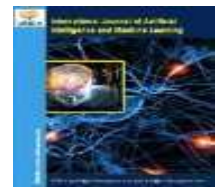




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Research Paper

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Techno-Economic Assessment of Decarbonisation of Indian Railways: An Integrated Fuzzy DEMATEL–AHP–TOPSIS Framework

Jayendra Malhotra¹, Dr Dipti Ranjan Mohapatra², Dr. Tapan Kumar Nayak³

¹Research Scholar, Amity College of Commerce and Finance, Amity University Uttar Pradesh Noida, Pin Code: 201313.

E-mail: jayendramalhotra@gmail.com

²Professor, Amity College of Commerce and Finance, Amity University Uttar Pradesh, Noida, Pin Code: 201313.

E-mail: drmoapatra@amity.edu

³Professor, Jaipuria School of Business, Shaktikhand IV, Indirapuram, Ghaziabad -201014. E-mail: drtapankumarnayak@gmail.com, ORCID iD- 0000-0003-0084-9461

Abstract:

As global energy consumption surges, the imperative for energy efficiency and the shift towards sustainable energy sources intensifies, particularly in the context of fossil fuel reliance and its environmental ramifications. This paper examines the potential for Indian Railways as significant player in the transportation sector, to adopt low-carbon energy solutions to meet increasing energy demands. This study uses cost-benefit analysis to assess the viability of adopting low carbon energy options. Sensitivity analysis is used to verify the robustness. To achieve sustainability targets, Indian Railways must make the shift to low-carbon energy alternatives. Further, an integrated Fuzzy, DEMATEL-AHP-TOPSIS Frame has been applied as a remedy to the uncertainty and interdependence among different decarbonization influencing factors such as economic, technical, environmental, institutional and operational.

The causal relationships are identified by Fuzzy DEMATEL, the criterion weights are determined by Fuzzy AHP and the alternative decarbonization and priorities is determined by Fuzzy TOPSIS.

Keywords: Decarbonisation, Indian Railways, Low Carbon Energy, Fuzzy DEMATEL, Fuzzy AHP, Fuzzy TOPSIS, Multicriteria Decision Making, Renewable Energy, Sustainable Transport

1.0 Introduction

Indian Railways (IR), the world's fourth-largest railway network, hopes to become a greener mode of transportation by lowering its carbon footprint. After the wide gauge lines are fully electrified, the railways would need about 30.13 billion units of power. The anticipated increase in electricity consumption upon complete electrification is based on the current electricity consumption for traction operations of Indian Railways (IR). The future volume of passengers and cargo on Indian Railways will determine the true demand. With an annual consumption of over 18 TWh, or about 2% of India's total power generation, IR is currently the second-biggest railway network in the world and the country's major electricity consumer. Additionally, IR uses for 3.2% of India's total diesel usage in the transportation sector. Additionally, as the number of passengers increases, it is anticipated that IR's energy demand would quadruple to 49 TWh by 2030. Moving away from a diesel-powered rail network and toward an electrified one is a crucial first step toward decarbonizing IR. India's railway sector contributes 4% of the country's 12% greenhouse gas emissions from the transportation sector.

In many regions of the world, boosting rail transport's electrification is considered to reduce emissions and adjust the industry to stricter environmental standards. Because electricity is less expensive than diesel fuel, electrification can economically lower energy expenses. Because an electric locomotive has fewer moving parts than its diesel counterpart, maintenance costs are also lower for the former (Zenith et al. 2019).

Indian Railways has electrified 60,814 km of broad-gauge lines as of November 2023. India is dedicated to being a "net-zero" carbon emission nation by 2030, and IR has made major efforts to lower its fuel expenses and carbon footprint. Reducing energy use, using renewable energy to meet energy demand, and electrifying the entire broad gauge railway network are some of its main decarbonization efforts. With around 3,450 MW of renewable energy capacity in the works, IR presently has 220 MW of renewable energy capacity. Greenhouse projected that greenhouse gas (GHG) emissions might be cut by about 40% if renewable energy is used in the transportation industry. With 115,000 track kilometers, 8,500 stations, and 12,000 trains running daily, IR is the largest railway network in Asia. It is also one of India's biggest fossil fuel consumers, using over 2.7 billion liters of diesel yearly. By 2031–2032, it is anticipated that 60% of

passenger travel and 80% of rail freight will be powered by electricity.

Overhead line equipment (OLE) electrification rates vary widely amongst nations, ranging from 99% in Switzerland to 62% in the EU and 1% in the USA (IEA, 2017)

The significance of raising the proportion of low-carbon renewable energy sources, such solar and wind, in the overall energy mix has already been considered by Indian Railways. IR is thinking about aiming for 10,000 MW of renewable energy by 2030 (IR own estimates).

The economic rationale for the railways to further lower their power costs and simultaneously increase the proportion of renewable energy, especially solar, in their energy consumption mix is strengthened by the recent sharp decline in solar prices. The open access procurement of renewable energy might further reduce the cost of power for the railways, as solar tariffs are frequently on pace with or less expensive than the traditional grid tariff (Ramji, 2015). The state solar policies' control period should be followed if these renewable energy benefits are to be realized.

Previous studies on hydrogen trains have concentrated on the technological feasibility (Marin et al., 2010, Hoffrichter, et al., 2012) and impact on emissions (Haseli, et al., 2008 and Hoffrichter, et al., 2016). More recently, reports have also examined the economic aspect of hydrogen trains for specific cases, but mainline freight rail applications have received little attention.

Baykasoğlu et al. (2013) discussed DEMATEL, fuzzy and TOPSIS framework for land transportation companies to solve highly complex truck selection problem.

Indian Railways is attempting to lower its carbon emissions and increase its usage of low-carbon energy sources through energy efficiency, afforestation, nuclear power, electrification, solar power, wind power, and a Memorandum of Understanding with the United States.

Rooftop solar photovoltaic (SPV) systems may supply roughly 74% and 25% of the power needs of rail coaches during the summer and winter, respectively, according to a 2015 analysis of the Iranian railway network. 2016 research introduced the idea of integrating SPV on locomotive rooftops for the South African railway sector. Eventually, the transportation sector will be decarbonized through the widespread integration of renewable energy sources and the parallel adoption of e-transportation. India began using train SVP rooftops to generate electricity in 2011 on the Pathankot (Punjab) line and on the Kalka–Shimla line in 2019, following in the footsteps of Italy, France, the United States, and other nations.

Ortiz et al., (2021) used multi criteria decision making (MCDM) approach especially Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL), AHP and TOPSIS for taking strategic decision on suppliers' selection of forklift filters used in mining industry.

It is possible to integrate solar energy into both traction and non-traction processes. Compared to traction operations, non-traction energy makes it easier to integrate solar, even if it only makes up 15% of the railways' overall energy usage. The direct integration of solar energy for traction presents a few difficulties, such as the need for high voltage for extended periods of time. The risks involved in funding such projects must be acknowledged and assessed, even as Indian Railways seeks to expand its renewable energy portfolio. Along with the dangers, these projects' timeframes should be coordinated so that some of the bigger ones are started early, particularly in places where there are greater land banks. But choosing a project development strategy to build, own, and operate model, the RESCO mode, or the CAPEX method—is equally crucial. Given the amount of energy that Indian Railways uses, giving decarbonization top priority might help India meet its 2030 emissions reduction targets and increase energy security by lowering the import of fossil fuels. Furthermore, in the long term, decarbonization can prove to be a more economical choice than the conventional approach to IR. In this research, we have analysed the feasibility and cost-effectiveness of many possible routes to decarbonize IR by 2030.

Energy is necessary for a healthy global economy (Bhuiyan, 2022; Xie, 2022). In other words, energy use is required in every area that is either directly or indirectly related to economic growth and development. In recent decades, the need for energy has grown in both developed and developing nations. Living standards in wealthy nations have generally increased, but because of population growth, urbanization, industrialization, and rising living standards, developing nations have fallen behind in balancing energy supply and demand (Bhattarai, 2022; Bhuiyan, 2022). There were 557 Exajoules (EJ) of primary energy consumption worldwide in 2020 (BP, 2021).

There are still large gaps in energy access and use between the Global North and South. Together, North America and Europe use 33.3% of the world's energy (BP, 2021). On the other hand, 3.3% of the world's population lives in Africa, 6.5 percent in the Middle East, and 4.7 percent in South and Central America (BP, 2021). Furthermore, the growing energy demand and consumption of OECD member countries as well as rising economies like China, India, Brazil, and South Africa has resulted in a significant increase in energy-related carbon dioxide (CO₂) emissions in recent decades (Bhattarai, 2022). One About 31.5 GtCO₂ or more than 75% of all CO₂ emissions worldwide in 2020 were from energy-related sources (Friedlingstein, 2022). There is no question that decarbonization pledges are connected to economic considerations in two significant ways. The first is the necessity of cutting emissions while maintaining the economic expansion required to accomplish other SDGs; the second is the challenging issue of dividing the budget for existing emissions and emission reductions (Wang, 2021).

Their elasticity is roughly estimated by empirical research examining the relationship between CO₂ and GDP. According to a recent survey, for every 1% growth in GDP, the anticipated elasticities range from a 0.3% decrease in CO₂ emissions to a 2.5% increase (Wang, 2021). This uncertainty has made it more difficult for politicians to rely on empirical data when making decisions that may conflict with social goals. The long-term decarbonization pledges of some nations are not supported by numerous empirical research. To support policymaking in the direction of a fair decarbonization process, certain nations are creating quantitative studies. Additionally, several studies have examined the viability of decarbonization plans in various nations (Le Treut, 2021). The techno-economic viability, energy supply, and emissions implications of the energy supply and energy demand sectors (such as power, transportation, buildings, industry, etc.) are the main topics of these studies, which are primarily based on bottom-up energy accounting models (Emodi, 2017; Grande-Acosta and Islas-Samperio, 2017; Dioha, 2019).

Given the amount of energy that Indian Railways uses, giving decarbonization top priority might help India meet its 2030 emissions reduction targets and increase energy security by lowering the import of fossil fuels. Furthermore, in the long term, decarbonization can prove to be a more economical choice than the conventional approach to IR. In this research, we have analyzed the feasibility and cost-effectiveness of many possible routes to decarbonize IR by 2030.

A "modal shift" from driving freight to more efficient rail freight has been promoted as a means of lowering greenhouse gas emissions since rail is acknowledged as the most energy-efficient means of transporting both passengers and in-land freight (Hao et al., 2015).

The installer and the customer sign a power purchase agreement at a mutually agreed upon tariff. Table 1 displays the expected rail passenger transport prediction for three distinct scenarios through 2031–2032. The elasticity of passenger rail transportation is steadily rising, as this table shows. Kaja and Borawake (2025)

Table1: Rail passenger transport forecast

Year	Passenger transport in Billion Passenger Kilometer (BPKM)			Remarks
2010–11	979			Actual
2011–12	1047			
2012–13	1098			
2013–14	1140			
2014–15	1147			
Rail passenger transportation's CAGR (%) from 2010–11 to 2014–15	4.04			
GDP (%) CAGR from 2010–11 to 2014–15	7.0			
Rail transportation's actual elasticity from 2010–11 to 2014–15	0.58			
Year	Passenger transport in BPKM			Assumed
	Optimistic scenario	Realistic scenario	Pessimistic scenario	
CAGR of GDP (%) between 2015–16 and 2031–32	9	8	7	
Elasticity of rail passenger transport between 2014–15 and 2019–20	0.7	0.7	0.7	
Elasticity of rail passenger transport between 2020–21 and 2024–25	1.4	1.4	1.4	
Elasticity of rail passenger transport between 2025–26 and 2031–32	1.6	1.6	1.6	
Year	Passenger transport in BPKM			Remarks
2019–20 ^a	1557	1506	1457	Forecast
2024–25	2818	2561	2325	
2030–31	6317	5276	4396	
CAGR (%) of rail passenger transport between 2010–11 and 2030–31	9.77	8.79	7.8	

Effective elasticity of rail passenger transport between 2010–11 and 2030–31	1.1	1.1	1.1	
Extra rail passenger service from 2014–15 to 2031–32	5170	5276	4396	

Source: Computations based on Statistics Times (February 18, 2016), Ministry of Railway.

This is how the remainder of the paper is organized. The literature review is presented in the second section. It evaluates the features of the chosen research emphasizing the effects of decarbonization. The third section presents the study's objective. The approach used in this study is covered in the fourth part. The fifth section presents the data structure. The study's conclusions and implications are covered in the sixth part. The final portion consists of the limitations.

2.0 Literature Review

Recent research has emphasized the critical role that policy will have to play, notwithstanding the paucity of studies on how rail might be decarbonized while utilizing the current infrastructure (Rungskunroch et al., 2021).

India has the lowest rate of energy consumption per Tonne-Kilometre (TKM) for goods by rail among the countries considered (OECD/IEA 2015), which is a plus for rail transport. However, given the expansion plans of Indian Railways and the increase in demand due to population and GDP growth, Indian Railways' energy consumption is expected to increase.

The ambitious goal of 6559 billion TKM of freight transport for railways in 2031–2032—which would represent 50% of rail's modal share in freight transport—and 5765 billion PKM of passenger transport for railways in the same time frame was set by the India Transport Report—Moving India to 2032 (NTDPC 2014). For Indian Railways, this presents both a difficulty and an opportunity since; by obtaining its operational energy from renewable sources, India may increase its freight transportation and modal share, taking advantage of rail transportation's low carbon footprint. Choudhary et al. (2025)

To go green and decarbonize, Indian Railways is implementing a multifaceted strategy that includes electrifying its traction network, lowering its energy usage, and increasing the amount of renewable energy it sources. By 2030, it aims to achieve net-zero carbon emissions. And it has big intentions to achieve this objective (Kainth, 2022).

Making the switch from a diesel-powered rail network to an electrified one is a necessary step in the decarbonization process. While clean fuel options are scarce, an electrified rail network may more readily switch to clean energy sources like solar and wind power. The following advantages are anticipated if Indian Railways' electricity usage is fully (100%) decarbonized by 2030 such as reduction of 45 million tons in CO₂ cumulative emissions; 150 million tons in SO₂ cumulative emissions; and 210 million tons in NO cumulative emissions. For the decarbonization of IR to be successful, the decarbonization pathway must be both practically and economically viable (Konda et. al. 2017). To lower overall transportation-related emissions, Indian Railways plans to increase the percentage of freight it moves from roughly 35% in 2015 to 45% by 2030. (Awathy & Mishra 2021).

According to the International Energy Agency's (IEA) base case scenario, the total energy used for rail worldwide was 53 million tonnes of oil equivalent (Mtoe) in 2017, and by 2050, it is expected to reach 88 Mtoe. The IEA's high-case scenario, which is more ambitious, projects a 125% rise (125 Mtoe) by 2050 (IEA, 2022).

Given how crucial energy is to many facets of human endeavours and the economy, shocks in the energy sector are likely to ripple into other industries and impact macroeconomic results. Among other things, the effects could be quantified in terms of employment, welfare, investment costs, and gross domestic product impacts. Most recent attempts to examine the macroeconomic and multi-sectoral effects of decarbonization have relied on bottom-up models. Several studies have examined the energy, emissions, and macroeconomic effects of mid-century decarbonization schemes using top-down models, such as computable general equilibrium (CGE) models, with varying degrees of success (Schers, 2018, Delagado, 2020, Gupta, 2020).

Energy consumption for train operations is measured in per tonne-km, train-km, car-km, seat-km or per passenger-km (Andersson and Lukaszewicz 2006). In the latter instance, the number of passengers utilizing the real train or the number of passenger kilometers generated is correlated with energy usage. However, Indian Railways does not have data on electrical energy consumption for rail transportation in terms of train-km, car-km, seat-km, PKM of different classes, or TKM. Husain et al. (2023)

There are several options for decarbonizing IR, and the viability and cost-effectiveness of each were evaluated to identify the best one. We contrasted the expenses of each option with a business-as-usual, non-decarbonization scenario to assess cost-effectiveness.

In a related study, case studies from Norway and the USA were utilized to evaluate decarbonization solutions such as electrification via overhead lines, hydrogen, and batteries for freight railroads using techno-economic analysis (TEA) (Zenith et al., 2020).

Hydropower (using the potential and kinetic energy of water), geothermal energy, bioenergy, wind energy (derived from solar energy), solar power (direct, photovoltaic, and thermal), and more are examples of renewable energy sources (RES) (Bostan et al., 2013; Marks-Bielska et al., 2020 & Oyekale et al., 2020).

As previously stated, even if high-speed and urban trains are powered by electricity in some jurisdictions, like Europe, they must be powered by "green" electrical sources like solar, wind, and hydro to be considered low-CI operations (S. Rajendran & M. Popfinger, 2022)

There are numerous actual instances of trains around the world using renewable energy. The creation and testing of a solar-powered Diesel Electric Multiple Unit (DEMU) train by Indian Railways is a noteworthy example. Between Sarai Rohilla in Delhi and Farukh Nagar in Haryana, Indian Railways' first solar-powered DEMU train was introduced in 2017 from Safdarjung railway station (Express Web Desk, 2017).

The train's roof is covered with sixteen solar panels, each of which can produce 300 watts of electricity. Additionally, it has a battery bank to store extra power so the train may continue to run when there is little sunlight. On a single charge, the train may run for up to 72 hours. During its successful testing in Jodhpur, Rajasthan, this solar-powered DEMU train was found to save up to 21,000 liters of fuel annually, which translates into an annual decrease of almost 54 tons of carbon dioxide emissions.

Only electrified portions of a railway network are suitable for electric locomotive operation. The main source of electricity is the diesel locomotive, which transforms diesel fuel into electric energy as it burns for traction. With electric locomotives, the only places where pollution is evident are at the power plant or where electricity is generated. According to Gangwar and Sharma (2014), electric traction has an efficiency of around 28–30%, but diesel engines have an efficiency of about 35% (assuming grid-to-loco efficiency of 98%, power plant efficiency of 30–35%, transmission losses of 10%, and locomotive losses of 2%). Considering the current inefficiencies in power generation and delivery, diesel locomotives have a slightly higher end-to-end energy efficiency than electric locomotives. Nonetheless, as power generation and distribution significantly improve, electric locomotive efficiency will inevitably rise.

Additionally, using batteries and photovoltaic (PV) panels reduces the need for grid power, which results in more stable distribution system voltage levels. This illustrates how solar energy has enormous promise as a sustainable substitute for conventional train power sources.

According to an assessment by Ramakrishnan (2018), the Indian Railways' ability to achieve 100% decarbonization by 2030–31 depends upon:

Transport haulage by electricity: In 2030–31, the Indian Railways would be able to transport 80% of passenger traffic and 100% of freight traffic with electric traction due to the anticipated expansion in IR track electrification.

Energy usage within vehicles during passenger transportation: Approximately 45–59% of passenger transportation in 2030–31 would be by AC classes due to the growing demand for AC travel. Since an AC class requires about 70% of the energy required to drive an AC passenger car, the overall energy consumption per unit of passenger transportation would increase significantly until 2030–31. At least during the day, rooftop solar panels could help offset some of the AC coaches' internal energy needs.

Electrical energy required for rail transport and the solar power capacity to be created:

A 1MW solar power plant typically produces 1.5 million units of energy (Zolt energy, n.d.). To meet the railways' whole electrical energy needs, 90,000–150,000 MW of solar capacity must be developed by 2030–31, producing 136–225 billion units. Indian Railways would only produce 10% of carbon emissions if it switched to solar power its entire business.

Ocampo et al. (2020) used integrated fuzzy model approach for sustainable manufacturing which evaluated the interdependencies of decision options.

Abdullah et al. (2023) developed integrated multi-criteria fuzzy MCDM model to evaluate the influence of Industry 4.0 technologies on manufacturing strategies.

2.1 Research Gap: The difficulties of combining hydrogen-powered trains with the current electrified rails are one of the research gaps in decarbonizing Indian Railways. Since green hydrogen generation is still in its infancy in India, these issues include the safety considerations around hydrogen fuel, the high upfront costs, and integration with current electrified tracks.

A small number of additional studies found the followings:

- After examining Indian Railways' energy supply side, the Climate Policy Initiative (CPI) determined eight decarbonization routes.
- The CEEW concluded that if the Railways met a 5 GW target, 25% of its electricity could come from renewable sources.
- The CSTEP investigated the possibility of deploying green hydrogen-powered trains, while the ICRIER examined the viability of fully decarbonizing the railways.

Decarbonization objectives have been established by Indian Railways, including raising the proportion of low-carbon renewable energy sources like wind and solar. In the upcoming years, it intends to install wind and solar power plants. Additionally, by 2030, it wants to have 10,000 MW of renewable energy. Studies on the economic feasibility of Indian Railway's low-carbon energy alternative are scarce.

Research Hypotheses

- H1: The decarbonization potential of Indian Railways depends upon interdependence of economic, technological, operational, environmental and institutional factors.
 H2: The decarbonization of Indian Railways depends on the effects of institutional and economic factors on investment, infrastructure and implementation capacity.
 H3: The low carbon pathways depend upon combined results of economic viability and technological feasibility and environmental performance.
 P4: The prioritization of decarbonization is based on integrated Fuzzy DEMATEL–Fuzzy AHP–Fuzzy TOPSIS framework.

3.0 Objective:

This objective of this paper is to

- (i) Determine the energy system decarbonization investment costs in IR
- (ii) Evaluate the economic feasibility of low-carbon energy options for the Indian Railways.
- (iii) Identify and prioritize alternative decarbonization pathways for uncertain factors such as economic, environmental, technical, operational and institutional using an integrated fuzzy DEMATEL-AHS-TOPSIS framework

4.0 Methodology

4.1 Economic Analysis: Economic evaluation seeks to support Indian Railway's adoption of the low-energy option, by assessing its viability considering the anticipated advantages for the national economy. Comparing cost and benefit streams over a predetermined analysis time under both "without adoption of low energy option" and "with low energy option" conditions is the process of economic evaluation. Capital expenditures, along with maintenance and operating costs, are the key expenses. To represent the actual resource cost to the economy, all costs and benefits were valued monetarily and expressed in economic prices.

The results have been given using the Economic Internal Rate of Return (EIRR) and the Net Present Value (NPV) at a 12 percent discount rate. These were calculated using an annual stream of net cash flows that accumulated during the study's time horizon and the discounted cash flow (DCF) technique. As expenses and benefits are incurred at various times, discounting is applied. By contrasting the EIRR with the 12% opportunity cost of capital, the viability of low energy option by Indian Railway was assessed.

4.2 Sensitivity analysis:

Quantitatively estimating the relationship between input uncertainty and model output uncertainty is the main goal of sensitivity analysis (SA). Specifically, we outline forward sensitivity (FSA) and adjoint sensitivity analysis (ASA) for mathematical models that are deterministic (not stochastic). FSA quantitatively determines the impact of small changes to a model parameter p on the output solution u to our mathematical model, or some response function(al) $J(u)$, as shown in Fig. 1. In FSA, if the solution and functional are differentiable with respect to a parameter p , we calculate the derivatives $\partial u / \partial p$ and $\partial J(u) / \partial p$ and find the normalized sensitivity indexes (SI).

$$S_{u_p} := \lim_{\delta p \rightarrow 0} \left(\frac{\delta u}{u} \right) \left(\frac{\delta p}{p} \right)^{-1} = \left(\frac{p}{u} \right) \left(\frac{\delta u}{\delta p} \right) \dots \dots \dots \text{Eqn. 1}$$

$$S_{j_p} := \lim_{\delta p \rightarrow 0} \left(\frac{\delta J}{J} \right) \left(\frac{\delta p}{p} \right)^{-1} = \left(\frac{J}{p} \right) \left(\frac{\delta u}{\delta p} \right) \dots \dots \dots \text{Eqn. 2}$$

With a slight relative change in the input $\delta p/p$, the normalized SI calculates the relative change in the output $\delta u/u$ or $\delta J/J$ (Arriola and Hyman, 2009).

SA is used to assess how resilient Indian Railway's transition to low-carbon energy sources is economically in the face of shifting cost and benefit streams brought on by unfavourable changes in the key variable based on EIRR. This helps to determine the strength of the project to withstand the future risk and uncertainties.

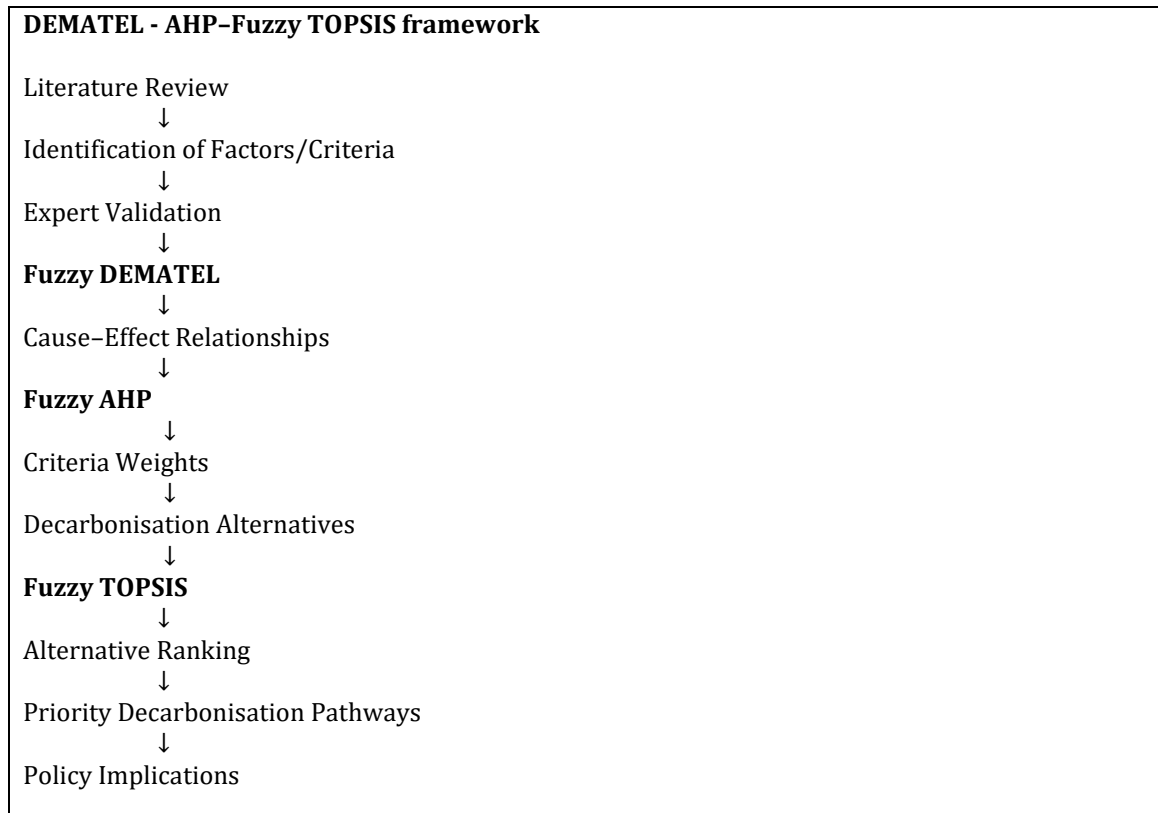
The following are the primary steps in the economic evaluation:

- Estimation of the capital and yearly operational expenses associated with Indian Railways' decarbonization for the study period ending in 2032.
- Calculation of the decarbonization process's immediate advantages. The indirect advantages for users, non-users, and the economy have not been considered.

- The accounting rate of return of 12 percent, the lowest expected return for any wise investment choice, is contrasted with the project's Economic Internal Rate of Return (EIRR).
- This is done by comparing the annual streams of costs and benefits and estimating the EIRR and Net Present Value (NPV) using the Discounted Cash Flow (DCF) technique.

4.2 Integrated Fuzzy DEMATEL–AHP–TOPSIS Framework

There is a necessity of using the Integrated Fuzzy DEMATEL–AHP–TOPSIS framework for understanding decarbonisation as it dependent upon many integrated factors such as economic, environmental, technological and institutional factors which are uncertain. This approach is based on causal relationship, determination criteria weights and ranking decarbonization alternatives. The framework is provided below.



5.0 Data

The decarbonization of Indian Railways requires huge investment cost. The cost is related to technology advancements, electrification, and the incorporation of renewable energy. Long-term savings on fuel, maintenance, and operational efficiency are anticipated to balance these expenses. Beyond long-term savings, there are certain additional financial advantages that will be realized, such as job creation, economic expansion, and environmental sustainability. However, sustained investment, cooperation with the private sector, and government policy support will be necessary to meet these ambitious decarbonization goals. The cost- and benefits of decarbonization of IR is presented in Table 2.

Table 2: Financial Investment required for Decarbonization of Indian Railways

Year	Investment Cost (₹ Crores)	Annual Savings (₹ Crores)	Revenue Impact (₹ Crores)	Key Initiatives	Source
2017	5,000	N/A	N/A	Start of large-scale electrification	Ministry of Railways (2017)
2018	6,500	N/A	N/A	Solar projects initiated	IRCTC (2018)
2019	8,000	3,000	2,000	Expansion of wind power projects	Ministry of Railways (2019)

Year	Investment Cost (₹ Crores)	Annual Savings (₹ Crores)	Revenue Impact (₹ Crores)	Key Initiatives	Source
2020	9,500	4,000	3,000	Increased electrification	Indian Railways Annual Report (2020)
2021	10,000	6,500	4,000	Hydrogen fuel pilot project	Ministry of Railways (2021)
2022	11,500	8,000	5,500	Record electrification and solar expansion	Ministry of Railways (2022)
2023	12,500	9,500	7,000	85% electrification milestone	IRCTC (2023)
2024 (Projected)	14,000	11,000	8,500	Completion of 100% electrification	Ministry of Railways (2024 Projection)
2030 (Projected)	20,000	15,000	20,000	Net-zero carbon emission target	Ministry of Railways (2030 Projection)

5.1 Project Costs: The project cost components are the investment cost such as capital cost and operations and maintenance costs as provided in Table 2.

5.2 Project Benefits: The difference between the total operating costs in the "Base Case" and the "With Project Case" is used to calculate the benefits of Indian Railways adopting low-carbon energy. The expected benefits include the years 2017 through 2024. The 2030 gains were derived by extrapolation. A standard conversion factor of 0.85 is used to convert the all the economic benefits arising out of low carbon energy option by Indian Railways. The details of total benefits are provided in Table 3

5.3 Data for Fuzzy DEMATEL–AHP–TOPSIS Framework

Indian Railway has achieved the electrification of broad-gauge network of 99.6% by July 2026. This has reduced 185 crore litres of diesel consumption during 2015-16 to 2024-25. Further railway has commissioned the solar and wind capacity by 1260 MW. Out of these 812 MW has been commissioned for solar and 93 MW for wind traction. Additionally, 1500 MW renewable capacity is used for round the clock (RTC) electricity supply by November 2025.

Table 3. The following codes have been used in the DEMATEL-AHP-TOPSIS Model

Code	Alternative
A1	Electric Railway (renewable)
A2	Solar-energy integrated with electricity requirement of Indian Railway
A3	Wind energy integrated with solar storage
A4	Traction that saves energy and supports regenerative braking
A5	Traction-Green-hydrogen
A6	Battery traction

Author's Assumption

6.0 Discussion

6.1 Discussion on Economic Analysis: To determine the net cash flow, the economic analysis of Indian Railways' low-carbon energy alternative was computed using an annual cost-benefit analysis. The discounted cash-flow technique was used to calculate the EIRR and NPV at a 12% discount rate. The net cash-flow statement is calculated presented in Table 3.

Table 4: Net Cashflow Statement for Indian Railway (in ₹ Crore)

Year	Total Expenditure	Total Benefits	Net Benefits
2017	4250.00	850.00	-3400.00
2018	5525.00	1275.00	-4250.00

Year	Total Expenditure	Total Benefits	Net Benefits
2019	6800.00	5880.00	-920.00
2020	8075.00	7245.00	-830.00
2021	8500.00	9000.00	500.00
2022	9775.00	10665.00	890.00
2023	10625.00	12075.00	1450.00
2024	11900.00	13740.00	1840.00
2025	12435.50	15114.00	2678.50
2026	12995.10	17381.10	4386.00
2027	13579.88	19988.27	6408.39
2028	14190.97	22986.50	8795.53
2029	14829.57	26434.48	11604.92
2030	17000.00	30399.65	13399.65
2031	17170.00	34959.60	17789.60
2032	17341.70	40203.54	22861.84
		EIRR	0.312
		NPV	₹20,412.36

Author's Calculation

The EIRR of low carbon energy option for Indian Railways worked out be 31.2%. The NPV at 12% is ₹20,412 Crore. The opportunity cost of capital is 12%, a rate of return of 12% is deemed ideal for infrastructure investments. The result proved that the project is economically viable.

6.2 Discussion on Sensitivity Analysis:

The purpose of the sensitivity analysis is to determine how resilient the suggested investment is to shifting cost and benefit conditions. The viability of the adoption of low carbon energy options by Indian Railways is checked in the following changing scenario of cost and benefit streams:

- (i) the cost increased by 15% and
- (ii) benefits decreased by 15%
- (iii) Both the cost increased by 15% and benefits decreased by 15%.

The robustness of Indian Railways' adoption of the low carbon energy alternative is demonstrated by the sensitivity analysis as shown in Table 4. With 15% increase in cost, the EIRR calculated as 19.10% while the EIRR is 17.31% when there is a 15% decrease in benefits. The IRR turn out to be 6.78% when both costs increased by 15% and benefits decreased by 15%.

Table 5: Cash- Flow Statement of Sensitivity Analysis (in ₹ Crore)

Year	Cost increased by 15%	Benefit decreased by 15%	Both costs increased by 15% & benefit decreased by 15%
2017	-4037.50	-3527.50	-4165.00
2018	-5078.75	-4441.25	-5270.00
2019	-1940.00	-1802.00	-2822.00
2020	-2041.25	-1916.75	-3128.00
2021	-775.00	-850.00	-2125.00
2022	-576.25	-709.75	-2176.00
2023	-143.75	-361.25	-1955.00
2024	55.00	-221.00	-2006.00
2025	813.18	411.40	-1453.93
2026	2436.74	1778.84	-170.43
2027	4371.41	3410.15	1373.17
2028	6666.89	5347.56	3218.91
2029	9380.48	7639.74	5415.31

2030	10849.65	8839.70	6289.70
2031	15214.10	12545.66	9970.16
2032	20260.59	16831.31	14230.05
EIRR	19.10%	17.31%	6.78%

Author's Calculation

6.3 Evaluation Criteria of Fuzzy DEMATEL-AHP-TOPSIS Framework

Table 6 : Evaluation Criterion

Code	Criterion	Type
C1	Capital cost	Cost
C2	Lifecycle cost	Cost
C3	CO ₂ reduction potential	Benefit
C4	Renewable-energy utilisation	Benefit
C5	Technology maturity	Benefit
C6	Infrastructure compatibility	Benefit
C7	Operational feasibility	Benefit
C8	Scalability	Benefit
C9	Existing Indian Railways deployment/policy support	Benefit
C10	Implementation simplicity	Benefit

Author's Evaluation

This evaluation criteria requires quantitative data which can be compared. In absence of the above-mentioned empirical data, the 1-10 scale criteria approach has been adopted with 1 as very poor, 5 as moderate and 10 as very strong. The score is calculated based on current evidence, existing deployment, technological maturity and nature of pathways. The evidence-informed score is presented below.

Table : 7 : TOPSIS Alternative

Alternative	C1 Cost	C2 Lifecycle	C3 CO ₂	C4 Renewable	C5 Maturity	C6 Infrastructure	C7 Operational
A1	7	9	10	9	10	10	10
A2	8	9	8	10	9	8	9
A3	6	7	9	10	7	7	7
A4	9	10	7	6	10	10	10
A5	4	4	9	9	4	3	5
A6	5	6	8	7	6	5	6

Alternative	C8 Scalability	C9 IR support /deployment	C10 Simplicity
A1	10	10	8
A2	9	10	8
A3	9	8	6
A4	10	10	9
A5	4	6	4
A6	6	5	6

Author's Assumption

In above table A1 have high technological maturity and infrastructure scores as the railway network is already 99.6% electrified. Similarly, A5 have a lower technology-maturity and infrastructure score because hydrogen traction is in early operational stage.

The Criterion weight has been allocated as per the requirement based on literature and is presented in the table below.

Table : 8 :Fuzzy AHP Criterion Weight

Criterion	Weight
C1 Capital cost	0.08
C2 Lifecycle cost	0.12
C3 CO ₂ reduction	0.18
C4 Renewable-energy utilisation	0.10
C5 Technology maturity	0.10
C6 Infrastructure compatibility	0.10
C7 Operational feasibility	0.10
C8 Scalability	0.07
C9 Existing IR deployment/policy support	0.10
C10 Implementation simplicity	0.05
Total	1.00

Author's calculation

6.4 Fuzzy-TOPSIS Ranking

The closeness coefficient ranking is calculated using the criterion weights, benefit -cost normalization table and decision matrix mentioned above.

Table 9 :Fuzzy-TOPSIS Ranking

Rank	Alternative	Closeness coefficient
1	A1 Renewable-powered electrified railway	0.5945
2	A2 Solar-energy integration	0.5121
3	A4 Energy efficiency & regenerative braking	0.5085
4	A3 Wind-solar-storage integration	0.4957
5	A5 Green-hydrogen traction	0.478
6	A6 Battery-electric traction	0.3583

Author's Calculation

7.0 Results and Conclusion

7.1 Economic Analysis

The economic analysis of adoption of low carbon energy option by Indian Railways is a viable option. The techno-economic CO₂ mitigation strategies highlight how important it is to implement several decarbonization initiatives, like boosting energy efficiency and converting to low-carbon transportation, to reduce CO₂ emissions. There is little doubt that Indian Railway's decision to decarbonize will help to reduce CO₂ emissions. These tactics have a great chance of reaching net-zero goals.

The proposal has huge social implications. Indian Railways' embrace of low-carbon energy option will have a huge positive impact on society. There would also be some intangible benefits, such as environmental benefits, in addition to the benefits that were assessed for economic analysis. By reducing Indian Railways' reliance on fossil fuels, the low-carbon energy choice will lessen the environment pollution and will generate employment in the direct and indirect employment in related sectors. India's railway sector contributes 4% of the country's 12% greenhouse gas emissions from the transportation sector. Decarbonization will therefore aid in lowering GHG emissions.

The decarbonization of Indian railway will have the following implications as well such as creation of jobs in the renewable energy sector, better public health from lower air pollution, and increased energy security through energy source diversification.

7.2 DEMATEL - AHP-Fuzzy TOPSIS

Empirically it signifies that is going to be challenging times for Indian Railways as it is no longer an issue with respect to infrastructure as approximately 99.6% of the broad gauge network has been by this July 2026 electrified which is second to Switzerland. More interestingly "diesel consumption for railway traction falls from 293 crore litres in 2015-16 to 108. Crores litres in 2024-25, saving forex and reducing

carbon emissions", as per PIB released on 22nd July 2026. Significant reduction of approximately 63.1%. This is a clear indication time has come for Indian Railways to emphasise now on to three major components which are low carbon intensity of electricity supply, integration of renewable energy and how can energy efficiency be improved.

Renewable-powered electrification is the top ranked pathway in TOPSIS analysis (Closeness coefficient of 0.5945). Pathway Rankings have been given which are Rank 1 renewable-powered electrification 0.5945, Rank 2 Solar energy integration 0.5121, Rank 3 Energy-efficiency and regenerative-braking measure 0.5085, Rank 4 Wind-solar storage integration 0.4957, Rank 5 Green-hydrogen traction 0.4780, and lastly Rank 6 Battery-electric traction 0.3583.

It is quite evident from the above data that focus now has to be shifted to only component which is the renewal. This is in-line with the current scenario where infrastructure of broad gauge network is almost completely electrified raising another compressing issue where one understand that any additional investments in conventional electrification will not give any yield or rather it will be a question of diminishing yield.

Solar Energy integration can also bring a drastic a significant impact as suggested by the Pathway Rankings. Indian Railways has already matured itself by a pilot-level intervention to large scale visible component. This November 2025 Indian Railways had already commissioned approximately 812 MW of solar capacity. In line with the expectations and hope of Indian Railways. clearly demonstrates the shift from large scale investments to utilisation of unconventional use of energy which is in abundance in India. To add to the above components the usage of energy efficiency and regenerative-braking can also improve the energy requirements during braking. Wind-solar-integration is also a tested and globally acceptable form of unconventional ways to generate power. The only factor which leads to its set back is storage and system integration. Indian Railways has been progressing in this direction. Green hydrogen could also be a part in efficiently progressing towards Decarbonisation. This is quite evident from India's first hydrogen train on the Jind-Sonipat section. There are basic issues related to hydrogen production, storage and refuelling. Infrastructure needs to significantly improve to create more efficiency and effectiveness. Being the lowest in the Pathway ranking is Battery-electric Traction, which should never be read as rejected technology. But deployment of large scale battery, its charging technology and specific railways requirements still needs more to it.

Overall, Indian Railways needs to focus on these three parameters. Firstly, Maximisation of environmental benefits of already electrified railways using renewable electricity and energy-efficiency measure. Secondly, storage and integration of renewable-energy which is a must part to make it more financially compatible. Lastly hydrogen and battery could be chosen on the basis of availability(both operational and economical advantage) and must be pursued selectively.

8.0 Limitation:

This study has not considered the intangible benefits. Including intangible benefits like the environmental impact would have increased the IRR. Further, higher product costs could result from the shift to low-carbon paths. Therefore, it might become essential to adopt suitable pricing mechanisms for environmental impact. To enable precise assessments of environmental impacts, more study is required on the lifetime assessment of emissions reductions.

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