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The analysis of the use of hydrogen in commercial vehicles

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The article first presents current trends in power sources for selected heavy-duty vehicles (HDVs) and non-road mobile machinery (NRMM). The next part of the paper focuses on selected examples from the city bus and rail vehicle sectors. The article attempts to capture solutions in the research/design phase as well as post-production and implementation (operation). In the context of the obtained vehicle/rolling stock availability indicators, maintenance facilities and activities (current assessment of technical condition and restoration of serviceability) are important. Therefore, in addition to the use, aspects related to vehicle maintenance areas are also outlined. In addition, the paper analyzes methods to increase the volume of compressed hydrogen gas in tanks. The main idea is hydrogen in transportation applications. The paper addresses several of the more important issues mentioned above.

Key words: *railway, vehicles, buses, hydrogen, exploitation*

1. Introduction

The growing need to reduce fuel consumption and the resulting CO_2 emissions in transport means that alternative solutions are sought to achieve this goal. The requirements for reducing energy intensity result from, among others:

- the levels and stability of prices of fuels and raw materials necessary for the production of vehicles and their components
- the access to fuels and raw materials, which is an element of energy independence and security
- the state of the infrastructure for fuel and energy production, its storage, transmission and distribution and the need to maintain its stability.

The solution may be alternative drives, which not only reduce fuel consumption but also offer diversification and reduce the risk of becoming dependent on one technology. The market offers combustion engines powered by alternative fuels (CNG – Compressed Natural Gas, LNG – Liquified Natural Gas, biogas, ethanol, HVO – Hydrotreated Vegetable Oil, etc.), hybrid drives in various versions (MHEV – Mild Hybrid Electric Vehicle, HEV – Hybrid Electric Vehicle, PHEV – Plug-in Hybrid Electric Vehicle), battery-powered electric drive systems (BEV – Battery Electric Vehicle), and recently also hydrogen-powered vehicles. The latter can use hydrogen as a fuel for combustion engines (H2ICE – Hydrogen Internal Combustion Engine) or for direct electricity generation in fuel cells (FCEV – Fuel Cell Electric Vehicle) [7, 17]. In the future, we can expect further development of synthetic fuel production technology, based on the chemical binding of hydrogen and carbon captured from the atmosphere and biomass [11].

With such a wide range of possibilities, choosing one specific solution can be difficult, especially since most of these technologies are still in development and it is often difficult to estimate target functionalities, parameters, or costs of use [20].

Basically, the choice for each case should be made individually and be preceded by a detailed analysis of the needs, where the main selection criterion, apart from price, should be the level of access to infrastructure and ease of use, related to the available driving range, time and frequency of refuelling/charging.

The task of selecting the right technology for a given user will become even more difficult when hybrid energy storage technologies appear on a large scale, e.g. BEV charging stations supported by battery energy storage units and hydrogen-powered energy generators. From the perspective of heavy transport, a sufficiently large driving range, short refueling/charging times and access to infrastructure are key criteria for selecting technologies, apart from price [23].

One of the previously mentioned technologies that meets or may meet the above requirements in the future is hydrogen fuel cell electric vehicle (FCEV) technology. This is basically a hybrid drive in which a hydrogen-powered PEM fuel cell acts as the primary energy source responsible for the driving range. The secondary energy source that drives dynamics is electrochemical batteries. Their role is to stabilize the operation of the hydrogen fuel cell, which increases its efficiency and allows for energy storage, e.g. during regenerative braking [3]. Electrochemical batteries also power the drive during low-load operation, allowing periodic shutdown of the fuel cell.

Among the various types of fuel cells, PEM (Proton Exchange Membrane) fuel cells are mainly used in means of transport due to their ability to operate at ambient temperatures, short start-up and shut-down times, resistance to shocks and vibrations, and the ability to be powered by oxygen taken from the air [5]. In addition to oxygen, fuel cells require fuel – hydrogen, which has a very high gravimetric energy density of 120 MJ/kg (LHV – Lower Heating Value). Unfortunately, high gravimetric density does not go hand in hand with volumetric density, which is very low in ambient conditions (approx. 10.8 MJ/m^3). This requires transporting hydrogen in high-pressure tanks, stored as a gas at 35–70 MPa [4]. Such high pressures require special refueling infrastructure and affect the time and energy costs of refueling.

The problems and energy costs result from the laws of thermodynamics, which cause hydrogen to be compressed during filling and thus heated, which further increases its pressure. As a result, after the gas temperature has equalized with the ambient temperature, the pressure in the tanks is lower than it was in the final phase of filling. This can result in incomplete use of the tanks and a limited range [24]. An alternative is to extend the refueling time and/or cool the supplied hydrogen, which requires additional energy [12].

2. The analysis of the city buses market

The share of the hydrogen buses is still not big and in 2020, there were 5648 fuel cell buses all over the world (93.7% in China) [26]. In Europe on 1st January 2023, there were 370 fuel cell buses in operation. Registrations of these kinds of buses in Europe remain marginal, with numbers such as 207 in 2023 and 378 in 2024 [30]. In 2023, the fuel cell buses had only a 4.6% share in the zero-emission bus market in Europe, where the rest of the market belongs to battery electric buses [30]. Despite many manufacturers of fuel cell buses, actually, the fuel cells are used, manufactured mainly by Ballard Power Systems or Toyota [2, 26, 30].

The hydrogen city bus demonstrators were developed in the 1990s. The first fuel cell buses were rather the smaller versions (approx. 9–10 m long), which probably resulted from the low power output of the initial fuel cells and problems with hydrogen storage (limited range) [25]. Toyota and Hino cooperated from 2000 onward in the field of hydrogen city bus development. This cooperation resulted in Toyota FCHV-BUS, which was equipped with two 90 kW PEFC fuel cells and two 80 kW traction motors (Fig. 1) [25].

Nowadays, despite over 30 years of fuel cell bus development, this propulsion system still has an economic disadvantage compared to battery-electric and diesel buses [14, 21, 30]. A study from September 2023 by Eurac Research, which compared the operating costs of battery electric buses with those of fuel cell electric buses, revealed that battery electric buses are 2.3 times cheaper to run per kilometer than fuel cell electric buses (0.55 Euro vs 1.27 Euro) [8, 30].

According to manufacturers, the fuel cell electric buses should combine the advantages of diesel and electric buses. Because the charging time for an electric bus is about 4–5 hours, it is not possible to replace a diesel bus with an electric bus [14, 30]. Hydrogen tanks refueling takes less time than electric battery charging (approx. 15 minutes), which is very similar to diesel refueling [14], and the fuel cell bus does not emit any toxic compounds into the air. Additionally, thanks to a smaller traction battery, the fuel cell bus can be up to 5000 kg lighter than a battery electric bus [25, 26, 31].

The main component of the fuel cell bus drive system is the fuel cell, which produces the electric energy for the electric motors to drive the wheels or charge the batteries. The fuel cell buses are also equipped with an electric battery with much less capacity than in electric buses. In Solaris Urbino Hydrogen, the battery capacity is 29 kWh [30], whereas in Solaris Urbino Electric, it can exceed 520 kWh. In the fuel cell buses, the battery is used only for acceleration and energy recuperation during braking. Very important in fuel cell buses are the hydrogen tanks, which in the past were mainly made of metal (steel and aluminum alloys). The metal technology tanks were cheap, but also heavy. The maximum pressure was about 20 MPa. Currently, the tanks are made of composites. Modern technology enables pressure up to 35 MPa (in some cases, up to 50–70 MPa), increasing vehicle range at a lower mass [19].

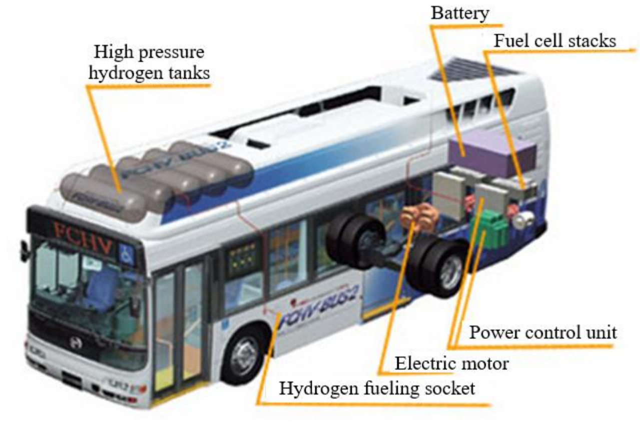

Fig. 1. The propulsion system components of Toyota FCHV-BUS [25]

Table 1. Technical data of Solaris buses with different drive [26, 30]

	Solaris Urbino 12 Electric	Solaris Urbino 12 Hydrogen
Fuel cell power [kW]	–	70
Traction motors power [kW]	200 (option: 2×125)	2×125 (option: 220)
Traction battery capacity [kWh]	200–600	Lithium-ion 29.2

Most solutions use a small traction battery (approx. 30 kW in Solaris Urbino 12 Hydrogen) and a large fuel cell (70 kW in Urbino 12 Hydrogen) – Table 1. It should be mentioned that there are also concepts that use a small fuel cell and a large traction battery. One example is Safra, with a 132 kWh traction battery and a 30 kW fuel cell [30]. According to measurements taken in real driving conditions across three routes, a Solaris Urbino 12 Hydrogen consumes 8.78–9.11 kg of H_2 per 100 km [16].

Another concept presented by Mercedes-Benz is the eCitaro REX, where the battery electric bus (392 kWh batteries) uses a 60 kW fuel cell as a range extender. This vehicle is equipped with hydrogen tanks that store 30 kg of hydrogen. According to the manufacturer, the range exceeds 300 km [26, 30, 31].

3. The railway market analysis

The chapter presents the status quo of selected commercial or R&D projects undertaken by leading entities in the rail vehicle manufacturing industry. It should be noted that among them, well-known Polish companies – rolling stock manufacturers – have experience with hydrogen drives.

The most advanced work on the use of hydrogen in rail transport in Poland (passenger and freight) can be proud of PESA Bydgoszcz S.A. For years, PESA's Hydrogen Ready strategy has been communicated, primarily regarding passenger vehicles (hydrogen multiple units based on the Regio 160 platform). Nevertheless, the first solution with a hydrogen drive was the design of the SM42-6Dn Hydrogen shunting locomotive. It was created as a result of a thorough modernization and redesign of the SM42 locomotive, commonly used in Poland. There are numerous press reports and publications related to this vehicle [10]. Currently, PESA Bydgoszcz, after a long period of attempts to acquire a partner for longer tests of the vehicle (talks were held with, among others, Orlen) and a hydrogen drive solution (fuel cells), has concluded a cooperation agreement with the operator/carrier Pol-Miedź Trans from the KGHM Polska Miedź S.A. Group.

The field tests at Pol-Miedź Trans are certainly an important stage in the commercialization of hydrogen technology in the Polish railway industry, moving it from the research and development phase to practical operation under difficult industrial conditions.

At H. Cegielski FPS, recent months have culminated in the completion of a multi-year R&D project at the Poznań factory, which operates in the field of modernization and the production of new rail vehicles, mainly passenger cars. In the summer of 2024, the PLUS 227M vehicle (a 2-unit dual-drive multiple unit) obtained homologation, while at the beginning of 2025, the PLUS 228M vehicle (a 3-unit dual-drive multiple unit) was approved for operation on Polish railway lines. Importantly, the H. Cegielski FPS company recently signed a contract to deliver 6 electric multiple units based on the PLUS platform for the Lubuskie province (where the 227M and 228M vehicles were also delivered). This is proof that the family of vehicles from the PLUS platform will be developed.

In 2022, a letter of intent was signed with Łukasiewicz – Poznań Institute of Technology (design work) and Impact Clean Power Technology (supplier of the drive, including the hydrogen component) regarding work on the development of the PLUS vehicle for a hydrogen version (fuel cells or hydrogen combustion in a conventional piston engine). So far, a feasibility study for the project has been conducted in cooperation with the leading design office in the country.

An important platform for the exchange of knowledge and operational experience in the country is the cyclical conference Hydrogen4rail – Future of Transport, initiated by the then Łukasiewicz – Rail Vehicles Institute "TABOR", organized in cooperation with the Polish Chamber of Railways. The main substantive content of the past 5th edition on 16–17.06.2025 was as follows: Hydrogen as an energy carrier in transport - science and practice, Prospects and conditions for the development of hydrogen transport, Strategic planning: hydrogen, diesel or electrification, The process of admitting systems and parts of compressed hydrogen storage systems for hydrogen-powered vehicles in Poland, Introduction of hydrogen technology on the railway in Poland – safety aspects at a railway hydrogen refueling station.

By the way, this event is an example of an evolution towards the potential dissemination of hydrogen fuel in the rail sector and of practitioners' approach to vehicle maintenance (for example, P1–P5 reviews in Poland). After quite optimistic voices in 2021–2022, statements took on a subdued tone in the face of market realities, even from precursors in the implementation of the first homologated vehicles in Europe (Alstom Coradia iLint). This is primarily the result of the market debuts of more vehicles in Germany. After a period of several months of operation (mainly 2023–2024), the efficiency of operation and maintenance of hydrogen-powered EMUs (Electric Multiple Units). The main barriers to development include the high cost of hydrogen fuel, problems with its current supply, and ensuring the absolutely required high quality of the fuel (there are known cases of contaminated hydrogen being supplied to power mass transport vehicles) [13, 22]. In addition, there were technical problems with the traction unit drive systems (high failure rate). Currently, unexpectedly, transport organizers in German states that purchased hydrogen vehicles have to put vehicles with Compressed Ignition engines (Diesel) into operation as a substitute transport, often as a result of long-term rental from rolling stock pools, i.e. companies such as ROSCO (Rolling Stock Company).

Siemens Mobility is also one of the manufacturers that has placed its hydrogen vehicles on the global market. Its Mireo Plus H has undergone tests, among others, on German rail routes in regional traffic. Siemens recently won a contract to supply its solutions. By the end of 2026, three Siemens Mireo Plus H (Fig. 2) trainsets will start operating on the Südostbayernbahn network in Bavaria [28, 29].

Fig. 2. Mireo Plus H by Siemens in two drive versions [29]

The RS ZERO is Stadler's latest regional train offering, designed to replace the popular Regio-Shuttle RS1, which has been the backbone of German and Czech regional rail transport for almost three decades [27]. The RS ZERO's main feature is its low emissions, achieved through modern drive technologies. The RS ZERO is available with two eco-friendly drive systems (Fig. 3):

Hydrogen (Hydrogen-hybrid Electric Multiple Unit – HEMU): uses fuel cells that convert hydrogen into electricity to power the engines. This is a good solution for non-electrified or partially electrified lines, where traditional electric trains cannot be used, and investments in full electrification are unprofitable.

Battery (Battery Electric Multiple Unit – BEMU): operates entirely on batteries, making it suitable for shorter, partially electrified routes and for charging at stations or under the catenary.

The market debut of the RS ZERO prototype with hydrogen drive took place at the InnoTrans 2024 trade fair in Berlin. Stadler also signed an agreement with the Thuringian authorities and the operator Erfurter Bahn to launch a pilot project using the RS ZERO with a hydrogen engine, with passenger test runs planned for mid-2026.

Fig. 3. RS ZERO vehicle produced by Stadler

4. Hydrogen in the light of vehicle maintenance

According to the Office of Rail Transport (UTK) and other National Security Authorities (NSA): the Maintenance Management System (MMS) includes a set of procedures and instructions aimed at minimizing the risk associated with maintaining a railway vehicle and, as a result, ensuring that the maintained vehicles are able to move safely on the railway network [32].

In order to improve the efficiency of the processes of maintaining rail vehicles in a state of fitness for use, specialist software (based on database systems) has been used. There are tailor-made solutions (depending on the specifics of the fleet of vehicles) and so-called boxed solutions (with no possibility of modifying the software or its functionality).

Systematizing detailed issues concerning maintenance management systems is included in Regulation 2019/779. It specifies the requirements that a maintenance management system must meet. It also indicates the criteria used in the certification process to assess it (due to the security of sensitive data). The main feature of a maintenance management system is its division into 4 component functions [32]:

- a management function, which enables supervision over the three so-called maintenance functions (defined below) and their coordination; it also enables ensuring the safe condition of a railway vehicle in the railway system
- a maintenance development function; its task is to shape the vehicle maintenance documentation (DSU – maintenance system documentation) based on the vehicle design documentation and experience from its operation
- a rolling stock maintenance management function; its task is to manage the withdrawal of a vehicle from operation and its subsequent reintroduction into it
- a maintenance performance function; enables the required maintenance of a vehicle or its parts to be carried out.

In summary, the system should ensure that vehicles are maintained in accordance with the vehicle's maintenance documentation and the applicable regulations, including TSIs, and the guidelines and provisions resulting from those regulations. All entities responsible for maintenance are required to develop and implement a maintenance management system.

Digital maintenance management systems will also be needed for hydrogen-powered vehicles. The operation of hydrogen-powered rail vehicles requires special attention due to the unique properties of hydrogen and the technologies used. The key aspects to look out for are listed below [22].

Leak detection: Advanced hydrogen detection systems that can quickly detect even small leaks should be used. Hydrogen is odourless and colourless, making it difficult to detect without specialist sensors.

Ventilation: Vehicles must be equipped with effective ventilation systems to prevent hydrogen accumulation in enclosed spaces, especially in the event of a leak.

Location of tanks and fuel cells: Hydrogen is lighter than air and rises quickly. For this reason, hydrogen tanks and fuel cells are often mounted on the roof of the train so that in the event of a leak, the hydrogen is released into the atmosphere, minimizing the risk of fire or explosion.

Impact resistance: Hydrogen tanks must be designed to withstand extreme loads in the event of a collision or accident, minimizing the risk of hydrogen release. Composite tanks reinforced with carbon fiber are often used.

Emergency procedures: Detailed procedures for handling hydrogen leaks, fires or other incidents must be developed and regularly trained. Emergency services (fire brigades) must also be trained in the specifics of interventions on hydrogen vehicles.

Grounding and protection against electrostatic discharge: Hydrogen is flammable, so proper grounding and measures to prevent electrostatic sparks must be provided, especially during refuelling.

Specialized training: Service personnel must be properly trained in the operation and maintenance of hydrogen systems (fuel cells, tanks, gas systems), as well as traction batteries (if they are part of a hybrid system).

Fuel cell monitoring: Fuel cells have a finite lifespan and require regular monitoring of their performance and condition.

Hydrogen tank condition: The integrity of hydrogen tanks must be regularly checked for mechanical damage, corrosion or leaks.

Cooling systems: Fuel cells generate heat, so cooling systems must be efficient and effective.

System integration: Hydrogen vehicles are often complex hybrid systems (fuel cell + battery). Care must be taken to ensure that all components are properly integrated and interact.

5. Potential to increase driving range

The vehicle's driving range depends almost proportionally on the amount of fuel that can be stored in the tanks. In the case of hydrogen, in addition to tank volume, its amount is also affected by pressure, temperature, and state of matter.

Currently, three hydrogen storage technologies are being considered for use in transport. These are hydrogen storage technologies in the form of:

- gas compressed to a pressure of 35–70 MPa, stored at ambient temperatures in type IV composite tanks, with a density of 20–40 kg/m^3
- liquid, stored at temperatures below –253°C, at a pressure of 0.1–0.4 MPa, in type I cryogenic steel tanks, with a density of 62–65 kg/m^3
- gas compressed to pressures of 50–100 MPa and simultaneously cooled to temperatures from –200 to –240°C,

so-called cryogenic gas, stored in type III steel tanks, reinforced with carbon fiber, with a gas density of 72–90 kg/m^3.

The first of the mentioned technologies (storing hydrogen as a gas compressed to 35–70 MPa at ambient temperature) is already widely used commercially. For passenger cars, the standard of 70 MPa is used, and for trucks, 35 MPa, although work is already underway to introduce the 70 MPa standard in heavy transport, which will extend driving ranges by up to around 67% (by increasing the density from approx. 24 kg/m^3 to approx. 40 kg/m^3 in standard temperature). This will require adapting the tanks' design and modifying the communication protocols between the refuelling station and the vehicle. Communication between the hydrogen refuelling station and the vehicle is the responsibility of standards developed by SAE International, in particular:

- SAE J2601 – a standard that specifies hydrogen refueling protocols for fuel cell vehicles. It defines parameters such as pressure, temperature and refueling time to ensure safe and efficient filling of hydrogen tanks
- SAE J2799 – a standard that describes the communication interface between a vehicle and a hydrogen refueling station. It enables the exchange of information such as vehicle identification, tank status, and refueling preferences, allowing the optimization of the refueling process.

The technology for storing hydrogen in liquid form is still in development, although the first public liquid hydrogen refuelling station using sLH_2 (subcooled Liquid Hydrogen) technology, developed jointly by Daimler Truck and Linde Engineering, has been launched in Wörth am Rhein, Germany. This station enables trucks to be refuelled quickly and safely in 10 to 15 minutes, providing a range of over 1000 km for vehicles such as the Mercedes-Benz $GenH_2$ Truck [15].

The technology of storing hydrogen in the form of a compressed and simultaneously cooled gas, the so-called cryogenic gas, is the most complicated, which is why it is also at the earliest stage of development. However, it offers the greatest possibilities, which is why its progress should be monitored. It is being developed, among others, by the German company Cryomotive as part of the CryoTRUCK project [6].

Looking further ahead, rail transport could explore the use of alternative hydrogen-bearing chemical compounds that would enable direct utilization in fuel cells – particularly MCFC units – thus eliminating the need for upstream reforming processes. In all of the above cases, the operation of fuel cells in transport applications must be supported by batteries or supercapacitors [18].

In the context of the above technologies, the simplest way to increase range is to optimize the compressed gas refueling process.

When refueling a pressure tank, the first law of thermodynamics applies in the form [24]:

$$\Delta U = \Delta Q + \Delta H_{in} \tag{1}$$

where: ΔU – change in internal energy of the gas in the tank, ΔQ – heat supplied (+ sign) or given off to the environment (–sign), ΔH_{in} – enthalpy of the gas supplied to the tank.

In the above equation, ΔQ defines the heat delivered or released to the environment. Since the temperature of the gas in the tank increases during refueling and is usually much higher than the ambient temperature, it can be assumed that this is heat released to the environment by convection and described by the relationship:

$$\Delta Q = \int \dot{Q} dt = \int \alpha \cdot A \cdot (T - T_{amb}) \cdot dt \tag{2}$$

where: α – heat convection coefficient [W/(m^2·K)], A – heat exchange surface (tank) [m^2], $T - T_{amb}$– temperature difference of gas in tank T and environment T_{amb} [K].

The enthalpy of the gas supplied to the tank $\Delta H_{in}(P_{in}, T_{in})$ depends on its thermodynamic parameters, i.e. pressure P_{in}, but most of all temperature T_{in}. In order to limit the temperature increase of the gas collected in the tank, i.e. $\Delta U(T)$, it is possible to minimize the enthalpy of the gas supplied to the tank $\Delta H_{in}(P_{in}, T_{in})$ on the one hand by cooling the supplied hydrogen (low values of T_{in}) and/or by effectively releasing heat ΔQ to the environment through convection.

In the case of convection, the parameter that determines its effectiveness is, among other things, time, which is why slow, long-term filling of tanks is preferred. Unfortunately, this often contradicts the requirements of users who expect the shortest possible refueling times, which is why in such cases a more expensive solution is used, consisting in cooling the refueled gas (low T_{in}values). Cooling the supplied hydrogen to a specific temperature T_{in}before refueling requires appropriate energy.

The amount of energy required to cool hydrogen is increased by the Joule–Thomson effect, which for hydrogen in refueling conditions takes on negative values. The Joule–Thomson coefficient η_{JT} is defined by the relationship:

$$\eta_{JT} = \partial T / \partial P \tag{3}$$

and determines how the temperature ∂T changes when the pressure ∂P changes, occurring at constant enthalpy.

Negative values of the Joule–Thomson coefficient η_{JT} indicate that hydrogen heats up by a certain amount after expansion. During refuelling, hydrogen flows from the buffer tank of the refuelling station (higher pressure) to the vehicle tank (lower pressure) – these results from the fact that after the pressure reducer of the buffer tank, hydrogen has a reduced pressure (adapted to the pressure in the vehicle tank), but a higher temperature than in the buffer tank. In extreme cases, temperature increases can reach 50 degrees and significantly affect the energy balance of the refuelling process [24].

Figure 4 shows a comparison of hydrogen tank refueling processes, initiated at an ambient temperature of 273 K, from a mass of 0.2 kg (point 1) to 5 kg (black continuous line).

For refuelling in adiabatic conditions (i.e., without heat exchange with the environment), the process occurs along the red curve from point 1 to point 2. The lack of heat exchange with the environment, in simplified terms, corresponds to the conditions of very fast refuelling, when the refuelling time tends to zero. Such rapid refuelling, even when the supplied gas is cooled, can raise the tank temperature by several dozen degrees. The increase in temperature, in turn, causes an additional rise in gas pressure in the tank and creates additional stresses in the tank structure. Leaving the tank refuelled in this way for a longer period allows it to cool to ambient conditions through convective heat transfer. During heat exchange with the environment, the gas pressure decreases by several to several dozen MPa, moving from point 2 to point 3, along the black continuous line of constant mass.

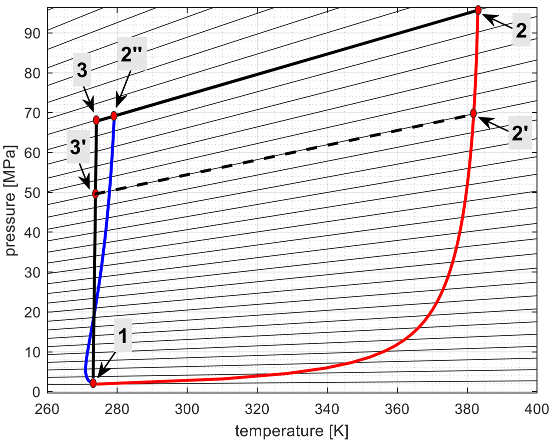

Fig. 4. The comparison of hydrogen tank refueling processes: adiabatic (red curve 1–2), adiabatic with strong cooling (blue curve 1–2") and isothermal (black line 1–3)

Therefore, during quick refuelling, a decision should be made whether to refuel "to the full", but with excess pressure at the end of filling (point 2), or whether it is better to end the refuelling at point 2' not exceeding the nominal gas pressure at the end of refuelling (approx. 70 MPa), but at the cost of a smaller fill after the tank cools down (point 3' at the end of the black dashed line of constant mass).

The adiabatic refueling situation shown in Fig. 4 (along the red curve) is extreme and theoretical, because in reality, even a short 3–5 minute refueling allows some heat to be dissipated to the environment. In reality, the increases in temperature and pressure will be slightly lower, but the problem will still be significant.

An alternative solution presented in Fig. 4 is isothermal refueling, i.e., maximizing heat exchange with the environment, e.g., by extending the refueling process as far as possible (vertical black line from point 1 to point 3). With such refueling, the tank will be filled to full capacity (point 3) without any excess, unnecessary increases in temperature and pressure, but at the cost of a very long filling time.

The next, most efficient, but most complicated and unfortunately the most expensive method is the option of fast refueling in adiabatic conditions, to full and without significant excess temperature and pressure increases (blue curve from point 1 to point 2’’ in Fig. 4). Such refueling is theoretically possible, but requires cooling the supplied gas to very low temperatures of even from –100°C to –120°C. In this case, all the benefits are achieved, i.e. short refueling time, to full and without unnecessary temperature and pressure increases, but at a very high price of energy invested in strong cooling of the supplied gas.

Mixed variants are also possible, combining the above-mentioned solutions, e.g. refueling extended in time to a dozen or so or several dozen minutes, allowing for the release of more heat to the environment, while cooling the supplied hydrogen to a temperature of around –40°C (a standard commonly used in refueling passenger cars). In such a case, a compromise will be reached among refueling time, excess temperature and pressure, and hydrogen-cooling costs. The exact parameters of the refueling process can be selected for a specific case using simulation research methods.

6. Summary

Hydrogen technologies in heavy-duty transport – including city buses, rail vehicles and trucks – are shaped by a set of common requirements. These types of vehicles must achieve long driving ranges, maintain high operational availability, and allow refuelling times similar to diesel solutions, all while keeping the associated energy and economic costs at acceptable levels. As the article shows, these factors strongly influence the choice of hydrogen storage and refuelling strategies in each transport segment, even though the specific vehicle architectures differ. Despite this diversity, the fundamental challenges remain shared across the sector.

Meeting these requirements is not straightforward. Achieving long ranges depends not only on tank capacity but also on hydrogen density, system pressure, refuelling temperature and the thermodynamic behaviour of the gas during filling. Transport operators demand rapid refuelling, while designers face the laws of thermodynamics, which result in significant increases in temperature and pressure during rapid hydrogen transfer. These effects directly influence tank durability, safety margins and the amount of fuel that can be stored after cooling. Therefore, selecting an appropriate refuelling strategy involves a compromise between refuelling time, system pressure, cooling of the supplied hydrogen, and the economic and energy costs associated with each option.

The theoretical considerations presented in the article, including the formulation based on the first law of thermodynamics and the influence of the Joule–Thomson effect, provide important tools for evaluating these trade-offs. They demonstrate how the shape of the refuelling process – adiabatic, isothermal, or mixed – affects the final mass of hydrogen in the tank, the required infrastructure, and operational costs. Such modelling can support the selection of optimal strategies for different categories of heavy-duty transport, where the balance between time, cost and achievable range is essential.

In addition to compressed hydrogen storage (35–70 MPa), which currently dominates vehicle applications, the article also highlights emerging technologies with significantly higher volumetric energy density. Liquid hydrogen (LH_2) and cryogenic compressed hydrogen (CcH_2) offer the potential for even greater driving ranges and may play a key role in long-haul heavy transport in the future. Their development could substantially reshape the technical and economic landscape of hydrogen refuelling systems.

Many facts, as well as strategies and plans (including the EU and individual vehicle manufacturers), indicate that efforts to improve the efficiency of hydrogen fuel use will not cease [3, 7]. The time horizon will depend on the pace of development of individual technologies in the so-called entire value chain. Starting with fuel production, components used to build vehicles, and finally, the technology used to manufacture end products.

Local environmental effects or ecological benefits in areas where people live, resulting from the use of hydrogen-fueled vehicles, should be considered alongside all issues related to the construction and operation of rolling stock. As shown by the first experiences of carriers and the commercial use of vehicles, mostly on regional lines, engineers still have a lot of work to do to improve the efficiency of H_2-powered mass transport vehicles. The rolling stock availability indicators required by contracts are also important. The reliability of the solutions is expected to be at the highest possible level. Despite the challenges in improving the properties of fuel cell vehicles, H_2 as a fuel is, in many respects, a better choice for energy storage, for example, in electrochemical energy storage systems [1].

Without a doubt, it is necessary to remember the education and training of specialists who will be able to provide the appropriate scope of vehicle maintenance. The homologation requirements (TSI) and maintenance requirements (MMS/ECM – Entity in Charge of Maintenance) for hydrogen vehicles are greater. For safety reasons, great attention must also be paid to procedures, especially in emergency or crisis situations.

Overall, the article demonstrates that while hydrogen-powered buses, rail vehicles and trucks operate in different environments and serve different transport roles, they share remarkably similar technological challenges. Their effectiveness ultimately depends on the same set of factors: hydrogen storage density, safe and fast refuelling, energy efficiency of the process, infrastructure readiness and long-term operating costs. This shared foundation enables the development of common engineering principles and analytical tools – as presented in the paper – that support informed decision-making and guide the future development of hydrogen technologies for heavy-duty transport.

Nomenclature

BEV	battery electric vehicle	LHV	lower heating value
CNG	compressed natural gas	LNG	liquefied natural gas
DSU	maintenance system documentation	MMS	maintenance management system
ECM	entity in charge of maintenance	NRMM	non-road mobile machinery
EMU	electric multiple units	NSA	National Security Authority
FCEV	fuel cell electric vehicles	PEM	proton exchange membrane
HDV	heavy-duty vehicles	ROSCO	rolling stock company
HEV	hybrid electric vehicles	TSI	technical specifications of interoperability
HVO	hydrotreated vegetable oil	UTK	Office of Rail Transport

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