Analysis of hydrogen use as an energy carrier in transport

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Abstract. The subject of the analytical review is the power units of electric vehicles using hydrogen fuel cells. A prerequisite of the research is the ever-increasing urgency of developing vehicles with zero emission of carbon dioxide and other harmful substances. Materials are taken both from open sources of information (Internet) and from scientifically reliable sources of information (peer-reviewed publications). The scientific methods of performing this analysis include an informative review of sources. Originality lies in the choice of the topic and the findings from the analysis. As a result of the analytical review the tendencies of the automobile market development have been revealed; the technical advantages of hydrogen fuel cells as compared to batteries have been given; the conclusions have been drawn about the availability of the programs of carbon dioxide emission reduction in the European Union, the USA, Japan, China, Korea as well as about the readiness of the technology of the fuel cells use in the traction electric drive for the introduction, including the patenting of the technologies by the leading automobile manufacturers; the most promising segments of transport for this purpose have been described. The results of the analysis are applicable to the design of electric vehicles and their power plants by vehicle designers and manufacturers.

1. Introduction

Currently, one of the main global trends in the development of the automotive industry is the development of environmentally friendly vehicles, since emissions from vehicles are a serious environmental problem, especially in megacities. The content of CO₂ has now reached 0.042% in the vicinity of St. Petersburg and 0.083% in Moscow and continues to increase. In Moscow, cars are the main source of carbon dioxide emissions (85% of all emissions from CO₂ in 1998 and about 92% in 1999). The Intergovernmental Panel on Climate Change (IPCC) has repeatedly reported on the link between global warming and increasing concentrations CO₂ (1990, 1995, 2001, 2007, 2014). In 1992, the Kyoto Protocol was adopted - an international agreement, an additional document to the UN Framework Convention on Climate Change, adopted in Kyoto (Japan). It commits developed countries and countries with economies in transition to reduce or stabilize greenhouse gas emissions.

In this situation, one of the measures to partially reduce the content of CO₂ and other harmful substances, including carcinogenic ones, is the transition of motor vehicles from internal combustion engines to electric drives or combined power plants (CPP) in large cities. However, while electric cars have really zero emissions, cars with a CPP have only partially reduced emissions. In addition, safety standards for cars with internal combustion engines are constantly revised towards stricter standards for harmful emissions in exhaust gases. For example, a number of environmental standards Euro 0 → Euro
1 → Euro 2 → Euro 3 → Euro 4 → Euro 5 → Euro 6. Our country has adopted the Euro 5 standard and is mastering Euro 6 fuel production technologies.

One of the technical solutions with zero emission of CO₂ and other harmful substances is the use of hydrogen fuel cells (HFCs) on electric vehicles.

2. Cars on HFCs
Hydrogen fuel cells as an electric power source for motor transport are one of the main directions of energy efficient motor transport development in the world [1]. Modern and future-oriented intelligent transport is increasingly in need of power through the introduction of additional systems such as ADAS (Advanced Driver Assistance Systems) or multimedia [2,3]. In the USSR and Russia the development of the following prototype vehicles on hydrogen fuel cells was carried out:

- hydrogen minibus KVANT-RAF developed by "Kvant" Research and Production Association and "RAF" plant, with an alkaline fuel cell battery with capacity of 2 kW and nickel-zinc battery with a capacity of 5 kWh. (1982),
- models of passenger cars "AvtoVAZ" (based on VAZ-2131 "Niva" and VAZ-2111), "Electric Transport Technologies" LLC with the participation of specialists from the Center of Competences of National Technical Initiative Institute of Chemical Physics of the Russian Academy of Sciences and "InEnergy" LLC,
- commercial truck "NAMI" with a 25 kW fuel cell battery, developed in St. Petersburg (Central Research Institute of Marine Electrical Engineering and Technology).

Then the demonstration of passenger cars on hydrogen fuel cells became a frequent phenomenon. The total number of passenger car models on hydrogen fuel cells in the period 1990-2017 is 141 pcs. (Figure 1). Detailed information on the models can be found on the site at the link [4].

![Figure 1. Number of hydrogen fuel cell passenger car models by years. Almost all models are demo models. Exceptions are the models presented in Table 1, which are also taken into account in the figure.](image)

Almost all leading car manufacturers presented samples of passenger cars on fuel cells at different times. 2014-2015 can be considered as the beginning of commercialization (beginning of serial shipments of Mirai in Japan). The companies that have transitioned to serial production are presented in Table 1.
Table 1. Mass production of passenger cars on fuel cells

| Manufacturer, model | Status |
|---------------------|--------|
| Honda FCX Clarity   | Manufacture in Japan, 2016 – Series shipments to USA (California) |
| Toyota Mirai FCHV-adv (2008) | 2010 – Beginning of a three-year demonstration trial of one hundred specimens on US roads.  
2014 – Mirai serial supply in Japan.  
2017 – Mirai serial supplies to USA.  
2017 – global sales amounted to 5300 Mirai (the USA – 2900 units, Japan – 2100 and Europe – 200) |
| Mercedes-Benz GLC F-CELL | 2010 – limited edition production (500 copies) of Mercedes-Benz A-class F-Cell for European consumers.  
2019, spring – market launch. |
| Hyundai ix35 FCEV | 2013 – production start |

Other leading automobile companies have developed fuel cell car concepts. Among them are: Alfa Romeo, Audi, BMW, Chang’an Automobile (Group) Co., Ltd., FAW Group, Chrysler, Daimler, Fiat, Ford, General Motors, Kia, Mazda, Mitsubishi, Peugeot, Renault, Subaru, Suzuki, Volkswagen.

In Russia, fuel cell cars are represented by demonstration models developed by JSC "AVTOVAZ": Antel based on VAZ-2131 "Niva" (2001) and Antel-2 based on VAZ-2111 (2003), in which alkaline fuel cells were used. One can also add a demonstration of the car in October 2019 at the forum "Open Innovations" (Figure 2).

![Figure 2](image-url)

**Figure 2.** Fuel cell car (a), developed by "Electric Vehicle Technologies" LLC, 2019. Label on Car: «Electric Car on Hydrogen». The fuel cell system and hydrogen cylinders are located in the trunk of the car (b).

The car was developed by "Electric Vehicle Technologies" LLC with the participation of specialists from the Center of Competences of National Technical Initiative Institute of Chemical Physics of the Russian Academy of Sciences and "InEnergy" LLC [5]. The basis for this is the electric car Lada Ellada, produced in 2012 by AvtoVAZ in the amount of 100 pieces. The car was re-equipped with a hybrid power unit including a 24 kWh battery and a fuel cell battery. The fuel cell system with hydrogen cylinders occupies the entire trunk, which will not be approved by the consumer. This solution is unlikely to have a future. The reconfiguration will mean the development of a new car.
One of the promising segments for commercialization of hydrogen passenger cars is the taxi sector. For example, the European division of Toyota supplied 35 Mirai electric cars for the passenger transport company Noot Personenvervoer. Thus, in the Netherlands (The Hague) the first hydrogen taximotor park appeared [6]. Eco Taxi Deutschland GmbH in Wiesbaden has added two Hyundai ix35 FCEV on fuel cells to its park. Commercialization through the taxi segment is justified, as in the case of one owner it is easier to organize the operation of a new type of car, especially if the owner has the competence to service the car.

3. Trucks
Some truck manufacturers also have concepts working on HFCs (Hyundai, Mercedes-Benz, Ford, Skoda, Tata, Toyota). At this stage, manufacturers have not yet entered the stage of serial production and are conducting trial operation of the vehicles under development. The number of samples to be tested is calculated in tens in each case. At the same time, there is information about immediate plans for their wider deployment. For example, Norway aims to deploy 1,000 hydrogen fuel cell trucks by 2023.

The French project ROAD is testing a refrigerator on fuel cells. The project presented the world's first hydraulically driven refrigerated semi-trailer (coupled truck), which entered French roads for the first time on 4 July 2019 for testing [7].

Hydrospider intends to produce “green” hydrogen in Hessen, using hydroelectric power to supply the first 50 fuel-cell trucks for use on Swiss roads by 2025. The total planned number of trucks is 1600. Trucks will be produced by Hyundai Hydrogen Mobility, a joint venture between South Korean car manufacturer Hyundai Motor Company and H2 Energy [8].

The Singapore-based company Horizon Fuel Cell Technologies has signed a Memorandum of Understanding for the supply of 1,000 fuel cell batteries with a capacity of 100 kW or more (each battery) for heavy-duty trucks over the next three years, beginning in 2019. This is one of the largest deployments of heavy fuel cell vehicles in the world [9].

4. Forklifts and load carts
The most dynamic direction of fuel cell commercialization is loading and unloading equipment and machinery for moving cargoes in large logistics centers and warehouses. Such equipment includes 3- or 4-wheel forklifts or small load carts for transporting goods only horizontally. The power range of power units for this equipment is relatively small and amounts to 5-30 kW.

The first prototype of a forklift truck on a hydrogen fuel cell was created in 2000. In 2013 more than 4000 fuel cell forklift trucks were already used in the USA. In 2019, 23,000 forklifts were used. This segment is also developing in Europe and Japan.

Figure 3. Photo of forklift (a) and traction controlled cart (b).
The size of the fuel cell battery is almost identical to the size of the storage batteries. That's why HFCs can easily fit in the loader design.

The cost of a separate fuel cell forklift is higher than that of a battery-operated forklift. Economic efficiency is manifested when comparing the cost of maintaining the fleet of a certain number of units. An evaluation by the U.S. Department of Energy's National Renewable Energy Laboratory (note: evaluation was conducted in 2013) shows that with intensive operation (2-3 shifts per day, 6-7 days per week), the cost of maintaining 60 fuel cell loaders is lower than maintaining the same number of battery-powered loaders with comparable characteristics [10].

To fill the batteries of fuel cells with hydrogen, a hydrogen filling station shall be installed at the place of their use.

Advantages of fuel cell technology (as compared to batteries):
- filling time is 3-5 minutes;
- one refill provides a full shift (8-10 hours);
- longer service life than batteries (approximately twice as long);
- filling space is 75% smaller;
- 15% increase in productivity;
- power saving up to full fuel consumption;
- maintaining power at low temperatures (declared to -30 ºC), which is important when working in open space (at low temperatures, battery capacity drops by 50% or more);
- no risk of acid spill.

The use of forklifts is appropriate in large logistics centers, where the fleet of forklifts is relatively large.

In July, the famous American giant Walmart acquired 55 million shares of one of the pioneers of hydrogen energy - the company Plug Power, announcing plans to equip its 30 centers with hydrogen fuelling stations for loaders. Now 22 American Walmart centers are equipped with such filling stations. In April this year, Amazon.com also bought more than 50 million shares of Plug Power and began to equip its warehouses with hydrogen fuelling [11].

5. Buses

In recent years, the world has been actively developing prototypes and small-scale models of buses that use the energy unit based on fuel cells as the main source of energy for driving the engine and bus auxiliary systems.

The hydrogen bus H2 City Gold (Figure 4) was developed by two companies. Toyota, actively developing hydrogen engines, was responsible for the power plant, and the rest was done by the Portuguese company CaetanoBus, engaged in the design and manufacture of such equipment.

Geely brand subsidiary, New Energy Commercial Vehicle Group (GCV), Yuan Cheng, introduced its F12 hydrogen fuel cell city bus and the C11 rechargeable public transit bus. Both are zero emission vehicles, with the hydrogen bus being the first for Geely.

As for the bus Toyota SORA Fuel Cell Bus 4K 2 HD, the acronym SORA symbolizes the water cycle in nature: Sky, Ocean, River and Air. Compressed hydrogen is in 10 cylinders with a total capacity of 600 liters under pressure of 70 MPa in the front of the roof. Electricity is stored in nickel-metal hydride batteries, which are located on the roof, just behind the cylinders.

Xcelsior CHARGE H2. It goes up to 300 miles after refueling without recharging the onboard electricity. Fast filling time varies from 6-20 minutes (depending on the bus model and operating conditions). It is powered by Ballard fuel cells. Regenerative deceleration, which recharges the batteries and reduces power consumption, as well as extends the range of action.

Wrightbus Street deck FCEV. The bus works on fuel cell Ballard FCveloCity, Siemens transmission and traction battery with a capacity of 48 kW. The fuel cell system on Streetdeck FCEV is manufactured by Ballard Power Systems. Operating range is 200 miles and the extended storage option extends the range up to 265 miles. Filling the bus with hydrogen takes about 7 minutes.
6. Other examples

Abundance of scooters in the Asian region is a source of environmental pollution. In Taiwan, the company "APFCT" has successfully implemented a program of fuel cell scooters production. The Taiwanese Ministry of Economic Affairs has issued reliability and safety standards for hydrogen fuel cell motorcycles to regulate mass production of such vehicles. The park of 80 scooters was tested in Pindong County. Twenty scooters were meant for the local government, the remaining 60 were distributed among 17 hotels in Kenting National Park to provide visitors with rental. Each site is equipped with a point of replacement of hydrogen tanks. Company "APFCT" is working on a scooter project in Hawaii. Hawaii is 90% dependent on imported fuel, and vehicles using fuel derived from solar electrification are an attractive option [12].

7. Conclusion

The development of hydrogen transport in Europe is carried out within the framework of the European Hydrogen Road Map [13], which considers the structural transformation of the energy sector as a whole. According to the road map, transport makes a major contribution to climate change by emitting 32% of emissions CO₂ in the European Union. According to the scenario, the region should reduce CO₂ emissions from transport by 72% by 2050, which is approximately 82 Mt.. This requires a transition from hydrocarbon fuel to renewable energy sources, which not only requires the introduction of new energy units in vehicles, but also a fundamental change in the entire energy supply chain.

There are similar programs in the United States, Japan, China and the Republic of Korea.

Deployment of fuel-cell vehicles in the near future is the most attractive for commercial taxi- and truck fleets used within municipalities, where their advantages are most relevant and the obstacles to infrastructure are lower than in other segments. Commercialization of forklifts is already underway.

Intensive and continuous investment in R&D has made hydrogen transport technologies ready for implementation. Currently there are five models of fuel cell cars on the market, and another 25 models will be announced within the next five years. Some manufacturers announced mass production of trucks with fuel cells. Two of them announced their entry into the European market.

Fuel cell power plants appear on the railway, river and sea transport.

Leading companies have the necessary package of patented technologies both in the field of vehicles and filling stations. The leaders are Japan, USA, China, Europe and Republic of Korea.
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