributed to all the coaches, for providing electricity to other equipment such as train lighting, air conditioning, etc. With the intensification of HOG technology, IR has saved more than 500M tons of HSD fuel since 2018-19 resulting in reduction of GHG emission & a having a greener footprint [17].

Along with adoption of HOG technology, regenerative braking systems, is also an emphatic step towards carbon neutrality. Regenerative braking plays a vital role in enhancing energy efficiency and promoting sustainability in railway systems. By converting kinetic energy into electrical energy during braking, it significantly reduces energy consumption that would otherwise be wasted as heat. This recovered energy can be fed back into the power grid or stored for later use, lowering overall power demand. Additionally, regenerative braking reduces reliance on mechanical brake systems, minimizing wear and tear and cutting maintenance costs. Its integration into modern locomotives, such as India's Vande Bharat trains, contributes to a more sustainable and environmentally friendly transportation network by conserving energy and reducing emissions.

To augment its green initiatives holistically, IR, in collaboration with CII, is working towards Green Industrial Units & buildings, such that more than 50 Workshops & Production Units & 20 Railway establishments have been certified with Platinum/Gold or Silver ratings depending upon their energy conservation practices having a direct impact on the quantum of emissions. Moreover, energy demand optimisation is being achieved by performing energy audits, green building certifications for offices & station buildings, implementing smart metering, installing 100% LED lighting and high-star appliances, blending Bio-fuel with HSD, increased pace of production of electric locomotives, utilising performance-based contracting to produce high-powered locomotives etc.

Indian Railways is a championing the cause of carbon neutrality to become Net zero by 2030 by following the dedicated path of strategies (as discussed above), to reduce its carbon footprint & transform into a sustainable transporter. To appreciate these green initiatives of IR towards its decarbonisation, it is important to understand that, the latest figures of CO_2 emissions, which stand at approx. 30 MT could have doubled if business as usual was to be followed utilizing only fossil fuel-powered electrical supplies.

With these actively planned interventions by IR, the CO_2 emissions in 2029-30 are bound to come down by 5 times in comparison to their current levels; as shown in the chart below:

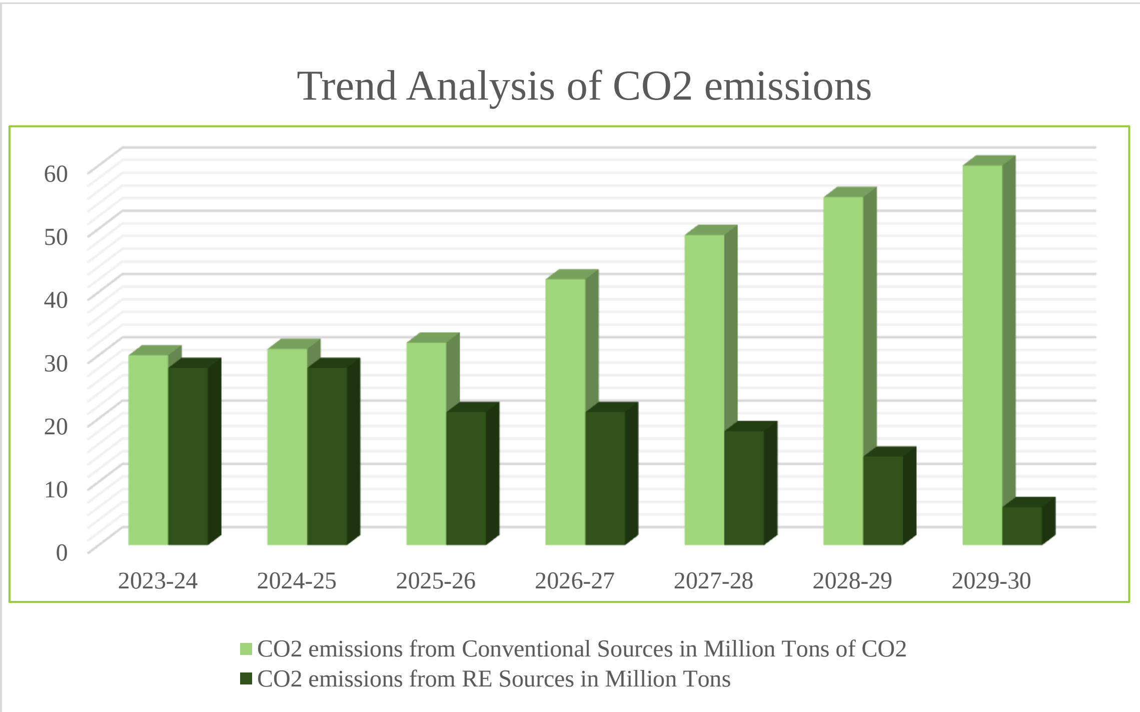

Figure 9: Trend Analysis of Reduction in CO_2 by 2029-30, due to increased usage of Renewable Energy. Source - [18].

6. Challenges & Limitations

IR is taking every step possible to achieve its committed target of achieving Net zero carbon emissions by 2030. However, the planned mix of renewable energy through various sources, RTC power systems & even by introduction of HFC technology in rail transport is a gateway to environmental sustainability, but has multiple challenges.

First & foremost, the switch over from conventional to RES is highly cost intensive. That is, the assessed cost of installation of the proposed transition from thermal to Renewable Energy is indeed very high, in contrast to other alternatives. Even though the life cycle cost of a Solar powered plant/park is less, given its long-term environmental benefits, but the initial or upfront capital investment cost is quite high. A cumulative investment of approx. of more than a 1000 billion in INR would be required from the budgetary outlay over the next 5-6 years to transform the carbon neutral goals into the required physical infrastructure, detailed by the tabulation as under:

Table-II: Cumulative Investment required by IR by 2030 to become Net Zero by 2030

<table>
<tr><th colspan="7">Cumulative Investment required for Energy Mix of Renewable Energy by 2030
(approx. figures)</th></tr>
<tr><th>Phase</th><th>Year</th><th>Thermal</th><th>RTC</th><th>Wind</th><th>Solar</th><th>Cumulative Investment in INR Crores.</th></tr>
<tr><td rowspan="2">I</td><td>2023-24</td><td>93%</td><td rowspan="2">3%</td><td rowspan="2">1%</td><td>3%</td><td>6,000</td></tr>
<tr><td>2024-25</td><td>92%</td><td>5%</td><td>8,000</td></tr>
<tr><td rowspan="3">II</td><td>2025-26</td><td rowspan="3">40%</td><td rowspan="3">50% - 60%</td><td rowspan="5">< 1%</td><td rowspan="5">5%-6%</td><td rowspan="3">90,000</td></tr>
<tr><td>2026-27</td></tr>
<tr><td>2027-28</td></tr>
<tr><td rowspan="2">III</td><td>2028-29</td><td rowspan="2">< 8%-10%</td><td rowspan="2">85%-90%</td><td rowspan="2">1,50,000</td></tr>
<tr><td>2029-30</td></tr>
</table>

Another challenge of integrating RES as a sustainable solution is its variability & intermittent supply. Location & geography plays a pivotal role in the availability & efficacy of the energy supply, making Solar and wind energy as inherently intermittent, making it very challenging to maintain a consistent and reliable power supply. For instance, extreme weathers lead to reduced or erratic power supply which directly impact safe running of trains. Such variations in renewable energy generation may disrupt the required voltage balance, & have the potential to compromise the stability of existing power grid systems.

Moreover, there remains various technological barriers which hinder the large-scale adoption of RES. These roadblocks reduce system reliability & stunt the pace of building & operating the required solar farm, storage facilities & grid integration etc.

Further, these plants or technological infrastructures take approx. 2-3 years on the planning & construction front and another 4-6 months to be commissioned & operationalised. Thus, have a long gestation period & require intervention at multiple levels.

Integrating renewable energy into railway infrastructure is a key measure in advancing environmental sustainability goals. This transformation not only reduces dependence on fossil fuels but would also aid Railway to reap the long-term economic and environmental benefits. Unlocking these gains requires sound management practices and thoughtful policy design. The role of governments and public bodies is critical in driving this transition forward. Establishing strong governance structures is essential to foster public confidence and ensure the effective implementation of renewable energy solutions. To achieve this transition in a time bound manner, at this massive scale, IR has formulated a very judicious and detailed strategy to achieve its ambitious target.

7. Policy Recommendations

IR aims to become Net Zero by 2030 & thereafter aims to sustain its decarbonisation through the following short-term, medium-term & long-term goals, which are discussed as under:

Short Term Goal: Deployment of this multi-pronged strategy of Energy efficient systems, Renewable Energy amalgamated with green, fuel-efficient technology, is the key to transform IR into an Environmentally sustainable transport carrier soon. Moreover, to cleanse the power supply sources through green technology like RTC power systems, is the most judicious approach to augment this evolution of power requirements in IR while ensuring sustainability. is. However, even the RTC power supply system has at least a 10%-15% mix of conventional energy sources like thermal power (which are still fossil fuel dependent) and given the quantum of power requirement of IR, even this 10%-15% burning of fossil fuel would cause sizeable greenhouse gas emissions.

Medium Term Goal: IR has taken another significant step towards reducing its carbon footprint by investing into indigenised R&D to use hydrogen- *the cleanest fuel*, to power its Rolling Stock in the next 3-5 years (medium-term goal). A hydrogen Fuel cell is a device in which Hydrogen is used to generate electricity through a chemical reaction in the presence of oxygen with water as the by-product. IR has already launched in a pilot project for HFC (Hydrogen Fuel Cell) by converting/retrofitting a 1200 HP Diesel Electric Multiple Unit (DEMU) (*a diesel engine that drives an electrical generator or an alternator which produces electrical energy*) rake, on a route of approx. 90 kms, capable of being attaining a max. speed of approx. 100 km/h, with a passenger capacity of more than 2500 [12]

Field trials of the prototype are also being undertaken. This hydrogen-powered train, has been manufactured by the ICF in Chennai, establishing a new global benchmark in railway technology. In comparison to European hydrogen trains, which are generally limited to a power output of 500–600 horsepower, the Indian model delivers an exceptional a 1,200 horsepower, making it the top-notch Hydrogen fueled train in the world [12]. Further, IR envisages manufacturing trainsets with fuel cell-based propulsion systems to provide traction energy from HFC. Moreover, IR is also planning to commence the "Hydrogen for Heritage" policy, wherein approx. 30-35 heritage & hill route train-set rakes for narrow and Meter gauges are proposed to be run on HFC technology along with due development of the ground infrastructure. Even though the current cost of running these Hydrogen trainsets is expected to be much higher than the other Renewable energy sources, it is expected to come down with series production.

This safe and sustained use of HFC technology in train operations has far-reaching benefits, such as reduced dependence on fossil fuel, zero GHG emissions and thereby promoting a sustainable rail transport for India.

Long-Term Goal: In the long run, IR may also dwell into carbon capture or sequester to offset any future or unpredicted emissions and remain carbon neutral or even carbon negative. Lastly, IR may also set a long-term goal of introducing carbon emission standards for its designated rolling stock, very much like the practice prevalent in the European Union for commercial vehicles, to monitor the overall CO_2 emissions per rolling stock rake [30] IR could also focus on green financing so that the captive generation of RE technologies can be utilized and adopted at an economical rate. Further, IR could also plan to invest in carbon credit options to incentivize efforts of the industry & the government alike in areas of carbon emission reductions.

India is certain to realize its vision of 'Viksit Bharat;' a developed India by 2047 & achieving Net zero emissions in IR by 2030, would be a milestone towards this journey. It is understandable that many policy prescriptions may be innovative approaches & might require long term sustained efforts, but with this continued commitment of IR, it would emerge as the new architect of the developed & modern India. Intelligent policies with collaborative effort from all the stakeholders would be a mantra for IR to achieve a sustainable tomorrow.

8. Conclusion

In pursuit of becoming a global leader in sustainable rail transportation, IR under the Paris Agreement 2015 has pledged to progressively phase out the use of greenhouse gas (GHG) emitting fossil fuels and transition towards the adoption of renewable and environmentally sustainable energy sources. The 4th largest railway network in the world is dedicated to the country's vision of increasing its percentage share of Renewable energy from 10% to 100% in tractive power in the current decade [28].

The 1st phase target of IR's Green initiative is almost on the verge of completion, with less than 5% electrification remaining for its Broad-Gauge network [23]. For the 2nd phase target set by IR is to increase and stabilize the percentage of renewable energy in Railway Electrification [23], so that the overall emissions of Greenhouse gases are reduced from the rail transport sector in India & Railways attain a green carbon footprint.

Currently IR along with other modes of transportation account for a consumption of approx. 50% of total conventional fuel in India. But despite the mammoth size of fleet of locomotives, IR emits less than 5% of the total GHGs emitted by the other modes. Thus gives IR a relative advantage & a head start to promote movement of more passenger & freight by rail. A policy shift to switch over to rail transport would be the key for India to attain its environment sustainability goals.

Through this technical paper we glanced through the measures being undertaken or initiated by the transportation system which holds the position of being the nerve-center of the country. To uphold the commitment of the nation in reducing carbon emissions by 33%, IR has pledged to become a sustainable transport carrier by decarbonising itself by 2030. Railways has initiated its journey towards cutting down its carbon emissions by investing into a varied mix of Renewable Energy sources that are being used to source its tractive and non-tractive demands.

With approximately 3,500 MW of additional capacity under process, IR currently has an installed capacity of approx. 200 MW of renewable energy [16]. To achieve the goal of 100% decarbonisation of Railways by 2030, IR is extensively working on a broad mix of Solar, wind energies in the form of Hybrid Smart grid models connected to the traction substations, as suggested by the NITI Aayog [20] along with piloting HFC into its fleet. This assorted approach of IR is expected to provide a stable energy profile with cost efficiency [20].

Solar power has a huge potential in India, with Solar panels on rooftops & Solar farms on vacant land parcels or along railway tracks, IR can unleash its untapped potential of renewable energy & accelerate its goal of '*Atmanirbhar Bharat*' (self-sufficient India) in energy requirements. IR already planned a mega solar power plant of 20 GW capacity, to be set up by 2030, on its unutilized areas [29]. Further, orders have been placed for the installation of approx. 200 MW of solar rooftop capacity for more than 500 stations, and the projects are currently under execution. Integrating this Solar potential with round the clock power supply units fueled to generate electricity for traction purposes. This agglomeration of Renewable energy sources with Energy Storage systems, would not only lead to stable operations but also pave the future of rail transport in India. The Dahod project, which is a hybrid plant planned to allow both solar power generation as well as storage of solar energy in a battery, is a pilot initiative expected to be completed very soon [13].

Renewable energy is the fuel of the future & is being vastly propagated and being assimilated by IR. Even though, there exists certain challenges in integrating RES into the energy supply fabric, its cost benefit analysis towards the society outweighs all its lacunae. There is a possibility of reduction of CO_2 levels (than their current values) by 20%, from the adoption of RES in IR, socio-economic & environmental benefits of which cannot be quantified. Energy efficient rolling stock manufactured with state of the art, innovative technology is the need of the hour, which would complement the use of RES in IR. Moreover, the benefits are expected to only multiply further, with the ever-increasing ridership & freight haulage in the future. This enhanced resilience of the energy supply through Renewable energy sources, is most essential from India's perspective, as it would aid in fulfilling the broader perspective of environmental sustainability for the country by fulfilling the goals of Paris Convention to fight climate change & become a role model for other Railway systems worldwide.

The vision of a *Viksit Bharat* is no longer a distant dream, as Indian Railways is propelling India onto the global stage alongside a select group of developed nations that have embraced hydrogen fuel technology. With a clear focus on innovation, IR has introduced policy measures to integrate HFC) technology, beginning with the rollout of a prototype rake and the approval of similar projects to expand its hydrogen-powered fleet is underway. The adoption of HFC would mark a significant milestone for Indian Railways, positioning it as a global leader in sustainable mass transportation & offering solutions that are not only cost-effective but also environmentally responsible.

With these concentrated efforts & initiatives, along with the dedicated team of officials, IR is bound to achieve its target to mitigate carbon emissions & Net zero by 2030, by fully utilizing the potential of Renewable Sources to power Railway Electrification across the country.

The key takeaways from this technical paper underscore Indian Railways' unwavering commitment to advancing sustainability and environmental stewardship, with a clear target of achieving Net-Zero carbon emissions by 2030. To realize this ambitious vision, IR is undertaking a multi-pronged approach that includes full electrification of its vast network powered by renewable energy, the deployment of energy-efficient rolling stock, and the integration of cutting-edge technologies. This forward-looking strategy, supported by robust stakeholder collaboration and policy alignment, positions Indian Railways as a frontrunner in the global transition to green mobility. It reflects not only a dedication to climate action but also a broader commitment to sustainable and inclusive development.

To uphold its commitment towards green energy, IR has signed four MoUs with the Ministries of Power and New & Renewable Energy to promote electricity transmission, energy efficiency, and renewable energy adoption. The focus of these agreements is to reduce power costs, implement energy-saving technologies, and utilize vacant Railway lands for solar projects. This collaboration is a medium to for knowledge sharing regarding world class technologies, capacity building, and explore innovative options for funding. The MoU is aligned with India's climate goals, & aims to make Indian Railways a leader in renewable energy and efficient power use, by showcasing how joint efforts among various ministries can deliver sustainable, cost-effective energy solutions for the nation [33].

It is well established that the use of HSD results in the emission of various GHGs, contributing to global warming and deteriorating air quality. To support a greener planet and position itself as a global leader in sustainable transportation, Indian Railways (IR) must align with international best practices, such as those recommended by the International Energy Agency (IEA). A key strength of Indian Railways is its complete ownership by the Government of India, allowing decisions to be driven not solely by economic returns but also by social advancement and environmental sustainability. This unique positioning has been instrumental in achieving near-complete electrification of IR's broad-gauge network in a focused and forward-thinking manner.

The integration of renewable energy into railway systems is not just an environmental imperative but also a strategic investment in the future of sustainable transportation. By reducing dependence on fossil fuels, cutting emissions, and lowering long-term operational costs, renewable energy paves the way for a cleaner, more resilient, and energy-efficient railway network. As nations work toward climate goals and energy security, embracing renewables in rail transport will play a crucial role in shaping a greener and more responsible mobility ecosystem for generations to come.

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