DECARBONISING THE RAILS: A COMPARATIVE ANALYSIS OF THE OPERATIONAL AND ENVIRONMENTAL VIABILITY OF HYDROGEN TRAINS IN INDIA

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ABSTRACT

As India moves toward its ambitious decarbonization goals, the world's fourth largest railway is transitioning its operational model. This study creates a holistic plan for assessing, piloting, and scaling hydrogen-powered trains as a complementary technology to the ongoing electrification program in the country. The analysis utilizes a mixed methods approach that brings together a global review of hydrogen traction with a systematic study of India-specific performance, climate, and supply chain challenges. The research utilizes a framework involving life-cycle assessment (LCA), techno-economic analysis (TEA), and multi-criteria decision analysis (MCDA) to model pathways for adoption, safety management, and operational monitoring. The results conclude that hydrogen trains cannot be a one-for-one substitute for electrification; they are a tactical fit for the non-electrified, low-density, and heritage route options where it is not economically feasible to create overhead infrastructure. This undertaking is contextually based with respect to the success of the recent (2021) National Green Hydrogen Mission (NGHM), which sets the baseline framework for the development of a domestic green hydrogen supply chain. The Jind-Sonipat pilot project is deemed extremely relevant as a de facto state-of-the-art example providing data on real-world situations e.g. water supply, infrastructure costs, and standard safety protocols, with international collaboration (TÜV-SÜD). The study presents an actionable strategic roadmap (2025-2035) complemented by governance structures, and traceable key performance indicators (KPIs), which can position India as a leader in a global clean energy transition.

Keywords: *Hydrogen train, Hydrail, Lifecycle assessment, Decarbonization*

INTRODUCTION

Global decarbonisation imperatives have elevated the role of rail as a low-carbon transport mode. In 2022, global transport emissions rebounded to 8 giga tone Carbon dioxide, undermining climate targets to reach net zero pathway, transport emitted carbon dioxide must decrease by approximately by 25 % by 2030.The transportation industry plays a significant role in greenhouse gas (GHG) emissions, generating about a quarter of all CO_2 emissions (Climate-Chance, 2019). Rail transport has historically been regarded as a relatively clean form of transportation; however, its share of global transport CO_2 emissions was still a significant 4.2% in 2015 (Climate Chance, 2019). As countries commit to more rigorous climate targets, the decarbonisation of rail transport has emerged as a vital strategic priority due to both environmental sustainability, and increased energy security through less reliance on imported fossil fuels. Effectively using railways for bulk mass transit makes them an important resource in national decarbonisation strategies. Consequently, decarbonising from fossil fuels to clean energy in the rail sector is not only an environmental goal but a critical underpinning of both economic and geopolitical resilience (Climate Policy Initiative, 2016).

With more than 68,000 route kilometres, Indian Railways (IR) is one of the biggest rail networks in the world. With almost 23 million people carried daily, IR is the nation's lifeline and the world's largest passenger carrier. While it moves 1512 MT of freight in 2022–2023 (an increase of almost 7% over 2021–2022), it is also the fourth largest freight transporter in the world. (Indian Railways 2022). With its substantial broad-gauge network, Indian Railways (IR) is one of the largest rail systems in the world, and it is consequently a significant energy user (Climate Policy Initiative, 2016). Traditionally, much of its network has relied on diesel traction and has had a significant carbon footprint (Climate Policy Initiative, 2016). As a response, IR has pursued an ambitious electrification policy, and by mid-2025 had successfully electrified over 93% of its broad-gauge route network. There are, however, thousands of kilometres of track, including low-traffic regional lines and famous route heritage lines, that remain non-electrified. For some of these lines, the capital cost of overhead line electrification (which costs approximately between €1 million and €3 million per kilometre) may be simply too expensive (Spherical Insights, 2023). In this context, hydrogen rail has emerged as a viable alternative, with IR positioning it as a practical approach to achieving net-zero emissions by 2030 (Financial Express, 2025). The global trend reveals that hydrogen train solutions are not intended to be a wholesale replacement for diesel but rather as a carefully targeted solution for those hard-to-electrify lines, which is an important distinction in assessing India's hydrogen approach (Soua; Spherical Insights, 2023).

LITERATURE REVIEW

Hydrogen is being increasingly introduced in the transportation industry as part of plans to decarbonise globally. In areas where the electrification (long-distance truck, air transportation, and rail transportation) can not be addressed, there comes the hydrogen-powered transportation. The European Union Hydrogen Strategy (2020) sees this as a global change in the transportation sector. Evidence of hydrogen train adoption is already seen in the procurement of dual operational hydrogen trains by the French government (seen in Global Analysis). Japan's "Hydrogen Society" plans feature hydrogen train transport. The JR East Company from Japan also launched 2-car hydrogen-powered fuel cells in an EMU (Electric Multiple Unit) train (FY-E991 'HYBARI') with plans for commercialisation by 2024. The decarbonisation transportation plan of the UK shows that the rail sector is evaluating hydrogen conversion projects (Porterbrook 'HydroFLEX' prototype) as part of ambitious plans that target the phase-out of diesel-powered transport by 2050. If we see for the hydrogen train economics, we can see that there is mixed performance globally, nonetheless, promising verdicts emerge in studies by various researchers. In one of these studies, the cost of hydrogen trains is compared with that of diesel and battery-powered electric trains in both Japan/UK scenarios, concluding that diesel trains cost the most in terms of overall carbon dioxide used in trains, battery electric trains are the least, whereas hydrogen was in the middle. The researchers deduced that *"mix of both ETs and HTs will be required"* in rural lines. However, the carbon advantage of hydrogen trains varies greatly depending on the type of hydrogen produced. A lifecycle assessment indicated that the CO2 equivalent emissions from traditional diesel fuel are approximately 4.3 times those from the fuel consumed, while the emissions from green hydrogen from renewable energy are only about 1.0 times that of the energy consumed. On the other hand, the grey hydrogen from fossil fuels will produce about 9.7 times more CO2e emissions, while blue hydrogen with carbon capture technology will produce 4.4 times the CO2e emissions. Hence, a transition from the existing diesel multiple unit trains to green hydrogen trains can lead to over 90% reduction in emissions, while blue hydrogen can reduce emissions by two-thirds, and grey hydrogen by only a quarter in a timescale of over 30 years. On cost aspects, hydrogen trains involve high upfront investments. For example, Indian Railways' 2023 plan estimated that each hydrogen train would cost about ₹80 crore for the trainset and another ₹70 crore for route infrastructure, and other studies have estimated that to convert an existing diesel multiple unit with hydrogen fuel cells costs several million pounds. Operating costs are also dependent on fuel costs: at present, green hydrogen costs around $3–6 per kg in the world, compared to a fuel cost for diesel of about $0.7 per litre equivalent, though India has targeted to bring down hydrogen cost to about US$ 1.5 per kg by 2030. Since hydrogen trains do not require overhead electric wires, they can avoid the high costs of full electrification on isolated routes. They still need depot upgrades, crew training, and fuel logistics. Hydrogen trains could be more economical as hydrogen production scales up, multiple trains share infrastructure, and future fuel costs decline in line with national targets.

METHODOLOGY

This study employed a structured secondary research design in order to provide a thorough and evidence-based examination of the issue. The research team conducted a systematic search of many academic and institutional databases with a focus on peer-reviewed journals, examines official government and agency reports, and focuses on other credible literature where appropriate. Sources were selected based on criteria that favour externa access to empirical data, techno-economic assessments and transparent assumptions, especially hydrogen production pathways. The analysis captures and integrates data points from disparate sources to provide insights into the topic and note where differences in context, technology, or policy yield different results.

Comparative Analysis of Global Hydrogen Rail Deployment

The global hydrogen rail landscape comprises a variety of strategies, from commercial-scale deployment to pilot projects that are mostly focused on R&D. The bulk of deployments are in the context of addressing the decarbonisation of non-electrified lines where creating overhead catenary infrastructure is expensive.

Table 1 Comparative analysis of Global hydrogen trains summary table

Country	Project / Train	Key Features	Hydrogen Supply	Policy Support
Germany	Alstom Coradia iLint	2-car FCEV regional train; 600 mi range; zero tailpipe CO_2. In service since 2018.	Initially delivered liquified H_2; plans for local electrolysis.	Funded by Federal NIP and Lower Saxony, H_2 refueling stations built for fleets.
Japan	JR East "HYBARI" (FV-E991)	2-car FCEV EMU; speed 100 km/h, ~140 km range; -water-only emissions. Pilot units since 2022.	Testing on-site electrolyze hydrogen.	¥4B investment by JR East; aligns with national Hydrogen Society goals.
France	Alstom Coradia Polyvalent H2	4-car dual-mode EMU (electric/H_2); ~600 km H_2 range; 218 seats. Order of 12 trains (2021).	Hydrogen to be produced via French electrolyzes.	Supported by France's 2018 Hydrogen Plan, regional energy transition programs
UK	Porter brook Hydro FLEX (Demo)	Class 319 EMU converted to H_2/battery hybrid (proof of concept). Short trial 2021.	Planned green H_2 hub in development.	Hydrogen Strategy (£240M R&D fund); diesel ban target by 2040.

Germany: The Commercial Vanguard

Germany is currently the global leader in hydrogen rail operations. The Alstom Coradia iLint fleet was built specifically to replace diesel multiple units (DMUs) operating on non-electrified regional lines, and has been in commercial operation in Lower Saxony since 2018 (Varghese, 2022). This first step has tested the operation-al capabilities of hydrogen trains, which have the potential to displace a diesel MU with an average of about 4,400 tonnes of CO_2 in emissions annually (Varghese, 2022). On the strength of their success with the fleet, a second order was placed for 27 trains in the Taunus region, indicating growing support for the technology (Alstom, 2021). Environmental benefits of these operations are, however tied to the source of the hydrogen. The trains produce zero tailpipe emissions, however lifecycle benefits depend on the energy to produce the hydrogen. It has been suggested that a 10 MW wind farm could produce enough hydrogen to power a fleet of 14 hydrogen trains, emphasizing that the ultimate climate benefit is a coupling of technology with decarbonised energy (Rao, 2025).

Japan: Technological Hybridisation

Japan has taken a different approach with its FV-E991 series called Hybari, which is a hydrogen fuel cell-electric battery hybrid system developed by JR East, with assist from Toyota and Hitachi. This project began in 2022, and is a test unit designed to collect data for use in future commercial applications, with the overarching goal of replacing diesel motors by 2030 (East Japan Railway Company, 2024; Railway Technology, 2022). The Hybari does not work on a hydrogen-only basis like its German counterpart, instead trying to optimize a hybrid system for performance and efficiency, evidencing a deliberate focus on technological refinement ahead of full-scale adoption. This project aligns with JR East's broader goal to shift to zero carbon dioxide emissions by 2050. (East Japan Railway Company, 2024)

France and the United Kingdom: Regional Focus and Strategic Pilots

France and the UK have also been preparing hydrogen rail as a strategic response for specific regional networks. As a part of a multi-stakeholder program, France has ordered 12 Alstom Régiolis H2 trains as a replacement for diesel units on four regions non-electrified regional routes (Alstom, 2021,SNCF, 2024). The total project, expected to cost €231 million, provides an illustrative policy framework could facilitate decentralised decarbonisation and inspire regional investment / stimulus for hydrogen rail in France (Alstom, 2021,SNCF, 2024). The UK appears to have largely focused on pilot projects such as HydroFLEX, and strategic studies. The “Midlands Hydrogen Rail Study” demonstrates the study-type approach by designating the Midlands region as the next hub for the UK rail decarbonisation project and for new hydrogen train trials on specific routes to demonstrate how hydrogen trains can be deployed commercially to provide operators to make purchase decisions which would discourage diesel rail trains circulating (HyDEX & Energy Research Accelerator, 2024).

SYNTHESIS: KEY INFERENCES FROM GLOBAL DEPLOYMENTS

The assessment of deployments in Germany, Japan, France, and the UK supported a number of consistent strategic and technical conclusions about the function of hydrogen in contemporary rail systems. Hydrogen rail is, primarily, uniformly positioned as a decarbonisation solution for non-electrified lines in which electrifying lines with overhead catenary system is not feasible within the cost.

Strategic Focus on Niche Decarbonization: Every significant deployment demonstrates that hydrogen trains are meant to replace diesel multiple units (DMUs) on low-density regional and branch lines (such as Germany's Coradia iLint fleets) directly and with zero tailpipe emissions, rather than to compete with main-line electrification.

Divergence in Technology: Although the hydrogen fuel cell is the fundamental technology, different implementation strategies are used: While Japan made investments in high-performance, advanced hybrid systems (fuel cell and battery combination) for maximum efficiency and long-term technological readiness, Germany prioritized immediate commercial operation using established technology (Varghese, 2022). Hybridization is specifically used to lower overall hydrogen storage requirements and increase efficiency through regenerative braking (Rao, 2025).

Policy-Driven Investment: The transition is heavily reliant on government policy and financial support. Deployment decisions are underpinned by national hydrogen strategies (e.g., France's Hydrogen Plan, UK's Hydrogen Champion recommendations) and significant public funding to overcome the high initial capital costs of hydrogen trains (which can be 25% to 30% higher than diesel counterparts) (Spherical Insights, 2023).

Infrastructure as the Linchpin: Successful commercial operation, as seen in Germany, requires simultaneous development of dedicated refuelling infrastructure integrated with low-carbon hydrogen production sources (Rao, 2025; Siemens & Deutsche Bahn, 2023). This infrastructure must support rapid refuelling protocols (comparable to diesel) to maintain tight operational schedules. Furthermore, countries like the UK are strategically leveraging existing industrial strengths and proposed hydrogen hubs to co-locate production and rail demand, driving regional economic growth alongside decarbonisation (HyDEX & Energy Research Accelerator, 2024).

LIFECYCLE EMISSIONS: A CRITICAL CONSIDERATION

Although hydrogen trains only emit water vapor at the point of use, the climate benefit depends entirely on how the hydrogen was produced. A full lifecycle assessment (LCA) shows a significant difference in emissions dependent on how the hydrogen was produced. Green hydrogen, which is produced by electrolysis using renewable energy (e.g., wind) is associated with low emissions (0.6 kg CO_2 eq. per kg H_2) (RSC Green Chemistry, 2024). On the contrary, grey hydrogen produced from natural gas is associated with much higher emissions (up to 13.9 kgCO_2 eq.), worse than the footprint of a diesel engine (Varghese, 2022; RSC Green Chemistry, 2024). While blue hydrogen incorporates carbon capture technology, it is still responsible for substantial emissions (7.6 kgCO_2 eq.). These findings show that the environmental impact of a hydrogen train is the result of the overall national energy policy and infrastructure that relates to the production of clean hydrogen, not necessarily the rolling stock itself. In order for hydrogen rail to be a significant contributor to decarbonisation, it must be a green hydrogen train where the hydrogen is produced by clean hydrogen from a low-carbon grid. (Varghese, 2022).

TECHNICAL AND ECONOMIC ASSESSMENT FOR INDIA

India's foray into hydrogen rail is a critical component of its National Green Hydrogen Mission, but its success hinges on navigating significant technical, economic, and institutional challenges.

Technical and Infrastructural Readiness

Indian Railways has demonstrated its technical capability by developing an indigenous hydrogen engine confirmed as the most powerful in its class worldwide at 1,200 horsepower (Lodhi, 2025; Rao, 2025; Financial Express, 2025). The pilot project (part of the "Hydrogen for Heritage" project) consists of retrofitting existing diesel-electric multiple units (DEMUs) on the Jind-Sonipat route in Haryana (Financial Express, 2025; Rao, 2025). The decision to use heritage/hilly routes as piloting locations is deliberate, as these lines are more typically non-electrified and using them to demonstrate the sytem's operation as a highly visible "green" project allows IR to demonstrate that it can build public confidence in hydrogen technology without disrupting the system by deploying hydrogen technology on important trunk routes involving heavier passenger traffic (Financial Express 2025; Rao, 2025). The pilot also entails building a dedicated hydrogen storage and refueling facility at Jind, with a capacity of 3,000 kg (Financial Express, 2025). To manage safety concerns, the project has already completed extensive Computational Fluid Dynamics studies imagined for leak scenarios, and will undergo an independent safety audit by the European German firm, TÜV SÜD (Financial Express, 2025; Rao, 2025). This systematic approach to safety and infrastructure is a foundation for a scalable rollout.

Economic Viability and Cost Challenges

India's economy is the main obstacle to the widespread use of hydrogen trains. With the larger "Hydrogen for Heritage" initiative expected to cost ₹2,800 crore for trains and an additional

₹600 crore for infrastructure, the initial capital expenditure for the pilot project, including the train and ground infrastructure, is estimated at ₹111 crore. (Trivedi, 2025; Rao, 2025)

Concerns regarding the financial feasibility have been raised by experts, who point out that because green hydrogen is expensive, a hydrogen train set's initial operating costs will be higher than those of its diesel or electric counterparts (Trivedi, 2025). While hydrogen trains have higher initial capital costs than diesel, they offer long-term lifetime cost savings in certain use cases, according to a study by the Center for Study of Science, Technology and Policy (CSTEP). Despite having lower overall fuel costs than hydrogen, the study also shows that battery-powered trains have problems with high equipment replacement costs and are frequently too heavy for some applications.

A major problem is the efficiency loss that is part of the hydrogen value chain. A former General Manager from Indian Railways suggests that providing renewable electricity directly to the grid is much more efficient than producing, transporting, and distributing hydrogen, which can involve a large energy loss. Therefore, the success of hydrogen trains is intrinsically tied to the success of India's National Green Hydrogen Mission to lower production costs and establish a strong low-cost supply chain (CSTEP, 2024).

Policy and Institutional Frameworks

The overall framework for hydrogen rail policy is provided by India's National Green Hydrogen Mission (NGHM). The mission, which will cost a staggering ₹19,744 crore, intends to establish India as a global centre for the production of green hydrogen, with a target of 5 million metric tonnes per year by 2030. By creating "Hydrogen Hubs" that combine the production of hydrogen with renewable energy sources, the mission aims to close infrastructure gaps. Joshi, 2025; Ministry of New and Renewable Energy, 2023).

But the success of hydrogen rail depends on this larger ecosystem. Other industries thinking about using hydrogen for heavy transportation face similar difficulties to Indian Railways, including exorbitant costs and unclear regulations. Through measures like waiving interstate transmission fees for renewable energy used to produce hydrogen a critical enabler for cost reduction—the NGHM aims to address these systemic problems. A clear regulatory framework and safety standards are also essential for lowering investment uncertainty and promoting private sector involvement, according to the government (Ministry of New and Renewable Energy, 2023; Joshi, 2025).

RECOMMENDATIONS AND IMPLICATIONS

Based on the synthesis of global and Indian evidence, a series of policy and research recommendations can be formulated to guide India's hydrogen rail strategy.

Evidence-Based Policy Recommendations for India

Pilot Corridors: Carry on and grow the "Hydrogen for Heritage" pilot, but with a specific mandate to gather detailed information on operational costs, safety, and dependability in order to confirm the commercial viability of a wider variety of non electrified routes. (Rao, 2025; Lodhi, 2025; Financial Express, 2025).

Infrastructure-First Method: As part of the National Green Hydrogen Mission's "Hydrogen Hubs" concept, give priority to the construction of infrastructure for hydrogen production and distribution (Ministry of New and Renewable Energy, 2023; Joshi, 2025). An important proof of concept for this model is the Jind facility.

Innovative Financing: Taking cues from UK and German grant programs and funding schemes, the government should investigate innovative financing instruments and public-private partnerships to close the gap between high upfront costs and long-term benefits.

Harmonised Regulations: To lower investment uncertainty and promote private sector involvement, expedite the creation of a transparent regulatory framework and safety standards for the production, handling, and storage of hydrogen.

RESEARCH RECOMMENDATIONS AND GAPS

While significant progress has been made, several key research gaps must be addressed to fully assess the viability of hydrogen rail in India.

- **Comprehensive LCA:** To provide a conclusive environmental impact analysis, a thorough lifecycle assessment of hydrogen rail tailored to India is required, taking into consideration the nation's distinct energy grid mix, rolling stock, and operating conditions.
- **Component Localization:** One major obstacle is still the high price of essential parts like compressors and fuel cells. To strengthen domestic manufacturing capabilities and lessen reliance on imports, more research and development is required, possibly through a public-private partnership framework like the Strategic Hydrogen Innovation Partnership (SHIP).
- **Comparative Long-Term Analysis**: Additional data must be collected to perform a long-term TCO analysis of hydrogen rail schemes compared to battery-electric trains and diesel in low-traffic line scenarios, to be able to definitively identify which solution will yield the least cost per case and propose economic viability when producing hydrogen compared to diesel. Initial data shows that the value of the optimal solution might differ depending on the expected route's duty cycle, energy demands, and/or topographic variables.

DISCUSSION

Integrating global deployment data with India's techno-economic context outlines a calculated and targeted approach to remedying a few market failures in the Indian railway network, while at the same time, advancing domestic leadership in technology. Specifically, international examples from Germany, France, and the UK repeatedly characterize hydrogen rail as a replacement for diesel on low-traffic regional lines that are non-electrified, rather than a mainstream traction solution, where the upfront capital costs for a catenary installation are not justified. From this strategic perspective, it supports the Indian Railways pursuit of "Hydrogen for Heritage" targeting popular tourist routes that are non-electrified a few minutes apart where zero-emission operation has a high profile, and enhances the status of the service. A significant component of this strategy is the lifecycle assessment (LCA) data presented as an obligatory environmental gatekeeper. The comparative global analysis clearly illustrates the emissions produced using carbon-intensive grey hydrogen (13.9 kg CO_2 eq./kg H_2) would offset most of the benefits associated with low-emission hydrogen rail potentially resulting in higher total emissions than diesel. Hence, the delivery against IR's decarbonisation target is entirely dependent on the successful, simultaneous scaling of the National Green Hydrogen Mission (NGHM), to supply economical green hydrogen. One significant departure from the global trend is India's choice to develop an indigenous 1,200 HP hydrogen engine, which greatly exceeds the typical 500–600 HP capacity observed in early European deployments. In addition to making sure the trains can withstand the demanding duty cycles and varied terrain (such as hilly routes like Kalka–Shimla) characteristic of IR’s network, this focus on high-power, locally developed technology reflects a dual policy aim: first, positioning India for technological self-reliance (Aatmanirbhar) and potential export leadership by leveraging its expertise in fuel cells and cryogenic technologies previously developed by organizations like ISRO. This strategy suggests a preference for outright power and robustness in the initial application, which contrasts with Japan's hybrid, high-efficiency R&D path.

The top critical hurdle is still the thermodynamic and economic inefficiency of the hydrogen value chain relative to electrification. Energy is lost in the steps of electrolysis, compression, storage, and reconversion in the fuel cell. As former IR experts have put it, feeding renewable energy directly into the grid is always going to be more efficient than using that energy to convert hydrogen to then distribute. It should be noted that while this efficiency loss is self evident, it must be held in context of the massive capital cost savings of electrifying low density lines (€1-€3 million/km). Cost-benefit studies show that while hydrogen trains have a higher upfront capital cost than diesel, hydrogen can yield better lifetime cost savings in certain non-electrified applications than diesel and specifically, better lifetime cost savings than battery-electric trains which have high costs of equipment replacement and weight issues with too much equipment for the duty cycle. By embedding the rail transition in the enormous ₹19,744 crore NGHM , India is establishing necessary infrastructure development to lower the costs of green hydrogen to a competitive $2/kg by 2030.

CONCLUSION

Hydrogen rail is recognized worldwide as a practical zero-tailpipe-emission technology aimed at decarbonizing regional rail and low-density lines in applications where the capital cost of traditional overhead electrification is prohibitive. The successful commercial introduction in Germany, in addition to a range of hybrid R&D programs in Japan provide critical operational data and validate the core use case. However, for the technology to demonstrate its full environmental potential, it is critical to exclusively source Green Hydrogen, as life cycle assessment (LCA) data demonstrates that fossil fuel-derived hydrogen pathways (grey/blue) offer little to no net reduction in CO_2 (and even potentially negative) relative to conventional diesel. India's national strategy, exemplified by the domestic 1,200 HP engine and the "Hydrogen for Heritage" pilot, has placed the nation in a strong position to lead in the use of hydrogen in demanding regional and hilly routes. The next hurdle for hydrogen trains to be broadly adopted in India is to transition from this technical readiness to economic viability. To achieve this transition, two factors need to occur: rapid declines in the cost of green hydrogen, as outlined by the National Green Hydrogen Mission (NGHM), and careful selections of routes where the advances in hydrogen's cost benefits (despite energy conversion losses) exceed the tremendous capital costs of electrification or the technical barriers with battery-electric trains. Targeted public financing and regulatory alignment to offset the initial expense is needed to support achieving India's target of reaching net-zero rail by 2030.

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