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Use of Hydrogen Fuel Cells in Rail Transport

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Summary

The article presents the most technologically advanced alternative propulsion of rail vehicles that, at the same time, has great development potential, i.e. hydrogen fuel cells. The current condition of the rolling stock and electrification of the traction network is described, and domestic and foreign plans for the deployment of fuel cells are presented and accompanied by legislative work aimed at the application of environmentally friendly solutions.

Keywords: hydrogen propulsion, fuel cells, railway transport

1. Introduction

At the end of 2019, the national network of active railway lines comprised slightly more than 19500 km of routes, of which almost 7500 km were non-electrified lines (38%), on which train traffic was operated by diesel-powered vehicles [9]. Although for several years there has been a trend among passenger carriers to reduce the number of diesel locomotives (Fig. 1), the number of diesel multiple units has actually increased. This is partly related to the restoration of traffic on non-electrified routes by new carriers (e.g. Lower Silesian Railways, and Łódź Metropolitan Railway). At the same time, there is a clear disproportion between passenger and freight transport in terms of the number of combustion vehicles used (Fig. 2).

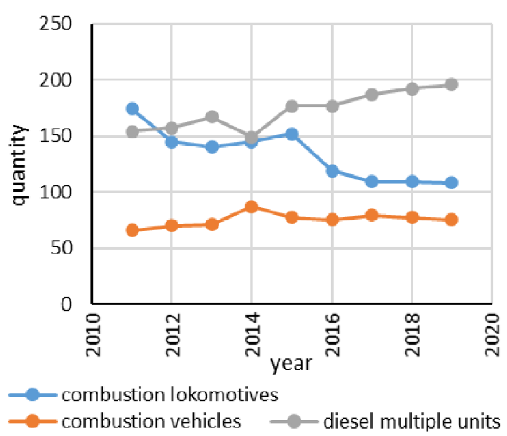

Fig. 1. Change in the number of different types of combustion vehicles between 2011 and 2019 in passenger transport; author's study based on [9]

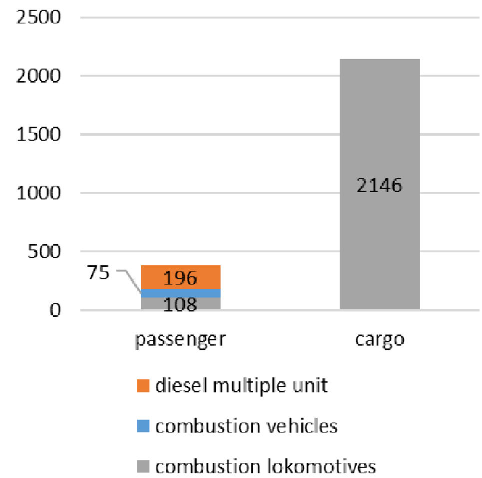

Fig. 2. Number of used combustion vehicles by type of transport; author's study based on [9]

The average age of diesel locomotives used by passenger carriers (108) was just over 42 in 2019. In the case of freight transport (2146 diesel locomotives) it was 39. [9]. This indicates the upcoming need to replace or generally upgrade a large part of the fleet, which is a potential opportunity to switch to alternative energy sources. An additional motivation to look for alternative forms of propulsion is the fact that all deposits of crude oil (both those currently being exploited and those which may potentially be explored) will be exhausted over the next 100 years, assuming unchanged production volumes. With an increase in oil consumption of only 2%, this time will be reduced to 55 years [5]. Before the oil disappears completely from the market, it will go through a phase of drastic

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price increases for final consumers, which will restrict its use to the few branches which, for various reasons, will not have switched to alternative power sources by then. Already 20% of PKP Cargo's expenditure is the cost of fuel for locomotives. It can also be expected that additional charges will be introduced for the use of combustion engines or, in the longer term, that the possibility of using combustion engines in rolling stock will be restricted by law, as has been announced for road transport.

The average level of electrification of railway lines in the European Union is currently around 62%, with the remaining lines operated by diesel-powered vehicles. In total, it is estimated that around 20% of rail transport in the EU is operated with diesel vehicles [11]. For a long time now, the European Commission has been actively trying to switch transport to low-emission sources by adopting a number of legislative initiatives, including: a European strategy for alternative fuels, a European strategy for low-emission mobility, the Clean Mobility Package and, finally, the last of the planning documents adopted in July 2020, the so-called European Green Deal, which assumes a significant reduction in greenhouse gas emissions. Currently, preparations have begun for the European Railway Agency (ERA) to amend the Technical Specifications for Interoperability, which in the revised version are to include regulations resulting from the Green Deal, in particular as regards the so-called green freight transport and the use of vehicles with new sources of propulsion (hydrogen, battery and other potential fuel cells). Proposals to amend the TSIs are due by mid-2022 [12].

Polish legislative bodies are also actively creating a legal framework for the use of low-carbon sources in the national economy. The adopted Transport Sustainability Strategy until 2030 (SRT2030) [10], lists a fifth direction of intervention: reducing the environmental impact of transport. The scope of activities in this area includes:

- fleet upgrade (vehicles and infrastructure for alternative fuels);
- supporting low-emission transport, including shifting freight from road to rail;
- as well as promoting means of transport powered by alternative energy sources (reducing the dependence of the transport sector on conventional fuels).

The strategy also provides for a number of innovative and technological measures, including the launch of electric battery charging stations along the TEN-T core network, CNG filling stations and, if cost-effective, also hydrogen filling stations.

The possibilities of using hydrogen fuel cells in rail transport were also the subject of a meeting held in August 2020 at the Office of Rail Transport, which was attended by representatives of science, rolling stock manufacturers and operators [11]. As the office claimed, the participants favoured the initiative to develop a strategy for the deployment of hydrogen propulsion in Poland.

2. Fuel cells

There are many types of fuel cells, differing in both design and operating temperature, but only low-temperature cells with PEMFC (Polymer Electrolyte Membrane Fuel Cells) have been used as drives for means of transport (rail, buses or trucks) (Fig. 3).

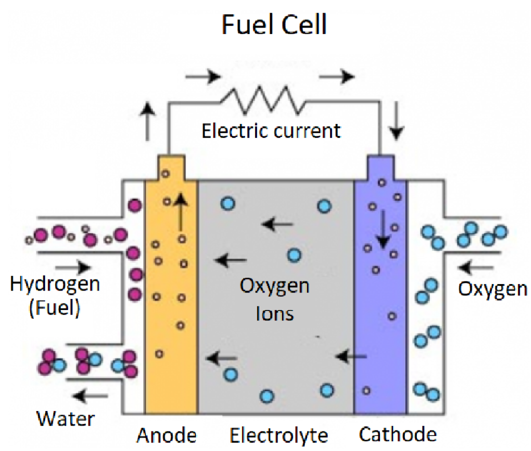

Fig. 3. Hydrogen fuel cell structure [Virtual Gas Museum, www.wmgaz.pl]

The fuel of the cell is pure hydrogen and oxygen, fed respectively on the anode (H_2) and cathode (O_2), which are separated by an electrolyte where there is a reaction in which electricity is generated and transferred to the battery and the by-product is pure water:

$$2H_2 + O_2 = 2H_2O.$$

The power density of the fuel cells is assumed to be 650 W/kg. For example, the TRAXX freight locomotive (Bombardier), which has a capacity of 5.58 MW, requires 8.6 t of cells, which translates into a volume of 8.6m3. Assuming that hydrogen is stored in containers at a pressure of 35 MPa, an energy density of 1633 Wh/kg or 0.533 MWh/m^3 by volume is obtained. The efficiency of the actual cell depends on the current load and ranges from 40% to 60%. Hydrogen has the highest value of energy per unit mass compared to the most popular conventional fuels today (Fig. 4) and, at the same time, is the most common element on Earth – hydrogen constitutes 92.7% of atoms in the universe [4].

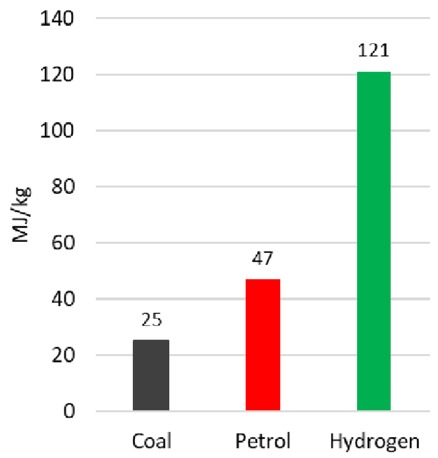

Fig. 4. Energy per unit mass for different fuels; author's study based on [4]

A key barrier to the use of hydrogen as a fuel is the fact that it occurs in a form combined with other elements, requiring energy to be supplied to release it (an example of an almost inexhaustible source is water). So far, the problem in the production of pure hydrogen (e.g. in electrolysis) has been the unfavourable energy balance of such a process. Meanwhile, the use of electricity generated by renewable energy sources (RES) e.g. photovoltaic panels or offshore wind turbines is increasingly discussed. There are three varieties of hydrogen, depending on how it is produced:

- Grey hydrogen – methane reforming or carbon gasification (currently 76% of the hydrogen produced is made by this method);
- Blue hydrogen – extraction from natural gas using carbon capture and storage (CCS) technology, and
- Green hydrogen – in the process of electrolysis, which in the case of energy supply from renewable sources (e.g. wind farms) is the most ecological type of fuel (0.1% of production).

3. Current and planned deployment of fuel cells in railways

The first fuel cell train to be introduced into public transport was the Coradia iLint multiple unit manufactured by Alstom in Salzgitter, which, since September 17, 2018, has been operating on an approximately 100-km route from Cuxhaven to Buxtehude in Lower Saxony (Germany) [2]. Figure 5 shows a schematic arrangement of the key components of the propulsion system.

The maximum train speed is 140 km/h and it is possible to cover 1000 km on one filling [11], which, with 10 scheduled daily runs, gives one filling per day, which is currently performed at a mobile station provided by Alstom under the contract [2]. The two iLint units tested during that time have travelled a total of over 180,000 km. After a successful test period, Alstom received an order to deliver another 14 iLint units to Lower Saxony. At the same time, in September 2020, the testing of iLint as part of regular passenger services by the ÖBB Austrian federal operator began, which will last until the end of November this year [1].

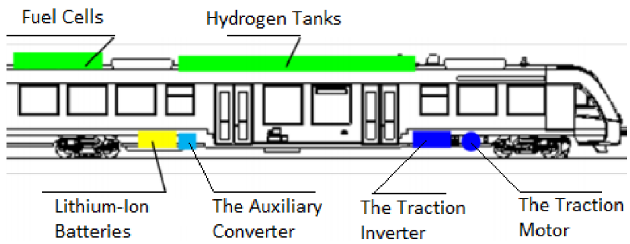

Fig. 5. Diagram of the Coradia iLint train propulsion system; author's study based on [2]

The next deliveries of hydrogen versions of Coradia will take place in 2022 for the German RMV (27 units) and BEG (10 units) operators and for the French national SNCF operator (15 units), which is considering the complete abandonment of diesel trains in favour of hydrogen propulsion systems in the next 15 years [7]. In the same year, Breeze trains are to be introduced in the UK, based on the EMU 321 class, which, unlike the iLint, will use hydrogen power generators, enabling the combustion of hydrogen with a lower purity than that used in fuel cells. The plans of the British are to decommission all diesel rolling stock by 2040 [7].

The United States, despite the currently much less profitable hydrogen technology due to the low cost of diesel fuel, is also interested in the development of zero-emission transport. The state of California in November last year contracted Stadler to deliver the Flirt H2 hydrogen-powered train [3]. In June 2019 in Japan, the world's largest passenger operator, the East Japan Railway Company, announced, in cooperation with Toyota, the launch of fuel cell train tests. Commercial deployment is planned in 2024.

A hydrogen-powered version is also being developed by Siemens [8], which, together with the Canadian fuel cell supplier – Ballard Power, intends to develop two variants – 120 and 160-person Mireo Plus H electric multiple units, with tests to be implemented in 2021.

The latest European development initiative in the field of fuel cells in rail transport is the project to build a prototype hybrid train on the basis of the existing Civia three-car unit. The concept chosen by the Fuel Cell and Hydrogen Joint Undertaking (FCH JU) assumes the use of a prototype fuel cell train powered by lithium-titanium batteries with the additional possibility of using an overhead contact line. The project, the budget of which is estimated at 10 million Euro [6], will be implemented by a consortium with the Spanish CAF as the leader.

Poland, which is one of the largest hydrogen producers in the world (about 1 million tonnes per year) [3], is also developing hydrogen projects in the railway industry. The Lotos Group, the owner of one of the world's most modern refineries in Gdańsk, is implementing a project to build a hydrogen purification and distribution plant – Pure H2. On the other hand, Lotos Kolej and Lotos Lab (part of the Lotos Group) have been cooperating with the Warsaw University of Technology since September 2018 on the upgrading of two shunting locomotives, one of which has batteries constituting the primary source of energy and supported by fuel cells [3]. At the end of 2019, PKN Orlen, the country's largest fuel and energy company, which is also the leader of petrochemical companies in Central and Eastern Europe, signed a letter of intent with the rolling stock manufacturer PESA Bydgoszcz, under which a prototype locomotive powered by fuel cells will be developed [14]. At the same time, Orlen plans to start production of pure hydrogen fuel (99.999%) in Trzebinia in 2021, used in the operation of fuel cells [3, 17].

PKP Cargo, the second largest rail transport company in the EU, cooperates with Jastrzębska Spółka Węglowa and Fabryka Pojazdów Szynowych H. Cegielski in the implementation of joint ventures related to the use of hydrogen fuel. The JSW Group currently produces about 0.8 billion m3 of hydrogen per year, which, after purification, is a volume that can power 800 city buses throughout the year [3].

4. Conclusions

Powering the electric drives of rail vehicles using the overhead contact line is currently the most common solution in Europe. Nevertheless, the costs of electrification constitute a significant barrier to increasing the share of traction in the entire rail transport system, and in combination with high fuel costs for the diesel rolling stock, they create favourable conditions for the search for alternative energy sources. The first tests in passenger traffic and studies have shown that fuel cells can be used as a replacement for diesel engines. This applies in particular to low-frequency routes (up to 10 daily runs) and relatively long routes (over 100 km).

The cost-effectiveness of fuel cells depends to a large extent on the cost of electricity needed to produce clean hydrogen (the lower the cost, the more cost-effective they are) and diesel, which is the closest competitor to fuel cells. For example, the low price of crude oil in the US means that diesel drives are currently more profitable while the development of fuel cell technology is expected to change the profitability system in favour of the cells as early as 2030 [16].

The implementation of cell technology on a larger scale will still require significant expenditure, both financially and in terms of promotion. However, due to the involvement in the development of hydrogen fuel on the part of rolling stock manufacturers, potential hydrogen suppliers and the European Commission, there are clear indications that this energy source has a good chance of success. It is estimated that, in 2030, one in five newly-delivered rail vehicles in Europe will be powered by fuel cells [11].

Most of the development work on the use of fuel cells in rail transport is now concentrated in Europe, which is also an excellent starting point for national railway producers, who can, together with their European partners, gain the necessary experience in new technology and then expand into developing markets. Developed in 2006 under the Act on Biofuels (Journal Of Laws of 2019, item 1155 as amended) the Low Carbon Transport Fund is a stable source of financial support for the development of alternative fuels and the development of the infrastructure needed to promote them. In addition, Poland, which is already one of the largest suppliers of hydrogen in the world, with the potential to convert it cheaply into pure hydrogen using electricity from offshore wind turbines, could also become a leader in the green transport industry.

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