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Prospects for the development of fuel cells in railway applications

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In recent years, there has been a huge increase in interest in fuel cell technology, which has undergone a period of rapid development. In the automotive market and in the railway industry, there is a growing trend in the production of transport containing fuel cells. The European Union is also striving to minimize greenhouse gas emissions in order to achieve climate neutrality by 2050. The article discusses the current use of hydrogen fuel cells in the railway industry. It shows groundbreaking projects of hybrid rail vehicles in the last few years. It also presents a brief overview of hydrogen fuel cell technology, its advantages and further challenges that need to be addressed to develop the market.

Key words: *fuel cells, rail vehicles, hydrogen, greenhouse gas emissions, hybrid vehicles*

1. Introduction

Nowadays, in the 21st century, one of the biggest challenges has become global warming. The whole world is striving to minimize the use of fossil gases and the emission of greenhouse gases (GHGs) that cause them. Legislation (Directive 2003/87/EC) suggests that new vehicles should be zero emission by 2035. In 2050, the European Union is to achieve climate neutrality - zero net emissions (NZE). To achieve this, the International Energy Agency (IEA) informs that CO_2 emissions in the transport sector must decrease radically by more than 3% per year by 2030 [29].

Railways are considered to be an economical, environmentally friendly form of transport. They have a very large load capacity, and the tracks take up very little space compared to roads [16]. However, this method of transport can also be improved to become zero-emission. It is equally important to continue to encourage more and more passengers to use this form of transport. Diesel-powered railway vehicles, which burn oil, are currently very popular on low-frequency long-distance routes. These engines are characterized by high thermodynamic efficiency and high torque [4]. However, burning oil causes very large greenhouse gas emissions (approx. 2,69 kg CO_2/dm^3). So far, electric or hybrid vehicles have been designed to minimize carbon monoxide emissions into the atmosphere [33]. However, electric vehicles have many disadvantages, including long charging time, low cell life, and the existing hybrid systems do not meet CO_2 emission limits. Currently, in order to reduce greenhouse gas emissions in railways, they are being electrified.

The history of the first electric railways dates back to the 19th century, when the first electric train designed by Werner von Siemens was presented in Berlin in 1879 [33]. However, the electrification of railway lines and the related construction of new infrastructure (supply lines, power substations, rectifier stations) are associated with very high costs. Therefore, the electrification of railways took place only in places with high traffic, mainly in urban railways. Such drastic zero emission requirements dictated by the European Union force the creation of new hybrid systems containing hydrogen fuel cells. An increase in the interest of manufacturers in investing in the electric drive sector can be observed in the automotive and railway markets [3]. Currently, there are several types of hydrogen cells, depending on the type of fuel used. However, hydrogen has found the greatest application in transport due to its high reactivity both at high temperatures (even 500^oC) and low temperatures [26]. Initially, fuel cells were mainly used in road transport – cars and buses. However, currently there are also attempts to implement hybrid drives using hydrogen fuel cells in rail transport [33]. There are studies [8, 22] that show that the diesel rail vehicles used so far can be replaced by a hybrid drive using hydrogen fuel cells and a cooperating battery energy storage unit. The only additional element related to infrastructure and the related cost is refueling stations.

The principle of the fuel cell was discovered by chemist Christian Friedrich Schoenbein in 1838. The scientist discovered it by accident during an experiment related to electrolysis. He disconnected the battery from the electrolyzer and connected two electrodes. He observed that the current flowed in the opposite direction, and oxygen and hydrogen were consumed. However, the chemist could not cope with the corrosion of the electrodes, which is why it was commonly believed that it was useless. At that time, he used sulfuric acid as an electrolyte. Several decades later, chemical engineer Francis Bacon resumed work on fuel cells. He changed the acid electrolyte to alkaline (KOH solution) and used powdered nickel as electrodes. Thanks to this, he obtained a higher power density of the cell and dealt with the problem of electrode corrosion [13].

2. Principle operation of hydrogen fuel cells and their types

2.1. Introduction

The operation of a fuel cell is based on the reverse electrolysis process. Hydrogen fuel cells convert chemical energy into electrical energy as an exergonic reaction of hydrogen with oxygen (oxidation-reduction reaction-redox). The principle of their operation was known in the 19th century, but they did not find application until the use of a cell with polymer membranes in the Gemini and Apollo space missions to power NASA satellites and space capsules [37].

A hydrogen fuel cell consists of an anode, a cathode, and an electrolyte. Hydrogen is continuously supplied to the anode, and oxygen is continuously supplied to the cathode. Theoretically, during the oxidation-reduction (redox) reaction, each atom changes its oxidation state. The catalyst at the anode splits the hydrogen into protons and electrons. Then the electrolyte allows only protons to pass to the cathode. And the electrons move to the cathode via an external electrical circuit. At the cathode, electrons and protons combine with oxygen to form steam of water, which escapes from the cell [23, 32].

Basic chemical reactions occurring in a hydrogen fuel cell:

– Near the anode in an acidic solution, a hydrogen molecule is adsorbed on the catalyst surface and dissociates into a proton and an electron:

$$H_2 \overset{\leftarrow}{\rightarrow} 2H^+2e^- \qquad E_a^0 = 0\ V \tag{1}$$

– The protons then flow through the electrolyte; at the cathode, oxygen is reduced and steam of water molecules are formed:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \overset{\leftarrow}{\rightarrow} H_2O \qquad E_e^0 = 1.23V \tag{2}$$

The total reaction can be written using the equation:

$$H_2 \overset{\leftarrow}{\rightarrow} 2H^+2e^- \qquad E_a^0 = 0\ V \tag{3}$$

There are several types of hydrogen fuel cells currently in use and they may differ depending on the way the fuel is used, the operating temperature of the cells and the type of electrolyte used [18, 23, 38].

Table 1. Classification of hydrogen fuel cells

Fuel cell	Electrolyte	Catalyst	Fuel	Operating temperature (0°C)
LT PEMFC	Polymer membrane (H^+)	Fri	H_2	40–90
HT PEMFC	PFSA (H^+)	Fri/Fri	H_2	90–1000
AFC	Alkaline solution (most often KOH solution), (OH^-)	Fri/Mon Sun	H_2	60–220
MCFC	Li or K carbonates (CO_3^{2-})	No	H_2	600–700
SOFC	Zr oxides (O^{2-})	–	H_2	600–1000

Types of cells and their classification:

a) Depending on fuel use:
   - direct hydrogen supply
   - indirect – the fuel is obtained in the reforming process.

b) Depending on the operating temperature of the cells:
   - low temperature 25–100°C
   - high temperature – above 100°C

c) Depending on the type of electrolyte used:
   - with polymer membrane (PEMFC)
   - alkaline (AFC)
   - carbonate (MCFC)
   - oxide ceramic (SOFC)

Table 1 presents the classification of hydrogen fuel cells taking into account their characteristic features. The type of electrolyte used, the temperature range at which the cell operates, and the catalysts used (both on the anode and cathode) are taken into account [18, 37].

2.2. Low temperature fuel cells

The most popular due to safety and energy efficiency is the low-temperature hydrogen cell with polymer membrane LT PEMFC. The electrolyte is a polymer containing sulfonic groups (most often Nafion) [1, 5]. It is formed into a membrane covered with porous platinum, acting as a catalyst. The electrodes are two graphite sheets. The whole is pressed at a high temperature. Due to the presence of platinum in the electrolyte, PEMFC cells are very sensitive to carbon monoxide – at a CO concentration of 10–20 ppm and an operating range of 60–80°C, the catalyst is "poisoned" [5]. Hydrogen used as fuel in these cells must be very pure (≥ 99.97% – the maximum content of pollutants must not exceed 300 ppm); it cannot come from reforming. Therefore, another, better application may be HT PEMFC cells operating at temperatures above 100°C LT PEMFC cell stacks provide energy efficiency of up to about 60% [15].

The oldest, one of the first fuel cells, is the alkaline AFC cell. It was thanks to alkaline fuel cells that the first American space missions were successful. Traditional AFC cells, like PEMFC, can also operate at room temperature (40–75 °C). However, they have an electrolyte that is highly sensitive to CO_2 (35–85% wt. KOH solution); it degrades when in contact with carbon monoxide. In addition to traditional cells with a liquid electrolyte, alkaline fuel cells also include more modern solutions – fuel cells with a polymer anion exchange membrane (AEMFC). AEMFC cells can be used in a slightly wider temperature range of 50–90 °C and are characterized by a much higher current density of 300–9700 mA cm^{-2} (compared to traditional cells, 100–300 mA cm^{-2}). However, to date, they have only found laboratory applications [12, 18]. Compared to other fuel cells operating at low temperatures, alkaline cells do not have noble metals such as Pt or Pd used as a catalyst.

2.3. High temperature fuel cells HT PEMFC

Higher operating temperature fuel cells are attracting increasing attention because they do not require expensive metal catalysts and because the exhaust heat can be efficiently managed by other thermal cogeneration systems. High-temperature fuel cells also have higher efficiency compared to low-temperature fuel cells [23]. Such fuel cells include polymer membrane HT (PEMFC), carbonate MCFC, oxide ceramic (SOFC), and zinc air (ZAFC) [34, 46].

One type of hydrogen-polymer cells with a polymer membrane, but suitable for use at temperatures above 100°C, are HT PEMFC cells. The best solution for PEMFC cells is to use pure hydrogen as fuel, but currently, this is a very expensive solution. Hydrogen is most often obtained by reforming organic fuels, including natural gas and gasoline. Hydrogen produced in this way usually contains about

0.1–2% of impurities. HT PEMFC cells, compared to LT PEMFC, are more resistant to catalyst poisoning. The entropy of the adsorption phenomenon of carbon monoxide on Pt is negative, so adsorption preferentially occurs at low temperatures. At the same time, at higher temperatures, when using high-temperature cells, the adsorption of harmful gases on the catalyst is slower, which is why they show greater tolerance to these gases. Another challenge for PEMFC cells is their efficiency. The use of HT PEMFC cells reduces the problem of the need for cooling technology, because they can operate at higher temperatures. However, the main problem with using PEMFC cells at higher temperatures is that the membranes and catalysts degrade much faster. HT PEMFC cells do not have platinum as a catalyst. They can also be powered by hydrogen produced by the reforming process. The energy efficiency of the fuel cell is typically 35–60% [4, 18, 46].

The generated electricity from fuel cells is transferred directly to the rail vehicle drive system or to energy storage (most often batteries). The use of hydrogen fuel cells as the only source of energy is associated with many disadvantages, including their high cost, shorter service life, and slow response to changes in dynamics. Therefore, in rail vehicles, in order to minimize gas emissions and demand for fossil fuels, a hybrid system is usually designed, in which the primary power source is hydrogen fuel cells, and the storage is batteries. A hybrid system is designed, consisting of a fuel cell and an ESS (energy storage system); additionally, appropriate control algorithms are needed to manage energy from these sources [4, 31, 35]. There are various energy storage devices, most often currently these are lithium-ion Li-on batteries, nickel-cadmium NiCd batteries, and newer solutions, such as $LiFePO_4$ and titanium batteries. Lithium-ion batteries are a very good solution due to their high energy density and low weight.

The EMS energy management system efficiently manages the energy between the PEMFC cells and the batteries to minimize fuel consumption and achieve high charging efficiency [22]. The PEMFC and the battery together provide power to the vehicle. There are three driving modes:

- Battery Drive Mode – When the total power requirement is supplied solely by the battery
- Fuel Cell Driving Mode – The battery charges, and the entire power requirement is supplied by the fuel cell
- Fuel cell and battery-powered driving mode – when the total power requirement is supplied by the fuel cell and battery.

There are many advantages to using hydrogen fuel cells in rail transport. These include:

- quiet operation of railway vehicles
- energy independence of states
- reduction of greenhouse gas emissions, including CO_2 (g)
- if hydrogen production and the entire hydrogen technology are introduced on a wide scale, the costs of hydrogen fuel cells will be reduced [23] (from USD 2.5 per kilogram to as much as USD 6.8)
- high efficiency of fuel cells (ok. 40–50%).

3. Overview of hydrogen drives in rail vehicles

3.1. Light Rail Vehicles (LRV) and suburban and regional multiple units running on non-electrified tracks

Taking into account all the given requirements and features of hydrogen cells, four types of rolling stock require a change of system. These are: light rail vehicles (LRV), suburban and regional trains running on non-electrified tracks, switch locomotives, and mining locomotives [20]. Over the years, there has been a tendency towards a growing interest in the topic of hydrogen-powered railways. In 2016, over 70 publications were written on the subject of "Hydrogen Trains", and in 2022, scientists undertook to write about 200 publications [16].

In 2017, the Chinese Tangshan Railway presented the first prototype of a light rail vehicle (LRV) powered by hydrogen fuel cells with batteries and ultracapacitors. This combination ensures completely wireless operation of the railway. The power of the hydrogen cells used was 150 kW. The supplier of hydrogen fuel cells was the Canadian company Ballard Power Systems. The LRV prototype has hydrogen tanks with a capacity of 12 kg, thanks to which it has a range of 40 km on a single refueling [20].

The first hydrogen traction unit was introduced to the market by Alstom [2, 39], which showed it at an event held in Munich in 2018 (Fig. 1). Alstom entered into cooperation with other companies producing fuel cells, batteries, and hydrogen tanks, including Selectron Systems, Hydrogenics, Hexagon Xperion, and Akasol [39]. Two prototypes underwent field tests on the Elbe-Weser line in Germany. The train, called Coradia iLint, is capable of reaching a distance of 1175 km without refueling at a maximum speed of 140 km/h. The fuel cells and hydrogen tank are situated on the roof of the train, while the rest of the hydrogen drive is located in the lower part of the train. The kinetic energy generated during braking is stored in lithium-ion batteries.

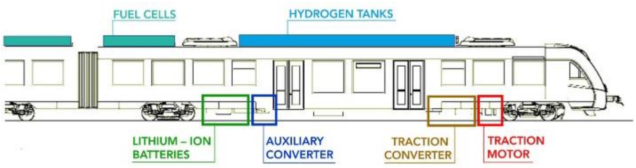

Fig. 1. A trainset manufactured by Alstom, using a hydrogen drive system [26]

Table 2 presents the basic data of selected Light Rail Vehicles (LRV) [11, 28, 29, 43, 44].

3.2. Shunting locomotives

In recent years, there has also been a development of large-scale prototypes of high-power traction vehicles. In 2009, Vehicle Projects LLC, a company consisting of leading US hydrogen production and storage companies, created a large-scale prototype of a hybrid shunting locomotive powered by hydrogen fuel cells and lead-acid batteries for use in cities and military bases [7, 15]. At 127 tons, the power reached 250 kW using a PEM fuel cell drive, and the transient power significantly exceeded 1 MW. This was the largest hydrogen fuel cell vehicle to date. Miller [6] described that the fuel cell stacks provide a mean power of 75 kW, with lead-acid batteries as an additional energy storage device, which provides peak power. The hydrogen was stored in compressed gas cylinders at a pressure of 350 bar [6, 17, 27]. The locomotive was tested at the Pueblo Test Facility. It was used as a shunting locomotive in Southern California and then transferred to the Oklahoma Railroad Museum in 2023 [6, 27].

Table 2. Basic data of selected Light Rail Vehicles (LRV)

Name of the traction unit	Year of produc-tion	Maximum speed	Maximum distance without refueling	Additional information
Mireo Plus H	2024	160 km/h	1200 km	Fuel cell power: 2 × 200 kW Traction power: 544 kW
Coradia Ilint	2018	140 km/h	1175 km	Traction power: 1.7 MW (battery and fuel cell)
Cinova H2	2024	200 km/h	1200 km	Fuel cell power: 4 × 960 kW
Hydro Flex	2019	130 km/h	1000 km	Fuel cell power: 200 kWh Hydrogen storage: 20 kg
FLIRT H2	2022	127 km/h	2803 km	Fuel cell power: 6 × 100 kW The fuel cells are placed in an additional car in the middle of the train

In 2012, China also began to take action to protect the environment and reduce greenhouse gases. The first PEMFC-based shunting locomotive was developed (Fig. 2). The locomotive's energy source is hydrogen, and the additional power source is lithium-ion batteries. The hydrogen storage system consists of nine 35 MPa cylinders that can store about 23 kg of compressed hydrogen. The hydrogen propulsion system is placed in the second half of the engine room. It consists of: a PEMFC stack module, an air supply module, a cooling module, and an auxiliary power module. The PEMFC stack has a rated power of 150 kW at 570–640 V. The locomotive was tested on a test line in Chengdu, Sichuan. Satisfactory results were obtained, which formed the basis for further modifications and development of hybrid locomotives [10].

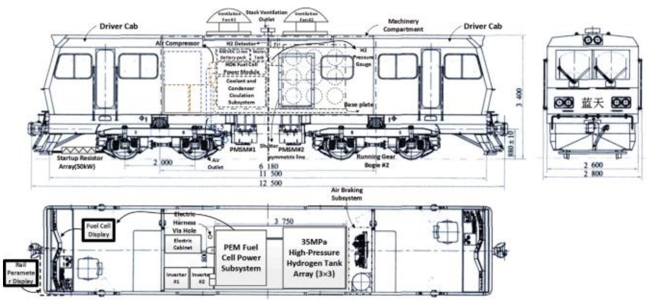

Fig. 2. System layout of the PEM fuel cell locomotive [10]

The next Chinese hybrid locomotive was designed by CRRC Datong and State Power Investment Corporation (SPIC) in 2021. The locomotive is designed for both shunting and regular line service. It is capable of operating continuously without refueling for 24.5 hours at a maximum speed of 80 km/h. The company claims that the locomotive reduces greenhouse gas emissions by about 80 kg per 1000 ton-km compared to a diesel locomotive [14].

3.3. Mining locomotives

Mining vehicles, due to their specific nature and closed workplace, should have be safe; an explosion could threaten a tragic accident. The advantage of a vehicle using hydrogen fuel cells compared to a locomotive using crude oil is the lack of extracted pollutants. The first prototype (Fig. 3) of a hydrogen-powered locomotive was developed and demonstrated in the USA by Vehicle Projects Inc. in 2002 [27, 36, 42]. The vehicle was powered by a polymer membrane fuel cell, and the energy was stored using metal hydrides and batteries. The vehicles were to be used in mining for platinum extraction. In 2012, the first commercial introduction of four 10-ton locomotives took place in South Africa as a mining vehicle. The locomotives have a metal hydride storage system, 22 kW fuel cells and a lithium-ion battery. The mining vehicle has a maximum power of 17 kW. Due to the use of a metal hydride energy storage system, it operates at a pressure of 10–15 bar, unlike other energy storage systems [19, 27].

Fig. 3. First hydrogen fuel cell-powered mining vehicle [25]

4. Challenges for hydrogen fuel cells

The biggest challenge for fuel cells is the cost of producing the fuel cells themselves, the cost of hydrogen production, its storage and transport, the cost of hydrogen power plants and the cost of investing in hydrogen fuel stations. The main factor contributing to the increase in the cost of fuel cells is the cost of, among others, the catalyst (usually platinum). Considering the use of fuel cells in transport, the cell systems would have to have a similar service life to alternative, current systems. Comparing the durability of current car engines, the durability of fuel cells after approx. 1000 h decreases significantly [9]. As for the costs of the technology itself and the hydrogen infrastructure, it depends on its mass production and hydrogen production. The assumption is based on the statement that long-term costs will be reduced with the increase in the number of hydrogen refuelling stations built and the entire infrastructure. Hydrogen refuelling stations are much more problematic to build compared to conventional stations due to the physical properties of hydrogen. Special tanks, cooling units, and compressors are needed [16]. Considering means of transport, the lack of commercialization of the entire hydrogen-based technology, including hydrogen refueling stations, will result in a lack of demand for fuel cell vehicles. However, if the automotive industry does not produce hydrogen fuel cell vehicles, there will be no demand for companies to build hydrogen refueling stations. The entire issue is called a "chicken and egg" by the automotive industry and research institutes [30]. This is one of the reasons why governments around the world are currently strongly supporting and subsidizing the fuel cell industry. If the entire hydrogen investment gains momentum, the cost of cells and hydrogen itself should drop significantly. Another important challenge is waste management technology towards sustainable and low-emission transport [30].

One of the biggest controversies is also the aspect of the safety of using hydrogen. Hydrogen is stored in special tanks under pressure, usually 70 MPa. For safety reasons, they are placed separately on the roofs of trains or in separate carriages [45].

5. Conclusions

The examples of existing hydrogen fuel cell technologies in rail transport presented in this article clearly show that hydrogen cells are a beneficial alternative to existing common solutions based on, among others, fossil fuel engines or electric motors.

There are a number of advantages to hydrogen fuel cells, including:

- elimination of greenhouse gases (GHGs) – if hydrogen is produced only from renewable energy sources [46]
- the speed of refueling vehicles with hydrogen (compared to charging electric vehicles)
- low noise level compared to combustion engines
- high efficiency of fuel cells compared to diesel engines (fuel cell vehicles can reduce energy consumption by up to 58% compared to diesel engine vehicles) [45].

However, there are also a number of challenges that are still waiting to be solved. The biggest of them are: the high costs of hydrogen, the entire technology of hydrogen production and fuel cells, hydrogen refueling stations, and the durability of fuel cells. Thanks to government support, many countries have decided to introduce hydrogen vehicles and develop hydrogen infrastructure on their territory. Recently, there has been a large development of rail transport powered by hydrogen fuel cells. Currently, the leading companies that are involved in the production and introduction of rail transport powered by hydrogen cells include Alstom, Siemens Mobility, Vehicle Projects, and Stadler.

Most often, rail vehicles are designed as hybrid vehicles with both hydrogen fuel cells as the main source of energy and batteries (most often lithium-ion) as an additional energy storage. Fuel cells themselves as an energy source have a slow response to changes in dynamics, so during acceleration, for example, additional energy comes from batteries.

Nomenclature

AEMFC	anion exchange membrane fuel cell
AFC	alkaline hydrogen fuel cell
EMS	energy management system
HT PEMFC	high temperature hydrogen proton exchange membrane fuel cell
IEA	International Energy Agency
$LiFePO_4$	lithium iron phosphate battery
LRV	light rail vehicle
LT PEMFC	low temperature hydrogen proton exchange membrane fuel cell
MCFC	carbonate hydrogen fuel cell
NZE	net zero emissions
Pd	palladium
Pt	platinum
SOFC	solid oxide fuel cell

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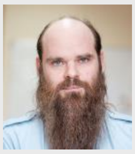

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