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HYDROGEN FUEL CELLS IN TRANSPORT

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Abstract: *This article examines the development of the transport sector. It demonstrates that it is one of the main consumers of hydrocarbons and man-made sources of carbon oxide emissions. Due to increasingly stringent environmental requirements, the transition to a low-carbon economy is becoming an incentive. Alternative energy sources are becoming a defining factor in ensuring the country's sustainable development. It is noted that, at the same time, vehicles with traditional internal combustion engines, which form the bulk of the global fleet, have lost their advantages due to their technical and environmental characteristics failing to meet modern requirements. The current role of alternative energy sources, including hydrogen, as renewable energy sources and energy carriers is defined. An analysis of the operating principles, classification, design, advantages, and disadvantages of hydrogen fuel cells was conducted, along with an assessment of their potential for use in transportation. A comparative analysis of the main types of fuel cells was conducted, identifying promising areas for their use. The key characteristics of fuel cell technologies were analyzed based on parameters such as efficiency, service life, cost, and environmental performance. A chain for converting H2 into electrical energy was developed. A model for converting hydrogen energy into electricity in a fuel cell was developed. The main advantages and disadvantages of these technologies were identified. A comparison of hydrogen fuel cell vehicles with battery-electric vehicles was conducted. It was shown that the use of hydrogen technologies is one of the most promising areas for the development of environmentally friendly transport.*

Аннотация: *Настоящая статья посвящена проблематике развития транспортного сектора экономики. Показано, что он является одним из основных потребителей углеводородов и техногенных источников выбросов оксидов углерода. В связи с ужесточением экологических требований переход к низкоуглеродной экономике становятся стимулом. Альтернативные источники энергии обретают статус определяющего фактора в обеспечении устойчивого развития страны. Отмечено, что в то же время транспортные средства с традиционными двигателями внутреннего сгорания, которые составляют основу мирового автопарка, утратили свои преимущества из-за несоответствия их технических и экологических характеристик современным требованиям. Определена текущая роль альтернативных источников энергии, в том числе водорода, в качестве ВИЭ и носителя энергии. Проведен анализ принципов работы, классификации, конструкции, преимуществ и недостатков водородных топливных элементов, а также оценка перспектив их применения на транспорте. Проведен сравнительный анализ основных видов топливных элементов. Выявлены перспективные направления их использования. Проанализированы основные характеристики технологий топливных элементов по параметрам: КПД, срок службы, стоимостные характеристики технологии, уровень экологичности. Сформирована цепочка преобразования H_2 на электрическую энергию. Построена модель преобразования энергии водорода в электричество в топливном элементе. Выявлены основные преимущества и недостатки этих технологий. Выполнено сравнение транспортных средств на водородных топливных элементах с аккумуляторными электромобилями. Показано, что использование*

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водородных технологий является одним из наиболее перспективных направлений развития экологически чистого транспорта.

Keywords: *transport, carbon oxides, ecology, hydrogen, fuel cell, PEMFC, hydrogen fuel, decarbonization of transport.*

Ключевые слова: *транспорт, оксиды углерода, экология, водород, топливный элемент, «PEMFC», водородное топливо, декарбонизация транспорта.*

Introduction. The transport sector is one of the largest consumers of fossil fuels and sources of greenhouse gas emissions. According to international estimates, transport accounts for approximately 20–25% of global carbon dioxide emissions [1]. Due to tightening environmental regulations and the need to transition to a low-carbon economy, interest in alternative energy sources is growing [2, 3]. Furthermore, a SWOT analysis revealed that internal combustion engines have lost their positive technical characteristics and do not meet modern technical and environmental requirements [4].

The transport sector is facing the need for a profound transformation of its energy base due to global climate change, rising greenhouse gas emissions, and tightening international environmental requirements.

With the implementation of international initiatives to decarbonize the economy, achieve carbon neutrality, and meet greenhouse gas emission reduction commitments, interest in alternative energy sources in the transportation industry is growing significantly. Particular attention is being paid to technologies that reduce the carbon footprint throughout the entire lifecycle of vehicles. Such solutions include battery-electric vehicles, hydrogen fuel cell vehicles, biofuels, synthetic fuels, and other renewable energy sources.

One of the most promising areas is the use of hydrogen as an energy source. Unlike internal combustion engines that use gasoline or diesel fuel, hydrogen fuel cells generate electrical energy directly through an electrochemical reaction without combustion.

Materials and methods. The purpose of this study is to analyze the operating principles, classification, design, advantages, and disadvantages of hydrogen fuel cells, as well as to assess their potential for use in transportation. This study utilizes an analytical research method based on a review of scientific and technical literature, open-access articles, international standards, and current developments in the field of hydrogen energy and transportation systems.

A comparative analysis of various fuel cell types, their technical characteristics, and operational parameters is also conducted.

Results. A hydrogen fuel cell is an electrochemical device that converts the chemical energy of hydrogen directly into electrical energy, heat, and water [5, 6].

Unlike batteries, a fuel cell does not store energy internally. Electricity is generated continuously by supplying fuel (hydrogen) and an oxidizer (oxygen) [7].

The basic reaction is:

$$2H_2 + O_2 = 2H_2O + Q$$

where: H_2 is hydrogen; O_2 is oxygen; H_2O is water; Q is the released energy.

The only reaction product is water vapor, resulting in virtually zero harmful emissions [8].

Fuel cells are classified by electrolyte type and operating temperature.

Table 1

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Main types of fuel cells

Type	Name	Operating temperature, °C	Application area
PEMFC	Proton Exchange Membrane Fuel Cell	60–90	Passenger vehicles
AFC	Alkaline Fuel	60–250	Space technology
PAFC	Phosphoric Acid Fuel Cell	150–220	Stationary power generation
MCFC	Molten Carbonate Fuel Cell	600–700	Power plants
SOFC	Solid Oxide Fuel Cell	700–1000	Power generation and heavy transport
DMFC	Direct Methanol Fuel Cell	50–120	Portable devices

Proton Exchange Membrane Fuel Cell (or **Polymer Electrolyte Membrane Fuel Cell**) (PEMFC) is the most promising solution for passenger and commercial vehicles due to its high power density, compactness and quick start.

Alkaline Fuel Cell (AFC) provides high efficiency, but is of limited use due to sensitivity to carbon dioxide.

Molten Carbonate Fuel Cell (MCFC) and **Phosphoric Acid Fuel Cell** (PAFC) focused primarily on industrial and municipal energy facilities.

Solid Oxide Fuel Cell (SOFC) demonstrates maximum energy efficiency and is suitable for stationary power generation.

Direct Methanol Fuel Cell (DMFC) in demand in low-power autonomous energy sources due to the use of liquid fuel.

Table 2

Characteristics of fuel cell technology

Fuel Cell Type	Efficiency, %	Service Life (hour)	Cost Characteristics	Environmental Friendliness	Technological Characteristics
PEMFC	45–60	5 000 – 30 000 h	High	Very High	Fast start-up, high power density, compact design; requires high-purity hydrogen and expensive platinum catalysts. Considered the most promising technology for automotive transportation
AFC	50–70	5 000 – 15 000 h	Medium	Very High	Offers high efficiency but is sensitive to CO_2 in both fuel and air. Mainly used in aerospace applications
PAFC	40–50	40 000 – 80 000 h	High	High	Well suited for stationary power generation and cogeneration systems; characterized by high reliability and long service life
MCFC	45–60	20 000 – 40 000 h	High	High	Can operate on natural gas and biogas without extensive fuel purification;

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					suitable for large-scale power generation facilities
SOFC	50–70	40 000 – 100 000 h	High	High	Provides the highest efficiency among commercial fuel cells; allows the use of various fuels, but requires heat-resistant materials and a long warm-up period
DMFC	20–40	2 000 – 10 000 h	Medium	High	Uses liquid methanol as fuel; offers easy fuel storage and is suitable for portable power systems

Structurally, the PEM fuel cell consists of the following elements, Figure 1.

The main structural element is a membrane that allows only hydrogen protons to pass through and prevents electrons.

To generate the required voltage, individual cells are combined into a battery containing from several dozen to several hundred cells.

The conversion of hydrogen energy into electricity in a fuel cell occurs as follows.

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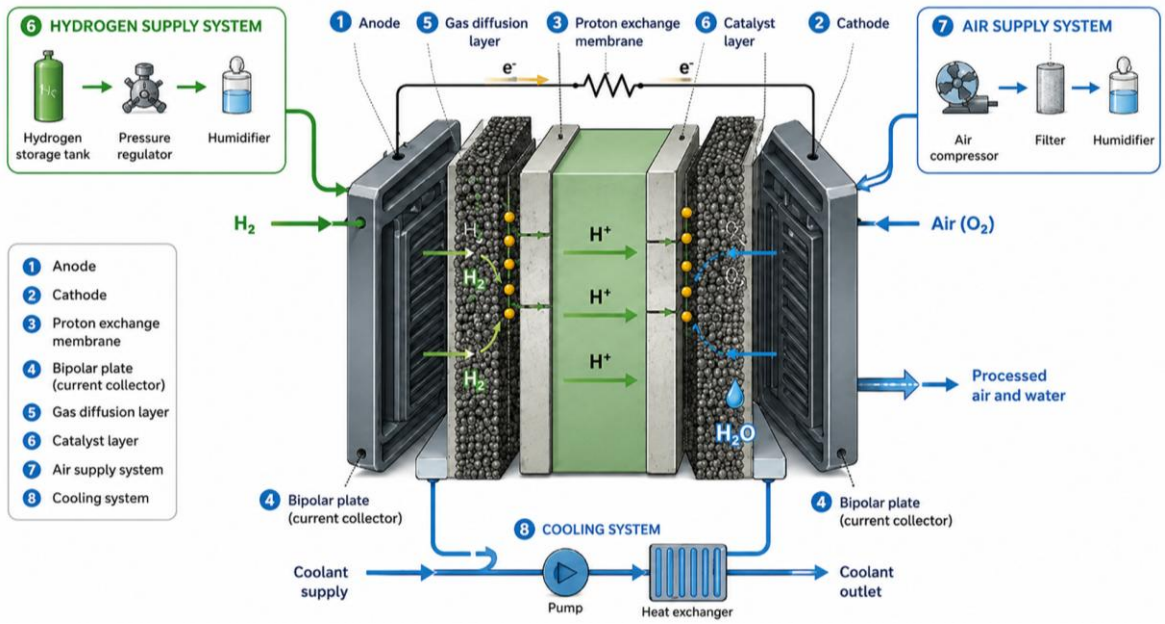

Figure 1. Schematic diagram of the REM fuel cell

The physical and chemical processes of converting hydrogen energy into electricity in a fuel cell occur as follows:

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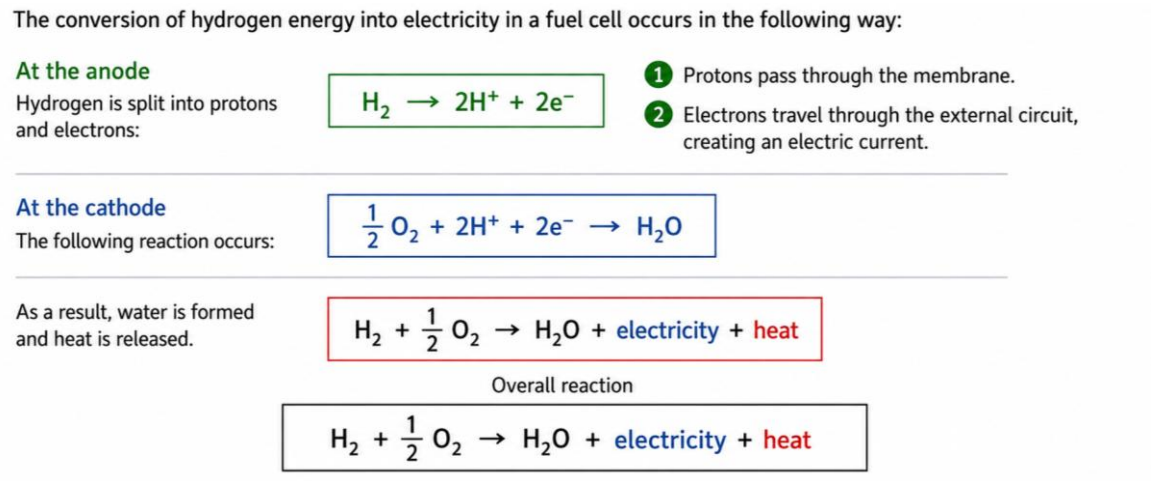

Figure 2. Hydrogen energy conversion model to electricity in the REM fuel cell

As the model shows, the chemical reaction results in the formation of water and the release of heat.

Thus, the chemical energy of hydrogen is converted directly into electrical energy without intermediate mechanical conversion.

The main advantages of hydrogen fuel cell technology are:

- High efficiency (45–60%, up to 70% in hybrid systems);
- No CO_2 emissions;
- Low noise levels;
- High energy density of hydrogen;
- Rapid fuel replenishment (3–5 minutes);
- Long driving range;
- Possibility of operating heavy vehicles;
- Reduced dependence on fossil fuels.

Modern hydrogen vehicles can have a range of up to 600–800 km without refueling [9, 10].

Despite their advantages, hydrogen fuel cells have the following disadvantages:

- High cost of platinum-based catalysts;
- Difficulty storing hydrogen;
- Requirement for high pressure (350–700 bar);
- Limited hydrogen fueling station infrastructure;
- Energy-intensive hydrogen production;
- Increased safety requirements.

Reducing the cost of membranes and catalysts remains a major challenge for modern science and industry.

Table 3

Comparison of hydrogen transport and battery electric vehicles

Parameter	Hydrogen Vehicle	Battery Electric Vehicle
Energy Source	Hydrogen	Battery
Refueling / Charging Time	3–5 min	30 min – 10 h
Driving Range	500–800 km	250–600 km
Energy Storage System Weight	Lower	Higher
Environmental Emissions	None	None
Infrastructure Cost	High	Medium
Energy Chain Efficiency	Lower	Higher
Application in Heavy-Duty Transport	High Efficiency	Limited Efficiency

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Analysis shows that battery-electric vehicles offer higher overall energy efficiency, but hydrogen technologies have advantages for trucks, buses, rail transport, ships, and aviation.

Discussion. The development of hydrogen energy is considered by many countries as a strategic direction for achieving carbon neutrality. Leading transport equipment manufacturers are actively implementing fuel cell technology in buses, trucks, locomotives, and ships.

In a passenger car, the use of hydrogen fuel cells is designed as follows. Figure 3.

The PEMFC hydrogen fuel cell vehicle (HEV) is an electric vehicle in which electricity is generated directly onboard the vehicle through the electrochemical reaction of hydrogen and oxygen in a PEMFC (Proton Exchange Membrane Fuel Cell) fuel cell. The key components include a hydrogen fuel tank, which stores compressed hydrogen under high pressure. The tank is made of composite materials and equipped with a pressure control and safety system. The PEMFC fuel cell stack is the primary source of electrical energy, consisting of multiple individual cells connected in series to produce the required voltage and power. The electric motor converts the electrical energy generated by the fuel cells into mechanical energy to propel the vehicle.

In addition to the aforementioned design elements, the efficient operation of fuel cells is ensured by: an air supply system, which supplies oxygen to the cathode portion of the fuel cells; a cooling system, which maintains the optimal operating temperature of the fuel cell stack and power electronics; and a control system, which monitors the supply of hydrogen and air, the operation of the electric motor, the battery status, and safety parameters.

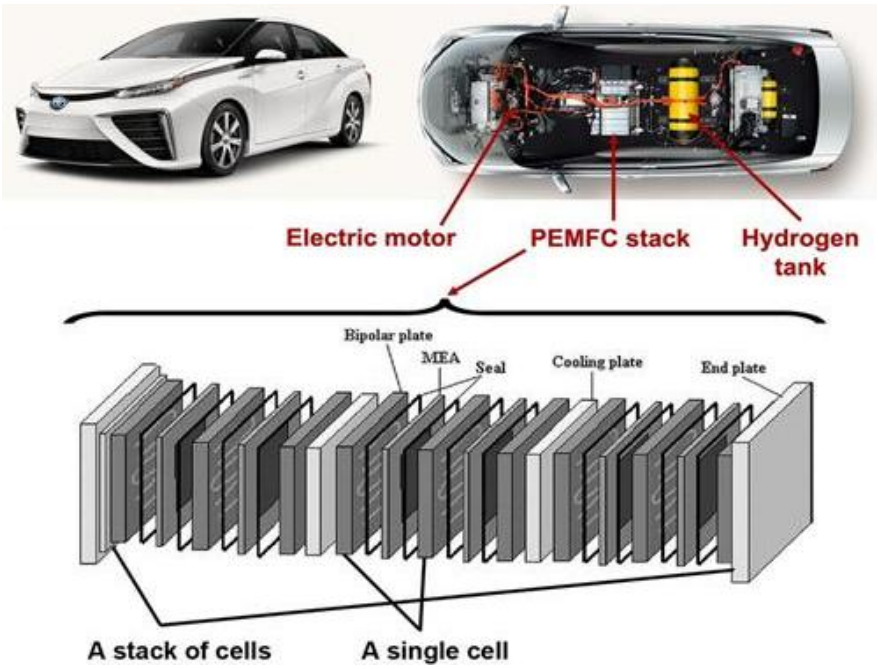

Figure 3. Structural model of hydrogen fuel cell placement in a passenger car

The PEMFC fuel cell stack consists of a set of identical electrochemical cells. Each cell includes bipolar plates, a membrane-electrode assembly (MEA), catalytic layers, seals, and cooling plates. Connecting the cells in series generates the power needed to drive a vehicle. The system works as follows: hydrogen from the tank is fed to the anode section of the fuel cell. Oxygen from the atmosphere is then fed to the cathode section. At the anode, hydrogen disintegrates into protons and electrons. The protons pass through a proton exchange membrane, and the electrons move through an external electrical circuit, generating an electric current. At the

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cathode, the protons, electrons, and oxygen form water. The resulting electrical energy is used to power an electric motor, and the generated heat is removed by a cooling system.

The design's advantages include high efficiency, zero emissions, fast hydrogen refueling, and a long driving range. The fuel cell's only byproduct is water, ensuring the vehicle's high environmental efficiency.

The comparative efficiency of gasoline, diesel, hydrogen fuel cell and battery powered vehicles is shown in Graph 1.

It should be noted that gasoline-powered vehicles continue to dominate the global vehicle fleet due to their developed infrastructure and relatively low production costs. Diesel vehicles retain a significant share in trucks, buses, and commercial vehicles. Battery electric vehicles (BEVs) are the fastest-growing segment [11].

Table 4

Distribution of the Global Vehicle Fleet by Powertrain Type as of January 1, 2026

Powertrain Type	Global Vehicle Fleet, million units (January 1, 2026)
Gasoline Internal Combustion Engine Vehicles	1120
Diesel Internal Combustion Engine Vehicles	290
Battery Electric Vehicles (BEVs)	95
Hydrogen Fuel Cell Electric Vehicles (FCEVs)	0,1

According to «Gartner», there will be approximately 116 million electric vehicles of various types on the world's roads by 2026, the majority of which will be passenger electric vehicles.

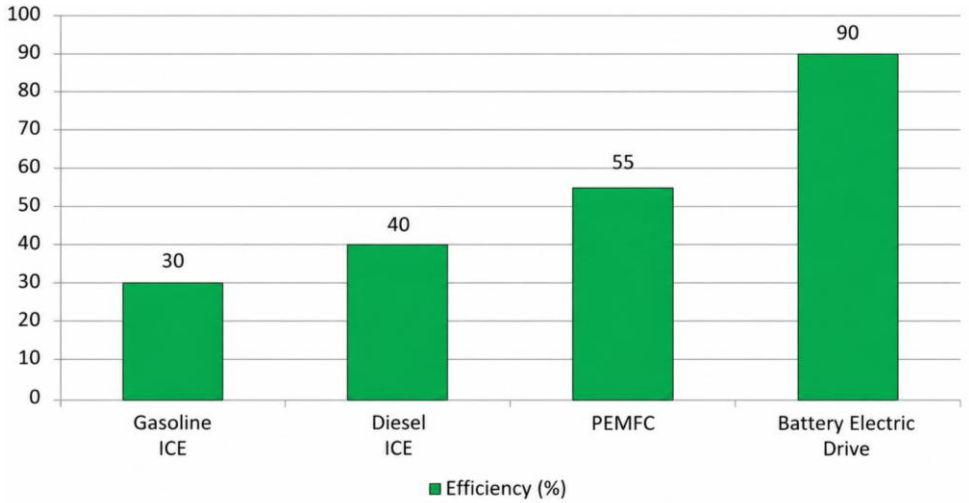

Figure 4. Efficiency of gasoline, diesel, hydrogen fuel cell and battery powered vehicles

Hydrogen fuel cell vehicles (FCEVs) remain a niche technology. The global fleet is estimated at approximately 90,000-100,000 units, concentrated primarily in Japan, South Korea, China, the United States, and Europe [12]. The graph shows the range of an electric vehicle, a hydrogen fuel cell, and a diesel engine.

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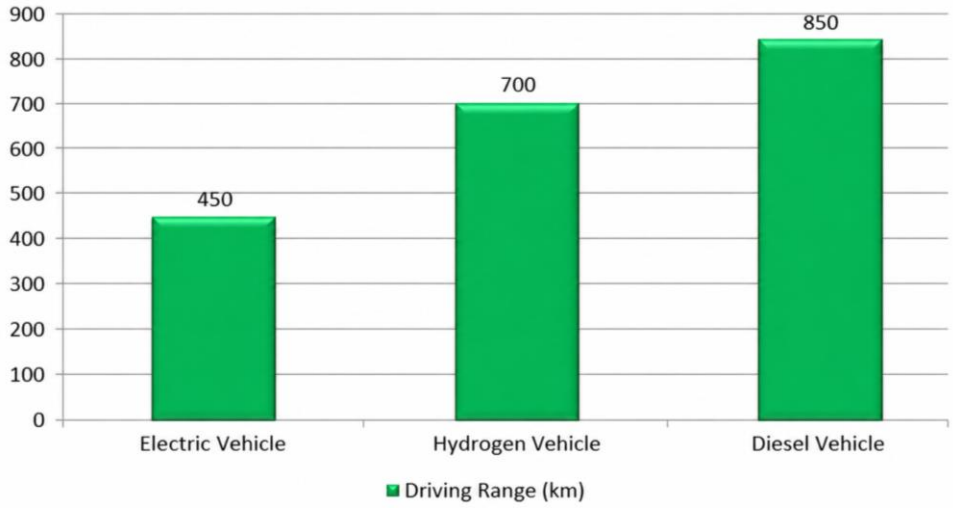

Figure 5. Comparison of electric vehicle, hydrogen fuel cell, and diesel range

In addition, the graph 3 shows comparative indicators of the time spent on restoring energy reserves.

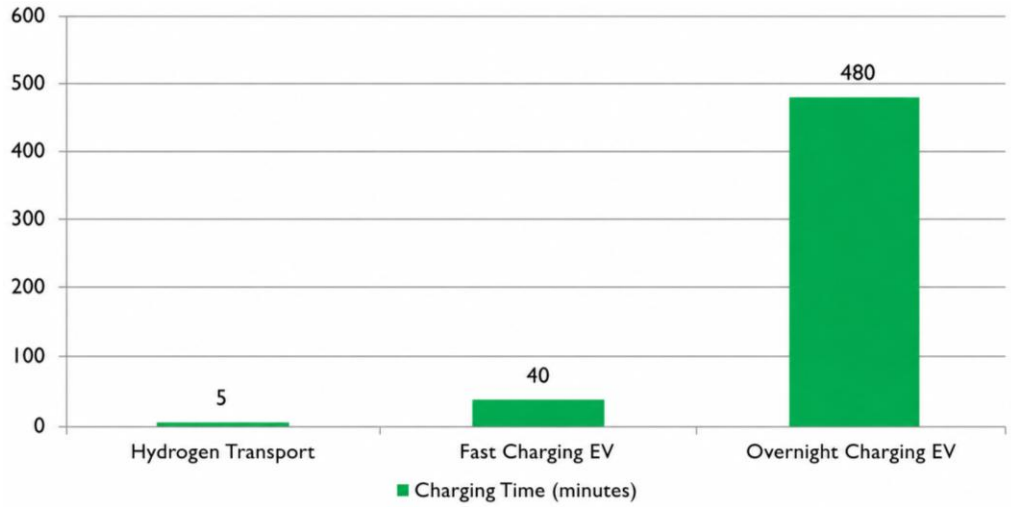

Figure 6. Comparison of the energy recovery time of a hydrogen fuel cell and an electric vehicle with fast and standard battery charging

The main areas of further research are:

- Increasing membrane durability;
- Reducing platinum content in catalysts;
- Improving hydrogen storage technologies;
- Developing green hydrogen production systems;
- Creating a global hydrogen infrastructure.

In the long term, hydrogen transport has the potential to capture a significant share of the heavy-duty vehicle market, where battery use is limited by weight and charging time.

Conclusion. Thus, tightening environmental standards, increasing demands on energy efficiency in transport systems, and the need to reduce dependence on fossil fuels are driving the accelerated development and adoption of alternative energy sources. The transition to low-carbon energy in transport is becoming a critical factor in ensuring environmental safety, sustainable economic development, and achieving global climate goals. Against this backdrop, hydrogen fuel cells are a promising technology for the clean transportation of the future. They operate by directly

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electrochemically converting hydrogen energy into electricity. The most common type for vehicles is proton-exchange membrane fuel cells (PEMFCs).

The main advantages of this technology are its long range, fast refueling, and the absence of harmful emissions. However, widespread adoption is hampered by the high cost of equipment and the insufficient development of hydrogen infrastructure. The prospects for the development of hydrogen transport are linked to the reduction in the cost of hydrogen production, the improvement of fuel cells, and the expansion of the hydrogen refueling station network.

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