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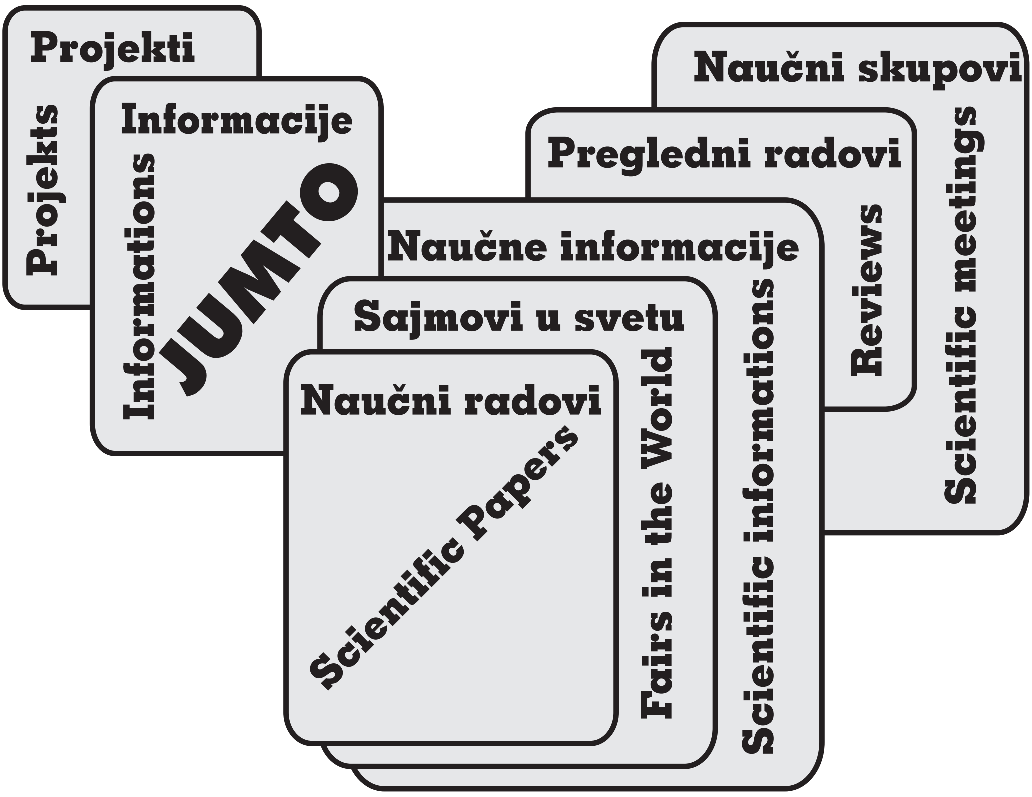

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Scientific paper

ANALIZA PRIMENE GORIVNIH ĆELIJA U BUDUĆNOSTI KAO ZAMENE ZA BATERIJE KOD TEŠKIH VOZILA

ANALYSIS OF THE APPLICATION OF FUEL CELLS IN THE FUTURE AS A SUBSTITUTE FOR BATTERIES IN HEAVY VEHICLES

Glišović J.,[1] Vasiljević S., [2] Lukić J.[3], Miloradović D.[4]

REZIME

Vodonik kao izvor goriva ima brojne prednosti koje pozicioniraju vozila sa gorivnim ćelijama kao potpuno održivu alternativu električnim vozilima. Neke od njih su brzo punjenje gorivom, veća gustina energije, skalabilnost za veća vozila, smanjeno opterećenje elektroenergetskih mreža, veći domet i korisnost nusproizvoda. Tehnologija vodoničnih gorivnih ćelija deluje posebno obećavajuće za upotrebu u teškim vozilima kao što su kamioni, autobusi, vozovi i čamci. Za ova vozila, gustina energije i brzina punjenja gorivom su kritične, a zahtevaju veliku količinu energije, što u slučaju električnih vozila znači upotrebu nepraktično velikih i teških baterija. Cilj ovog rada je da predstavi budući razvoj koji može ležati u kombinovanoj primeni vodonika, baterija i potencijalno neke treće tehnologije koja bi upotpunila raznovrstan energetski ekosistem, gde se različita tehnološka rešenja dopunjuju u globalnim naporima za smanjenje emisije štetnih gasova.

Ključne reči: Gorivne ćelije, vozila, električna, baterije, teška vozila.

SUMMARY

Hydrogen as a fuel source has numerous advantages that position fuel cell vehicles as a completely sustainable alternative to electric vehicles. Some of them are fast refuelling, higher energy density, scalability for larger vehicles, reduced load on power grids, longer range, and by-product utility. Hydrogen fuel cell technology appears particularly promising for use in heavy-duty vehicles such as trucks, buses, trains and boats. For these vehicles, energy density and refuelling speed are critical, and they require a large amount of energy, which in the case of electric vehicles means the use of impractically large and heavy batteries. The aim of this

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paper is to present the future development that may lie in the combined application of hydrogen, battery and potentially some third technology that would complete a diverse energy ecosystem, where different technological solutions complement each other in global efforts to reduce emissions of harmful gases.

Key words: Fuel cells, vehicle, electric, batteries, heavy vehicles.

INTRODUCTION

Just as in the early days of the automobile industry there was a battle between gasoline and diesel, so today we are witnessing a battle between battery electric cars and hydrogen fuel cell cars. One of the main advantages of hydrogen cars for long-distance driving is that the tank can be filled as quickly as in a vehicle that uses gasoline as a propellant. The owner does not have to worry about filling the car with hydrogen every day. Currently, an electric car takes at least 20 minutes to charge at a fast charging station. If the car is charged at home, using an ordinary socket, then charging can take several hours. This can be a real problem for those who drive long distances. Hydrogen cars have proven to be more efficient, lighter and faster. The heaviest part of an electric car is the battery. On the other hand, the hydrogen fuel cell system (including the hydrogen tank) is much lighter than the battery. This means that the electric motor in a hydrogen car does not use nearly as much power to push the weight of the vehicle. If you put the same engine in an electric car and a hydrogen car, it will turn out that the hydrogen car will have better acceleration and a higher top speed, because the engine has much less mass to drive.

Hydrogen is increasingly highlighting its candidacy to become the most realistic option to replace gasoline in internal combustion engines. Some manufacturers, such as Ford and Toyota, have patented their internal combustion engines that use hydrogen instead of gasoline. Such motors are much quieter in their operation. In addition, only water vapour comes out of the exhaust in this case. This would mean that the catalytic converter and other emissions systems become unnecessary when the car only emits water vapour. Due to the need for a large tank, the hydrogen engine has many disadvantages for use in passenger cars, as it takes up a lot of interior space.

While being a backbone of the European economy, the road freight sector is also responsible for a significant amount of CO_2 emissions. Reducing the carbon footprint of heavy-duty trucking is therefore key to achieving the EU's ambitious climate protection targets. Due to their high operational flexibility and relatively short refuelling time, FCH HDT (Fuel Cell and Hydrogen Heavy-Duty Trucks) are particularly suited for long-haul operations. FCH technology is a very promising zero-emission powertrain solution for the heavy-duty trucking industry. With scaled-up production of FCH trucks and hydrogen offered below 6 EUR/kg, FCH heavy-duty trucks (FCH HDT) provide the operational performance most comparable to diesel trucks regarding daily range, refuelling time, payload capacity and TCO (Total Cost of Ownership) [1].

As is displayed in Fig. 1, passenger cars dominate the global fleet of FCVs, amounting to 80% thereof. In other words, every four of five registered FCVs belong to the category of passenger cars. Buses make up the second highest share in the pie chart, with 9%. In total, both truck categories, namely heavy- and medium-duty, even have a higher share of 10% in total with 5% in each truck category. The light commercial vehicles only have a share of 1%. It should be noted here that in some countries, the numbers of light commercial vehicles are included in the figures for passenger cars. However, this detail does not change the general trend displayed in

Fig. 1.

The process of comparing alternative powertrains, presented in this paper, is complex and certain uncertainties should be considered. Technology adoption depends on different requirements in infrastructure, regional differences in regulations and incentives, varying customer preferences as well as the total cost of ownership. Overall, zero-emission powertrains for trucks have yet to reach full commercial readiness. Considering the lack of available truck products in the market, the key challenge remains the development of commercially competitive zero-emission heavy-duty trucks. From a technology competition standpoint, hydrogen and fuel cell technology competes against other heavy-duty road transport applications that are being pushed forward in parallel.

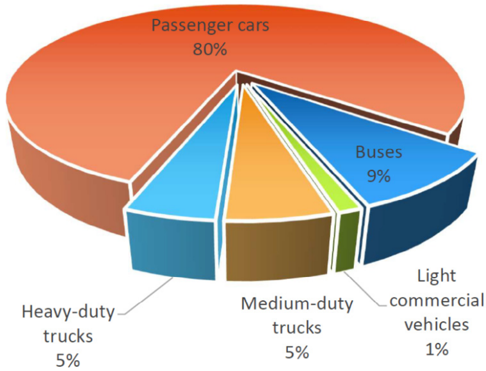

Fig. 1. Shares of different vehicle categories as of the end of 2022[2]

HYDROGEN USE IN ROAD TRANSPORT

The use of hydrogen as a means of decarbonising road transport continues to expand, increasing more quickly in 2023 (by around 55%) than in 2022 (around 40%) due, in particular, to growth in heavy fuel cell trucks and buses in China. In spite of this, hydrogen demand in road transport reached just 60 kt in 2023 (less than 0.1% of global demand). For decarbonisation, the hydrogen used must be low-emissions, although today hydrogen demand in transport is met with a variety of sources, including unabated fossil fuels (Fig.2).

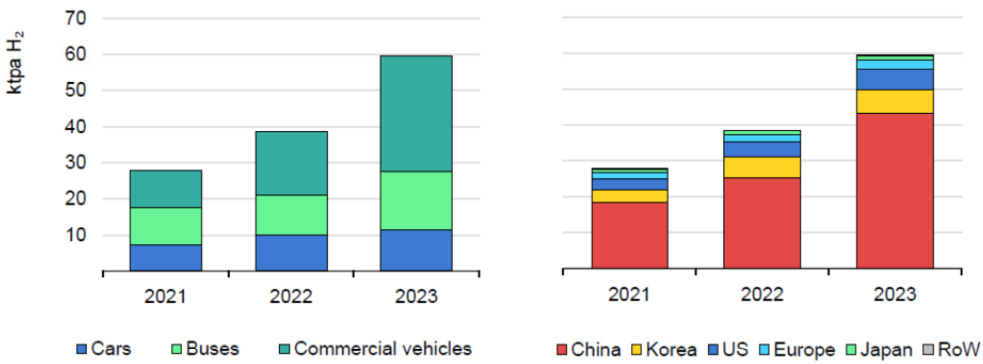

Fig. 2. Hydrogen consumption in road transport by vehicle segment and region, 2021-2023. RoW = Rest of World; US = United States. Commercial vehicles include light commercial vehicles and medium and heavy-duty trucks [3].

Fuel cell technology has versatile applications beyond passenger vehicles.

1. Public Transportation: Fuel cell-powered buses are already operating in several cities worldwide, offering a cleaner and quieter alternative to diesel buses.
2. Heavy-Duty Trucking: Fuel cells are suitable for longhaul trucking, providing longer range and faster refuelling compared to battery electric vehicles.

3. Speciality Vehicles: Fuel cells are used in various speciality vehicles, including airport movers, wheelchairs, unmanned vehicles, boats, small planes, submarines, and small military vehicles [4].

Hydrogen use in road transport increased by around 55% in 2023, with heavy-duty vehicles accounting for almost 85% of this growth. In China, fuel cell electric vehicle (FCEV) deployment has focused on heavy-duty vehicles, which have relatively high mileages, meaning that in 2023, consumption of hydrogen for road transport grew almost twice as fast as in the United States, and over three times as fast as in Europe. In Korea and Japan, the light-duty vehicle segment continues to be a focus for FCEVs, although growth in this segment is slowing down, and hydrogen use in road transport in these countries reached only around 7 kt combined in 2023. Growth in fuel cell passenger car stock slowed significantly in the past year, falling from more than 35% in 2022 to just under 15% in 2023, with slow sales continuing into the first half of 2024. In contrast, healthier sales in fuel cell buses and trucks increased the stock by 25% and more than 50%, respectively, between 2022 and 2023. The total stock of FCEVs across all road modes, as of the end of June 2024, stands at around 93 000 (Fig.3).

Trucks

According to global industry analysis, the size of the HD FCEV (heavy-duty fuel cell electric vehicle) and BEV (battery electric vehicles) market is expected to have a notable compound annual growth rate of 41% from 2022 to 2030 (USD 43.7 billion). Presently, FCEV and BEV trucks deploy newly developed innovative technology built using SiC-based power electronics, embedded energy and thermal management strategies, advanced proton exchange membrane fuel cells, supercapacitors and Li-ion batteries. Replacing conventional HD trucks with their FCEV counterparts will require establishing new hydrogen production and refuelling infrastructure, leading to increased electricity consumption if electrolysis is used to produce the fuel. Assuming that new H_2 production infrastructure is built considering focused as well as decentralised renewable energy sources and used to power the electrolysers, current fuel cell HDVs have a higher technical potential over battery electric trucks because of their longer range, fast refuelling and higher payload capacity [5].

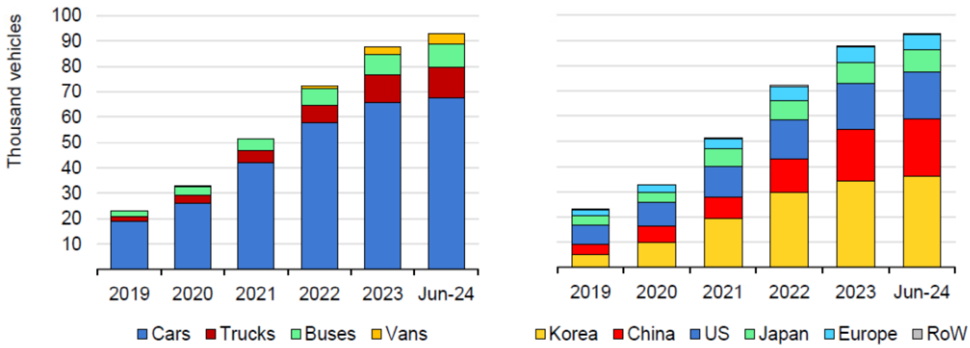

Fig. 3. Fuel cell electric vehicle stock by segment and region, 2019-2024. RoW = Rest of World; US = United States. Commercial vehicles include light commercial vehicles (LCV), medium freight trucks and heavy freight trucks. Includes data until June 2024 [3].

Growth in FCEVs was strongest in the truck segment for the second year in a row. Trucks are the fastest-growing sector for fuel cell vehicles, with the stock increasing by over 50% in 2023, more than twice as fast as buses, and three times faster than cars. As of June 2024, the global stock stands at more than 12 000, but – as in 2022 – around 95% of these are in China. Nevertheless, this should not hide the substantial growth seen in both the United States and Europe, albeit from a lower base. By the end of 2022 there were around 135 fuel cell trucks in Europe, but that had increased to around 350 as of June 2024. In the United States, over the same period, fuel cell trucks increased from just 10 to around 170. The share of trucks in the global FCEV fleet has therefore risen from less than 9% in 2021 to almost 13% as of June 2024.

Commercial trials to prove the technology and gather data on performance in different use cases are being undertaken around the world, including in the United Kingdom, New Zealand and Saudi Arabia. There have also been new commitments to the technology in the United States, for example through orders for Nikola's fuel cell truck, which officially entered the market in 2023, with 35 units delivered in 2023. An order has been placed for a further 100 trucks in 2025, contributing to the growing hydrogen hub at the Port of Los Angeles, as well as another 50 trucks ordered by a haulier that deemed battery electric trucks insufficient for their needs after an almost 2-year-long trial. Despite this positive news, Nikola still faces considerable headwinds, having incurred losses of almost USD 1 billion in 2023. Another fuel cell truck maker from the United States, Hyzon, have halted their operations in Europe and Australia, in part due to having accumulated losses of over USD 275 million. This decision can, at least in part, be attributed to lower-than-expected demand following the cancellation of purchase announcements, such as by Glasgow City Council (United Kingdom).

Innovations to fuel cell trucking are still being made, such as through a hydrogenelectric hybrid system in which the fuel cell acts as a range extender, thereby making the powertrain technology suitable for a larger share of duty cycles. Elsewhere, Daimler and Linde have jointly developed a novel liquefied hydrogen refuelling process aimed at providing ranges of more than 1 000 km, which is now being deployed in Germany. The two companies also aim to support the establishment of a common refuelling standard for liquid refuelling, to enable commercial use of the technology. The use of hydrogen combustion engines in trucks may also support emissions reductions compared to conventional diesel trucks. MAN is due to launch such trucks in 2025, and Volvo Trucks will begin testing in 2026. This technology may have a particular role to play in the medium term, while fuel cells continue to face challenges such as high costs, lower durability in difficult operating conditions, and uncertainty around the availability of skilled technicians and spare parts.

Model availability is an important factor in increasing deployment of fuel cell trucks, particularly in the short to medium term, so as to offer customers choice and options suited to their needs, and model options are expanding around the world (Fig. 4). However, given that China has the highest sales of trucks, but a smaller number of models available than North America, it is also clear that policy – and not just model availability – is influencing uptake. Europe has fewer models available than North America or China, though new additions are being announced, such as by Symbio (expected in late 2025). Partnerships between Honda and Isuzu, and Quantron and Ford, are also expected to add to model availability in the coming years. Retrofitting of existing trucks, where the diesel engine is replaced with an electric fuel cell powertrain, can also increase vehicle availability. H2X Global, who specialise in retrofitting, have announced the development of both a smaller 3.5 t truck as well as trucks in the range of 16 t to 44 t in 2024.

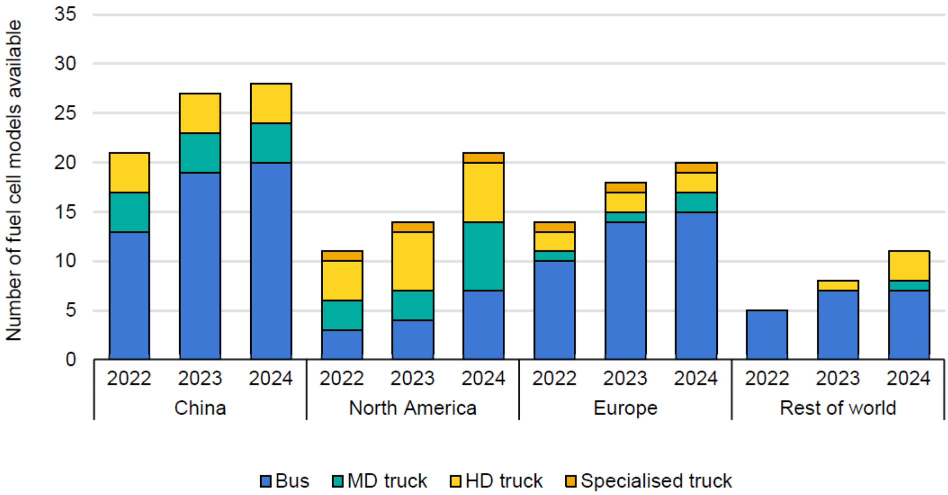

Fig. 4. Fuel cell electric vehicle models by original equipment manufacturer headquarters, type of vehicle, and release date, 2022-2024. MD = medium-duty; HD = heavy-duty [3].

In the context of evaluating the complementarity between hydrogen-electric and battery-electric vehicles, the mileage and energy consumption thresholds of the vehicles can help determine the most suitable solution, as illustrated below. Thus, battery-electric technology is well-suited for the majority of urban delivery vehicles, which typically cover less than 80,000 km per year. Beyond this threshold, particularly for the segment of heavy-duty regional distribution, hydrogen-electric technology is particularly relevant and becomes the primary zero-emission alternative for annual mileages estimated at 100,000 to 150,000 km (as shown in Fig. 5). Hydrogen-electric technology is also particularly well-suited when vehicles have high energy consumption due to auxiliary systems, such as refrigerated compartments.

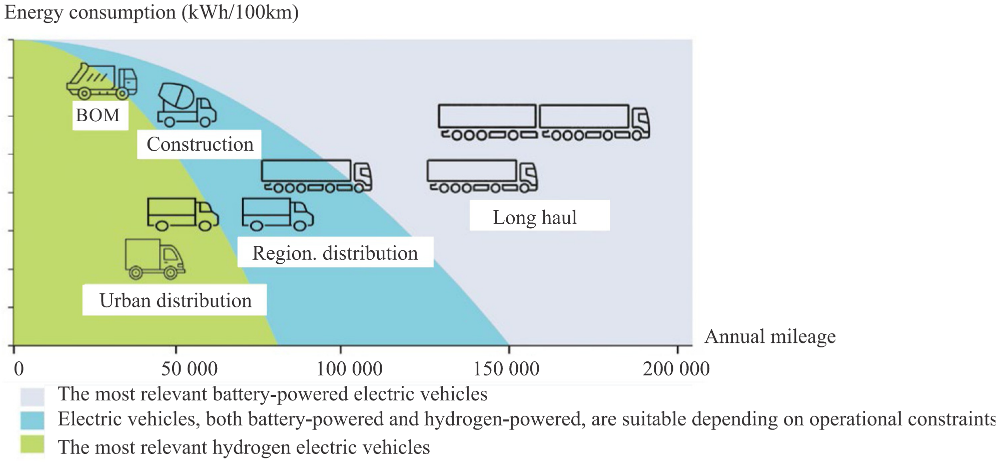

Fig. 5. Complementary nature of battery-electric and hydrogen-electric solutions, depending on the vehicle's annual mileage and energy consumption.

Buses

Fuel cell bus stock increased by almost 25% in 2023 compared to 2022. China again accounted for the majority of new additions, deploying over 75% of the more than 1 500 fuel cell buses added in 2023, thereby constituting a similar share of the global stock of more than 9 100 fuel cell buses as of June 2024. In terms of year-on-year stock growth, Europe and Japan have similar rates to China, between 20% and 25%, while Korea experienced an annual growth rate of 130%. Similarly to trucks, fuel cell buses continue to be trialled, often alongside battery electric models. Many European cities have taken delivery of or placed orders for fuel cell buses, such as Barcelona (Spain), Bologna (Italy), Cottbus and Oberberg (Germany), Paris (France) and Wałbrzych (Poland). Several German cities that already have fuel cell buses in operation, such as Frankfurt and Cologne, among others, have opted to expand their fleets. In Duisburg (Germany), a previous decision to use battery electric was reversed in favour of fuel cell buses, with cost being cited as a deciding factor. The city of Cheonan, Korea, will deploy 350 fuel cell buses and the necessary refuelling infrastructure by 2027, through a partnership with SK E&S, expanding on the Incheon fleet announced last year. Both will be supplied by SK E&S's plant which liquefies by-product hydrogen for use in transport. However, there have also been several high-profile incidences of cities ending trials or retiring existing fleets, citing issues of reliability and cost. Examples include Montpellier and Pau in France, Carinthia in Austria, and Wiesbaden in Germany.

Key to the increasing sales of fuel cell buses is sufficient availability. In Europe, companies such as Solaris and Wrightbus are expanding production. In Korea, Hyundai has expanded its capacity from 500 to 3 000 units per year in order to keep pace with deployment. In North America, NFI Group are signing fuel cell supply agreements to capitalise on emerging demand. However, by far the largest range of models (and variations thereof) are being produced by a relatively small number of Chinese OEMs, in order to supply both their large domestic market and growing overseas markets, such as Australia. Hydrogen retrofits also have a role to play, as demonstrated by Green Corp, who are installing their technology in 50 coaches in France, in a segment often deemed difficult to electrify. Finally, the continued introduction of hydrogen range extenders for buses can enable the decarbonisation of routes currently deemed unsuitable for battery electric buses, and demonstrates the potential to combine the two technologies.

FUTURE DEVELOPMENT OF FUEL CELL ELECTRIC VEHICLES

Fuel cell electric vehicles (FCEVs), should be considered an additional technology that will help battery-powered vehicles to reach the aspirational goal of zero-emissions electric mobility, particularly in situations where the customers demand for longer driving ranges and where using batteries would be insufficient due to bulky battery trays and time-consuming recharging [6].

Fuel cells are often combined with other auxiliary energy sources to form a hybrid system to supply energy to hybrid electric vehicles. These auxiliary power sources are batteries, ultracapacitors (UCs), superconducting magnetic energy storage (SMES), solar photovoltaics (SPVs), and flywheels.

Tab. 1. Summary of common FCHEVs' topologies. [7]

Topological Classifications	Main Advantages	Main Disadvantages
Fully FCEV	Simple structure Easy to implement control strategies	Unable to recover energy
FC + Battery hybridization	High energy density(battery) Ability to recover energy	Slow dynamic response
FC + UC hybridization	Fast dynamic response Ability to recover energy	UC is more expensive than battery Low energy density(UC)
FC + battery + UC hybridization	High energy density(battery) Fast dynamic response(UC) Ability to recover energy	Control strategies are complex and difficult to implement

Fuel cell hybrid vehicles usually use fuel cells as the main power source and are equipped with batteries or ultracapacitors as auxiliary energy sources. The working conditions of automobiles driving on the road are very complex. They often face various emergencies, and the required power demand will also have large fluctuations and sudden changes. However, if only fuel cells are used as the energy source, the output of large fluctuations in power can reduce the life of the fuel cell. Therefore, the role of the auxiliary energy source is necessary. Batteries and ultracapacitors can play good roles in auxiliary energy sources. Batteries can recover excess energy and provide power to the system simultaneously with fuel cells when the load demand power is high. The ultracapacitor has the characteristics of a fast dynamic response, fast energy recovery, and high specific power, which can play the role of a timely response in the face of rapid changes in load demand. At present, there are three main system structures of fuel cell hybrid vehicles. The first type is a hybrid system composed of fuel cells and batteries. The second is a hybrid system composed of fuel cells and ultracapacitors. The final type is a hybrid system composed of fuel cells, batteries, and ultracapacitors. The power system structure has been studied and analysed for different types of fuel cell hybrid vehicles [7].

HYDROGEN STRATEGY OF THE REPUBLIC OF SERBIA IN ROAD TRANSPORT

In accordance with the expected development of technologies for its production, it is predicted that the production of green hydrogen could begin in 2025, that in 2035 its production could use 0.5 to 3%, and in 2050 between 2 and 8% of the total electricity produced in Serbia.

Tab. 2. Energy production in 2021 and potential production of green hydrogen by water electrolysis [8].

Type of RES	Production in 2021 (Mten)	Hydrogen (ton)
Solid biomass	1,192	-
Biogas	0,018	-
Total hydropower	0,832	-
HPP without reversible	0,733	-
Small HPP	0,028	-
Solar photovoltaic	0.001	2200
Wind energy	0,093	20600
Total	2,065	22800

Solar and wind energy are the main national potential energy sources for the production of green hydrogen. For the following analysis, the document "Energy Balance of the Republic of Serbia for 2021" ("Official Gazette of the Republic of Serbia", No. 156/2020) was used, which states (quoted): "The total planned production of primary energy from renewable energy sources in 2021 is 2.063 Mtoe. The planned use of solar energy in 2021 is 13 GWh, 0.0011 Mtoe. The planned use of wind energy in 2021 is 1077 GWh or 0.0926 Mtoe". Based on the above, the quantities of hydrogen produced based on water electrolysis are shown, Table 2. As can be seen from Table 2, if all available wind and solar PV capacity were used to produce green hydrogen, the total amount would be around ~23,000 tons of hydrogen per year.

The use of hydrogen in internal combustion engines (ICEs) is not fundamentally different from the use of fossil fuels and it is possible in principle to use existing engines. A serious problem is the tendency for flame drag, which some engine manufacturers have been dealing with for some time. A minor increase in nitrogen oxide emissions and low CO_2 emissions can be expected as a possible environmentally unfavourable effect. In recent years, several car manufacturers have been intensively developing ICEs that use hydrogen as fuel. Unlike piston engine manufacturers, gas turbine manufacturers have gone a step further and have already adapted and commercialised some of their gas turbines for the use of hydrogen, both for the production of electricity and for the combined production of electricity and heat. There are commercialised gas turbines that also use 100% hydrogen as fuel. Serbia needs to define its policy towards hydrogen energy, prepare appropriate infrastructure for storage, transport and distribution of hydrogen, pumping stations, legal acts, standards, regulations, educate and train engineers and technical staff to work in hydrogen energy technologies. In order to competently monitor the situation and make optimal solutions related to hydrogen, Serbia needs momentum in the field of research and application of hydrogen and galvanic fuel cells, in order to generate a scientific, research and expert knowledge base, which would allow it to keep pace with the EU countries and the world. Insufficient knowledge and experience in the field of hydrogen energy transition can have serious consequences for the national economy and energy sector.

As a first step towards decarbonization, Serbia should consider the use of hydrogen in transport, primarily in public transport and transportation. Serbia should also consider the construction of gas-fired combined heat and power plants as a transitional solution for the production of electricity and heat. Of particular interest are the possibilities of plants based on gas turbines with multi-fuel properties, which, in addition to gaseous fuels, including 100% hydrogen, also use liquid fuels. The possibility of choosing more fuels, their storage, significantly contributes to the security of the national energy sector. It should always be borne in mind that it is possible to introduce up to 30% hydrogen into natural gas and use it in existing combustion plants, with appropriate modifications.

For transport needs, as a first step towards the practical application of hydrogen in our country, it can be estimated that by 2030 the needs will amount to 2,000 tons of hydrogen per year, for which about 10% of the current wind energy capacities will be sufficient. If natural gas is accepted as a transitional solution at the EU level as a green investment, it is pragmatic to think about hydrogen production by reforming natural gas, for which Serbia has extensive experience and capacities. Serbia should carefully monitor EU policy and make decisions that are in the national interest [8].

CONCLUSION

Fuel cell heavy-duty trucks (FCH) show substantial market potential, as they are one of the most promising zero-emission alternatives for trucking. Industrial-scale production, affordable green hydrogen and the build-up of the associated hydrogen-refuelling infrastructure are deemed to be key elements for FCH technology uptake. More importantly, achieving a high sales share of zero-emission solutions in the early 2030s is crucial to phase out the majority of diesel-powered trucks over their lifetime by 2050. The study shows that fuel cell and hydrogen technologies and applications are pivotal for a carbon-neutral future of the heavy-duty trucking and logistics industry. A concerted political and industrial push by a broad coalition of industry and public stakeholders is needed to deliver on this breakthrough moment. By transitioning to FCH heavy-duty trucks in the upcoming years, the trucking industry will achieve the competitive, clean, quiet and innovative mobility solutions in line with the EU's ambitious climate protection efforts and emission reduction targets.

Given that there is currently no use of hydrogen in transport in the Republic of Serbia, in order to achieve the share of hydrogen estimated by the Energy Community, it is necessary to overcome the barriers, which are primarily the introduction of legal regulations, the establishment of supporting infrastructure, as well as the economic aspect of introducing hydrogen-powered vehicles.

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