DOI: 10.7251/JTTTP2402124M
UDC: 656.073:656.121.072

PRELIMINARY REPORT

Application of Fuel Cell and Green Hydrogen Technology in Buses for Public Urban Transport Passengers

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Received: May 31, 2024
Accepted: September 23, 2024

Abstract: The system of public urban passenger transport is one of the most important functions of any city. The bus subsystem is still the most prevalent in most cities of the world. In addition to the proven advantages in use, the main demands placed on the bus subsystem are environmental suitability and neutrality, through the increasing use of buses with zero and low emission of harmful exhaust gases. Fuel cell-powered buses using green hydrogen are currently a technology with great potential with the goal of completely decarbonizing carbon dioxide (CO_2) emissions originating from the bus subsystem. The paper will present the basic characteristics of fuel cell buses, legal frameworks for application in the countries of the European Union, and experiences in the application of this drive concept in some cities.

Keywords: Fuel cell buses, green hydrogen, public urban passenger transport.

INTRODUCTION

The public urban passenger transport system is one of any city's most important functions. Buses powered by diesel fuel and compressed natural gas (CNG) are still the most prevalent driving system in most cities of the world but with a constant trend of decreasing representation and their substitution with buses with zero emissions of harmful gases, which are electrically powered buses and buses powered by hydrogen H_2 using fuel cell technology. According to UITP data, in 2018 the share of diesel-powered buses in sales was around 80% [1], and in 2023 their share would be below 40% [2].

Seen from the aspect of environmental performance, diesel-powered buses had a constant trend of refinement and improvement, as the requirements through the EURO norms were increasing (especially pronounced in the first 20 years of the 21st century). Public city transport buses powered by compressed natural gas (CNG) have been present in many cities worldwide for many years, thus becoming a proven alternative to diesel-powered buses.

Their mass use, primarily in EU cities (Madrid, Barcelona, Rome, Turin, Nantes, Bordeaux, Porto, The Hague, Malmö, Ninberg, Seville, Florence, Ljubljana, Zagreb...) was recorded in the period from 1992 to 2015, as one of the effective solutions for reducing the emission of harmful exhaust gases from vehicles and savings in exploitation costs.

After 2015, there was a noticeable stagnation in the mass use of CNG buses in public city transport systems as a result of the appearance on the market of buses with hybrid (diesel-electric) drive, and then fully electric buses (E-bus). In the last two years, buses powered by hydrogen H2 using fuel cell technology have become increasingly common. The Buses powered by fuel cells according to EU Directive 2019/1161, which entered into force in August 2021, are categorized as vehicles with zero emission of harmful gases and, together with electric buses, represent an application strategy with the aim of substitution of diesel-powered buses, so that from 2033, zero-emission buses (E-bus, fuel cells) should have absolute primacy in use in the public urban transport system of cities.

According to the aforementioned Directive, all EU member states must, according to the prescribed quota, have a representation of buses with low and zero emissions when purchasing new buses. For the period until 31.12.2025. year, the most developed countries of the EU (Germany, the Netherlands, Sweden...) must have a total participation in the procurement of new buses with low and zero emissions 44% of which 22% must be buses with zero emissions. EU member states that are less economically developed (Bulgaria, Romania, Croatia) have a set quota for the participation of buses with low and zero emissions between 28% and 32% [3].

Tendencies of increasing use of buses with zero and low emission of harmful exhaust gases are shown through the number of newly registered buses for public city transport for EU 27 countries, including Norway, Iceland and Switzerland in 2023: 6,354 buses with electric drive, 4,022 buses with hybrid (diesel-electric drive), 2,883 CNG-powered buses and 181 hydrogen-powered (fuel cell) buses, while the number of newly registered diesel-powered buses is 6,570 [2].

It is also important to mention the EU Directive 2014/94 [4], which refers to the use of alternative fuels in the transport sector, namely: Electricity, natural gas, biomethane, biofuels, hydrogen, synthetic diesel, liquefied petroleum gas, which should reduce the use of fossil fuels (diesel, gasoline) in the transport sector, where the share of the use of hydrogen as an energy source in the so-called energy mix in the transport sector is defined for each EU country.

It is known that hydrogen as a chemical element does not exist freely in nature, but it is present in the largest number of compounds. Its presence in water gives it the character of an alternative fuel with inexhaustible reserves. Industrial production of hydrogen H_2 is possible in two ways [5].

- Through the process of electrolysis of water, $H_2O = H_2 + ½ O_2$, Anode: $2OH = ½ O_2 + 2 H_2O + 2 e-$, Cathode: $2 H_2O + 2 e- = H_2 + 2 OH$.
- Through the process of carbon-hydrogen reformation (most often natural gas-methane),
- $CH4 + H_2O = CO + 3 H_2$

In both cases, it is necessary to provide a large amount of electricity for the production process. The question arises as to how to obtain the electricity that is used in the production of hydrogen. If electricity obtained from thermal power plants where the primary energy source is coal is used, as a result, we have large amounts of carbon dioxide CO2 produced in the process of burning coal, which hurts the occurrence of the greenhouse effect and climate change.

The way electricity is produced and transmitted is of essential importance when analyzing the environmental performance impacts of electric buses on a regional or national level, i.e. analysis from «well to wheel», WTW (Well to Wheel). The analysis of WTW carbon dioxide emissions is important to understand and compare the emission levels emitted by buses with different propulsion systems, including fuel cell buses.

The aspect of carbon dioxide emission that occurs during the electricity production phase is particularly important, given that electricity is obtained from different sources, which can be represented by the value of the standard factor of the total carbon dioxide emission expressed in gCO2eq/kWh. The values of the gCO2eq/kWh factor for European countries in 2019 are shown in Figure 1 [6].

Countries with a greater share of renewable sources such as hydro power plants, wind parks, and solar power plants have a significantly lower value of CO_2 emissions (Iceland, Sweden, Norway...) than countries where electricity production is primarily from coal (Poland, Greece, Serbia), BiH...). Only the use of electricity obtained from completely renewable sources (hydropower plants, wind parks, solar power plants) for the production of hydrogen by the electrolysis process, which will be used for vehicles with fuel cells, is a sustainable solution to decarbonize transport. The hydrogen obtained in this way represents "green hydrogen". Figure 2 shows the production, storage, and distribution of green hydrogen.

The green hydrogen produced in this way has the full effects of application in the transport sector: It is completely ecologically suitable due to zero CO_2 emissions, the dependence on the use of fossil fuels is reduced, and it promotes the development and implementation of innovative technologies. A typical plant (electrolyzer) for the production of green hydrogen where electricity is obtained from photovoltaic panels with an installed capacity of 2 MW has a production of 18 kg H2/h and storage tanks of 1,013 kg, which is enough to serve a fleet of 10 fuel-cells buses.

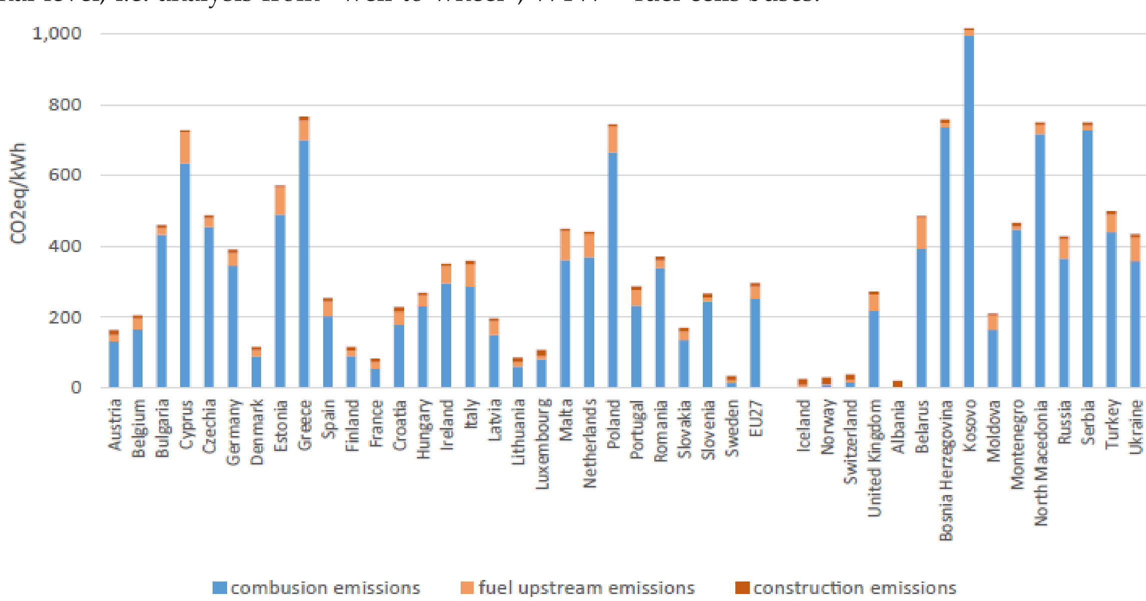

Figure 1. Total CO_2 emission (gCO2eq/kWh) in the process of electricity production in European countries

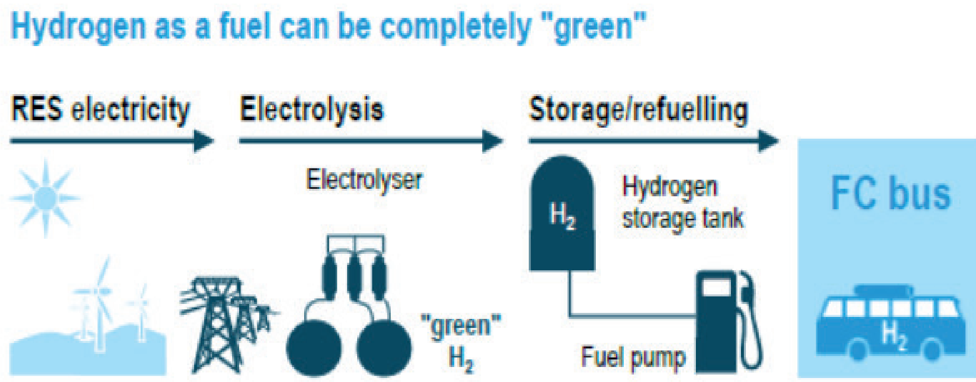

Figure 2. The way of producing, storing and distributing green hydrogen

Such a facility with a complete charging infrastructure costs around 10.7 million Euros [7]. Figures 3 and 4 show a hydrogen production facility (electrolyzer) and a hydrogen bus filling station in South Tyrol (Italy) [8].

Figure 3. Hydrogen production plant (electrolyzer)

Figure 4. Basic components of a fuel cell bus

FUEL CELL ELECTRIC BUSES

Buses powered by fuel cells, FCEB (Fuel Cell Electric Bus) use hydrogen (H_2) stored in tanks and oxygen (O2) from the atmosphere to generate electricity that is generated through an electrochemical process and which is accumulated in batteries. This type of vehicle drive is a possible solution to the global energy problem because it uses hydrogen (H_2), which is found in nature primarily in water in unlimited quantities.

The main advantage of using this type of drive is that there are no emissions of harmful substances in the process of obtaining electricity, so this bus concept has zero impact on the environment. The presentation of the basic components of a bus powered by fuel cells is shown in Figure 5, and Figure 6 shows the principle of operation of a fuel cell [9].

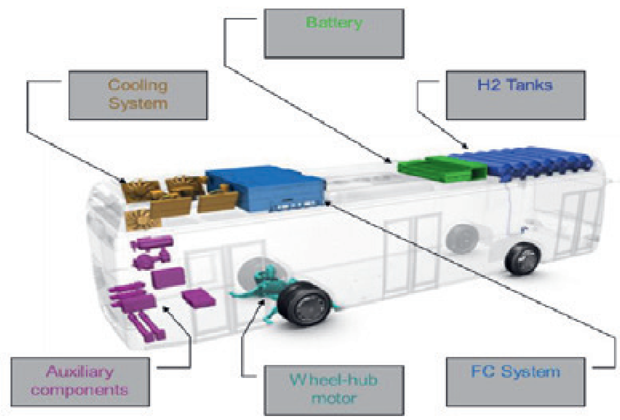

Figure 5. Basic components of a fuel cell bus

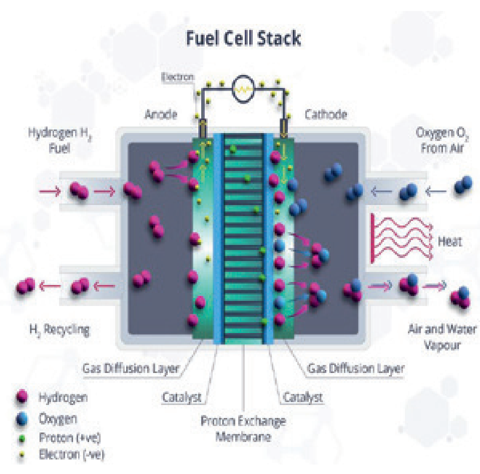

Figure 6. The principle of operation of the fuel cell

Hydrogen is stored in special tanks under a pressure of 350 bar, which are located on the roof of the vehicle. After reducing the pressure to an operating pressure of 8 bar, the hydrogen is delivered to the fuel cell module. The two modules consist of several fuel units (cells) that are interconnected. Each cell separately represents one current source. In the fuel cell module, oxygen

Figure 7. Caetano H2 City gold

Table 1. Technical characteristics of the Caetano H2

Type: Caetano H2 City Gold
Tank capacity H_2: 37,5 kg
Pressure in tanks: 350 bar
Toyota Fuel cell system: 70 kW
Capacity of Li-battery: 44-80 kWh
Charging time: max 10 min
Drive system: Siemens, PM, 180 kW
Consumption H_2 : 7-9 kg/100km
Autonomy of movement: 400-500 km
Price H_2: 6 €/kg
Pass.capacity: 87 passengers
Availability: > 95 %

(O_2) is taken from the air and also injected into the module. Each fuel cell has an anode and a cathode, as well as a catalytic membrane. By bringing hydrogen (H2) and oxygen (O_2) molecules into the cell, electrons between the anode and cathode establish a circuit, while free protons passing through the catalytic membrane bind to oxygen molecules to which a part of the electron from the cathode is added, thus making water (H_2O) and heat as a byproduct of the reaction. Cooling of the module and ensuring the working temperature of 70÷80 is done through the cooling system.

The current produced in the cells is collected in high-capacity lithium batteries, after which it is inverted into alternating three-phase current, with a voltage of 500÷900 V and a frequency of 400 Hz. The current obtained in this way starts the drive electric motor whose torque is transmitted to the automatic transmission and further to the drive wheels [9]. Figure 7 shows a bus powered by fuel cells manufactured by Caetano-Toyota, where 8 buses are in regular operation in Barcelona. Table 1 shows the techno-exploitation indicators [10].

Buses powered by fuel cells have an increasing tendency to be used in EU and UK cities. Table 2 shows the number of buses in use by year [11, 12].

Table 2. Number of fuel cell buses in European Union and United Kingdom cities

Year	Number of FC buses in EU and UK cities
2017	50
2020	115
2023	370
2025	1200

According to the UITP the share of buses powered by fuel cells in the sale of new buses on the EU market will have a constant upward trend. Thus, in 2025, it will amount to about 7.4%, while in 2030, the share will increase to 12.5%, which can be seen in Figure 8 [13].

Buses powered by fuel cells are produced and marketed by almost all leading manufacturers of city transport buses: Solaris bus, Mercedes, VDL, Skoda, Van Hool, Caetano bus, Rampini, Safra, Wright bus, Alex-

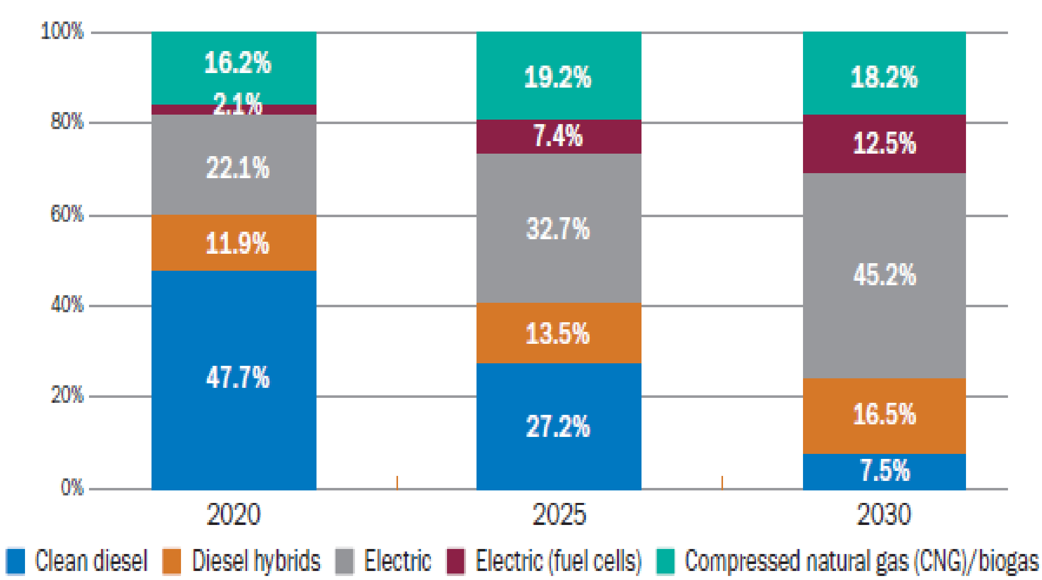

Figure 8. Representation of buses for city transport by drive systems on sale in EU

ander Denis. One of the measures to encourage larger purchases is the limited maximum price of buses with a standard length of 12 meters in the European Union, which is around 625,000-650,000 € [11,14].

DEMO PROJECTS WITH FUEL CELL BUSES

The potential of using this type of drive as completely environmentally friendly was recognized earlier, and the first demonstration projects were realized at the beginning of the 21st century. The CUTE (Clean Urban Transport for Europe) project was particularly significant and resulted from the initiative of the EU Commission for Energy and Transport in cooperation with Daimler Chrysler - Evobus [15]. The main goal of the project was to review the technical, technological, ecological, and economic aspects of using fuel cell technology in public transport vehicles. The project lasted in the period 2001-2006. year and included over 40 participants (vehicle manufacturers, hydrogen companies, refueling companies, public transport operators, scientific institutes, universities, etc.).

Based on the criteria related to the experimental use of buses (climate, geometric characteristics of the routes, lines passing through the central city area), hydrogen production, and distribution systems, 9 EU cities were selected (Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm, Stuttgart). Subsequently, Reykjavik (Iceland) and Perth (Australia) were included in the STEP (Sustainable Transport Energy for Perth) project. Since July 2006, Beijing (China) has also joined this project.

Projects where the possibilities of using buses powered by fuel cells in public city transport systems were considered, so far had several phases, depending on the number of cities that took part and the defined periods in which the techno-economic analyses were considered. The most important projects are:

- CUTE / Clean Urban Transport for Europe, 2001-2006. year
- ECTOS / Ecological City Transport System, 2001-2006. year
- STEP / Sustainable Transport Energy for Perth, 2004-2007. year
- Hy Fleet-CUTE / Hydrogen fleet for Clean Urban Transport for Europe, 2006-2009. year
- CHIC / Clean Hydrogen in European Cities Project, 2010-2017. year

Projects JIVE/JIVE2 (Joint Initiative for hydrogen Vehicles across Europe)

The JIVE/JIVE2 project is the most important project of the European Union to introduce fuel cell buses and infrastructure for the production of green hydrogen in EU cities as much as possible. The project started in 2017 and brought together 19 cities from the EU and the United Kingdom to start the permanent and mass use of fuel-cell buses.

The JIVE/JIVE2 project provides financial support to participating cities for the purchase of vehicles and the construction of infrastructure. All the biggest manufacturers of this type of bus (Solaris bus, VDL, Van Hool, Caetano bus,...) and equipment Siemens energy, Ballard, Shell..., are included. Table 3 shows the cities included in the JIVE/JIVE2 project [16].

Table 3. Cities participating in the JIVE/JIVE2 project

Projects JIVE/JIVE2 City, Region	Number of FC buses
Aberdeen, UK	21
Auxerre, France	5
Barcelona, Spain	8
Birmingham, UK	20
Brighton, UK	22
Charleroi, Belgium	10
Cologne, Germany	50
Dundee, UK	12
Emmen, The Netherlands	10
Gelderland, The Netherlands	10
Groningen, The Netherlands	20
London, UK	20
Pau, France	5
Rhein Main, Germany	10
South Holland, The Netherlands	20
South Tyrol, Italy	12
Toulouse, France	5
Velenje, Slovenia	6
Wuppertal, Germany	20

From the table it can be seen that in the mentioned cities the most common number of vehicles in the fleet is between 10 and 20, the exception being Cologne (Germany) where 50 buses with fuel cells are in operation, which represents the largest fleet in Europe.

CONCLUSION

The introduction of hydrogen-powered buses using fuel cell technology is one of the most effective strategies that should contribute to the reduction of harmful gas and carbon dioxide emissions from public urban transport vehicles in cities. The use of green hydrogen as completely carbon neutral is an additional quality of this drive concept compared to electric buses that take electricity for charging from the public distribution network whose production method comes from fossil fuels.

The introduction of buses powered by fuel cells in the cities of the European Union has a constant trend of growth and for now, it is present only in the most developed cities/regions. It is expected that in the coming period, the number of buses powered by fuel cells will be even higher. The limiting factors for more mass use, above all in countries with less economic power, are the high investment costs of building hydrogen production facilities, the still significantly higher price of buses compared to conventionally driven buses, high safety standards, specific maintenance, training, etc.

REFERENCES

[1] UITP: Large-Scale Bus Electrification, The impact on business model, 2021.

[2] Sustainable Bus: https://www.sustainable-bus.com, European E-bus market 2023, pristupljeno sajtu 14.02.2024.godine.

[3] Directive (EU) 2019/1161 of the European Parliament and of the Council of 20 June 2019.

[4] Directive 94/2014/EC: *On the deployment of alternative fuels infrastructure*, 22 October 2014, L 307/1.

[5] Wuppertal Institut: Shell Wasserstoff-Studie Energie der Zukunft-Nachhaltige Mobilitat durch Brennstoffzelle und H2, Hamburg, 2017.

[6] Scarlat, N., Prussi, M., Padella, M., 2022, *Quantification of the carbon intensity of electric production and used in Europe, Applied Energy* 305 117901, pp.1-15, https://doi.org/10.1016/j.apenergy.2021.117801

[7] Sanchez,G,F., Municipal Transport Company of Madrid-EMT Madrid, UITP Bus Division Meeting, Madrid, 20 October 2022.

[8] Piffer Petra, Zero Emission public transport, Project SASA, 2021

[9] Мишановић, С., Енергетске и еколошке перформансе аутобуса на електрични погон у систему транспорта путника, докторска дисертација, Факултет инжењерских наука Универзитета у Крагујевцу, 2021.

[10] Transports Metropolitans de Barcelona: Hydrogen in TMB-Apuesta de la red de Autobuses de TMB por las energias , 2022.

[11] Boillot Lionel: Hydrogen buses-their time is now, Fuel cells and Hydrogen Joint Undertaking, 2021.

[12] Sustainable Bus: https://www.sustainable-bus.com, Fuel cell projects in the spotlight: fleets,manifactures, trends, pristupljeno sajtu 11.04.2024.

[13] UITP: ZeUS project and UITP VEI Committe, 2019

[14] Buss, K., Stolzenburg , K., Whitehouse, N., Whitehouse, S: JIVE/JIVE2 Second Best Practice Information Bank Reaport, 2022

[15] Projecat CUTE (Clean Urban Transport for Europe), 2004

[16] UITP: Fuel cell buses-Best practices and commercialisation approaches, 2020.