Exploring the Potential of Using Hydrogen Fuel Cell Technology for Locomotives in Saudi Arabia

Ali Alsahli

November 25, 2024

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2021) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

The 1st International Conference on Smart Mobility and Logistics Ecosystems (SMiLE)

September 17-19, 2024, KFUPM, Saudi Arabia

Exploring the Potential of Using Hydrogen Fuel Cell Technology for Locomotives in Saudi Arabia

Ali Abdullah Alsahli , Ph.D.

King Saud University, Riyadh 11421, Saudi Arabia

Abstract

Hydrogen fuel cell trains have emerged as a promising solution for sustainable transportation, offering the potential to reduce greenhouse gas emissions and dependence on fossil fuels. This study conducts a comprehensive examination of the applicability of hydrogen fuel cell trains within the transportation framework, with a specific focus on Saudi Arabia. Through an extensive literature review and rigorous analysis, this research endeavors to elucidate the current state of hydrogen fuel cell train technology and its suitability for various operational contexts. The findings reveal that while the existing technology may not be optimized for heavy freight operations, hydrogen fuel cell trains demonstrate considerable potential for passenger transportation, particularly on shorter routes. Leveraging insights from previous studies and ongoing advancements in hydrogen technology, this paper anticipates a trajectory towards expanded applications of hydrogen fuel cell trains, encompassing heavier and longer-distance operations. Notably, the imminent testing of the first freight train in 2025 underscores the evolving landscape of hydrogen fuel cell train technology. Beyond the confines of Saudi Arabia, this study posits broader implications for the global transportation sector. The analysis underscores the pivotal role of hydrogen fuel cell trains in contributing to decarbonization efforts and fostering sustainable mobility solutions. Moreover, the research identifies opportunities for further exploration and implementation, both within the kingdom and on an international scale. In essence, this research serves as a scholarly inquiry into the feasibility and potential of hydrogen fuel cell trains, laying the groundwork for future academic inquiry, policy development, and technological innovation in the realm of sustainable transportation.

Keywords: Saudi Arabia, Railway, Fuel cell, Hydrogen.

1. Introduction

Heavy-duty powering systems are not only crucial in rail transportation but also play vital roles in aviation and marine transportation sectors. These heavy-duty subsectors of transportation combined release approximately 16.2 megatons of CO_2 equivalent every year in Canada, constituting around 10% of the total emissions by the Canadian transportation sector [1]. The potential of hydrogen fuel cell technology for locomotives is evident in several studies highlight the successful development and testing of hydrogen-fueled fuel cell-battery hybrid locomotives, with the former emphasizing their ability to reduce air and noise pollution [2]. Fuel cell locomotives are expected to be slightly more energy efficient than diesel locomotives, and be-cause their fuel infrastructure will be homologous to that of diesel, they should have similar fuel infrastructure costs [3]. In this scenario, electric power grid-fed rail systems appear to be the most mature and proven technology. However, the required huge investments in electrical infra-structure restrict them to heavily loaded corridors, in which high demand levels help dilute the high fixed costs, resulting in lower unit costs (cost per passenger or per freight unit). Conversely, low to medium loaded corridors, which require an autonomous traction system, currently rely on noisy and CO_2-emitting diesel multiple units (DMU) or diesel-fueled locomotives. It is noteworthy that, despite advances in diesel engine aftertreatment technology, emissions remain a concern, indicating potential hindrances for train leasing companies to invest in new diesel train fleets [4].

Battery-powered trains, a potential environmentally friendly alternative, are im-paired by low availability primarily due to charging requirements, ultimately affecting the on-the-job performance of rail vehicles. However, fuel cell-driven rail vehicles, with their inherent environmental performance and operational flexibility, offer a significant opportunity to decarbonize and reduce local pollutant emissions from the rail industry, especially through an autonomous operational approach. Besides their clean output, fuel cell powertrains provide smart power management and flexible energy storage potential. Electrical energy can be supplied on demand, with the fuel cell required to operate at full capacity during acceleration and almost completely powered down during coasting, while also enabling energy regeneration to the batteries [5]. Saudi Arabia aims to increase the adoption of environmentally friendly fuels as part of its Vision 2030, thus investing in clean energy transportation systems such as hydrogen trains. Fuel cells offer a promising and efficient alternative to traditional combustion-based power generation, with applications ranging from transportation to stationary power generation. They provide advantages such as high efficiency, low emissions, and potential for use with renewable fuels. However, challenges such as cost, durability, and infrastructure remain areas of ongoing research and development.

1.1. Hydrogen Fuel Cell Concept

Fuel cell technology operates on the fundamental principle of converting chemical energy directly into electrical energy through electrochemical reactions. Variations in fuel cells stem from the use of different electrolytes and reactants to facilitate these reactions. Key components include an electrolyte, electrodes (anode and cath-ode), and catalysts. During operation, fuel, such as hydrogen, is supplied to the an-ode, while an oxidizing agent (often oxygen from the air) is directed to the cathode. At the anode, fuel undergoes oxidation, typically releasing electrons. These electrons traverse through an external circuit, generating electrical energy, before reaching the cathode where they combine with the oxidizing agent, typically oxygen, and ions from the electrolyte to produce water or other byproducts. The choice of electrolyte and reactants varies depending on the type of fuel cell. For instance, Polymer Electrolyte Membrane (PEM) fuel cells utilize a proton-conducting polymer membrane as the electrolyte, whereas Solid Oxide Fuel Cells (SOFC) employ a solid ceramic electrolyte.

The discussion delves into various fuel cell technologies, commencing with Polymer Electrolyte Membrane (PEM) Fuel Cells. PEM fuel cells employ an electrolyte capable of conducting H+ ions, often utilizing Nafion material. Widely used, particularly in the automotive industry, PEM fuel cells are esteemed for their efficiency and rapid start-up capabilities. Nevertheless, challenges such as thermal and water management persist, alongside the high cost of noble metal catalysts. Following this, Alkaline Fuel Cells (AFC) are outlined, historically employed in spacecraft. Operating at temperatures below 100°C, AFCs benefit from using non-noble metal electro-catalysts, like nickel. However, their sensitivity to CO_2 significantly impacts performance and durability, prompting ongoing efforts to mitigate CO_2 effects and enhance suitability for diverse applications. The exploration extends to Solid Oxide Fuel

Cells (SOFC) and Phosphoric Acid Fuel Cells (PAFC). SOFCs operate at high temperatures between 800°C and 1000°C, offering higher power outputs but encountering challenges concerning material compatibility and corrosion. In contrast, PAFCs utilize phosphoric acid as an electrolyte, operating at temperatures above 200°C, boasting longer lifetimes and finding utility in stationary power generation. Both technologies witness continuous research endeavors aimed at enhancing efficiency, durability, and cost-effectiveness [6-8].

1.2. Hydrogen Locomotives

Another study conducted by Ewing [9] focused on heavy-duty vehicles in Canada utilizing alternative fuels such as dimethyl ether (DME) and its potential to reduce greenhouse gas emissions by 60% if produced from renewables within Canada. While hydrogen stands out as the most promising alternative to fossil fuels, public perception still regards it as dangerous and unsafe [10].

It's noteworthy that hydrogen or battery trains offer viable alternatives to diesel trains in the railway sector. While utilizing catenary lines proves to be energetically and economically efficient, global railway electrification rates remain relatively low. Northeast Asia and Europe boast electrification rates exceeding 60%, whereas the rest of the world, including the Americas, Africa, and Australia, lags below 10%. To address routes lacking catenary lines, battery trains can serve as short distance trams within cities, while hydrogen trains can function as multiple unit or long distance, high powered locomotives. The subsequent table presents recent activities in hydrogen powered locomotives as reported by [11].

Table 1. Fuel Cell Powered Rail and Locomotive Performance Overview [11]

Institution	Year	Power (Fuel Cell)	Hydrogen
Alstom (France)	2016	390 kW (250 kW)	250 kg
CRRC (China)	2017	200 kW (200 kW)	12 kg
KRRI (Korea)	2021	200 kW (200 kW)	166 kg
Siemens (Germany)	2022	400 kW (400 kW)	-
JR East (Japan)	2022	240 kW (240 kW)	25 kg
Hyundai (Korea)	2023	400 kW (400 kW)	40 kg
PESA (Poland)	2021	600 kW (180 kW)	175 kg
CRRC (China)	2021	700 kW (400 kW)	-
CP (Canada)	2022	1200 kW (1200 kW)	-
CZ LOKO (Czech)	2023	800 kW (800 kW)	-
KRRI (Korea)	2024	1800 kW (1200 kW)	70 kg

The components of a hydrogen train, as described in the passage, include [12]:

- Hydrogen PEM Fuel Cell: This is the prime mover of the hybrid vehicle.
- Auxiliary Energy Storage Device: must store sufficient energy to provide power in excess of the continuous power rating of the fuel cell and must do so continuously under operation of the duty cycle.
- Fuel Cell Power Plant: This consists of three primary subsystems; fuel cell stack modules, air delivery, and cooling. The power module contains two Ballard Power Systems P5 TM fuel cell stack modules.
- Fuel Cell Stack Modules: These contain Ballard Mk902 stacks; each rated at 150 kW gross power at 624 V, for a total of 300 kW gross power at 624 V. Each fuel cell stack module includes the auxiliary components for air and hydrogen humidification, water recovery, hydrogen recirculation, and hydrogen purge.
- Balance of Plant (BOP): These are the systems that provide the reactants (oxygen and hydrogen) for the fuel cell stack modules and support their operation.
- Cooling System: This rejects waste heat from the fuel cell stacks as well as auxiliary motors and electronics.
- Electrical Distribution and Control Systems: These regulate power output, control various electrical devices, and monitor system parameters for faults.

- Hydrogen Storage Modules: Each module consists of seven carbon fiber composite cylinders that collectively store approximately 35 kg (70 kg for the vehicle as a whole) of compressed hydrogen at 350 bar (5,100 psi). They are mounted on the roof of the locomotive for safety.

2. Potential of Using Hydrogen Fuel Cell Technology

From an operational perspective, the duty cycle serves as a valuable tool for analyzing hydrogen-based locomotives, depicting the fluctuation of vehicle power over time [13]. In 2013, the University of Birmingham conducted a study on testing a narrow gauge prototype hydrogen locomotive to assess its potential for scaling up to full sized locomotives [14]. The locomotive in testing retained key drive train components, including compressed gas hydrogen storage, a PEM fuel cell based power plant, and a hybrid system utilizing batteries as energy storage devices. General performance observations revealed that the Hydrogen Pioneer exhibited superior performance during steady state operation compared to the overall duty cycle. However, at low speeds, the vehicle's performance suffered due to minimal utilization and loading of all components. Upon reaching normal operating speeds, typically between 5 km/h and 10 km/h, the power plant's efficiency stabilized at around 40%, with the vehicle’s efficiency reaching approximately 15%. Regarding energy efficiency and overcoming motion resistance, the study concluded that the power plant's performance suggested the suitability of a hydrogen fuel cell based prime mover for railway applications. Similarly, a prior study addressed the use of fuel cells for locomotives and concluded that fuel cell locomotives operating over long haul routes would offer distinct advantages over direct electrification, particularly for heavy freight. Additionally, the performance capabilities of fuel cells were deemed more suitable for diesel duty cycles rather than electric duty cycles, applicable to both passenger and freight services [15]. In another study, switcher locomotives were discussed to potentially benefit from reduced capital costs with hybrid power plants. However, this would come at the expense of increased complexity and lower thermodynamic efficiency. A hybrid locomotive would either require more fuel capacity or reduced operating time to maintain the same duty cycle [16]. Table 2 provides an overview of the suitability of fuel cell systems, including hydrogen based systems, for various railway operation applications in terms of available tractive power.

Table 2. hybrid fuel cell systems and railway application

Type of service	**Tractive power benefits**
Switcher , Line haul freight	Low
Light rail , High speed rail	Medium
Mass transit , Commuter rail , Intercity passenger	High

Likewise, another study noted that no dominant hydrogen storage technology has emerged for freight locomotives, primarily due to their requirement for higher energy densities owing to constant high power demand [17]. Regarding energy utilization for propulsion, it was observed that hydrogen assisted hybrid locomotives can either match or slightly exceed the energy utilization for traction compared to conventional diesel electric locomotives [18]. Distinguishing features of hydrogen from other popular fuel options include its nearly unique consumption, abundance, very low emissions, reversible production cycle, and reduced greenhouse effect [19]. Moreover, hydrogen fuel is recyclable and reusable [20]. However, a major drawback of using hydrogen as a fuel lies in the complexities associated with its production, which also entails significant financial investment [21]. Hydrogen storage poses a critical barrier to many applications [22], prompting consideration of onboard hydrogen production as a potential solution using aluminum electrolysis cells (AEC) [23]. Comparative analysis between light rail hydrogen trains and electric trains revealed that hydrogen trains exhibited superior performance in roundtrip comparisons. Additionally, hydrogen trains demonstrated greater energy output at the wheel [24].

3. Saudi Railway

The first railway line in Saudi Arabia was launched in 1952 to connect Riyadh and Dammam under the management of Aramco, and in 1966 the Saudi Railways Organization was established to manage the line between Dammam and Riyadh. Then in 2006, the Saudi Railway Company (SAR) was established to manage and operate railway lines in the north of the kingdom. In 2011, the North South Railway for cargo began operating, followed by the North South Railway for passengers in 2017. In 2018, the first trips on the Haramain High Speed Railway started. This table provides a comprehensive overview of Saudi Arabia's railway system, encompassing current operational lines, projects under construction, and ambitious plans for the future. The network caters to both passenger and freight transportation, with dedicated high speed lines, regional routes, and urban metro systems. Explore the details of each line, including length, route, rolling stock, and key features, to understand the expanding role of railways in the Kingdom's transportation landscape.[25-27]:

Table 3. Saudi Railway network

Line	**Length**	**Route**	**Rolling Stock**	**Status**
North Train (Passenger)	1,250 km	Riyadh to Qurayyat	4 day trains, 2 night trains	Current
North Train (Freight)	1,550 km	Al Jalamid to Ras Al Khair	61 locomotives, various freight cars	Current
East Train (Passenger)	733 km	Riyadh to Dammam	102 diesel locomotives, 75 passenger cars	Current
East Train (Freight)	566 km	Dammam to Riyadh	2,596 freight cars	Current
Haramain High-Speed	450 km	Mecca to Medina	30 trains, each with 13 cars and 417 seats	Current
Riyadh Metro	176 km	Multiline network covering Riyadh	Automatic trains	Under Construction
Mecca Metro	18.1 km	One line	Supplied by Changchun Railway Vehicles	Current
Saudi Landbridge	2,255 km	Network connecting key industrial and commercial centers	To be determined	Under Construction (started in 2024)

4. Assessment of Hydrogen Fuel Cell Technology for Locomotives in Saudi Arabia

In 2023, the Saudi Railway Company (SAR) reported handling 24.7 million tonnes of freight and transporting 13.2 million passengers, including 2.1 million during the Al Hajj season via the Makkah metro. The northern freight operation, largely focused on mining, contributed 14 million tonnes, with trains carrying up to 12.5 thousand tonnes. SAR also signed an agreement with Alstom France to study and operate hydrogen trains for passenger transport, highlighting their commitment to advanced technologies and sustainable transportation. These developments emphasize SAR's focus on efficient and reliable solutions to meet the growing demands of both freight and passenger sectors while supporting global sustainability efforts.

With these operational dynamics in mind, SAR's operational requirements for both freight and passenger sectors become increasingly paramount. Table 4 shows the required power for each type of operation.

Table 4. Power requirement for freight and passenger*

Case	Type	Power
Phosphate train (longest set in SAR fleet)	Freight	28 MW
Makkah metro (largest passenger operation)	Passenger	519 kW

*this analysis used Davis formula to estimated the required force to overcome to run such train [28].

Based on Table 4, existing hydrogen trains are not applicable for freight operations but are suitable for passenger transportation. Even , early experiments have demonstrated that hydrogen-based locomotives can operate with similar maximum power at both the engine and wheel levels, making them a superior alternative to conventional diesel-electric engines. Hydrogen-based locomotives present a viable alternative to electric trains, particularly because they can operate on existing railway infrastructure without requiring additional structural modifications [36]. In regions like Saudi Arabia, where electrification of railway tracks is currently non-existent apart from the Haramain high-speed rail line, hydrogen-based locomotives offer a viable alternative to electric-electric locomotives.

The transition to hydrogen-powered trains should be facilitated by an adequate supply of hydrogen. Hydrogen production and distribution are expected to lead to a 40% reduction in diesel consumption, based on 2021 price estimates. Also, the implementation of hydrogen trains necessitates substantial investment in the supply chain, including the establishment of production facilities, storage systems, and distribution networks. [35].

The economic analysis necessitates the identification of several key factors, including infrastructure costs, locomotive costs, maintenance costs, and environmental benefits associated with the adoption of hydrogen based locomotives. The table below provided estimates the costs for the Saudi Arabian scenario. The scenario under consideration assumes a comprehensive evaluation of the economic viability of implementing hydrogen based locomotives within the passenger railway network of Saudi Arabia.

Table 5. Life cycle cost and benefits

Type of Cost	**Unit price**
Infrastructure cost [29]	$1.8 million per 200 kg of Hydrogen
Locomotive cost [30]	$1220/kW
Maintenance cost [31]	Fuel stack Replacement cost per 15 years for $ 244/kW Annual O&M $27/kW
Environmental benefits [32]	0.5 kg reduction of CO_2km^{-1} compered to conventional train ($0.13/kg CO_2 [33])

Based on the scenario outlined in Table 6, the Net Present Value (NPV) has been determined to be positive at discount rates below 1.5%. This finding underscores the feasibility of fully operating the northern and eastern railway lines using hydrogen trains. To meet the operational demands, an estimated total of 110 locomotives are required, with a collective daily operation spanning a total length of 1983 kilometers. Considering the power requirements, which amount to 519 kW, it's noteworthy that the longest range capable of meeting these specifications is 600 km. Consequently, refueling stations are strategically positioned at midpoints along the Northern route, resulting in a total of five refueling stations being established. The discount rate ranges from 0.5% to 5%, with the analysis period extending over 30 years. This comprehensive assessment delineates a robust economic model, validating the viability of integrating hydrogen trains into the Saudi Arabian railway network. Figure 1 shows the change of net present value with change of discount rate.

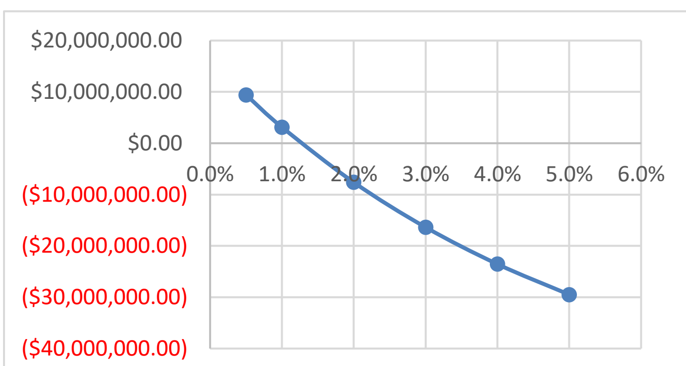

Fig. 1. Economic evaluation of Hydrogen trains.

5. Discussion

Hydrogen locomotives are particularly suitable for Saudi Arabia due to several factors. Firstly, hydrogen is available as a fuel at competitive prices, making it an economically viable option. Additionally, hydrogen trains operate at the same power levels as some conventional engines, ensuring they can meet the performance standards required for efficient operation. These locomotives can also be upgraded from conventional equipment, facilitating a smoother transition to hydrogen-powered systems. Furthermore, they can utilize existing tracks without necessitating new infrastructure, which is a significant advantage in regions with limited railway electrification. Most importantly, the environmental benefits of hydrogen locomotives outweigh the associated costs, contributing to sustainable transportation solutions.

However, there are some limitations to consider. Hydrogen locomotives require their own supply system for operation, which entails additional investment and logistical planning. They are also heavier than conventional trains, which might lead to increased maintenance issues over time. Currently, hydrogen locomotives are used in lighter operations, indicating that further development is needed to enhance their capabilities.

Despite these challenges, the specific case of hot weather in Saudi Arabia does not pose a significant issue for hydrogen locomotives. Fuel cell performance can be enhanced by increasing the operating temperature, making them well-suited for the region's climate[37].

6. Conclusion

This paper undertakes a comprehensive literature review of hydrogen fuel cell train technology and analyzes its applicability within the context of Saudi Arabia. The investigation reveals that the current state of technology is not yet conducive for heavy duty freight operations. However, the analysis demonstrates that passenger operations emerge as the more suitable application for this technology, particularly for shorter trips and medium scale operations. Furthermore, the paper highlights the promising advancements in hydrogen technology, indicating its potential for broader and more demanding applications in the near future. Anticipated developments suggest that hydrogen fuel cell trains will soon be viable for heavier and longer distance operations, with the first freight train slated for testing in 2025.

References

1. Al-Hamed, Khaled HM, and Ibrahim Dincer. "Comparative evaluation of fuel cell based powering systems for cleaner locomotives." Thermal Science and Engineering Progress 23 (2021): 100912.
2. Hess, Kris S., Arnold R. Miller, Timothy L. Erickson, and James L. Dippo. "Demonstration of a hydrogen fuel-cell locomotive." In Proceedings of Locomotive Maintenance Officers Association conference, Chicago. 2008.
3. Miller, A. R., K. S. Hess, D. L. Barnes, and T. L. Erickson. "System design of a large fuel cell hybrid locomotive." Journal of Power Sources 173, no. 2 (2007): 935-942.
4. Hoffrichter, Andreas. "Hydrogen as an energy carrier for railway traction." PhD diss., University of Birmingham, 2013.
5. Railway Technology - iLint: the world’s first hydrogenpowered train. 2018. Available at: https://www.railwaytechnology.com/features/ilint-worlds-first-hydrogen-powered train/.
6. Carrette, L., K. A. Friedrich, and U1 Stimming. "Fuel cells-fundamentals and applications." Fuel cells 1 (2001).
7. Kordesch, Karl, Viktor Hacker, Josef Gsellmann, Martin Cifrain, Gottfried Faleschini, Peter Enzinger, Robert Fankhauser, Markus Ortner, Michael Muhr, and Robert R. Aronson. "Alkaline fuel cells applications." Journal of Power Sources 86, no. 1-2 (2000): 162-165.
8. Bidault, F., D. J. L. Brett, P. H. Middleton, and N. P. Brandon. "Review of gas diffusion cathodes for alkaline fuel cells." Journal of Power Sources 187, no. 1 (2009): 39-48.
9. Ewing, Madeline. An Evaluation of Alternative Fuels and Powertrain Technologies for Canada’s Long Haul Heavy-duty Vehicle Sector. University of Toronto (Canada), 2019.
10. Bae, Choongsik, and Jaeheun Kim. "Alternative fuels for internal combustion engines." Proceedings of the Combustion Institute 36, no. 3 (2017): 3389-3413.
11. Kang, Daehoon, Sungho Yun, and Bo-kyong Kim. "Review of the liquid hydrogen storage tank and insulation system for the high-power locomotive." Energies 15, no. 12 (2022): 4357.

12. Hess, Kris S., Arnold R. Miller, Timothy L. Erickson, and James L. Dippo. "Demonstration of a hydrogen fuel-cell locomotive." In Proceedings of Locomotive Maintenance Officers Association conference, Chicago. 2008.
13. Miller, A. R. "Least-cost hybridity analysis of industrial vehicles." European Fuel Cell News 7, no. 2 (2001): 15-17.
14. Hoffrichter, Andreas, Peter Fisher, Jonathan Tutcher, Stuart Hillmansen, and Clive Roberts. "Performance evaluation of the hydrogen-powered prototype locomotive 'Hydrogen Pioneer'." Journal of Power Sources 250 (2014): 120-127.
15. Jones, L. E., G. W. Hayward, K. M. Kalyanam, Y. Rotenberg, D. S. Scott, and B. A. Steinberg. "Fuel cell alternative for locomotive propulsion." International journal of hydrogen energy 10, no. 7-8 (1985): 505-516.
16. Miller, Arnold R., John Peters, Brian E. Smith, and Omourtag A. Velev. "Analysis of fuel cell hybrid locomotives." Journal of Power Sources 157, no. 2 (2006): 855-861.
17. Böhm, Mathias, Abraham Fernández Del Rey, Johannes Pagenkopf, Maider Varela, Sebastian Herwartz-Polster, and Beatriz Nieto Calderón. "Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies." International Journal of Hydrogen Energy 47, no. 89 (2022): 38003-38017.
18. Hogerwaard, Janette, and Ibrahim Dincer. "Comparative efficiency and environmental impact assessments of a hydrogen assisted hybrid locomotive." International Journal of Hydrogen Energy 41, no. 16 (2016): 6894-6904.
19. Zhang, Guiju, Caiyuan Xiao, and Navid Razmjooy. "Optimal parameter extraction of PEM fuel cells by meta-heuristics." International Journal of Ambient Energy 43, no. 1 (2022): 2510-2519.
20. Leng, Hua, Xinran Li, Jiran Zhu, Haiguo Tang, Zhidan Zhang, and Noradin Ghadimi. "A new wind power prediction method based on ridgelet transforms, hybrid feature selection and closed-loop forecasting." Advanced Engineering Informatics 36 (2018): 20-30.
21. Hosseini Firouz, Mansour, and Noradin Ghadimi. "Optimal preventive maintenance policy for electric power distribution systems based on the fuzzy AHP methods." Complexity 21, no. 6 (2016): 70-88.
22. Little DJ, Smith MR, Hamann TW. Electrolysis of liquid ammonia for hydrogen generation. Energy Environ Sci 2015;8:2775–81. https://doi.org/10.1039/ c5ee01840d.
23. Dong BX, Ichikawa T, Hanada N, Hino S, Kojima Y. Liquid ammonia electrolysis by platinum electrodes. J Alloys Compd 2011;509:S891–4. https://doi.org/10.1016/j.
24. Hoffrichter, Andreas, Stuart Hillmansen, and Clive Roberts. "Conceptual propulsion system design for a hydrogen-powered regional train." IET Electrical Systems in Transportation 6, no. 2 (2016): 56-66.
25. Saudi Arabia Railways (SAR): https://www.sar.com.sa/ accessed on 20-3-2024
26. Riyadh metro : https://www.ratpdev.com/en/references/saudi-arabia-riyadh-metro accessed on 20-3-2024.
27. Makkah metro: https://themetrorailguy.com/metro-rail-systems/mecca-metro-information-stations-route-map-fare-prices-pass-hours-timings/ accesed on 20-3-2024
28. Hay, William W. Railroad engineering. Vol. 1. John Wiley & Sons, 1991.
29. CSR Qingdao Sifang Co. & Tsinghua University. Hydrogen fuel cell tram feasibility analysis report, 12; 2014
30. Miller, A. R., K. S. Hess, D. L. Barnes, and T. L. Erickson. "System design of a large fuel cell hybrid locomotive." Journal of Power Sources 173, no. 2 (2007): 935-942.
31. Steward, D., G. Saur, M. Penev, and T. Ramsden. Lifecycle cost analysis of hydrogen versus other technologies for electrical energy storage. No. NREL/TP-560-46719. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2009.
32. Logan, Kathryn G., John D. Nelson, Benjamin C. McLellan, and Astley Hastings. "Japan and the UK: Emission predictions of electric and hydrogen trains to 2050." Transportation Research Interdisciplinary Perspectives 10 (2021): 100344.
33. OECD. Effective Carbon Rates 2021. OECD Publishing, 2021.
34. https://www.railtech.com/innovation/2023/09/19/irish-rail-and-latvias-digas-to-trial-europes-first-retrofitted-hydrogen-freight-locomotive/
35. Atteridge, W. J., & Lloyd, S. A. (2021). Thoughts on use of hydrogen to power railway trains. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 235(2), 306-316.
36. Hoffrichter, A., Hillmansen, S., & Roberts, C. (2016). Conceptual propulsion system design for a hydrogen-powered regional train. IET Electrical Systems in Transportation, 6(2), 56-66.
37. Ozen, D. N., Timurkutluk, B., & Altinisik, K. (2016). Effects of operation temperature and reactant gas humidity levels on performance of PEM fuel cells. Renewable and Sustainable Energy Reviews, 59, 1298-1306.