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Prospects of using hydrogen fuel in railway transport

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ABSTRACT The use of hydrogen fuel in railway transport helps improve the environmental situation (this is particularly true about the so-called "green" hydrogen obtained by electrolysis using unconventional and renewable energy sources), reduce noise levels in comparison to diesel locomotives and diesel trains, and provide increased security and efficiency compared to locomotives with internal combustion engines. However, hydrogen fuel is expensive, resulting in the overall high cost of operating this type of transport (approximately 60% higher than rolling stock with diesel and electric transmission). What is also worth noting is the complex design, high cost of hydrogen tanks, and potential risk of explosion and fire in case of accidents and derailments. Storing hydrogen in the form of metal hydride compounds involves a number of technological difficulties. Hydrogen-powered vehicles have a shorter cruising range compared to diesel trains and a considerably shorter operating time for a shunting locomotive. The high cost of fuel cells necessitates the production of hybrid rolling stock with batteries.

When the hybrid scheme uses compressed hydrogen, a locomotive can only be used as a shunter. Due to a low weight of the power unit, it may be necessary to install ballast even where batteries are available, in order to provide the traction force for wheel-rail adhesion.

KEYWORDS: hydrogen fuel; ecology; hybrid locomotive; battery; decarbonisation; railway transport; electrification; fuel cells; electrolysis

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Научная статья

Перспективы использования водородного топлива на железнодорожном транспорте

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АННОТАЦИЯ Применение водородного топлива на железнодорожном транспорте способствует улучшению экологической обстановки (особенно это касается так называемого «зеленого» водорода, полученного в результате электролиза с использованием нетрадиционных и возобновляемых источников энергии), снижению уровня шума по сравнению с тепловозами и дизель-поездами, повышению надежности и КПД по сравнению с локомотивами, оснащенными двигателями внутреннего сгорания. Однако водородное топливо стоит дорого, что определяет общую высокую стоимость эксплуатации такого вида транспорта (примерно на 60% выше, чем подвижного состава с дизелем и электропередачей), также следует отметить сложную конструкцию, дороговизну водородных резервуаров и потенциальную опасность взрыва и пожара при авариях и крушениях. Хранение же водорода в виде металлогидридных соединений сопряжено с рядом технологических сложностей. Водородному транспорту свойственен меньший запас хода по сравнению с

дизель-поездами и существенно меньшее время работы маневрового тепловоза. Высокая стоимость топливных элементов вынуждает делать подвижной состав гибридным с аккумуляторной батареей.
При использовании сжатого водорода при гибридной схеме локомотив может использоваться только в качестве маневрового. Из-за малой массы силовой установки может потребоваться установка балласта даже при наличии аккумуляторных батарей для обеспечения реализации силы тяги по сцеплению колес с рельсами.

КЛЮЧЕВЫЕ СЛОВА: водородное топливо; экология; гибридный локомотив; аккумуляторная батарея; декарбонизация; железнодорожный транспорт; электрификация; топливные элементы; электролиз

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INTRODUCTION

The use of hydrogen as a transport fuel, including for railway transport, is one of the most promising areas in the field of alternative fuels. Although it was used as a motor fuel before, it is only now that the prospects for the development in this area have been defined. The reasons for good prospects of the technology include its environmental friendliness and the possibility to use hydrogen in various types of power equipment as:

- fuel for generating steam and operating steam turbines;
- motor fuel in internal combustion engines;
- fuel in a system with fuel cells.

Like conventional energy resources, such as oil, petroleum products, and natural gas, hydrogen can burn in oxygen or air and releases heat energy. Therefore it can be used in the same devices and machines where traditional types of fuel are used. However, unlike exhaustible energy resources, such as natural gas and petroleum products, the reserves of hydrogen are almost unlimited. At the same time, the use of hydrogen as a fuel for railway rolling stock is future-proof, and for air transport it is the only truly environmentally friendly type of alternative fuel.

USE OF HYDROGEN FUEL IN RAILWAY TRANSPORT

Hydrogen is the most common element, but it is almost never found in pure form on the Earth; therefore for hydrogen to become a real energy resource, it is necessary to produce hydrogen by extracting it from compounds available in nature. Depending on the method of production, the so-called “colour” classification of produced hydrogen is used [1, 2] (*Fig. 1*).

In terms of environmental protection, yellow and green hydrogen is of certain interest.

Where maximization of profit is the only focus, grey hydrogen and brown hydrogen are unconditional winners.

The cost of hydrogen is heavily dependent on the method of production: Grey hydrogen is the cheapest, selling at USD 0.98–2.93 per kg. Green hydrogen is the most expensive, ranging from USD 4 to USD 12 per kg in cost.

Hydrogen is treated as a type of fuel [3–7] which will considerably decarbonize railway transport on non-electrified sections. There are successful examples of its use. For example, since September 2018, some passenger transportation in the northern part of Germany has been carried out by hydrogen-powered Coradia iLint trains. In the future, France and Italia are planning to use rolling stock of this type. But we are still a long way from the large-scale introduction of the technology, since it is necessary to overcome a number of technological obstacles and win the competition over solutions that also involve decarbonisation

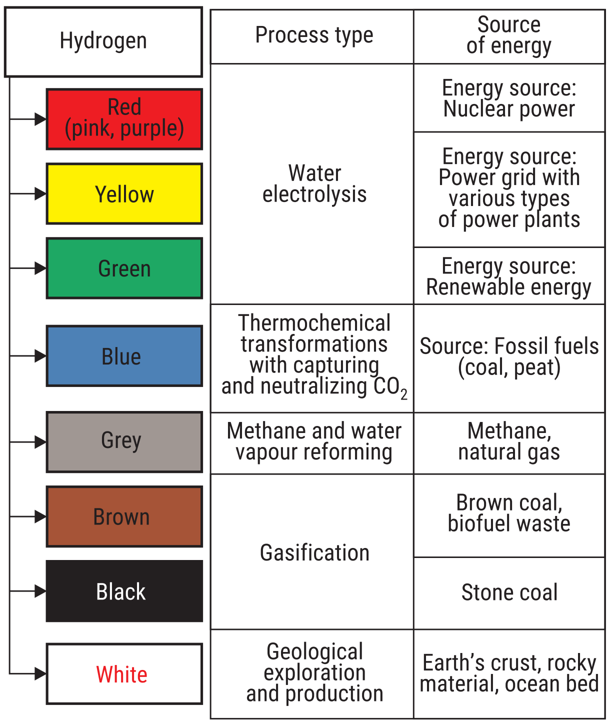

Fig. 1. Classification of hydrogen by type of production

(first of all, with the conventional electrified railway). The interest in hydrogen as a fuel can be, for instance, evidenced by the fact that the first reports on the use of hydrogen published on the l website of the International Railway Journal were dated 2012. Since 2017, the number of publications on the topic has been rapidly growing reaching its maximum in 2021, followed by a slight decline to 50–70 publications per year. While the first publications talk about experiments and prototypes, the latest ones were mostly dedicated to the commencement of rolling stock manufacturing and tenders for supply of locomotives and electric trains (mainly). Moreover, the geography of supplies extends from Alaska to India.

Production facilities relating to the hydrogen industry appear in many countries of the world, including Spain, where suppliers of this type of fuel are actively cooperating with rolling stock operators. Similar measures are intended to take place in the United Kingdom, where hydrogen could be used both in transport and in other sectors.

It should be noted that not only hydrogen can be used for decarbonisation of railway transport. According to some estimates, these solutions may fall into one of the following three categories: electrification, batteries, and hydrogen technologies as such. As a result, operators are increasingly entering into contracts for the supply of rolling stock, be it an electrodiesel multiple unit (EDMU), battery-powered electric multiple unit (BEMU), or a hydrogen fuel cell multiple unit (HEMU).

Nevertheless, many scientists, research organisations and railway companies are actively examining the technology, and manufacturers of rolling stock are eager to test hydrogen-powered rolling stock. Alstom, France, is considered to lead the railway sector in this field. They were first to offer a train powered by hydrogen fuel cells iLint (from the lithium-Ion battery composition) which was presented at the InnoTrans exhibition as early as 2016. Their competitors CAF and Talgo (Spain), Pesa (Poland), and Siemens (Germany) are also interested in entering the market. In early 2025 in Italy, the HEMU Coradia Stream train powered by hydrogen fuel produced by Alstom began to be tested.

Some countries continue to develop public strategies for the use of hydrogen as a fuel. These include the creation of large-scale production complexes for environmentally friendly production of this fuel, as well as for its transportation and storage. For example, the UK Hydrogen Strategy proposes to create a complex of low-carbon hydrogen production equivalent to the generation of 5 GW of electric power by 2030. In the transport sector, hydrogen is given a "complementary role", complementing the electrification of buses, trains and road freight transport.

PROBLEMS OF USE OF HYDROGEN

One of the problems related to the use of hydrogen is that it needs to be stored directly on a vehicle. While buses may, perhaps, sacrifice space in the passenger compartment to install a tank with the fuel, a train may need an entire separate tank wagon. In addition, it should be kept in mind that hydrogen is a flammable gas.

Electrification is still the preferred choice for propulsion of a heavy train. However, for some types of lines it is not suitable because of being costly. For many sections, these measures are not economically feasible, unlike the introduction of hydrogen-powered trains which are much more environmentally friendly than diesel trains.

Hydrogen is considered a very environmentally friendly fuel, but methods of its production are not. Most of electrolytic hydrogen available on the market is "grey": it is produced from coal, oil or gas. Therefore, in order to reduce carbon dioxide emissions, production of hydrogen, as well as its supply chains, should be decarbonised.

Decarbonisation of supply chains is an urgent issue due to life cycle emissions: an indicator rarely mentioned in popular articles on environmental compatibility of a particular transport mode, production process, or fuel. If we take it into account, then batteries (due to the potential carbon intensity of one or more links in the supply chain) and even nuclear power plants (which are built using concrete and its production releases a significant amount of carbon dioxide) can turn out to be environmentally unfriendly. Given the above, even green hydrogen may turn out to be not that much "green".

Another problem of using hydrogen in railway transport is building refuelling stations for rolling stock. It is preferable to have them at a traction maintenance depot. However, in the UK, this is impossible due to the legal restrictions on storing large amounts of hydrogen.

Another issue worth mentioning is pricing. Although electrification requires significant costs, it increases the throughput capacity of a railway and facilitates the uninterrupted transportation process. Besides, conventional electric trains are cheaper than those powered by batteries or hydrogen fuel cells.

An expert at the University of Birmingham, Professor Stuart Hillmansen, claims that the cost of hydrogen-powered trains is the same as that of rolling stock with batteries, but "a more detailed economic analysis is needed". A report of the Association for Electrical, Electronic and Information Technologies (VDE), Germany, considers battery-powered electric multiple units (BEMUs) and hydrogen fuel cell electric multiple units as an alternative to hydrogen-powered diesel electric multiple units (H-Diesel-EMU: HEMUs). It was found that BEMU rolling stock is 35% (EUR 59 million) cheaper than HEMUs (in terms of procurement and operating costs). It should be clarified that HEMUs considered in this study use green hydrogen which is more expensive than grey hydrogen.

The train length and the loading gauge also influence the economic feasibility of operating hydrogen-powered trains. In the UK, these are subject to certain restrictions that hamper the introduction of hydrogen technologies. Moreover, we should not forget about the infrastructure for supplying hydrogen, which currently hardly exists. Based on this, electrification becomes the preferred choice again. Indeed, according to Stuart Hillmansen, many current strategies for the development of railway transport reveal high interest in these activities, while hydrogen and batteries are given a secondary role. However, the expert believes that in the next 29 years companies will be able to make the two technologies very competitive.

Under certain circumstances, hydrogen technologies can indeed become a key to full decarbonisation of railway transport on sections that use diesel-powered traction. They are cheaper than electrification of railway infrastructure and hydrogen fuel cells feature a higher energy density than batteries. Moreover, there are already successful cases of operating rolling stock with this type of traction. A number of the world's developed countries give this sector a leading role in their strategies for climate crisis control.

But to ensure of the expediency of using hydrogen on railways, it is necessary to develop infrastructure for its transportation and refuelling and devise a relevant legal framework and safety measures, as the gas is highly explosive and fire hazardous. In addition, in order to implement a truly environmentally friendly policy and contribute to the full decarbonisation of the sector, life cycle emissions should be taken into account. It is essential to remember the preference of certain groups of large businesses: some benefit from supporting hydrogen, while others benefit from promoting electrification and batteries. Unfortunately, objective advantages of a particular technology play a minor role here.

In November 2019, Stadler entered into a contract with the San Bernardino County Transportation Authority (SBCTA), CA, U.S., to supply a fuel cell multiple unit for the Arrow commuter rail service. The United States' first fuel cell train was expected to be put into regular services in 2024. The train consists of three sections. The central one has fuel cell batteries and a hydrogen tank. Four more such trains are planned to be supplied in the future.

ADVANTAGES OF USING HYDROGEN TRACTION IN RAILWAY TRANSPORT

Professionals from S2R[1] have found that fuel cells generally provide a longer cruising range and shorter refuelling time than batteries. On multiple unit trains they will be able to compete with diesels when the cost of hydrogen production becomes lower. Perhaps, this can be achieved when railways share the use of electrolysis plants and refuelling infrastructure with other transport modes or non-transport consumers (*Table 1*).

The conventional system of traction power supply, as well as battery and fuel cell power supply systems have their own advantages and drawbacks and each of the options can have its own niche, experts believe.

Despite significant capital expenditures, electrification using a catenary system will remain the most efficient solution for lines with busy traffic. In terms of reducing CO_2 emissions, conventional electrification is preferable, as it usually ensures the lowest level of emissions for various methods of power generation.

The use of rolling stock powered by fuel cells may be appropriate on routes where traffic intensity is not sufficient to justify electrification and a significant duration of trips would require the installation of batteries with significant dimensions and weight. A considerable drawback of fuel cells is the need for double conversion of energy, leading to a certain increase in losses compared to a single conversion when batteries are used.

A traction drive with batteries has a better environmental profile than that with fuel cells, even if we take into account CO_2 emissions from the production of batteries. However, the weight of batteries limits the trip distance on trains fitted with them and in the near future the problem will persist. Batteries can be an efficient solution for powering shunting locomotives which usually have idle hours during a day when they can be recharged, as well as for battery-trolley rolling stock (powered by both catenary and batteries).

[1] Shift2Rail Joint Undertaking (S2R) is an international public-private partnership established to implement the first European rail initiative to seek focused research and innovation (R&I) and market-driven solutions by accelerating the integration of new and advanced technologies into innovative railway product solutions. Shift2Rail contributes to better competitiveness of the European rail sector and meets the EU's changing needs in transport. R&I carried out under this Horizon 2020 initiative develop the necessary technology to complete the Single European Railway Area (SERA) / https://rail-research.europa.eu/about-shift2rail/ / https://zdmira.com/tags/shift2rail

Table 1

Advantages of alternative (hydrogen-powered) traction over diesel and electricity

Sources of energy	Key advantages	Applications
Batteries	Easy to charge using a pantograph on sections with a catenary system. A relatively small need for additional infrastructure	Shunting at stations with significant downtime
Fuel cells	A considerably longer cruising range than that provided by batteries. More trains can be refuelled. Refuelling with hydrogen takes less time than charging batteries	Shunting and hauling operations with a haul distance of up to 200 km. Mainline locomotives and multiple unit trains for routes with long non-electrified sections Direct cross-border traffic between countries that use different systems of traction power supply. Low-traffic sections
Catenary	More power available. Energy is recovered and does not need to be accumulated. Smaller dimensions and weight of rolling stock because there are no batteries or hydrogen tanks. Higher cost efficiency when capital expenditures and operating costs are allocated to a large number of trains	High-speed lines. Heavy/long freight trains. Passenger traffic frequency is at least two trains per hour

Since the service life of rolling stock is rather long, diesel locomotives and diesel trains will remain in operation for a long period of time, especially in countries that do not pay enough attention to environmental protection. The development of incentive methods can contribute to the reduction of the carbon footprint of railway transport. Regardless of the obvious success of trains with fuel cells, the research on the use of hydrogen engine fuel continues [7–10]. After five to seven years, testing both systems will enable us to conclude on the preferred option based on their economic and environmental feasibility.

APPLICATIONS FOR HYDROGEN FUEL IN RAILWAY TRANSPORT

We can explore several possible applications for hydrogen fuel in railway transport both in the Russian Federation and abroad (*Fig. 2*).

Because of being environmentally friendly and producing no harmful emissions, hydrogen power units can be used where it is impossible to use internal combustion engines: in closed spaces, mines, and underground tunnels where power supply is inoperative.

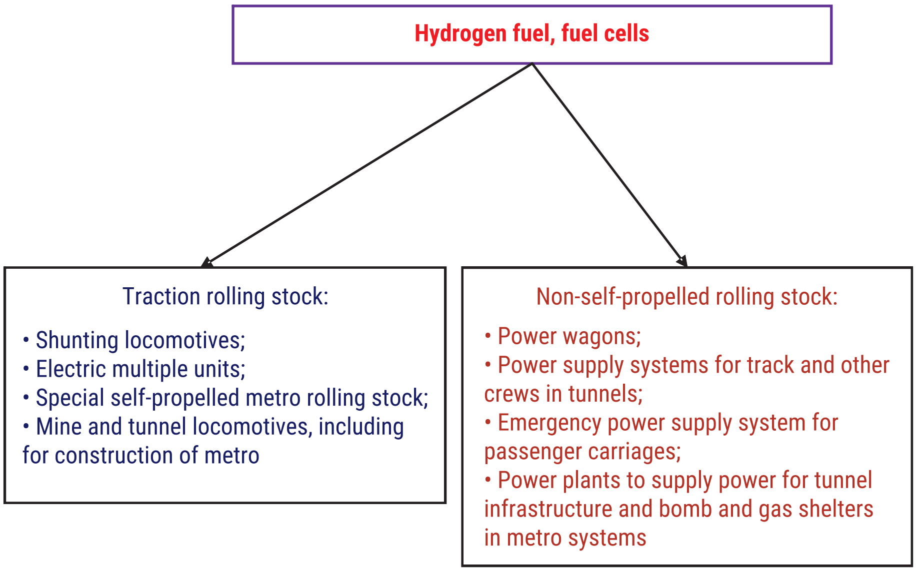

Fig. 2. Possible applications for hydrogen fuel and fuel cells in railway transport

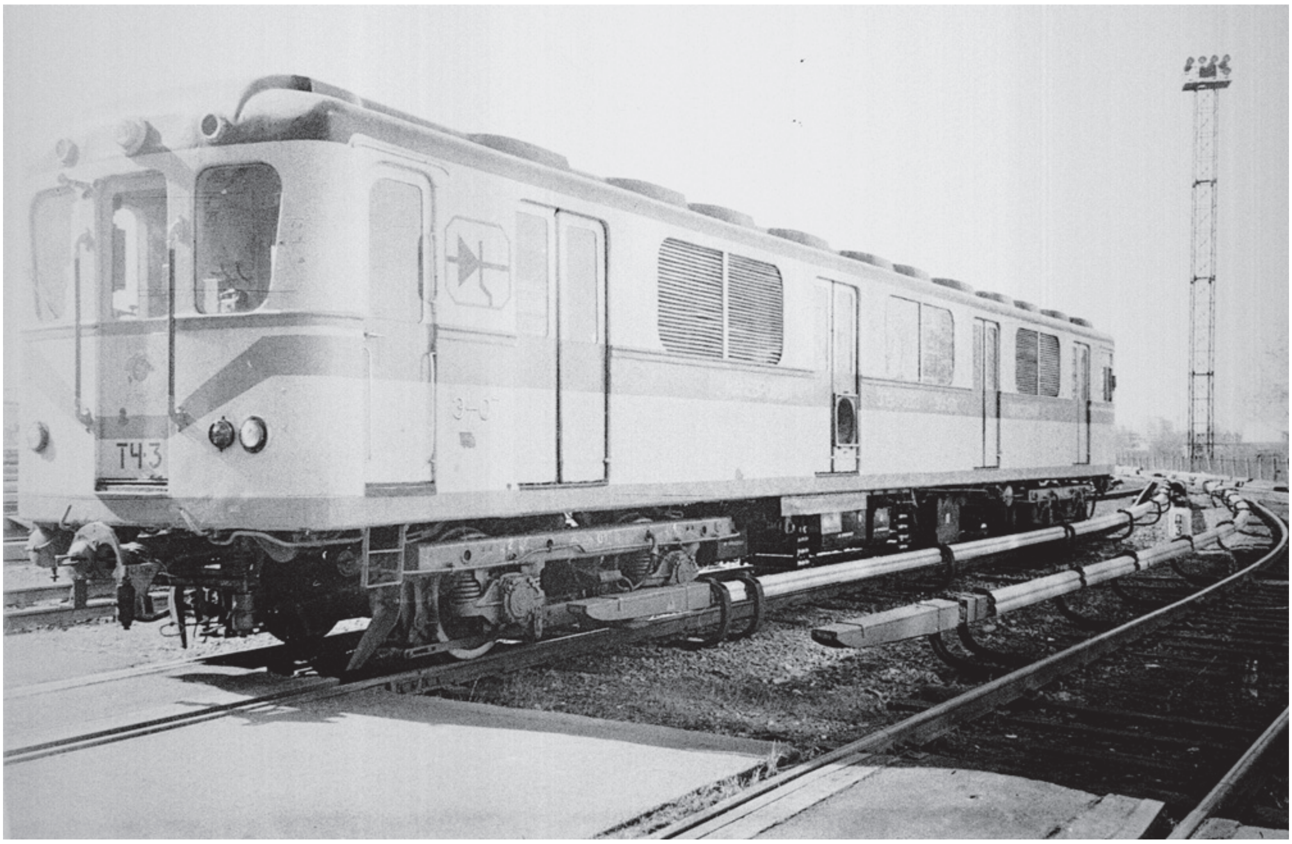

Fig. 3. Battery-trolley electric locomotive for the metro created by the Leningrad Institute of Railway Engineers (currently known as PGUPS) in cooperation with the Ural Electromechanical Institute for Transport (currently known as UrGUPS) and the Design Office of the Leningrad Metro

In Russia, battery-trolley locomotives are used for this purpose. As a matter of example, Ek/a-07T (the original spelling of the locomotive's name in Cyrillic characters is 'Эк/а-07Т') is an electric locomotive which was operated by the Moskovskoye electric depot of the Leningrad Metro for more than 15 years (beginning in 1987) (*Fig. 3*) [11].

The tests have shown that the use of a pulse converter increases the cruising range by approximately 15% compared to an electric locomotive with starting resistors and dynamic braking. The cruising range exceeded 30 km with a trailing load of 55 tonnes. The electric locomotive could run at night when electric supply voltage was removed from the third contact wire throughout the Moskovsko-Petrogradskaya metro line between the Moskovskoye and Vyborgskoye depots. But it was unable to return along the line due to a critical battery discharge. It was also unable to tow a coupling of more than two carriages because it had just one compressor to power the braking system, which was also determined by the battery capacity.

At present, the metro system operates more advanced electric locomotives, but increasing a cruising range when powered by batteries is still relevant. One of the ways to address this challenge is using a hydrogen accumulator and fuel cells. It should be noted that a battery-trolley electric locomotive is a hybrid which already has an on-board battery; therefore all that is left to do is to install a fuel cell module and a DC-DC converter. On the Ek/a-07T (Эк/а-07Т) electric locomotive, the converter occupied about 25% of the interior space inside the locomotive body. Modern IGBT-based converters are several times smaller in weight and dimensions than a thyristor-pulse converter, so the problem of their placement can be addressed successfully.

The second possible area of application is an emergency power supply system for passenger carriages. In recent years, switching from passenger carriages with an autonomous power supply system (individual undercarriage generators and a battery) to those with a centralized high-voltage system has been a mainstream trend in Russia.

However, these carriages are only intended to be operated on sections with electric traction. When there is no power supply these carriages become very uncomfortable, because air conditioners, environmentally friendly toilets, and heating systems in the winter time stop working. This may happen for a variety of reasons, such as involuntary rerouting to non-electrified sections, a failure of the electric locomotive or the

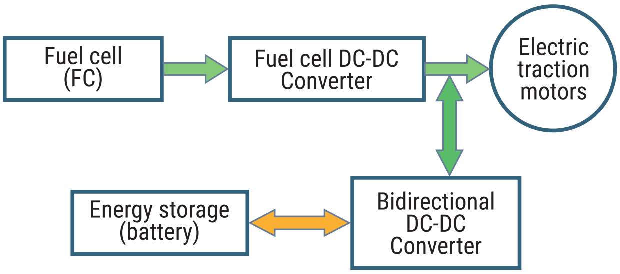

Fig. 4. Energy circuit for traction rolling stock with fuel cells and hydrogen fuel

undercarriage high-voltage main line or the carriage power supply unit, etc.

Passenger carriages need to be provided with an emergency power supply system and hydrogen is one of the options. Any other systems require that there is liquid fuel on board, which is unacceptable for fire safety reasons. Hydrogen can be stored as a chemical compound on board the train and obtained as and when necessary. In a bound form, hydrogen is not dangerous, and the heat can be used for heating carriages. An emergency power supply unit may be single-use, designed to operate for 10–12 hours.

In addition to the above, it should be noted that Rocket and Space Corporation "Energia" works in cooperation with Rostov State Transport University to create a train locomotive with fuel cells powered by hydrogen [12]. The capacity of the locomotive will be 2,100 kW. RSC "Energia", together with the Railway Research Institute (VNIIZhT JSC), has developed a power wagon with a fuel cell power unit which uses hydrogen as fuel. The wagon is designed to power track power tools during operations in tunnels [13]. Transmashholding is designing a train with a fuel cell power unit using hydrogen as fuel for the Sakhalin railway. The power unit will be placed in one of the wagons not intended for transportation of passengers [14].

The results of tests and pilot operation by researchers and specialists of Vehicle Projects LLC, TTCI, U.S., and other organisations are presented in[2] [15–17]. Based on these and an analysis undertaken by the authors, it can be stated that a fuel cell power unit with hydrogen as fuel is best suited for a shunting locomotive and a multiple unit train. Using hydrogen fuel for a train locomotive is complicated due to a low energy density in the existing storage systems. The specific performance features of the power unit and the above-listed rolling stock allow to achieve the maximum effect when using a hybrid scheme with energy storage devices based on batteries (it is also possible to use mechanical energy storage devices, such as flywheels).

According to the research results, the best performing is traction rolling stock with the energy circuit shown in *Fig. 4*.

The assessment of effects of a hybrid drive with fuel cells on the key criteria such as traction force and the recovery effect has shown that the highest advantages in terms of traction force can be achieved on commuter service lines. On a shunting locomotive, traction force is smaller because of the small weight of the power unit, and ballasting may be required. Besides, we should not expect a large effect from energy recovery due to low speeds during shunting operations. The greatest effect when using a fuel cell power unit can be achieved on suburban trains and interurban multiple units [8–12, 15].

CONCLUSION

We can note the following advantages and drawbacks of the rolling stock with a fuel cell power unit using hydrogen as fuel:

Advantages:

1) Environmentally friendly (especially when green and blue hydrogen is used);

2) Low noise levels compared to diesel locomotives and diesel trains;

3) Theoretically higher reliability (in case of large-scale production);

4) Higher efficiency compared to internal combustion engines.

Drawbacks:

1) High price;

2) High cost of hydrogen, resulting in the overall high costs of operation — approximately 60% higher than for rolling stock with diesel or electric drive;

3) A complex design and expensive tanks for high-pressure storage of hydrogen. There are a number of technological difficulties related with storing hydrogen in a bound form (metal hydride accumulators);

4) A high cost of fuel cells necessitates the production of hybrid rolling stock by adding a battery;

5) Complexity and high cost of refuelling infrastructure;

6) A somewhat smaller cruising range compared to diesel trains and a considerably shorter operating time for a shunting locomotive;

[2] Fuel cell-hybrid switcher locomotive: Brochure of the Institute of Fuel Cell Traction, U.S. – 2008 (in English).
Competition winner stode liver UK's first hydrogen transport trialsin Tees Valley. UK Government [official website]. URL: https://www.gov.uk/government/news/competition-winners-to-deliver-uks-first-hydrogen-transport-trials-in-tees-valley Date of publication: 17.08.2021 (in English).

7) Due to the low weight of the power unit, it may be necessary to install ballast even where batteries are available, in order to provide the traction force for the grip of the wheels on the rails;

8) When compressed hydrogen is used as fuel in a hybrid scheme, the locomotive can no longer operate as a hauler and becomes merely a shunter;

9) When hydrogen is stored under high pressure or in a bound state and then expands and goes into free state it cools down strongly, and a large heat release from working fuel cells necessitates designing complex liquid-based heating and cooling systems (often including heat-exchangers). These systems usually use glycol-based cooling fluids (antifreezes). The cooling systems are significantly more complex than diesel locomotive systems and require microprocessor-controlled circulating pumps and a large number of sensors;

10) A potential risk of explosion or fire during accidents and derailments.

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