Article citation info:
Radziszewski P, Urbański P, Rozynek Ł, Ciepły P, Barański M, Cierniewski M. Modular hydrogen fuel cell propulsion test stand for railway applications. Combustion Engines. 0000;XXX(X):xx-xx. https://doi.org/10.19206/CE-204513

Patryk RADZISZEWSKI
Patryk URBAŃSKI
Łukasz ROZYNEK
Piotr CIEPŁY
Mikołaj BARAŃSKI
Maksymilian CIERNIEWSKI

Combustion Engines
Polish Scientific Society of Combustion Engines

Modular hydrogen fuel cell propulsion test stand for railway applications

ARTICLE INFO

Received: 29 November 2024
Revised: 10 April 2025
Accepted: 29 April 2025
Available online: 21 May 2025

The article discusses the concept of using a hydrogen fuel cell as the primary energy source for a rail vehicle's propulsion system. The authors presented the idea of a stationary test stand for commissioning and testing of the hydrogen fuel cell, cooperating with a battery energy storage system and a traction inverter. At the same time, a modular installation of key components of the propulsion system was proposed, which allows flexible adaptation to different types of rail vehicles. Particular attention was paid to analyzing the potential of the above solution for easy application to existing vehicles. The described test stand allows not only testing of hydrogen propulsion control algorithms, but also lays the foundation for the development of a complete propulsion management system for rail vehicles, supporting the development of modern, environmentally friendly transportation solutions.

Key words: *fuel cell, rail vehicle, hydrogen, test stand, propulsion system*

1. Introduction

Transport is one of the main factors of economic growth and development. In the main, Internal Combustion Engines (ICE) are the primary source of propulsion in vehicles (99.8%) [26]. Due to the relatively low cost of purchasing and vehicle maintenance, mainly road vehicles, and the developed infrastructure, this type of propulsion is widely available around the world. At the same time, due to the popularity, the transport sector consumes significant amounts of energy, mainly relying on the use of petroleum products (95%) [31]. This means that a huge amount of fuels, such as gasoline and diesel, are consumed. As a result of the combustion reaction of hydrocarbon fuels, the main product of combustion is carbon dioxide (CO_2). Transport is responsible for about 20% of global CO_2 emissions [1]. In addition, incomplete and imperfect combustion also results in hydrocarbons (HC), nitrogen oxides (NO_x), carbon monoxide (CO), and Particle Matters (PM) in the exhaust gas. Emitted in huge quantities, CO_2 has a significant impact on the global climate change that is occurring. In turn, the other harmful compounds [15] contained in exhaust gases [37], have a negative impact on the environment, including human health and life [39].

For this reason, a number of initiatives and regulations have emerged to reduce fossil fuel consumption and exhaust emissions [51]. Mention should also be made of the European Union (EU) policy aiming to completely eliminate CO_2 emissions in the longer term [17]. Currently, reduction of harmful compounds from the exhaust fumes is possible through the use of exhaust aftertreatment systems [42, 44] and increasing the efficiency of ICEs [6]. Ultimately, however, this is or will be insufficient in many cases. For this reason, solutions have begun to be sought through the use of alternative fuels or the electrification of drive systems. In the case of automotive vehicles and urban mass transit vehicles, the use of hybrid powertrains is a common practice [2]. In the case of diesel rail vehicles, such solutions have been known for a long time. Much of the diesel rolling stock is equipped with an electric transmission, or power generator, which is driven by ICEs [3]. This means that a diesel rail vehicle with an electric transmission has an electric powertrain.

A more complex and costly solution [50] is to use hydrogen as a fuel for vehicle propulsion. This fuel can be used in adapted ICEs [10, 41, 43], in many cases, like rail vehicles [5], the marine industry, or power generators [4]. However, this method is characterized by lower efficiency than the use of hydrogen in fuel cells (FC) [12], where less thermal energy is lost. In addition, burning hydrogen at high temperatures may cause the formation of NO_x [35]. The second solution is the use of hydrogen in FC, including rail transport [16, 49]. Due to the nature of FCs operation, such systems have a higher efficiency of 35–70% [8] and local zero emissions, except water vapor. However, the use of FC in transport is still severely limited, and despite the commercially available hydrogen cars and the use of hydrogen buses, the most popular type of transport are still ICE vehicles. The situation is similar in the rail market, where a big share of the total number of vehicles are diesel vehicles [48].

Despite this, the rail hydrogen market is developing quite dynamically [45]. Concepts and prototypes [36] of vehicles using hydrogen FC have been developed [23]. The project in Canada was to build a hydrogen FC on a GP9 8637 switcher locomotive. The goal of this project was to determine if hydrogen-powered FC switcher locomotives could meet the operational demands and duty cycles of yard service [30]. In Japan, a passenger multiple unit (MU) called the Hydrogen-Hybrid Advanced Rail Vehicle for Innovation (HYBARI) was developed [29, 34]. In Poland, a hydrogen shunting locomotive, the SM42-6Dn, was created by retrofitting the drive in a diesel locomotive [13, 14]. In Germany, a hydrogen MU rail vehicle, the Coradia iLint, produced by Alstom, was put into regular service for the first time on a local passenger line [20]. More versions of passenger rail vehicles are currently under development and have been ordered by rail operators [29].

Hydrogen propulsion, in terms of numbers, currently represents an almost unnoticeable part in the transport sector. However, the use of this type of fuel in vehicles is being developed around the world. In addition, policies leaning toward zero-emission propulsion are, in a way, forcing the development of such solutions [27]. For this reason, innovative research and development works are necessary to increase the efficiency, including financial efficiency, of the application of hydrogen propulsion systems. However, in order for a final hydrogen vehicle to be developed, a lot of research is required regarding hydrogen fueling [40], on-vehicle storage, control system [9] and power flow [11], among others. This includes the ability to test and verify the created propulsion systems for development.

Various solutions have been developed to investigate hydrogen FC systems. Test benches and laboratories were created for testing hybrid-electric systems. However, the maximum power of FC is very often characterized by a low level, for example, 257.8 W [18], 200 W [7], or concerns the integration of a hydrogen system with an electric energy system for stationary use [22]. In the case of hydrogen FC power train systems, test benches dedicated to different types of vehicles, such as tractors [28] or aerial applications [21, 32], have been created, the results of which can be scaled. For railway purposes, research was also carried out on the use of FC in a vehicle. Some of the research concerned the simulation part [19], but real hydrogen FC test benches for railway application were created, also on a large scale up to 160 kW [46] and 200 kW [33]. Small scale test benches for railway applications for further results scaling are rather rare, and in the case of FC applications with greater power, are really unique. Therefore, research carried out at such test stands is of great value and usefulness.

The article presents information and ideas regarding the author's modular hydrogen propulsion test stand for railway application. Solution, using FC with a power of 103 kW and power electronics of up to 200 kW, has been developed and is in the implementation process. The project is to be designed for work on hydrogen propulsion systems for the railway sector. One of the most important advantages of the test stand is its modularity. This feature allows testing of different configurations and elements with various technical characteristics, depending on the research needs. This article describes the most important data and technical parameters of the ongoing project, which is unique test stand not only in Poland but also in Europe.

2. Test stand

2.1. Description

In order to ensure accessibility to each component included in the system and in view of the need for continuous monitoring of selected parameters, it was decided in the first stage to build the complete hydrogen propulsion system in a modular structure. These modules, in the form of containers, provide easy service access to each component of the system. The modular design of the stand ensures the separation of components with different characteristics of operation, particularly creating a controlled test environment for hydrogen fuel-related components.

The components of the propulsion system were built in two containers: a container containing the power electronics, and a container containing the hydrogen FC, along with the cooling system and inverter. The test stand additionally includes a supervisory container with computer workstations for operating the measurement equipment and social space (Fig. 1). Each module has a glazed area on one of the container's walls, which allows eyewitness observation of the system during operation and provides a quick view of the operation of the component equipment, while also serving a teaching and development function for hydrogen propulsion area.

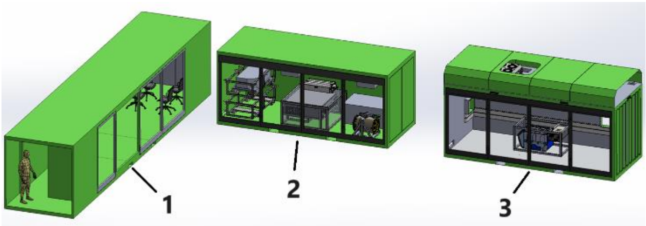


Fig. 1. Example test stand modules: 1 – social module, 2 – power electronics module, 3 – hydrogen module

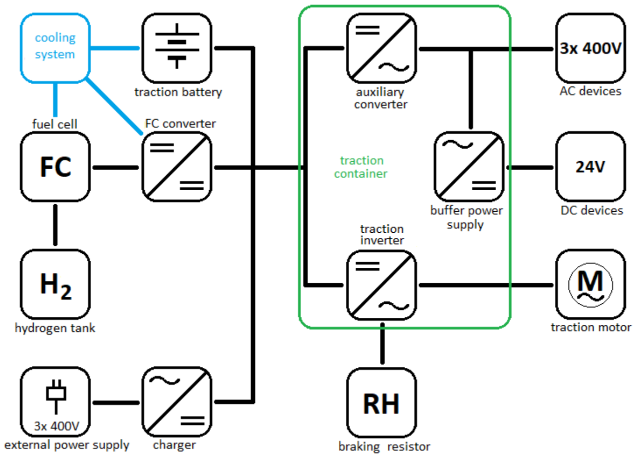


Fig. 2. Schematic diagram of the main circuit

The schematic diagram of the main circuit (Fig. 2) provides a simple illustration of the principle of the power system. The system is based on a common power line (HV bus), to which the FC inverter, traction battery and traction container are connected, seamlessly cooperating in power distribution on the basis of a diagnostic system that is an integral part of the control system developed in the project.

The traction (power electronic) container consists of a traction inverter section, a static inverter, and a buffer power supply. The traction inverter supplies power to the traction motor or other resistive-inductive loads. The static inverter provides power to the 3×400 V AC circuits, and the buffer power supply with a 24 V DC output powers the control circuits and manages the auxiliary low-voltage (LV) battery. The primary power source for traction purposes is a hydrogen FC along with a power cable harness, supported by a traction battery when energy consumption is at its highest. The cooling system provides conditioning for equipment requiring cooling/heating by means of liquid.

The traction battery in the case of an inactive hydrogen FC can be recharged using a buffer charger, which for this purpose can operate in plug-in mode using a three-phase 3×400 V AC grid.

2.2. Fuel cell module

The hydrogen FC module was built in a dedicated container. This allows the separation of the equipment associated with operating the cell from the operator and the external environment. Due to this, it is possible to create stable operating conditions for the system and convenient service access (Fig. 3).

The main and most important component that ensures the autonomy of the propulsion system is the hydrogen FC (Fig. 4). A FC with a net power of 103 kW, adapted to operate with a dedicated inverter, is planned for use on the test bench. FCs of this type are widely used in bus transportation, providing reliable operation and high component availability. They have been implemented in many applications operating in the transportation industry, making them a proven and reliable solution for such projects. The device has been built into a specially designed frame, taking into account the manufacturer's guidelines. All this to ensure easy service access and adequate vibration isolation in particular for further use on a vehicle. The basic parameters of the hydrogen FC are shown in Table 1.

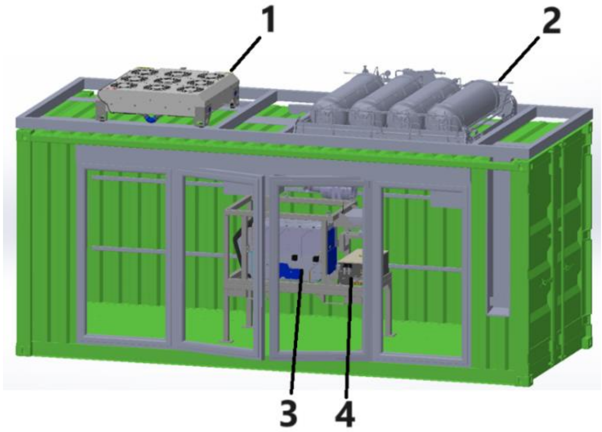


Fig. 3. Hydrogen container: 1 – cooling system, 2 – hydrogen tanks, 3 – hydrogen FC, 4 – hydrogen FC DC/DC converter

Fig. 4. Fuel cell

The supply system consists of a set of tanks with compressed hydrogen at a nominal pressure of 350 bar, a regulator for an operating pressure of 10 bar, and a series of valves to prevent leakage, explosion, and unfavorable operating conditions of the system. The hydrogen tanks were located outside the container and built on a specially designed roof support (Fig. 5). The hydrogen system is adapted for refueling the tanks with hydrogen fuel from outside the container using a specially adapted connection, widely used in the automotive industry.

Table 1. Hydrogen cell parameters

Parameter	Unit	Value
Max power	kW	103
Voltage	V	280–560
Min. start temp.	ºC	–25
Max. efficiency	%	57
Mass	kg	~250

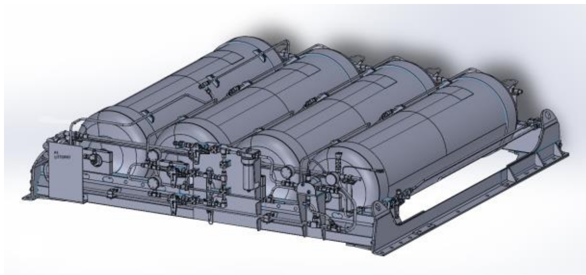


Fig. 5. Compressed hydrogen tanks located on the roof of the hydrogen container

An FC inverter is located in the hydrogen container. It converts the fluctuating voltage, depending on the phase and operating state of the FC, into a voltage supplying the main bus of the system. The key system of the hydrogen module is a distributed control and diagnostic system for selected operating parameters of the FC. This system is responsible for monitoring the operating status of the hydrogen FC and communicating with its internal controller and the FC's inverter. It makes it possible, due to the number of sensors and transducers, to study the operating characteristics of the hydrogen system.

2.3. Power electronics module

The power electronics module, analogous to the hydrogen FC module, was located in a dedicated container (Fig. 6). This isolates the operator during the operation of the station from the hazardous voltage and ensures ease of repair and modification of the system.

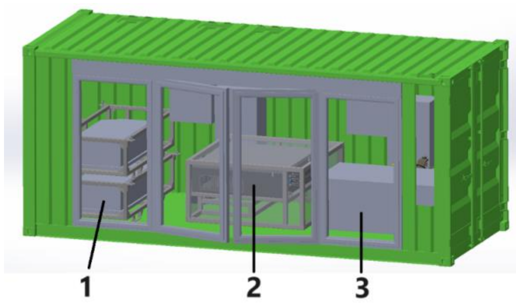


Fig. 6. Power electronics module: 1 – traction batteries, 2 – traction container, 3 – traction motor

Two lithium traction batteries (Fig. 7) were built into the power electronics module, connected directly to the high-voltage power line and equipped with individual battery management systems (BMS systems), communicating with the control system via CAN bus. They ensure the stable operation of the drivetrain during the initial start-up phase of the FC. They also cooperate under conditions of temporary increased power demand, for example, drive start-up. They also store energy recovered from the braking process. Additionally the system enables short-term battery drive without starting the FC, e.g. needed during rail vehicles shunting works. The basic parameters of the traction battery are shown in Table 2.

A key component of the module with power electronics is also a traction container containing an inverter and static converters along with a high voltage (HV) distribution board (Fig. 8). Using the voltage supplied by the HV line, the traction container provides power for the powertrain and auxiliary equipment of the planned future rail vehicle. The traction container also manages the LV battery, providing 24 volts for the control and diagnostic system, and allows charging from an external power source.

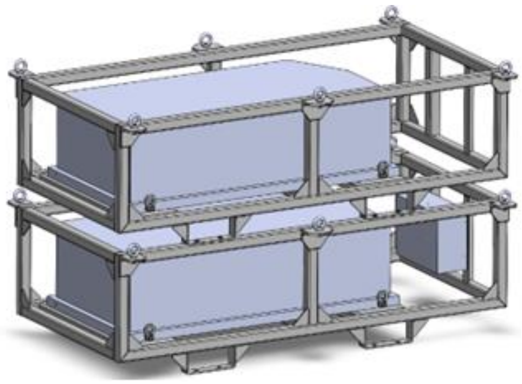


Fig. 7. Traction batteries built into a specially designed frame

Table 2. Parameters of the traction battery

Parameter	Unit	Value
Energy	kWh	100
Voltage range	V	540–765
Capacity	Ah	156

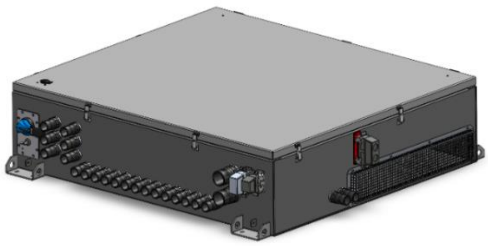


Fig. 8. Traction container

The equipment of the power electronics module also includes a three-phase traction motor (Fig. 9), which is the main energy consumer on the test stand. It is the primary source of propulsion for a rail vehicle with a maximum power of 200 kW. For design requirements, it operates at a limited power of 150 kW, with the possibility of increasing it depending on the target system application.

Analogous to the hydrogen module, also the power electronics module, of the described test stand, is equipped with an extensive diagnostic system. This system is monitoring the operation of each component, with particular attention to the power flow of the HV bus line for the development of an optimal control algorithm for the cooperation of the FC with traction batteries.

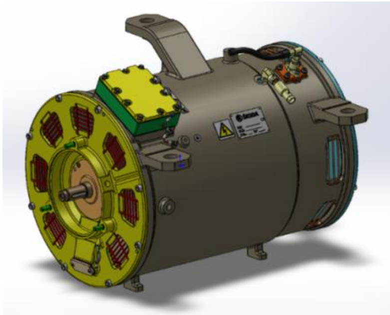


Fig. 9. Traction motor built in a container with power electronics components

3. Application of the solutions on vehicles

The test stand will allow accurate verification of simulation calculations and design assumptions in the vehicle design process. Tests of the hydrogen FC propulsion systems, under real vehicle operating conditions, will enable accurate analysis of operating parameters. This will make it possible to select the optimal powertrain components and layout the system on vehicles. The experience gained on the test stand will make it possible to create and then transfer a complete powertrain to a vehicle. Projects aimed at the application of hydrogen systems to newly designed vehicles, therefore, seem a natural direction (Fig. 10). The target group, considering current trends and operating conditions, are passenger MUs and shunting locomotives.

However, a group with significant potential are also vehicles, particularly diesel vehicles, for modernization. Indeed, it is worth noting the need to modernize vehicles, given their significant exploitation level, age, and the increasing difficulty of spare parts availability. Many units powered by ICEs are in urgent need of modernization to ensure reliable operation and compliance with current emission and noise standards.

Data from the Railway Transport Office shows that the average age of diesel rail vehicles in Poland exceeds 40 years [48]. From the perspective of modernization, it is possible to focus on diesel vehicles with the ICEs. The power of the ICEs should be close to the power of the designed power unit, powered by a hydrogen FC and traction battery.

The first group of vehicles that meet such criteria are light shunting locomotives, for example, the Polish Ls150, 2Ls150 and Ls180 series. These locomotives were produced in significant numbers (the Ls180 type alone is almost 900 units) and were intended for shunting work around industrial plants. A significant number of units are still in service. It should be mentioned that, according to available data, shunting locomotives spend most of their operating time idling 55%-89%, with an average of 69% [24, 25]. This is associated with fuel consumption despite the locomotive standing still. If FC is used on this type of vehicle, it will be possible to significantly reduce energy consumption, especially at standstill.

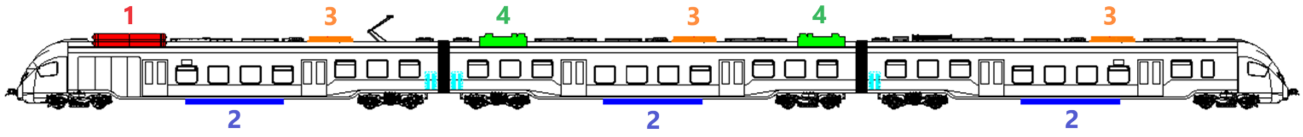


Fig. 10. Example of the location of hydrogen propulsion system components on the hybrid MU: 1 – hydrogen tanks, 2 – traction batteries, 3 – traction containers, 4 – hydrogen FC

The second group of vehicles, often forgotten, with the potential to be upgraded to a hydrogen propulsion system are rail auxiliary vehicles for special purpose works. Officially, according to the European Vehicle Number (EVN) in Poland in 2020, there were 3737 units, of which 1285 were self-propelled. The number of auxiliary vehicles is probably higher, due to the use of some of them exclusively in private areas and being separated from public railway lines. Auxiliary vehicles can be found on sidings and in enterprises, where these vehicles are not required to have an EVN [47]. The group of auxiliary vehicles can include motor trucks, ballast cleaners, scrapers, ballast profilers, working draglines, etc. The group of these vehicles is also characterized by a significant average age, for some groups exceeding 40 years.

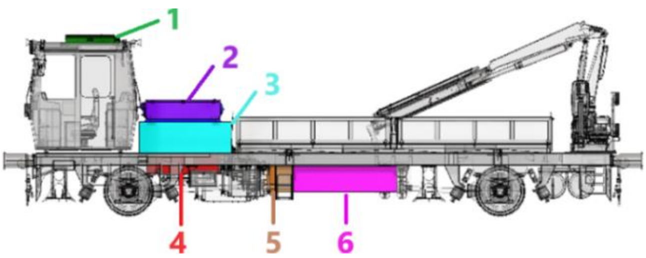


Fig. 11. Example of the location of components of the propulsion system on the WM-15A vehicle: 1 – braking resistor, 2 – hydrogen tanks, 3 – compartment with power electronics and hydrogen FC, 4 – traction motor, 5 – cooling system, 6 – traction battery [38]

One of the examples considered is the modernization of the WM-15A motorized truck, as drivetrain retrofitting. In this case, components selected during the tests (Fig. 11) can be built in place of the ICE's compartment, on the underframe and roof of the vehicle [38]. Such a solution is a cost-attractive and easy-to-implement option for adapting an existing fleet of auxiliary vehicles to meet the goals of energy and environmental requirements of the EU.

An analogous application of the system, along with lessons learned and experience gained during the development of the test bench, can be transferred to the powertrains of other vehicles. After appropriate scaling, these could include more elaborate vehicles, such as higher-powered or hybrid locomotives, as well as MU passenger vehicles.

4. Conclusions

The launch of a modular hydrogen FC propulsion test stand allows for the gathering of the experience needed to develop the FC vehicle control system. It is a milestone for the wider dissemination of hydrogen technology in rail vehicles. Despite the intense expansion of this type of solution, especially in Asian and European markets, it is still a marginal choice in the railway industry. The number of orders for hydrogen rail vehicles is significantly smaller compared to e.g. manufactured hydrogen buses.

The advantage of the modular test stand solution is that there are no space limits with the installation of measuring equipment, compared to testing on a real vehicle. Additionally, service access to individual components of the test stand is definitely easier. It is also possible to further expand the stand, as such a stand does not require such restrictive limits on the dimensions and weight of equipment as in the case of vehicles.

The use of an adjustable load function provides an opportunity to collect the operating parameters data of the FC under various conditions of the real operation. Simultaneously, the test stand will allow a convenient way to present the results obtained. On the other hand, taking into account the modular design, it will allow the transfer of the designed drivetrain components to the real rail vehicle.

The modular hydrogen FC propulsion test stand will be the base for the design and verification of propulsion systems. Therefore, the research and development work performed will then be able to be used in the implementation phase. The developed propulsion systems and other systems included in the project, such as the control system, will be able to find real application on rail vehicles. It is planned that the target group of vehicles, in which the results of R&D works will be applicable, will be newly designed vehicles and vehicles intended for modernization. The most favorable types of vehicles, for application of designed hydrogen FC propulsion systems, are shunting locomotives, MUs and auxiliary or special-purpose vehicles.

Acknowledgements

This article was written in connection with the project "Complete hydrogen vehicle control system" – H2CONTROL, subsidized from the state budget – grant from the President of the Lukasiewicz Center.

Łukasiewicz Sieć Badawcza   Łukasiewicz Poznański Instytut Technologiczny

Nomenclature

AC	alternating current	EU	European Union
CO	carbon monoxide	EVN	European Vehicle Number
CO_2	carbon dioxide	FC	fuel cell
DC	direct current	HC	hydrocarbon

HV high-voltage
ICE internal combustion engines
LV low-voltage
MU multiple unit
NO_x nitrogen oxides
PM particle matters

Bibliography

[1] Awan A, Alnour M, Jahanger A, Chukwuma OJ. Do technological innovation and urbanization mitigate carbon dioxide emissions from the transport sector? Technol Soc. 2022;71: 102128. https://doi.org/10.1016/j.techsoc.2022.102128

[2] Bajerlein M, Rymaniak L. The reduction of fuel consumption on the example of ecological hybrid buses. Appl Mech Mater. 2014;518:96-101. https://doi.org/10.4028/www.scientific.net/AMM.518.96

[3] Barbosa FC. Hybrid rail technology review: an intermediate pathway for electrifying. American Society of Mechanical Engineers Digital Collection. 2021. https://doi.org/10.1115/JRC2021-58271

[4] BeHydro. Dual fuel and 100% hydrogen engines. BeHydro. https://www.behydro.com/ (accessed on 28.01.2025).

[5] Collins P. Irish Rail diesel locomotive to be converted to H2 ICE. Hydrogen Europe. September 15, 2023 https://hydrogeneurope.eu (accessed on 28.01.2025).

[6] Dahham RY, Wei H, Pan J. Improving thermal efficiency of internal combustion engines: Recent Progress and Remaining Challenges. Energies. 2022;15(17):6222. https://doi.org/10.3390/en15176222

[7] D'Alvia L, Gagliardi G, Apa L, Cava C, Rizzuto E, Borello D et al. Scaled test bench for the measurement of a hybrid full-electric powertrain efficiency. Meas Sens. 2024:101433. https://doi.org/10.1016/j.measen.2024.101433

[8] Daszkiewicz P, Kurc B, Pigłowska M, Andrzejewski M. Fuel cells based on natural polysaccharides for rail vehicle application. Energies. 2021;14(4):1144. https://doi.org/10.3390/en14041144

[9] Deng K, Fang T, Feng H, Peng H, Löwenstein L, Hameyer K. Hierarchical eco-driving and energy management control for hydrogen powered hybrid trains. Energy Convers Manag. 2022;264:115735. https://doi.org/10.1016/j.enconman.2022.115735

[10] Depczyński WP, Marchenko A, Mishchenko S, Mishchenko M. The effect of hydrogen addition to traditional petrol engine fuel in a hybrid power plant on its environmental performance and fuel efficiency. Combustion Engines. 2025; 200(1):87-94. https://doi.org/10.19206/CE-199735

[11] D'Ovidio G, Ometto A, Valentini O. A novel predictive power flow control strategy for hydrogen city rail train. Int J Hydrog Energy. 2020;45(7):4922-4931. https://doi.org/10.1016/j.ijhydene.2019.12.067

[12] Durkin K, Khanafer A, Liseau P, Stjernström-Eriksson A, Svahn A, Tobiasson L et al. Hydrogen-powered vehicles: comparing the powertrain efficiency and sustainability of fuel cell versus internal combustion engine cars. Energies. 2024;17(5):1085. https://doi.org/10.3390/en17051085

[13] Durzyński Z. Hydrogen-powered drives of the rail vehicles (part 1). Rail Vehicles/Pojazdy Szynowe. 2021;2021(2):29-40. https://doi.org/10.53502/RAIL-139980

[14] Durzyński Z. Hydrogen-powered drives of the rail vehicles (part 2). Rail Vehicles/Pojazdy Szynowe. 2021;2021(3):1-11. https://doi.org/10.53502/RAIL-142694

[15] Dziubak T, Ślęzak M. Characteristics of pollutants emitted by motor vehicles and their impact on the environment and engine operation. Combustion Engines. 2025;200(1):37-55. https://doi.org/10.19206/CE-194628

[16] Ehrhart BD, Klebanoff LE, Mohmand JA, Markt C. Study of hydrogen fuel cell technology for rail propulsion and re view of relevant industry standards. 2021. https://rosap.ntl.bts.gov (accessed on 16.03.2022).

[17] European Commission. The European Green Deal. July 14, 2021. https://commission.europa.eu (accessed on 27.01. 2025).

[18] Farinha J, Silva LM, Matlock J, Afonso F, Suleman A. Hydrogen fuel cell integration and testing in a hybrid-electric propulsion rig. Int J Hydrog Energy. 2023;48(97): 38473-38483. https://doi.org/10.1016/j.ijhydene.2023.06.090

[19] Fragiacomo P, Piraino F, Genovese M, Flaccomio Nardi Dei L, Donati D, Migliarese Caputi MV et al. Sizing and performance analysis of hydrogen- and battery-based powertrains, integrated into a passenger train for a regional track, located in Calabria (Italy). Energies. 2022;15(16):6004. https://doi.org/10.3390/en15166004

[20] Gallas D, Stobnicki P. Adoption of modern hydrogen technologies in rail transport. J Ecol Eng. 2022;23(3):84-91. https://doi.org/10.12911/22998993/145291

[21] Graf T, Fonk R, Schröter J, Hoenicke P, Bauer C, Kallo J et al. Investigation of a fuel cell hybrid system with a new modular test bench approach for all electric hybrid power train systems. J Energy Storage. 2022;56:105999. https://doi.org/10.1016/j.est.2022.105999

[22] Heuschmann A, Vervoort J, Schalk K, Denecke N. Commissioning and first operation of the hybrid power system "Hydrogen lab bremerhaven." IET Conf Proc. 2024;2024(2): 158-163. https://doi.org/10.1049/icp.2024.1832

[23] Hoffrichter A, Fisher P, Tutcher J, Hillmansen S, Roberts C. Performance evaluation of the hydrogen-powered prototype locomotive 'Hydrogen pioneer.' J Power Sources. 2014;250: 120-127. https://doi.org/10.1016/j.jpowsour.2013.10.134

[24] Kałuża A. General statistics of diesel engines' idle time: shunting locomotives in industrial sidings in Poland 2009…2013. Transp Res Part Transp Environ. 2016;49:82-93. https://doi.org/10.1016/j.trd.2016.08.031

[25] Kałuża A, Kucharski R. Locomotive diesel engine idle time distributions: case studies from Poland, 2009–2013. Transp Res Part Transp Environ. 2018;62:524-535. https://doi.org/10.1016/j.trd.2018.02.019

[26] Leach F, Kalghatgi G, Stone R, Miles P. The scope for improving the efficiency and environmental impact of internal combustion engines. Transp Eng. 2020;1:100005. https://doi.org/10.1016/j.treng.2020.100005

[27] Logan KG, Nelson JD, McLellan BC, Hastings A. Electric and hydrogen rail: potential contribution to net zero in the UK. Transp Res Part Transp Environ. 2020;87:102523. https://doi.org/10.1016/j.trd.2020.102523

[28] Martini V, Mocera F, Somà A. Design and experimental validation of a scaled test bench for the emulation of a hybrid fuel cell powertrain for agricultural tractors. Appl Sci. 2023;13(15):8582. https://doi.org/10.3390/app13158582

[29] Nqodi A, Mosetlhe TC, Yusuff AA. Advances in hydrogen-powered trains: a brief report. Energies. 2023;16(18):6715. https://doi.org/10.3390/en16186715

[30] Oklahoma Railway Museum. BNSF Railway Hydrogen Test Locomotive Donated to Oklahoma Railway Museum. Oklahoma Railway Museum. August 21, 2023. (accessed on 27. 01.2025). https://oklahomarailwaymuseum.org

[31] OPEC. World Oil Outlook 2013. Organization of the Petroleum Exploring Countries.

[32] Ozbek E, Yalin G, Karaoglan MU, Ekici S, Colpan CO, Karakoc TH. Architecture design and performance analysis of a hybrid hydrogen fuel cell system for unmanned aerial vehicle. Int J Hydrog Energy. 2021;46(30):16453-16464. https://doi.org/10.1016/j.ijhydene.2020.12.216

[33] Peng H, Chen Z, Deng K, Dirkes S, Ünlübayir C, Thul A et al. A comparison of various universally applicable power distribution strategies for fuel cell hybrid trains utilizing component modeling at different levels of detail: From simulation to test bench measurement. eTransportation. 2021;9: 100120. https://doi.org/10.1016/j.etran.2021.100120

[34] Pielecha I, Dimitrov R, Mihaylov V. Energy flow analysis based on a simulated drive of a hybrid locomotive powered by fuel cells. Rail Vehicles/Pojazdy Szynowe. 2022;2022(1-2):68-76. https://doi.org/10.53502/RAIL-152703

[35] Pielecha I, Szwajca F, Skobiej K, Pielecha J, Merkisz J, Cieślik W. Analysis on monofuel: methane and hydrogen in passive TJI engine using center of combustion and lambda-value control. Int J Hydrog Energy. 2024;83:1170-1183. https://doi.org/10.1016/j.ijhydene.2024.08.159

[36] Piraino F, Genovese M, Fragiacomo P. Towards a new mobility concept for regional trains and hydrogen infrastructure. Energy Convers Manag. 2021;228:113650. https://doi.org/10.1016/j.enconman.2020.113650

[37] Puzdrowska P. Diagnosis of marine internal combustion engines by means of rapidly variable temperature and composition of exhaust gas as an alternative or support for currently used diagnostic methods. Combustion Engines. 2025; 200(1):19-30. https://doi.org/10.19206/CE-193951

[38] Radziszewski P, Cierniewski M, Stachowiak D. Analiza przepływu energii w pojeździe szynowym zasilanym wodorowym ogniwem paliwowym. Przegląd Elektrotechniczny. 2025;1(1):285-289. https://doi.org/10.15199/48.2025.01.60

[39] Rahman SMA, Masjuki HH, Kalam MA, Abedin MJ, Sanjid A, Sajjad H. Impact of idling on fuel consumption and exhaust emissions and available idle-reduction technologies for diesel vehicles – a review. Energy Convers Manag. 2013; 74:171-182. https://doi.org/10.1016/j.enconman.2013.05.019

[40] Rubio S, Nieto B, Martín J, Böhm M. Hydrogen refuelling and storage requirements for rail vehicles. Published online 2021.

[41] Shadidi B, Najafi G, Yusaf T. A review of hydrogen as a fuel in internal combustion engines. Energies. 2021;14(19): 6209. https://doi.org/10.3390/en14196209

[42] Siedlecki M, Szymlet N, Fuć P, Kurc B. Analysis of the possibilities of reduction of exhaust emissions from a farm tractor by retrofitting exhaust aftertreatment. Energies. 2022; 15(21):7963. https://doi.org/10.3390/en15217963

[43] Skobiej K. A review of hydrogen combustion and its impact on engine performance and emissions. Combustion Engines. 2025;200(1):64-70. https://doi.org/10.19206/CE-195470

[44] Sokolnicka-Popis B, Szymlet N, Siedlecki M, Gallas D. The impact of particulate filter substrate type on the gaseous exhaust components emission. Combustion Engines. 2020; 183(4):58-62. https://doi.org/10.19206/CE-2020-409

[45] Sun Y, Anwar M, Hassan NMS, Spiryagin M, Cole C. A review of hydrogen technologies and engineering solutions for railway vehicle design and operations. Railw Eng Sci. 2021;29(3):212-232. https://doi.org/10.1007/s40534-021-00257-8

[46] Trattner A, Klell M, Radner F. Sustainable hydrogen society – Vision, findings and development of a hydrogen economy using the example of Austria. Int J Hydrog Energy. 2022; 47(4):2059-2079. https://doi.org/10.1016/j.ijhydene.2021.10.166

[47] Urbański P, Michalak P, Gallas D, Cierniewski M, Bajerlein M, Radziszewski P. Auxiliary rail vehicles – characteristics of the polish rolling stock for special purpose works based on European Vehicle Number (EVN). Rail Vehicles/Pojazdy Szynowe. 2024;2024(1-2):59-65. https://doi.org/10.53502/RAIL-195507

[48] Urząd Transportu Kolejowego. Sprawozdanie z funkcjonowania rynku transportu kolejowego w 2023 r. Urząd Transportu Kolejowego. 2024. https://utk.gov.pl (accessed on 3.12.2024).

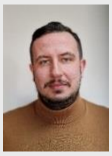
[49] Walters M, Sehr A, Dirkes S. Fuel cell systems for rail applications: development trends and challenges. Liebl J, (ed.). Der Antrieb von morgen 2020. Proceedings. Springer Fachmedien; 2021:216-234. https://doi.org/10.1007/978-3-658-35294-3_17

[50] Wróblewski P, Drożdż W, Lewicki W, Dowejko J. Total cost of ownership and its potential consequences for the development of the hydrogen fuel cell powered vehicle market in Poland. Energies. 2021;14(8):2131. https://doi.org/10.3390/en14082131

[51] Xinqun G, Dou D, Winsor R. Non-road diesel engine emissions and technology options for meeting them. American Society of Agricultural and Biological Engineers. 2010.

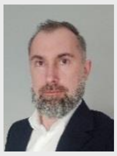
Patryk Radziszewski, MEng. – Centre for Modern Mobility, Łukasiewicz Research Network – Poznan Institute of Technology, Poland.
e-mail: *patryk.radziszewski@pit.lukasiewicz.gov.pl*

Piotr Ciepły, MEng. – Centre for Modern Mobility, Łukasiewicz Research Network – Poznan Institute of Technology, Poland.
e-mail: *piotr.cieply@pit.lukasiewicz.gov.pl*



Patryk Urbański, MEng. – Centre for Modern Mobility, Łukasiewicz Research Network – Poznan Institute of Technology, Poland.
e-mail: *patryk.urbanski@pit.lukasiewicz.gov.pl*

Mikołaj Barański, MEng. – Centre for Modern Mobility, Łukasiewicz Research Network – Poznan Institute of Technology, Poland.
e-mail: *mikolaj.baranski@pit.lukasiewicz.gov.pl*



Łukasz Rozynek, MEng. – Centre for Modern Mobility, Łukasiewicz Research Network – Poznan Institute of Technology, Poland.
e-mail: *lukasz.rozynek@pit.lukasiewicz.gov.pl*

Maksymilian Cierniewski, DEng. – Centre for Modern Mobility, Łukasiewicz Research Network – Poznan Institute of Technology, Poland.
e-mail: *maksymilian.cierniewski@pit.lukasiewicz.gov.pl*