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BEYOND ELECTRIFICATION: EVALUATING HYDROGEN TRACTION FOR INDIA'S NON-ELECTRIFIED RAILWAY CORRIDORS

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ABSTRACT

India's railway decarbonisation programme has made extensive electrification the principal pathway for reducing dependence on diesel traction. However, the economic and operational case for electrification is not uniform across the network. Low-density regional corridors, selected heritage routes and other hard-to-electrify sections may require alternative traction technologies. This study examines hydrogen fuel-cell rail as a complementary option rather than as a universal substitute for railway electrification. Drawing on secondary evidence from international hydrogen rail deployments and India-specific policy, technical and economic developments, the study evaluates hydrogen traction across four dimensions: route suitability, environmental performance, infrastructure requirements and economic viability. International evidence from Germany, Japan, France and the United Kingdom indicates that hydrogen rail is primarily being positioned for non-electrified regional services where fixed electrification infrastructure is difficult to justify. The Indian case, including the Hydrogen for Heritage initiative, the Jind–Sonipat pilot and development of an indigenous 1,200 HP hydrogen engine, demonstrates growing technological readiness. Nevertheless, high hydrogen costs, conversion losses across the hydrogen value chain, refuelling infrastructure requirements and unresolved route-level economics constrain large-scale deployment. The study argues that hydrogen rail should therefore be assessed through a route-specific decision framework that compares hydrogen with conventional electrification, diesel and battery-electric alternatives. Its strongest potential lies in corridors where traffic density and infrastructure conditions make overhead electrification economically unattractive, provided that low-carbon hydrogen is available at competitive cost. The paper concludes that India's hydrogen rail strategy should be selective, evidence-driven and integrated with the National Green Hydrogen Mission rather than pursued as a blanket alternative to electrification.

Keywords: Hydrogen rail; fuel-cell trains; railway decarbonisation; Indian Railways; green hydrogen; non-electrified corridors; techno-economic assessment

1. INTRODUCTION

The decarbonisation of railway transport is increasingly being shaped not by a single technological pathway, but by the need to match propulsion technologies with the operational and economic characteristics of individual rail corridors. Electrification through overhead catenary remains the dominant pathway for high-density and heavily utilised railway networks because of its operational efficiency and suitability for sustained traffic. However, extending electrification to every route may not always be economically or technically justified, particularly where traffic density is low, services are infrequent, terrain is challenging, or the cost of installing and maintaining fixed electrical infrastructure is disproportionately high. This creates a strategic space for alternative zero- or low-carbon traction technologies.

India provides an important setting in which to examine this question. Indian Railways has undertaken an extensive electrification programme and has substantially reduced its dependence on diesel traction across the broad-gauge network. Nevertheless, sections of the railway system continue to present distinct challenges for complete electrification. These include low-density regional corridors, selected heritage routes and routes where the capital expenditure associated with overhead electrical infrastructure may not be commensurate with expected traffic volumes. The question, therefore, is no longer whether railway electrification should continue, but whether complementary technologies can provide a more economically rational pathway for specific categories of routes.

Hydrogen fuel-cell rail traction has emerged internationally as one such alternative. Unlike conventional diesel traction, hydrogen fuel-cell trains can operate without direct carbon emissions at the point of use, while avoiding the requirement for continuous overhead electrical infrastructure. International experience, including commercial deployment in Germany and pilot development in Japan, France and the United Kingdom, demonstrates that hydrogen rail is increasingly being considered for non-electrified regional routes rather than as a universal substitute for electric railways. The relevance of these experiences to India, however, cannot be assumed. Differences in network scale, route characteristics, energy prices, hydrogen availability, infrastructure costs and policy conditions require a context-specific assessment.

The environmental case for hydrogen rail also requires careful qualification. The absence of tailpipe carbon emissions does not necessarily imply low lifecycle emissions. The overall environmental performance of a hydrogen-powered train depends substantially on the pathway through which hydrogen is produced, transported and supplied. Green hydrogen produced using renewable electricity can offer significant decarbonisation potential, whereas hydrogen produced through carbon-intensive pathways may substantially reduce or even undermine the environmental advantage of fuel-cell traction. Consequently, the assessment of hydrogen rail must extend beyond the train itself and consider the wider hydrogen-energy ecosystem.

Economic viability presents a second major challenge. Hydrogen traction involves expenditure on fuel-cell rolling stock, hydrogen production or procurement, storage, compression, refuelling, maintenance and safety systems. These costs must be assessed against the capital expenditure required for railway electrification and the operational limitations associated with alternatives such as battery-electric traction. The appropriate question is therefore not whether hydrogen is inherently cheaper or more efficient than electrification, but whether it provides a favourable solution under specific route-level conditions.

India’s emerging hydrogen rail initiatives provide an opportunity to examine this issue. The development of an indigenous hydrogen-powered train and the Hydrogen for Heritage initiative represent a transition from conceptual discussion towards technological demonstration. At the same time, the National Green Hydrogen Mission provides a broader policy framework for expanding domestic hydrogen production and infrastructure. These developments make India a relevant case for examining how hydrogen traction can be integrated into a broader railway decarbonisation strategy.

Against this background, this study examines the strategic suitability of hydrogen-powered trains within India's railway decarbonisation pathway. Rather than treating hydrogen as a replacement for railway electrification, the study evaluates its potential as a complementary technology for routes where conventional electrification may be economically or operationally constrained.This study has following research questions

- What lessons from international hydrogen rail deployments are transferable to the Indian railway context?
- Under what technical, environmental and economic conditions can hydrogen traction become viable on Indian railway routes?
- How can hydrogen rail be positioned within India's wider transition towards low-carbon railway transport?

The study contributes by linking international hydrogen rail experience with India-specific technological, infrastructural and policy conditions. It also shifts the assessment from a technology-centred question—whether hydrogen trains are viable—to a route-centred question concerning where and under what conditions hydrogen traction can create strategic value.

2. MATERIAL AND METHODS

Railway decarbonisation involves a portfolio of technologies rather than a single universally optimal solution. Conventional electrification provides high energy efficiency and is well suited to intensive services, but requires substantial fixed infrastructure. Battery-electric traction can avoid overhead infrastructure on selected routes, although vehicle mass, battery capacity, charging requirements and replacement costs may constrain deployment. Hydrogen fuel-cell trains convert stored hydrogen into electricity through fuel cells and can therefore provide zero-tailpipe-emission operation without continuous overhead catenary.

The strategic value of hydrogen consequently depends on the characteristics of the route and the surrounding energy system. A hydrogen train may be attractive where a route is long enough to challenge battery range, too lightly used to justify catenary investment, or operationally unsuitable for diesel replacement by other means. Conversely, where electrical infrastructure already exists or where traffic density supports electrification, hydrogen may be difficult to justify because of the additional energy-conversion steps and hydrogen infrastructure.

A second conceptual issue is the distinction between tailpipe and lifecycle emissions. Hydrogen rail should not be labelled inherently green merely because water is the principal direct by-product of fuel-cell operation. The environmental performance of the system depends on hydrogen production, electricity sourcing, compression, transportation and refuelling. This makes hydrogen rail simultaneously a transport technology and an energy-system question.

Global Evidence on Hydrogen Rail Deployment

Hydrogen is increasingly being examined for transport applications where direct electrification is difficult. Rail has become an important demonstration sector because fuel-cell trains can potentially replace diesel multiple units on regional routes without requiring continuous overhead electrical infrastructure.

Germany: Commercial Deployment

Germany provides the strongest commercial reference case in the supplied literature. Alstom's Coradia iLint was developed to replace diesel multiple units on non-electrified regional routes and entered commercial operation in Lower Saxony in 2018. The experience demonstrates the operational feasibility of hydrogen fuel-cell traction and has been followed by additional procurement interest. The case also illustrates that the environmental advantage of the train remains dependent on the carbon intensity of the hydrogen supply.

Japan: Hybridisation and Technology Development

Japan has pursued a more technology-development-oriented model through JR East's FV-E991 "HYBARI" system, which combines hydrogen fuel cells and batteries. The hybrid configuration is designed to improve efficiency and collect operational data before wider commercialisation. This approach highlights the possibility that future hydrogen rail systems may not rely on hydrogen as the sole energy-storage technology.

France and the United Kingdom: Regional and Pilot Approaches

France has pursued hydrogen trains for selected regional non-electrified routes, including the Régiolis H2 programme. The United Kingdom has concentrated substantially on demonstration and strategic studies, including HydroFLEX and regional hydrogen-rail assessments. Together these cases show that policy support, regional planning and hydrogen infrastructure development are central to deployment.

Cross-Country Lessons

Hydrogen rail is primarily targeted at non-electrified regional or branch routes rather than high-density mainline corridors.

Deployment requires simultaneous development of rolling stock, hydrogen supply and refuelling infrastructure.

Hybrid fuel-cell/battery configurations may improve energy efficiency and reduce hydrogen storage requirements.

Government policy and financial support are important because of high initial capital expenditure.

The environmental value of hydrogen depends strongly on the production pathway.

The study employs a structured secondary research design. Evidence was drawn from peer-reviewed and institutional sources, government and agency publications, industry materials and credible secondary reporting included in the supplied manuscript. The evidence was organised around four analytical dimensions: environmental performance, technical and operational suitability, economic viability, and policy and institutional readiness.

The comparative approach first examines international hydrogen rail deployments to identify recurring conditions for adoption. These findings are then interpreted against India's railway network characteristics, hydrogen policy framework, emerging pilot initiatives and infrastructure requirements. The methodology is therefore comparative and analytical rather than based on primary field data or an original engineering simulation.

The analysis specifically distinguishes between (i) technological feasibility, (ii) environmental benefit and (iii) economic viability. This distinction is important because a train may be technically feasible while remaining environmentally weak if supplied with carbon-intensive hydrogen, or environmentally attractive while remaining economically uncompetitive at current hydrogen prices.

India's Hydrogen Rail Readiness

Railway Electrification and the Remaining Challenge

Indian Railways has pursued an ambitious electrification programme, with more than 93% of the broad-gauge route network reported as electrified by mid-2025 in the supplied manuscript. The remaining non-electrified sections are not necessarily uniform: some are low-density routes, regional services or heritage corridors where the economics of fixed electrification differ from those of the main network. This creates the principal strategic context for evaluating hydrogen traction.

Hydrogen for Heritage and the Jind–Sonipat Pilot

The Hydrogen for Heritage initiative provides a practical Indian test case. The Jind–Sonipat project involves the retrofitting of existing diesel-electric multiple units and development of dedicated hydrogen storage and refuelling infrastructure. The supplied paper reports a planned hydrogen storage and refuelling facility at Jind with a capacity of 3,000 kg, alongside safety assessments including computational fluid dynamics studies and independent safety auditing.

Indigenous Technology Development

India has also developed an indigenous hydrogen engine reported at 1,200 horsepower. This technological development is strategically relevant because domestic engineering capability can reduce dependence on imported propulsion systems and potentially support localisation of the hydrogen rail value chain. It also creates an opportunity to adapt hydrogen traction to Indian operating conditions, including demanding gradients and diverse route environments.

Policy Ecosystem

The National Green Hydrogen Mission provides the broader policy environment for hydrogen rail. The supplied manuscript reports a mission target of 5 million metric tonnes of annual green hydrogen production by 2030 and identifies hydrogen hubs, renewable-energy integration and infrastructure development as key elements. Hydrogen rail, therefore, cannot be assessed independently from the success of the national hydrogen ecosystem.

Environmental, Technical and Economic Assessment

Environmental Performance

The environmental advantage of hydrogen rail is conditional rather than automatic. The supplied literature indicates substantial differences in lifecycle emissions between green, blue and grey hydrogen. Green hydrogen produced through renewable-powered electrolysis has substantially lower associated emissions, whereas fossil-based hydrogen can carry a much larger carbon footprint. The implication for Indian Railways is that hydrogen traction should be linked to credible low-carbon hydrogen sourcing if the technology is to deliver meaningful decarbonisation.

Energy Efficiency and the Hydrogen Value Chain

Hydrogen propulsion introduces additional conversion stages between renewable electricity and traction energy. Electricity must be used for electrolysis, followed by hydrogen compression, storage, distribution and reconversion through the fuel cell. This creates an efficiency penalty compared with direct use of electricity in electric rail traction. The penalty does not automatically eliminate hydrogen's value, because the relevant comparison on low-density routes may be against the capital cost of installing and maintaining overhead electrification rather than against an already-electrified railway.

Infrastructure Requirements

Hydrogen rail requires dedicated production or procurement arrangements, storage, compression, refuelling facilities, safety systems and trained personnel. Infrastructure must be sufficiently reliable to support railway operating schedules. The German experience demonstrates the importance of integrating hydrogen supply and refuelling with fleet deployment, while the Indian pilot provides an opportunity to generate route-specific evidence on infrastructure cost, water requirements, safety and operating reliability.

Economic Viability

The economic case remains one of the principal barriers to large-scale deployment. The supplied manuscript reports estimates of approximately ₹80 crore for a hydrogen trainset and ₹70 crore for associated route infrastructure in an earlier Indian planning context, while the Hydrogen for Heritage programme has substantially larger aggregate infrastructure requirements. Green hydrogen prices remain a major operating-cost variable. Consequently, hydrogen rail is unlikely to be economically attractive on every route.

The relevant economic comparison should instead be route-specific. Hydrogen should be evaluated against the cost of overhead electrification, diesel operation and battery-electric alternatives over the expected asset life. Capital cost, fuel cost, infrastructure sharing, utilisation, maintenance, replacement requirements and route duty cycle should all be included in such an assessment.

Safety and Institutional Readiness

Hydrogen introduces safety requirements associated with storage, handling, leakage, refuelling and emergency response. The Indian pilot's use of computational fluid dynamics analysis and independent safety assessment provides an important foundation for establishing operational standards. Wider adoption will require harmonised technical, regulatory and emergency-response frameworks.

3. DISCUSSION

The evidence supports a selective approach to hydrogen rail deployment. Rather than defining hydrogen as a national replacement technology, Indian Railways could classify routes according to operational and infrastructure characteristics.

Table 1. Railway hydrogen characteristics

Route characteristic	Hydrogen suitability	Alternative	Primary rationale
High traffic, existing/justified catenary	Low	Electrification	High utilisation supports fixed electrical

			infrastructure
Low-density, non-electrified regional route	Potentially high	Hydrogen / battery	Avoids continuous catenary investment
Short route with suitable charging windows	Moderate/low	Battery-electric	Direct electricity can be more efficient
Heritage/tourism route with limited traffic	Potentially high	Hydrogen / battery	Visibility plus avoidance of major fixed infrastructure
Longer non-electrified route with demanding duty cycle	Potentially high	Hydrogen	Range and energy-density considerations

This framework should not be interpreted as a quantitative decision model. It is a qualitative screening structure derived from the evidence in the supplied manuscript. A future empirical model should assign route-level weights to traffic density, route length, gradients, electrification cost, hydrogen availability, energy prices, battery requirements and lifecycle emissions.

The evidence indicates that the central policy question for India is not whether hydrogen rail is technically possible. Technical feasibility is increasingly demonstrated through international deployments and India's own pilot initiatives. The more difficult question is where hydrogen creates greater value than competing decarbonisation pathways.

Three findings are particularly important. First, hydrogen rail has a niche but potentially meaningful role in the railway decarbonisation portfolio. International cases consistently associate the technology with non-electrified regional routes. Second, environmental performance depends on the hydrogen supply chain. A hydrogen train supplied by carbon-intensive hydrogen may not achieve the intended climate benefit. Third, economic viability is highly route dependent because hydrogen's higher energy-system complexity must be weighed against the capital cost of extending fixed electrification.

For India, this suggests a portfolio approach. Electrification should remain the principal strategy for high-density corridors and routes where catenary infrastructure is economically justified. Battery-electric systems may be appropriate for selected shorter routes with favourable charging conditions. Hydrogen can be reserved for corridors where range, infrastructure or duty-cycle characteristics make these alternatives less attractive. Such differentiation would reduce the risk of technology lock-in and improve the efficiency of public investment.

The National Green Hydrogen Mission is therefore a critical external variable in the hydrogen rail case. Falling green hydrogen costs, domestic manufacturing, hydrogen hubs and improved supply logistics could materially change the economics over time. Conversely, if hydrogen remains expensive or carbon intensive, hydrogen rail may remain confined to demonstration and highly specific applications.

4. IMPLICATIONS

The Hydrogen for Heritage initiative should be leveraged to generate systematic operational evidence on hydrogen consumption, maintenance requirements, refuelling time, safety incidents, reliability, passenger service performance, and lifecycle costs, thereby providing a stronger basis for evaluating the feasibility and economic viability of hydrogen-powered railways in India. Investment decisions should be based on corridor-specific business cases that compare hydrogen with electrification, diesel, and battery-electric alternatives, taking into account operational requirements, infrastructure availability, energy costs, capital expenditure, maintenance, environmental performance, and route characteristics rather than relying on technology-wide assumptions. Hydrogen production and refuelling infrastructure should, wherever feasible, be developed around clusters of railway routes and other hydrogen-consuming sectors to improve asset utilisation, reduce supply costs, and strengthen economic viability. Hydrogen rail procurement should also include credible requirements concerning production pathways and lifecycle emissions to ensure that the environmental benefits of hydrogen are not undermined by carbon-intensive production. At the same time, the development of indigenous capabilities in fuel cells, hydrogen storage, compression, and control technologies could strengthen supply-chain resilience and reduce long-term dependence on imported components. Clear and harmonised standards for hydrogen storage, transportation, refuelling, emergency response, and railway operations are also necessary to reduce regulatory uncertainty, improve safety, and encourage private-sector participation. Several research gaps remain, including the need for a comprehensive India-specific lifecycle assessment incorporating the country's electricity mix, renewable-energy conditions, hydrogen production pathways, rolling-stock characteristics, and route operating profiles. Long-term total-cost-of-ownership studies should compare hydrogen, diesel, battery-electric, and conventional electrified alternatives across representative Indian route categories, while further empirical research should examine water requirements, hydrogen storage losses, refuelling cycles, maintenance needs, and component replacement under Indian climatic and operational conditions. Future research should additionally assess the potential for localisation of fuel cells, compressors, storage systems, and control technologies and develop multi-criteria route-selection models incorporating operational, economic, environmental, and safety indicators to identify railway corridors where hydrogen technology offers the greatest potential advantages over competing propulsion options.

5. CONCLUSION

Hydrogen rail has a credible but bounded role in India's railway decarbonisation strategy. The evidence reviewed in this study does not support treating hydrogen trains as a universal alternative to electrification. Instead, hydrogen is best understood as a complementary traction technology for selected non-electrified corridors where the capital cost or operational constraints of conventional electrification make a different solution desirable.

International deployments demonstrate that hydrogen rail can replace diesel traction on regional lines, while Japan's hybrid approach illustrates the continuing evolution of fuel-cell and battery integration. India's own initiatives, including the Hydrogen for Heritage programme, the Jind–Sonipat pilot and indigenous 1,200 HP engine development, indicate growing technological capability. These developments provide a foundation for evidence-based experimentation.

However, technological readiness alone is insufficient. The economic case depends heavily on green hydrogen costs, infrastructure utilisation and route characteristics, while the environmental case depends on the carbon intensity of hydrogen production. The additional energy losses associated with electrolysis, compression, storage and fuel-cell conversion also mean that direct electrification will generally remain more energy efficient wherever catenary investment is justified.

The strategic implication is therefore one of technology matching rather than technology replacement. Indian Railways should continue large-scale electrification where it is economically and operationally appropriate, evaluate battery-electric options on suitable shorter corridors, and deploy hydrogen selectively on routes where its range, infrastructure and operational characteristics provide a clear advantage. The strongest future case for hydrogen rail will emerge if India can simultaneously reduce green hydrogen costs, build reliable supply infrastructure, establish robust safety standards and generate high-quality route-level operating data.

A selective, route-specific and evidence-driven approach would allow hydrogen rail to contribute to India's decarbonisation objectives without creating unnecessary competition with technologies that may be more efficient or economical in other railway applications.

6. FUTURE RESERCH AND LIMITATION

The study is primarily based on secondary literature, policy documents and comparative evidence, and therefore does not provide extensive primary operational data from Indian railway corridors. The assessment of hydrogen traction is also constrained by limited long-term evidence on hydrogen consumption, maintenance requirements, refuelling infrastructure, safety, reliability and lifecycle costs under Indian operating conditions. In addition, the findings may vary across routes depending on traffic density, terrain, distance, infrastructure availability and the feasibility of alternative technologies such as electrification and battery-electric traction. Future research should undertake route-specific techno-economic and lifecycle assessments, generate empirical data from hydrogen train pilots, compare hydrogen with electrification and battery-electric alternatives, examine hydrogen production and refuelling infrastructure requirements, evaluate safety and maintenance performance, and assess the long-term environmental and financial viability of hydrogen traction across different non-electrified railway corridors in India.

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