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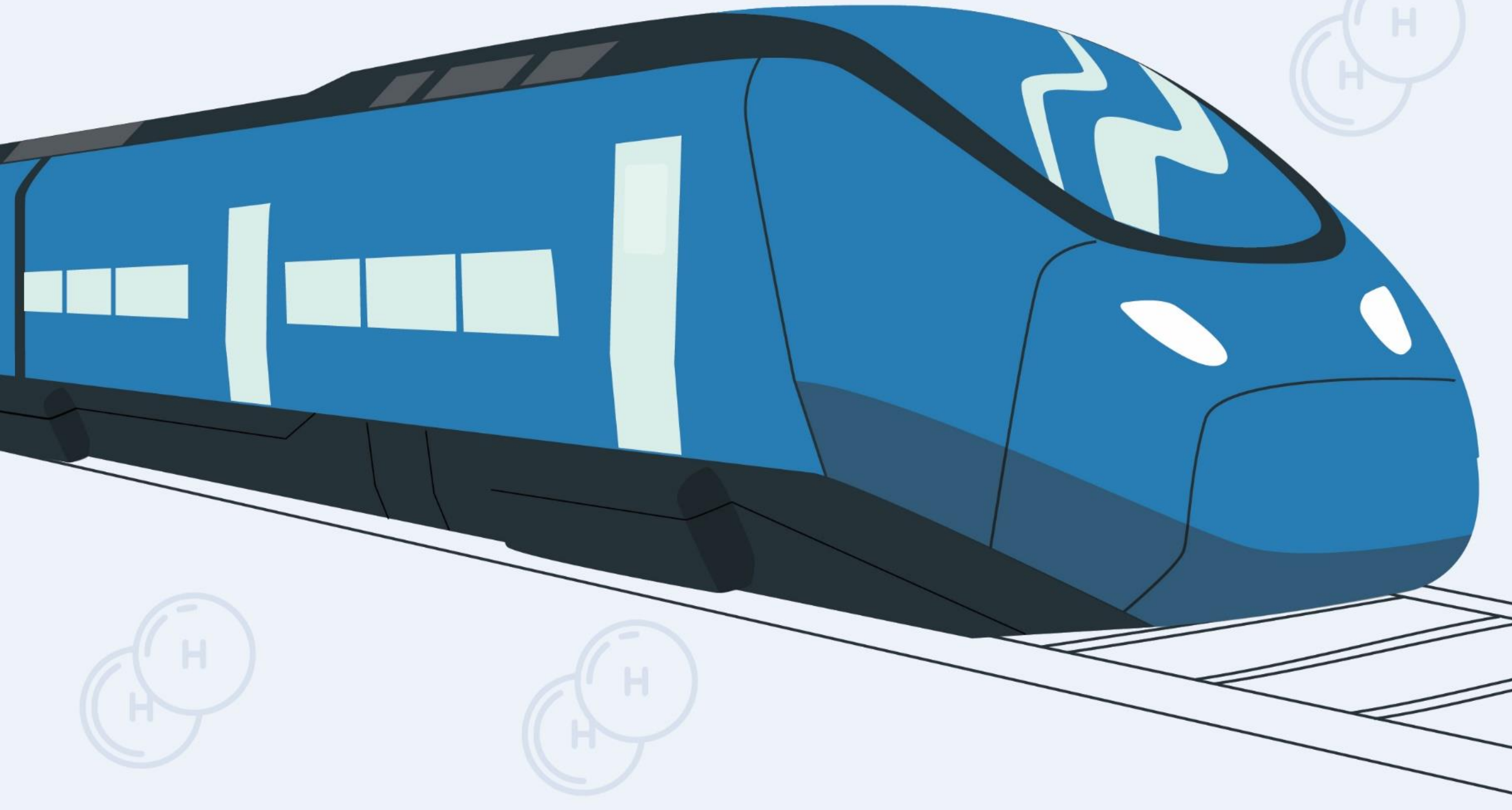
POTENTIAL AND CHALLENGES OF USING HYDROGEN TO DECARBONISE INDIAN RAILWAYS



Potential and Challenges of Using Hydrogen to Decarbonise Indian Railways

Dhiraj Kumar

Dhruv Rajeev

Vengdhanathan S

Vivek Gavimath

Center for Study of Science, Technology and Policy

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Editor: Shayantani

Designer: Pooja Senthil

Bengaluru

No. 18, 10th Cross, Mayura Street

Papanna Layout, Nagashettyhalli

RMV Stage 2, Bengaluru 560094

Karnataka (India)

Tel.: +91 (80) 6690 2500

Email: cpe@cstep.in

Noida

1st Floor, Tower-A

Smartworks Corporate Park

Sector 125, Noida 201303

Uttar Pradesh (India)

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Executive Summary

The Indian Railways is one of the largest railway networks in the world, transporting millions of passengers and tonnes of freight daily. It has had a historically high demand for fossil fuels to meet the operational energy requirements, resulting in high operational costs and a high emission footprint. The government aims to tackle these challenges through 100% electrification of the railway network by 2024 and by becoming a net-zero emitter by 2030. Although the rate of electrification has been significant (over 93% of broad-gauge routes are electrified at present), concerns remain on the economic feasibility of electrifying certain sections of railways. In this context, there is a potential for transitioning to other clean energy alternatives, such as green hydrogen. The Center for Study of Science, Technology and Policy (CSTEP) conducted a study to examine the potential for using green hydrogen on existing railway routes. The technical feasibility and financial viability of hydrogen-based trains were assessed based on two use cases:

- Kalka–Shimla route, a hilly terrain, and
- Industrial shunting yard route, used by public sector undertakings/private industries.

The potential hydrogen-powered trains were compared against existing diesel-powered trains, electrified lines, and battery-powered trains. The findings of the two use cases showed a favourable outcome for hydrogen trains.

Lifetime costs and emissions: Comparison of locomotives on the Kalka–Shimla route

	Diesel (base)	Green hydrogen	
Annual fuel consumption	3,45,816 L	40,895 kg	9.3 MWh (backup)
Capital cost (INR crore)	27	41–50	
Lifetime cost (INR crore)	103	70–85	
Annual greenhouse gas emissions (tonnes of CO_2/year)	899	6.5	

In the Kalka–Shimla route, hydrogen-powered trains had higher initial costs (approximately INR 41–50 crore) than diesel-powered trains (approximately INR 27 crore). However, owing to factors such as the expected drop in green hydrogen costs and achieving higher energy conversion efficiency, hydrogen trains may offer an overall lifetime cost savings of INR 18–33 crore compared with diesel-powered trains. Electric battery-powered trains were economically competitive from an initial cost perspective; however, although they had lower overall fuel costs than hydrogen-powered trains, the equipment replacement costs were high. Overall, the lifetime costs of battery-powered trains (INR 73 crore) and hydrogen-powered trains (INR 69 crore) were similar. However, the modelled train was excessively large in volume and was above the weight allowance. Hence, battery-powered trains could not be considered. Lastly, a comparison was made with trains running on electrified lines, but extremely high initial costs (~INR 150 crore) make it an economically unviable option for such low-frequency routes.

Lifetime costs and emissions: Comparison of locomotives on the industrial shunting yard route

	Diesel (base)	**Green hydrogen**	
Annual fuel consumption	4,32,000 L	76,800 kg	1.47 GWh
Capital cost (INR crore)	10	15–25	
Lifetime cost (INR crore)	109	83–109	
Annual greenhouse gas emissions (tonnes of CO_2/year)	1123	1046	

In the industrial shunting yard route, hydrogen-powered trains showed higher initial costs (INR 15–25 crore) than diesel-powered trains (INR 10 crore); this cost was lower than that for the Kalka–Shimla route because of the absence of bogeys. However, owing to factors such as the expected drop in green hydrogen costs and achieving higher energy conversion efficiency, hydrogen trains may offer an overall lifetime cost savings of up to INR 26 crore compared with diesel-powered trains. The electric battery-powered trains had higher initial costs (INR 20–35 crore); however, although they had lower overall fuel costs than hydrogen-powered trains, the equipment replacement costs were high. Overall, battery-powered trains had higher lifetime costs (INR 113–155 crore) than hydrogen-powered trains (INR 83–109 crore). Moreover, the modelled train was excessively large in volume and was above the weight allowance. Hence, battery-powered trains could not be considered. Lastly, a comparison was made with trains running on electrified lines, but extremely high initial costs (~INR 183 crore) make it an economically unviable option for such low-frequency routes.

This study indicated the potential for using green hydrogen-powered trains based on the techno-economics of their performance. However, it must be noted that there are several impediments to green hydrogen-based trains becoming a reality. Major concerns include hydrogen fuel safety and high initial costs. Given the high electrification rate of railway tracks in the country, there are also questions on how hydrogen-powered trains can be integrated with the current/future electrified tracks. Moreover, to replace the industrial shunting yard and Kalka–Shimla tracks, an estimated 117 tonnes of green hydrogen would be required annually. However, India's current green hydrogen production is still at a nascent stage and the required volumes cannot be produced at the aforementioned costs yet.

Based on the analysis, the immediate measures for increasing the uptake of hydrogen in the sector are given below:

- Identifying low-frequency railway routes that can be suitable for green hydrogen usage
- Building backward linkages (e.g. storage, refuelling, and hydrogen pipelines/trucks)
- Conducting more pilot projects to better understand the future challenges of green hydrogen usage in railways

In addition to these steps, the following broad measures are required to enable a thriving green hydrogen ecosystem to support any future demand for hydrogen from the railways:

- Mandating clean fuel use in industrial shunting zones
- Implementing regional clean air action plans to promote cleaner fuels such as green hydrogen
- Establishing a defined domestic manufacturing strategy for green hydrogen and its components (including storage and fuel cells), inclusive of targets and financing
- Aggregating orders from railways to drive down capital costs

Regardless of the overall benefits of electrified lines, the variety of technical challenges faced in railway operations necessitates a technology-agnostic approach to decarbonisation. Despite being a niche application, the potential benefits of the hydrogen economy must also be considered as a reason to promote green hydrogen usage in the railways sector.

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Abbreviations

CAPEX	Capital expenditure
CO_2	Carbon dioxide
DEMU	Diesel electric multiple unit
GHG	Greenhouse gas
NDC	Nationally determined contribution
PSU	Public sector undertakings
RDSO	Railway Development and Standards Organization
SFC	Specific fuel consumption

1. Background

India has set ambitious climate goals as part of its nationally determined contributions (NDCs) to tackle the climate crisis. Two of these targets are in the form of short-term measures such as reduction of the emission intensity of energy consumption of its gross domestic product by 45% and the installation of 50% of non-fossil fuel-powered capacity by 2030 (PIB, 2022). In the long term, India aims to achieve a net-zero economy by 2070. To meet these NDC targets, the Government of India has launched several schemes across multiple sectors, including agriculture, energy, infrastructure, sustainable mobility, and waste management.

The Indian Railways is one of the largest railway networks in the world. However, the sector's heavy reliance on fossil fuels for its energy requirements results in significant greenhouse gas (GHG) emissions. The railways sector has a substantial environmental impact as it is used to transport 3 million tonnes of freight and 24 million passengers daily. During 2020–2021 alone, the Indian Railways consumed 1.4 billion litres of fuel (Railways, 2021), leading to high GHG emissions. Thus, decarbonisation of the railways is a crucial step towards achieving these targets.

- **Global vs Indian scenarios**

Railway electrification is a proven and effective decarbonisation strategy, with substantial benefits including reduced GHG emissions, improved energy efficiency, and reduced operational costs. Globally, efforts are underway to electrify railway networks to meet the growing demand. Over 30% of 1.3 million km of tracks have already been electrified, although with a high geographical variance. More than 55% of the tracks in Western Europe have been electrified, whereas less than 2% of the major North American system has been electrified (Railway Pro, 2021). In recent years, most Asian economies, including China, South Korea, and India, have made rapid advances in electrifying their railway networks. Moreover, hydrogen trains are being explored in several countries, with projects in Germany and China making great progress. Coradia iLint™, the world's first hydrogen-powered train in Germany, is a passenger train built by Alstom that runs on hydrogen fuel cells to produce electricity (Coradia iLint, 2022). The first hydrogen-powered smart tram in China, built by the Chinese firm CRRC Qingdao Sifang Co Ltd, is currently operational in Tangshan (Alan, 2019).

The Indian Railways aims to achieve net-zero carbon emissions by 2030. It is taking proactive initiatives to reduce its fossil fuel consumption and achieve 100% electrification by 2024 (PIB Delhi, 2022). Overall, almost 94% routes, covering 65,536 km of the total broad-gauge routes, have already been electrified as of December 2023 (ETEnergyWorld, 2024).

Despite the benefits of railway electrification, challenges persist while electrifying areas with poor grid connectivity or difficult terrains. The high capital cost of installing electrification infrastructure, the technical feasibility of constructing electrified lines in hilly regions, and the cost-effectiveness and technical feasibility in low-frequency routes such as industrial shunting yards are important concerns.

- **Hydrogen as an alternative**

Green hydrogen produced via renewable energy sources is a viable clean alternative to diesel. It has a higher energy density than batteries and can be effectively stored/transported in large quantities. Several industries, including chemical and refining industries, have prior experience in handling hydrogen. Further, given the renewable energy potential in India, green hydrogen production would not primarily depend on energy imports. Importantly, green hydrogen production has lower infrastructure requirements than electrification strategies, with hydrogen-powered locomotives being technically capable of running on existing railway tracks. The uptake of green hydrogen in the Indian Railways would also be mutually beneficial for the larger hydrogen economy. If hydrogen trains are implemented, a significant and constant demand of hydrogen from the railways can be anticipated. At this nascent stage, increasing the scale of green hydrogen production can help reduce the costs of hydrogen fuel and associated technologies. This will help increase the penetration of green hydrogen into the broader economy.

Considering the challenges associated with railway electrification and the benefits of hydrogen-powered trains, the Indian government is looking at the possibility of running hydrogen-powered trains in areas harder to electrify, with an initial use case of eight heritage routes with harsh hilly terrain. Under the 'Hydrogen for Heritage' initiative, the Indian Railways has planned to launch 35 hydrogen trains on various heritage and hilly routes, at an estimated cost of INR 80 crore per train and ground infrastructure cost of INR 70 crore per route. In addition, a pilot project has been initiated to retrofit a diesel electric multiple unit (DEMU) rake with hydrogen fuel cells and related ground infrastructure at a cost of INR 111.83 crore, which is intended to operate on the Jind–Sonipat section of the Northern Railways. The first prototype of the retrofitted DEMU rake is expected to undergo field trials on this section by 2023–2024 (Shetty, 2023).

However, hydrogen remains a topic in theory for most applications, including railways, owing to several research and data gaps. India faces significant challenges in implementing hydrogen trains because of inadequate infrastructure and a lack of key technologies. Currently, India does not have the capability to produce green hydrogen at a commercial scale and faces a scarcity of the necessary raw materials, such as critical minerals, for manufacturing electrolysers. Furthermore, the country lacks a robust infrastructure for hydrogen transportation and storage and additional renewable energy generation, specifically dedicated to green hydrogen generation.

Nevertheless, the ongoing expansion of railway tracks in India provides a good opportunity for exploring green hydrogen application. In this regard, the current study aimed to assess the technical feasibility and financial viability of hydrogen-powered trains in a dynamic energy landscape like India, considering varying electricity prices and the growing market of hydrogen technologies.

1.1. Objectives

The main research objectives are given below:

1. Identifying use cases in Indian Railways where conversion to hydrogen trains is more suitable than electrification
2. Determining the basic techno-economic feasibility of replacing diesel engines with hydrogen fuel cell-powered engines (for freight and passenger trains)
3. Identifying research gaps in this field not covered in previous research or studies by other stakeholders (in the Indian and global context)
4. Monitoring emission estimation from diesel engine and comparing it with other alternatives

The study included two use cases in the Indian Railways (the Kalka–Shimla route and an industrial shunting yard route). In these cases, a potential hydrogen-powered locomotive was compared with the existing diesel locomotives and electric-powered locomotives. Our findings elucidate the techno-economic feasibility and emission benefits of these sustainable alternatives for the Indian railways, thereby aiding strategic decision-making towards a hydrogen-based sustainable future and green hydrogen-based energy transition.

2. Modelling and Analysis

2.1. Approach

The main components of the study methodology were as follows:

- Conducting a literature review of hydrogen technologies, diesel and electric locomotives, and current railway operations in India (including refuelling infrastructure) and exploring the existing research gaps;
- Performing a transport mode analysis based on the literature review and discussions with stakeholders to determine areas/routes unsuitable for electrification; and
- Analysing the techno-economic feasibility of hydrogen for freight and passenger trains.

Two railway routes were selected for a comprehensive techno-economic comparison of hydrogen trains against the existing options. This required building models of current engine usage in trains, identifying the appropriate type and size of hydrogen technologies to match the current requirements, financial modelling (capital and operating costs and total cost of ownership), and determining the systemic ramifications of conversion of trains.

The **Kalka–Shimla route** (a hilly terrain passenger train route) and an **industrial shunting yard route** (typically employed by public sector undertakings [PSUs] or private industries) were selected for the study.

We modelled a **hydrogen-powered train** and compared it with electric-powered trains (including **battery-powered trains** and **electrified lines**) and the existing **diesel trains (base scenario)**.

The models were compared based on their ability to meet the existing technical requirements for locomotives, the initial and lifetime costs of the trains, and the associated carbon dioxide (CO_2) emissions.

2.2. Study model

- **Diesel train (base)**

Currently, 37% trains in the Indian Railways system continue to rely on diesel as their primary fuel source, contributing significantly to GHG emissions (The Times of India, 2023). The fuel economy of these trains is measured based on their specific fuel consumption (SFC), which is defined by the amount of fuel consumed per unit of work done, to evaluate their overall performances. A lower SFC indicates a better fuel economy, highlighting the importance of improving efficiency to reduce emissions and promote sustainability in the railways sector.Table 1 displays the parameters considered in our case study for a diesel locomotive.

Table 1: Parameters considered for a diesel locomotive

	Kalka–Shimla	Industrial shunting yard
Fuel cost	INR 70/L	INR 70/L
CAPEX cost	INR 6 crore	INR 10 crore
SFC	6 L/km	9 L/km
Horsepower	700	1600

CAPEX: Capital expenditure; SFC: specific fuel consumption

- **Fuel cell train**

A hydrogen fuel cell utilises the chemical energy of hydrogen to generate electricity. The operation of a hydrogen fuel cell results in the production of electricity, heat, and water as its only by-products. This technology finds applications in various fields, ranging from transportation to emergency power backup, and can power systems of various sizes, from small electronic devices to large-scale power plants. Compared with traditional combustion-based technologies, fuel cells provide several advantages, including higher efficiency and reduced emissions. Hydrogen fuel cells are an environmentally sustainable choice because of the absence of CO_2 and other pollutant emissions during their operation. Furthermore, fuel cells operate quietly owing to their minimal number of moving parts, distinguishing them from combustion technologies.

Hydrogen has traditionally been produced from fossil fuel sources, such as natural gas and coal. However, the study model considered the use of green hydrogen (produced from the electrolysis of water and powered by renewable energy sources) to meet the decarbonisation criteria.

Table 2 shows the parameters for a hydrogen fuel cell locomotive considered in this study.

Table 2. Parameters considered for a hydrogen fuel cell locomotive

Parameter	Value
Fuel cell type	Proton exchange membrane (Ministry of Railways, 2020)
Fuel cell efficiency	60%
Fuel cell rating	90 kW (Ahluwalia et al., 2020)
Fuel cell volume	0.076 m^3 (Fuelcellworks, 2019)
Fuel cell cost (INR/kW)	INR 23,438/kW
Hydrogen storage technology	Compressed hydrogen (350 bar pressure) (Ministry of Railways, 2020)
Hydrogen storage volume	0.04607 m^3/kg
Weight of hydrogen stored in a single cylinder	5.6 kg
Cost of hydrogen refuelling station	INR 3.895 crore
Current cost of green hydrogen	INR 492/kg

- **Battery electric train**

There have been significant advancements in battery technology, expanding the potential applications of batteries beyond their previous niche uses. Although electrification of railway lines is considered more beneficial than battery-operated trains, the latter may prove to be viable under certain railway scenarios, despite their high initial purchase cost and the additional high weight of battery retrofitting. This is primarily due to the reduction of the substantial costs and maintenance efforts associated with full-line electrification. Table 3 lists the parameters for a battery-powered locomotive considered in this study.

Table 3. Parameters considered for a battery-powered locomotive

Parameter	Value
Battery cost	INR 12,300/kWh (Bloomberg, 2022)
Dimensions of a single battery unit	0.66 × 0.30 × 0.07 m^3
Weight of a 1 kWh battery	24.9 kg
Current electricity cost	INR 7/kWh

- **Electrified line**

The Indian Railways has achieved a remarkable feat by electrifying almost 94% of its broad-gauge routes (ETEnergyWorld, 2024). The Indian Railways has been actively driving this initiative and aims to accomplish 100% electrification by 2024. Over 65,000 km of the total broad-gauge routes have been electrified as of December 2023, resulting in several benefits including decreased GHG emissions, reduced operating costs, and enhanced energy efficiency.

Table 4 displays the parameters for electrified lines considered in this study.

Table 4. Parameters considered for electrified lines

	Kalka–Shimla	**Industrial shunting yard**
Additional cost factor considered due to terrain	20% CAPEX	0% CAPEX
Electrification infrastructure costs per km (INR crore/km)	1.6	1.35 (South Central Railway, 2022)
Duration of battery backup	60 min	60 min
Electricity cost	INR 7/kWh	INR 7/kWh (Shakti Sustainable Energy Foundation, 2019)

CAPEX: Capital expenditure

Table 5 lists the additional parameters considered for all four models in this study for precise calculation.

Table 5. Additional parameters considered in the study

Parameters	**Value**
Train lifetime	30 years
Grid emission factor	0.71 kg CO_2/kWh
Number of trips per year	300

3. Results

3.1. Case study 1: Kalka–Shimla route

The Kalka–Shimla route spans approximately 96 km and has an elevation gain of 1,620-m above sea level (Himachal Pradesh State Legal Service Authority, 2018). This heritage route is renowned for its narrow-gauge railway line and is home to five iconic toy trains. Each train has a lower capacity (up to eight carriages) designated for passenger transportation.

- **Diesel train (base)**

On the Kalka–Shimla route, the fuel cost of a diesel train for one round trip is INR 80,690 and the total diesel cost at the end of its lifetime is INR 72.6 crore. The capital expenditure (CAPEX) of this diesel train is INR 27 crore, and the total cost of ownership of the train after 30 years is INR 103.2 crore. The amount of CO_2 emissions on this route for 1 year is approximately 899 tonnes.

- **Hydrogen fuel cell-based train**

The utilisation of a hydrogen fuel cell retrofit kit, in conjunction with other storage modules, has been proposed as a replacement for the current diesel-powered locomotive. To ensure its feasibility, it is necessary to maintain an acceptable weight and a volume limit for retrofitting. Our study revealed that the total weight for retrofitting is 3.1 tonnes, which falls within the allocated value, and sufficient space is available for retrofitting.

Assuming hydrogen storage at a pressure of 350 bar, each cylinder can contain 5.6 kg of hydrogen, with a volume of 0.0258 m^3. The cost of each cylinder is INR 2.3 lakh. To power the engine, five modules of fuel cells, each with a capacity of 90 kW, and 25 cylinders for hydrogen storage are required. During one trip, the excess power requirement is fulfilled by the retrofitted battery that consumes electricity to charge. The remaining power can be generated by the hydrogen fuel cell. The amount of hydrogen required for one round trip is 136 kg.

At the end of the lifetime of the locomotive, the overall cost of the hydrogen fuel will be INR 22.7 crore and the overall electricity cost will be INR 9.1 lakh. The CAPEX of the hydrogen-powered locomotive is approximately INR 41–50 crore, and the total cost of ownership of the hydrogen train after 30 years is INR 70–85 crore. Equipment replacement costs (for items such as inverter, battery, motor, and hydrogen storage cylinder) have also been factored into the lifetime costs.

- **Battery electric train**

According to the Railway Development and Standards Organization (RDSO), the weight allowance for retrofitting all components of the toy train running on the Kalka–Shimla route is limited to 9.25 tonnes. However, the calculated weight of a battery alone amounts to 16 tonnes, which exceeds the weight allowance. Despite the technical limitation, the economic modelling and emissions were calculated considering potentially different circumstances in the future (such as a change in regulations and technological breakthroughs).

The overall electricity cost to charge these batteries will amount to approximately INR 12.6 crore at the end of their lifetime. The CAPEX for battery-powered trains is approximately INR 39–43 crore, and the total cost of ownership is approximately INR 73–90 crore. Equipment replacement costs (for items such as inverter, battery, and motor) have also been factored into the lifetime costs.

- **Electrified lines**

Based on our calculations, the weight of the retrofit kit falls within the allowable limit, making the case worthy of further study. However, it is important to note that the cost of laying overhead infrastructure for electric trains is substantial, resulting in a high CAPEX. Specifically, the CAPEX for an electrified train line is estimated to be around INR 150 crore, and the total cost of ownership for 30 years is approximately INR 165 crore.

Moreover, the operating cost of the electric train is a significant factor to consider. For instance, the electricity cost per round trip is INR 23,855, and the overall cost of electricity consumed over the lifetime of the train is approximately INR 12.5 crore. Equipment replacement costs (for items such as inverter, battery, and motor) have also been factored into the lifetime costs.

Overall, although the weight of the retrofit kit falls within acceptable limits, the high CAPEX and operating cost associated with electrifying this hilly terrain railway line necessitate a comprehensive evaluation of the potential benefits and drawbacks before implementation.

Table 6. Lifetime cost and GHG emissions of locomotives: Kalka–Shimla route

	Diesel (base)	Electric battery*	Electrified line	Green hydrogen	
Annual fuel consumption	3,45,816 L	1,022.4 MWh	1,013.6 MWh	40,895 kg	9.3 MWh (backup)
Capital cost (INR crore)	27	39–43	150	41–50	
Lifetime cost (INR crore)	103	73–90	165	70–85	
Annual greenhouse gas emissions (tonnes of CO_2/year)	899	725	719	6.5	

** Battery trains exceed the specified weight limit, which is a technical limitation.*

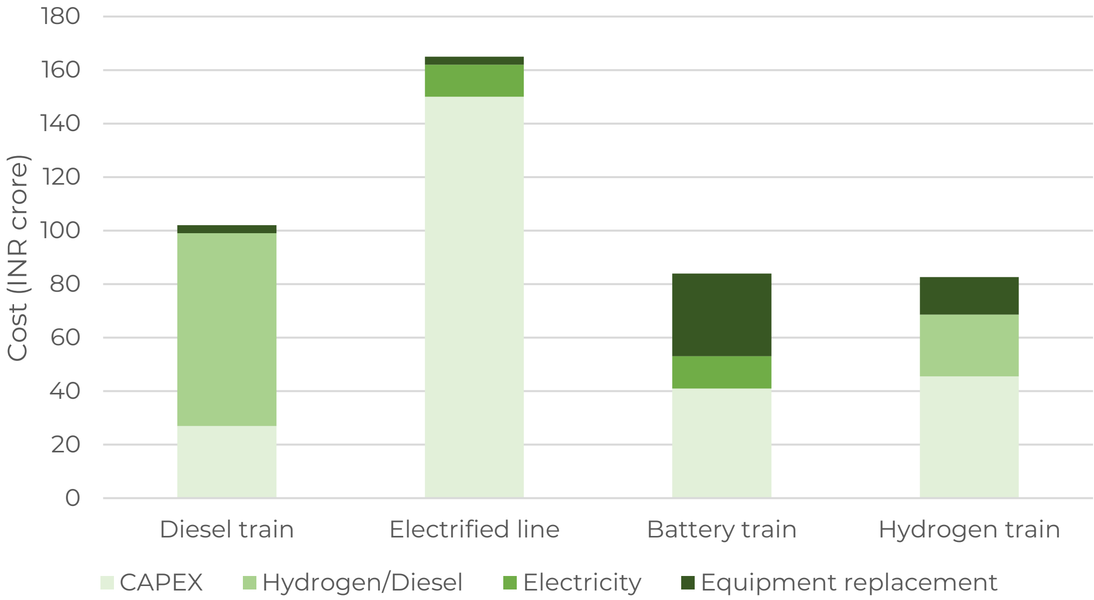

Figure 1. Lifetime cost of various locomotives on the Kalka–Shimla route

3.2. Case study 2: Industrial shunting yard route

Several major industries employ internal railway tracks to transport goods and facilitate material transfer in their yards, particularly for heavy loads. These locomotives typically cover short distances and operate for about 8–12 hours every day.

- **Diesel train (base)**

In industrial shunting yards, a diesel train running for about 8 hours per day incurs a fuel cost of INR 1 lakh for a round trip, with a total diesel cost of INR 90.7 crore over its lifetime. The train has a CAPEX of INR 10 crore and a total cost of ownership after 30 years of INR 110 crore, emitting approximately 1,123 tonnes of CO_2 emissions per year.

- **Hydrogen fuel cell-based train**

Our analysis revealed that retrofitting an existing diesel locomotive with a hydrogen fuel cell retrofit kit, in conjunction with other storage modules, is feasible while adhering to the acceptable weight and volume limits. The total weight for retrofitting is 7.1 tonnes, which is within the allotted value, and sufficient space is available. Assuming hydrogen storage at a pressure of 350 bar, each cylinder can contain 5.6 kg of hydrogen, with a volume of 0.0258 m^3. The cost of each cylinder is INR 2.3 lakh. The locomotive requires nine fuel cell modules, each with a capacity of 90 kW, and 46 hydrogen storage cylinders. The excess power requirement of 3,931 kWh during one trip is fulfilled by the retrofitted battery that consumes electricity to charge, with the remaining power generated by the hydrogen fuel cell. The lifetime cost of a hydrogen fuel cell-based train is approximately INR 83–108 crore. The CAPEX of the hydrogen locomotive is approximately INR 15–25 crore, and the fuel cost over 30 years (hydrogen and electricity) is approximately INR 57 crore. Equipment replacement costs (for items such as inverter, battery, motor, and hydrogen storage cylinder) have also been factored into the lifetime costs.

- **Battery electric train**

In accordance with the RDSO regulations, the weight allowance for retrofitting all components in a train of such power capacity is limited to 20.32 tonnes. However, the weight of the battery alone to power this train amounts to 45 tonnes, exceeding the acceptable limit.

The estimated electricity cost to charge these batteries over their lifetime is approximately INR 35 crore, and the CAPEX is approximately INR 20–35 crore. The total cost of ownership for a battery-powered train is approximately INR 113–155 crore. Equipment replacement costs (for items such as inverter, battery, and motor) have also been factored into the lifetime costs.

- **Electrified line**

Our analysis indicated that the weight of the retrofit kit is within the allowable limit, and further investigation of its feasibility is recommended. However, it is essential to consider the high CAPEX associated with the installation of the overhead infrastructure for electric trains. The estimated CAPEX for electrifying the train line is INR 183.8 crore, with a total cost of ownership of INR 221 crore over 30 years. The electricity cost per round trip is approximately INR 58,672, and the overall cost of electricity consumed over the lifetime of the train is expected to be around INR 30 crore. Equipment replacement costs (for items such as inverter, battery, and motor) have also been factored into the lifetime costs.

In summary, although the weight of the retrofit kit falls within the acceptable limits, the high CAPEX and operating cost involved in electrifying an industrial shunting line warrant a careful evaluation of the potential benefits and drawbacks.

Table 7. Lifetime cost and GHG emissions of locomotives: Industrial shunting yard route

	Diesel (base)	**Electric battery***	**Electrified line**	**Green hydrogen**	
Annual fuel consumption	4,32,000 L	2.86 GWh	2.51 GWh	76,800 kg	1.47 GWh
Capital cost (INR crore)	10	20–35	183	15–25	
Lifetime cost (INR crore)	109	113–155	221	83–109	
Annual greenhouse gas emissions (tonnes of CO_2/year)	1123	2033	1785	1046	

** Battery trains exceed the specified weight limit, which is a technical limitation.*

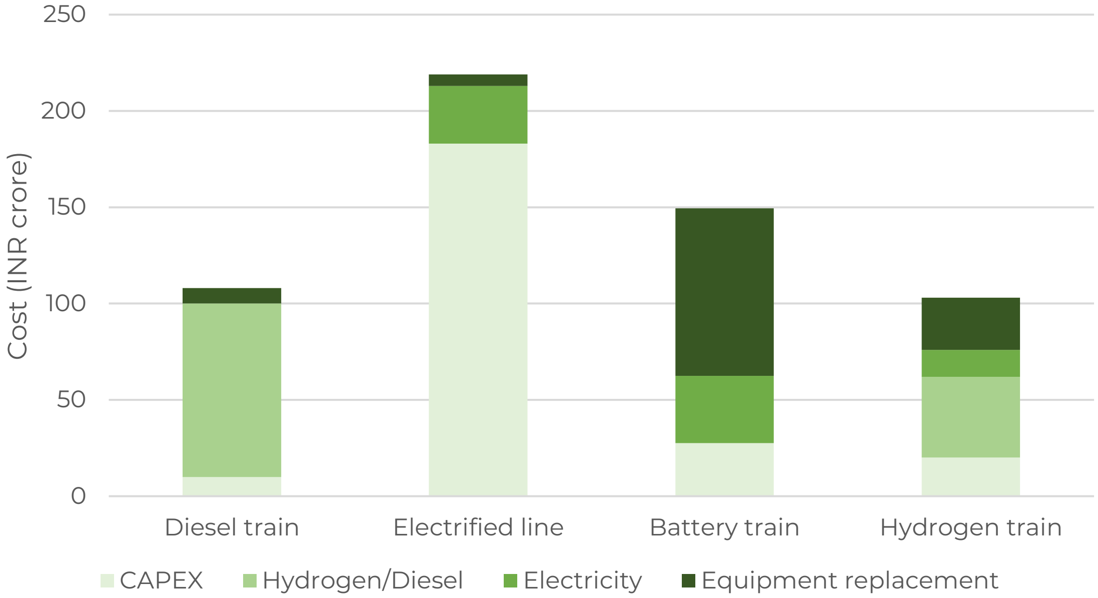

Figure 2. Lifetime cost of various locomotives on an industrial shunting yard route

4. Discussion

The implementation of hydrogen trains, similar to that of any new technology, presents several challenges that warrant further examination. The gaseous and explosive nature of hydrogen and the need for additional safety precautions for railway operations are some of the important concerns. This section discusses vital challenges and opportunities pertaining to our case studies.

4.1. Challenges

- **Current limitations of green hydrogen production**

For the two routes considered here, over 117 tonnes of green hydrogen is required annually. This study assumed the cost of green hydrogen production to be around INR 492/kg (equivalent to USD 6/kg). Given the nascent stage of the domestic hydrogen economy and the lack of necessary infrastructure to produce green hydrogen at a large scale, **achieving the required production capacity** and **the aforementioned costs** are significant challenges at present. For instance, currently, India does not have a high-capacity proton exchange membrane-based electrolyser plant required to produce green hydrogen from renewable energy sources and is thus heavily dependent on external entities to adapt to this technology. India also faces significant challenges in manufacturing its own electrolysers, as it lacks many critical minerals needed to produce these systems. Further, there is a scarcity of domestic manufacturers for most components. Currently, most of the hydrogen produced in the country comes from steam methane reforming (Anand, 2023). Despite being produced at a much cheaper rate of around INR 150/kg, grey hydrogen is deemed environmentally damaging owing to its high carbon footprint (about 9.3 kg CO_{2eq} emissions for every kg of hydrogen produced) and thus cannot be considered a decarbonisation alternative (IEA, 2023). In addition to other challenges in realising the potential of green hydrogen, India requires significant investments to develop the necessary infrastructure, overcome critical mineral constraints, and support technological innovation.

- **Infrastructure inconsistency**

At present, the Indian Railways face a shortfall in auxiliary infrastructure crucial for the seamless integration of hydrogen into their locomotives. This deficit encompasses vital components such as pipelines, refuelling stations, compressors, and control devices, which are instrumental in efficiently injecting hydrogen into the trains. Without a well-established infrastructure to support hydrogen transportation and refuelling, the feasibility and effectiveness of hydrogen trains in India remain uncertain. Thus, it becomes imperative to prioritise the development of the necessary infrastructure. Furthermore, domestically, a sense of uncertainty exists in terms of the economic feasibility of the transport and storage of hydrogen. There are valid questions regarding the cost-effectiveness of transporting hydrogen across the railway network and the establishment of storage facilities. Overcoming this ambiguity offers the potential opportunity for large-scale transport and storage of hydrogen. Thus, the Indian Railways must collaborate with relevant stakeholders, including energy companies, to devise comprehensive solutions for ensuring the cost-efficient and safe supply of hydrogen for trains.

- **Consumption conundrum**

The uptake of hydrogen trains domestically remains unclear, as there is no definite roadmap on the extent of hydrogen adoption in the Indian Railways, leading to an uncertainty in the demand for hydrogen trains in India. The lack of interoperability measures (connecting to existing or future electrified railway tracks) also adds to the challenge of integration of hydrogen trains in the operations of the Indian Railways.

4.2. Opportunities

The current fuel cost for hydrogen-powered trains exceeds the diesel costs of conventional trains by approximately 21%. However, this disparity is expected to diminish significantly with the increasing adoption of renewable energy sources, leading to a reduction in green hydrogen production costs. Moreover, the nascent hydrogen technologies hold immense potential for cost reduction through ongoing research and development. As these technologies mature and become more efficient, the lifetime cost of hydrogen trains is anticipated to decrease further. This trajectory points towards a future where hydrogen-powered trains could become a financially viable and sustainable alternative to conventional diesel-powered trains.

It is also essential to look at hydrogen-powered trains in conjunction with electric-powered trains from an energy independence perspective. With the help of possible synergies in renewable energy production, there exists a potential opportunity to unlock greater reduction in energy dependency across the railways sector as a whole.

Furthermore, the uptake and wider adoption of hydrogen trains domestically offer a potential opportunity to overcome the barriers to its adoption in other sectors of the economy through the benefits of technology development and large-scale production. However, it is worth noting that at this juncture, the production of green hydrogen in India is low and the hydrogen economy is only focused on the industrial sector.

5. Recommendations

In the previous Union Budget (2023–2024), there were relevant takeaways in terms of the adoption of clean technologies, from the 'Hydrogen for Heritage' initiative to the increased promotion of renewable energy and setting up of additional railway corridors in the country. The National Hydrogen Mission also acknowledges the potential role of the Railways Ministry. The Indian Railways can aid the advancement of hydrogen technologies by taking the following steps:

- **Conducting pilot projects:** Pilot projects offer several benefits, including testing feasibility, identifying challenges, refining strategies, and evaluating outcomes on a small scale before full-scale implementation. They provide valuable insights, minimise risks, and inform evidence-based decision-making for successful and efficient large-scale adoption. Thus, it is imperative that the Indian Railways implement hydrogen trains beyond heritage routes to other small stretches of regular commercial routes to evaluate their feasibility.
- **Establishing route supply chains:** For the successful adoption of hydrogen trains, in addition to technological advancement, additional efforts towards establishing a reliable and resilient supply chain(s) are vital. Building backward linkages on selected routes including storage facilities, transportation facilities (such as pipelines and trailer trucks), and refuelling stations is essential for the smooth operation of hydrogen trains.
- **Identifying suitable routes:** For low-frequency routes typically connecting low demand (remote) areas, hydrogen trains present a cost advantage over electrified lines. Railways can factor in this advantage along with learnings from pilot runs in their track expansion and rationalisation plans. Additionally, long-term network expansion goals and objectives should be duly considered while identifying favourable routes for the adoption of hydrogen trains.

In addition, although the railways will be the implementation authority for hydrogen trains, support is required from the renewables and environment ministries and PSUs to first build an overall system capable of supporting the hydrogen demands of railways.

- **Enforcing mandates:** Given the presence of internal railway tracks in PSUs, the government can mandate hydrogen usage in industrial shunting zones to a greater extent and disseminate hydrogen-powered locomotive technologies.
- **Revising clean air action plans:** The incorporation of hydrogen-powered trains should be contemplated as a solution within regional clean air action plans. Apart from fuel efficiency gains, the adoption of hydrogen trains can contribute to the

reduction of GHG and particulate emissions, particularly in environmentally protected areas and industrial zones where diesel trains currently operate.

- **Building domestic manufacturing strategies:** Hydrogen trains require a large supply of green hydrogen as well as components such as fuel cells and storage cylinders. A clear manufacturing strategy is required for meeting the demands in a cost-effective manner. The strategy must include clear manufacturing targets as well as financing and other enabling schemes (such as production-linked incentive scheme, subsidies, and tax rebates).
- **Implementing aggregation programmes:** The high CAPEX associated with fuel cells and electrolyser costs can be reduced through large-scale manufacturing (economies of scale). To achieve this, it is vital that manufacturers receive bulk orders, highlighting the need to aggregate the demand from different operators, i.e. Indian Railways and private operators. A relevant example is the demand aggregation of electric buses achieved across the country by the Convergence Energy Services Limited.

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CSTEP

CENTER FOR STUDY OF SCIENCE, TECHNOLOGY AND POLICY

Bengaluru

#18, 10th Cross, Mayura Street, Papanna Layout,
Nagashettyhalli, RMV II Stage, Bengaluru 560094,
Karnataka (India)

Noida

1st Floor, Tower-A, Smartworks Corporate Park, Sector 125,
Noida 201303, Uttar Pradesh (India)

www.cstep.in | +91 8066902500 | cpe@cstep.in | @cstep_India