SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2022
ORGANIZATION AND MANAGEMENT SERIES NO. 161

POSSIBILITIES OF USING HYDROGEN BUSES IN URBAN TRANSPORT

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Purpose: The aim of this paper is to present the possibilities of using hydrogen buses in urban transport taking into account technological, economic and environmental conditions.
Design/methodology/approach: Analysis of international literature, Polish literature and reports related to the development of alternative energy sources in vehicles and urban transport development.
Findings: The Polish government to achieve the environmental requirements of the European Union obliges local government units to ensure the share of zero-emission buses in the fleet of vehicles in use. On the basis of the conducted analysis we can say that a significant advantage of hydrogen vehicles is the total lack of emissions, a long range of up to 350-400 km and short charging times. However, a significant problem is insufficient infrastructure – not enough hydrogen stations. Despite this difficulty, more and more manufacturers are interested in producing hydrogen vehicles, and investors are seriously considering the costs and benefits of zero-emission buses. Unfortunately, none of the economic analyses that have been commissioned by Polish companies providing transport services have shown the viability of using hydrogen buses.
Originality/value: The paper shows the global trends in the development of city buses with particular attention to hydrogen buses.

Keywords: bus, hydrogen propellant, zero-emission vehicles.

Category of the paper: general review.

1. Introduction

Electricity is one of the fastest growing alternative energy sources in urban transport vehicles. However, as with conventional energy sources such as oil and coal, electricity is not the primary source of energy. A fully charged battery carries only energy from other, often conventional, sources. Electric vehicles with batteries (BEV) are very efficient in converting

http://dx.doi.org/10.29119/1641-3466.2022.161.4 http://managementpapers.polsl.pl/

energy from the grid into motive power. They can also recover energy while driving by using regenerative braking. One of the major disadvantages of BEVs is that they tend to be limited in range due to the size and cost of the batteries needed to power the vehicle and the energy requirement. Charging the battery systems can take several hours, not a few minutes as in a conventionally powered vehicle (CV). In order to make use of the advantages of both electric and conventional vehicles and to bridge the gap between CV and BEV, an alternative is being considered which could be a hydrogen fuel cell electric vehicle (FCEV). Hydrogen is a chemical energy carrier capable of generating electricity up to 39.39 kWh / kg, which exceeds the energy density of most batteries. A fuel cell (FC fuel cell) works in a similar way to an ICE internal combustion engine. The ICE converts the chemical energy of the fuel supplied to the engine to produce mechanical energy used to propel the vehicle. FC works in a similar way to ICE in that the chemical energy is directly converted into electricity in FC, but in an environmentally friendly process. Unlike a battery, which depletes when it is used to power electrical components, internal combustion engines and fuel cells act as continuously operating energy sources as long as they are supplied with fuel. Therefore, it is anticipated that a hydrogen fuel cell could overcome the disadvantages of BEV, making hydrogen the transport fuel of the future. Hydrogen produces zero harmful emissions, which is one of the most significant benefits of using FC (Manoharan et al., 2019).

A fuel cell (FC) is an electrochemical reactor that converts the chemical energy of the fuel and oxidant directly into electricity. The term fuel cell is used almost exclusively to describe a reactor that uses hydrogen as the main source of energy (Rosen and Koohi-Fayegh, 2016). Hydrogen and oxygen are supplied to the fuel cell separately (Fig. 1). The electrodes are separated by an electrolyte. The hydrogen molecules first enter the hydrogen electrode (called the anode) of the fuel cell. The hydrogen molecules then react with the anode-coating catalyst to release electrons to form a positively charged hydrogen ion. These ions pass through the electrolyte and reach oxygen in a second electrode called the cathode. The electrons 'flow' into the electric circuit, generating the current of the fuel cell system. At the cathode, the catalyst causes hydrogen ions and electrons to combine with oxygen from the air, creating water vapor, which is the only by-product of the process (Deloitte and Ballard, 2020).

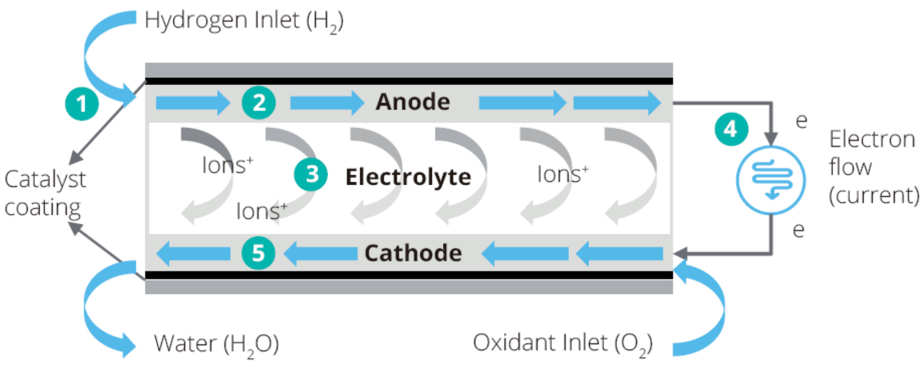

Figure 1. Principle of operation of a fuel cell. Adopted from Deloitte and Ballard, 2020.

The disadvantage of hydrogen fuel is its production cost, which today is about three times higher than the refining of crude oil (Rosen and Koohi-Fayegh, 2016; Chakraborty, 2019). According to the International Energy Agency (IEA, 2015), the structure of global hydrogen production consists of about 48% hydrogen produced from natural gas, 30% from crude oil and 18% from coal. The remaining 4% is produced by electrolysis of water. (Szałek et al., 2021). However, with the recent industrial-scale concept of producing green hydrogen offshore by deploying electrolyser systems on rebuilt oil rigs, this structure may change. Offshore wind farms are an inexhaustible renewable resource, but remote locations pose challenges in terms of connection to the electricity grid and irregular supply. Another issue is energy storage and the limited possibility of feeding electricity into the grid during peak production periods. Offshore hydrogen production will solve this problem by ensuring that electricity is received in the immediate vicinity of wind farms. It also aims to use existing platforms, pipelines, terminal infrastructure and maritime facilities (using existing infrastructure) to reduce costs. The hydrogen produced by these installations will also act as an energy reservoir during peak production periods.

As the hydrogen production technology by wind farms develops and "surplus" electricity from renewable sources is converted on a large-scale using electrolysers, it is electrolysis that will be the dominant future process in the production of renewable hydrogen. As a result of the electrolysis of water, hydrogen and oxygen are produced with a very high purity, above 99.999%. This is used when refueling hydrogen into fuel cell vehicles – no further purification is required. However, to obtain such pure hydrogen, the water must be pre-treated, which reduces the energy efficiency of hydrogen production from renewable sources. The current energy efficiency of hydrogen production by electrolysis is around 75%. Due to the dynamic development of renewable hydrogen production and the expected decrease in its production cost, it is justified to claim that fuel cells can be used in passenger cars, vans, trucks, buses and other means of transport (Szałek et al., 2021). The advantages of fuel cells as a means of transport include also high engine efficiency (65% for fuel cells compared to 35% for an internal combustion engine), better fuel efficiency and constant engine torque. In addition, fuel cells eliminate vibrations and noise associated with energy production. It is also worth mentioning that there are positive aspects influencing the quality of life of the society and the state of the environment, including the lack of fuel combustion when parked (Turoń, 2020; Granovskii et al. 2006).

2. Using hydrogen propellant in means of public transport

Buses are the most popular means of public transport in the world. They are used in virtually all conditions in which public transport operates. This is due to the great flexibility of this transport system. It does not require the construction of a special and costly transport infrastructure, except for stops and the infrastructure necessary to operate buses. They enable the easy creation and launch of new routes, have a large capacity and allow you to quickly respond to changes in the flow of passenger flows.

The analyzes of the works (Uhl, 2020; Sharma and Strezov, 2017; Onat et al., 2016) clearly show that the global trends in the development of city buses are moving towards the use of electric buses powered by fuel cells. This is confirmed by available reports of global consulting companies (McKinsey & Company, 2017), which indicate that in the near future heavy urban transport will be dominated by means of transport powered by hydrogen propulsion based on fuel cells and electric motors. This mainly applies to vehicles operated in an urbanized area, where the frequency of vehicle movement on the roads is high. Therefore, we are on the threshold of changes in the operated fleets from vehicles powered by internal combustion of fuels to electric vehicles, including hydrogen-powered vehicles, where electrochemical reactions are used to store or generate electricity.

The European Union plans to reduce pollution emitted by transport by 60% by 2050 compared to 1990. In addition, local government units in Poland are required to ensure the share of zero-emission buses in the fleet of vehicles in use, in the amount of at least 30% until 2028 (ZDR TOR, 2020; Dz.U. 2018 poz. 317).

In 2003, 3 Mercedes-Benz buses powered by hydrogen fuel cells were tested for the first time in Beijing. In 2017, the first commercially operated line of fuel cell buses in China was launched in Foshan Yunfu by Feichi Bus. As of 2018, more than 200 FCEBs operate in cities such as Shanghai, Foshan, Zhangjiakou and Chengdu. In 2018, Toyota Motor Corporation unveiled its first FCEB, the Sora (Figure 2), and then put more than 100 buses in service in the Tokyo metropolitan area in 2020 (Kane, 2018).

Figure 2. First hydrogen bus produced by Toyota Motor Corporation. Adopted from Kane, 2018.

2.1. Development of hydrogen fueled buses in Poland

The Polish bus manufacturer Solaris signed contracts for the delivery of Urbino 12 hydrogen buses (Figure 3) with urban transport operators in Germany, the Netherlands, Italy, Sweden, Spain, Romania, the Czech Republic and Austria.

Solaris has already delivered buses with hydrogen fuel cells to the public transport fleet in Cologne, Germany, Stockholm, Sweden and Bolzano, Italy. The first public transport operator in Poland to add a hydrogen bus to its fleet will be MZK in Konin. The contract signed with Solaris Bus & Coach provides for a four-year lease of the Urbino 12 hydrogen bus powered by hydrogen energy. The vehicle will be delivered to Konin in 2022 (Solaris A car Group Company, 2020). Three more cities, Poznań, Włocławek and Chełm, submitted applications for financing hydrogen vehicles under the Green Public Transport program, implemented by the National Fund for Environmental Protection and Water Management.

Figure 3. Urbino 12 Hydrogen bus. Adopted from Solaris A car Group Company, 2020.

Gdynia and Gdańsk were the first to conduct hydrogen tests of the Solaris Trollino 18 hydrogen trolleybuses in 2017 - it is a trolleybus equipped with fuel cells enabling the vehicle to operate beyond the reach of the traction line (Trollino). Currently, the Tri-City is applying for hydrogen trolleybuses under the same program. Warsaw is planning to purchase 10 hydrogen buses, while the Municipal Communication Plant in Bielsko-Biała has announced a tender to develop a concept for introducing hydrogen propulsion into the city's fleet.

In the plants of AUTOSAN sp. Z o.o. the first hydrogen-powered bus has also been built. It complements the family of vehicles intended for public transport under the common name of SANCITY. The zero-emission SANCITY 12LFH shown in Figure 4 is a low-floor bus with a length of 12 meters. It was designed on the basis of an electric bus. The bus has an electric motor with a fuel cell power module. The official premiere of the newest emission-free AUTOSAN SANCITY 12LFH bus with a hydrogen drive took place on October 27-29, 2021 during the 15th edition of the TRANSEXPO International Public Transport Fair in Kielce.

One of the main limitations in the development of hydrogen propulsion in Poland is the lack of hydrogen charging stations. PKN Orlen, which has hydrogen refueling stations in Europe, reports that it should launch similar points in Poland this year. The first Polish city with such a station is to be Poznań. Orlen is building a hydrogen hub in Włocławek, and another one in Płock. It is planned that such stations will be able to be serviced not only by buses, but also by passenger vehicles (Świat OZE, 2021).

Figure 4. A zero-emission hydrogen-powered bus SANCITY 12LFH. Adopted from Trans Expo Kielce 2021: Solaris displays four zero-emission buses.

Last year, the Ministry of Climate and Environment, informing about the commencement of public consultations of the Polish Hydrogen Strategy, announced that in 2025, 500 domestic hydrogen-powered buses are to be operated in Poland. In 2030, there will be four times more. Transport – according to the ministry – is to be one of the key sectors of the economy that uses hydrogen.

Fuel cell electric buses (FCEBs) are one of the main applications of fuel cells today. Buses usually have regular, predictable routes that do not require a large number of refueling stations. In addition, the performance of bus operators is significantly influenced by the emissions requirement imposed by public authorities, the use of hydrogen powered buses (FCEB) has become a very visible, green public transport initiative (Rosen and Koohi-Fayegh, 2016, Eudy and Post, 2018; FCH JU, 2018).

2.2. Buses used in the London public transport

Transport for London ("TfL") is the integrated transport body responsible for the day-to-day operation of the city's public transport network, including buses, underground, light rail, taxis, etc. (Transportation for London. What we do). In December 2003, TfL began testing the first generation of fuel cell buses in London to reduce air pollution in the city. The tests were part of the HyFleet: CUTE project, which brought together 31 industry and government partners from across Europe to accelerate the development of hydrogen-based transport systems in Europe. This project was funded by the European Union and the UK government. In 2010, as part of the Clean Hydrogen Cities ("CHIC") project, TfL purchased 5 next-generation hydrogen fuel cell buses and put them into service on the popular RV1 tourist route between Covent Garden and Tower Gateway. For the first time in the UK, the entire route was fully served by hydrogen-powered buses. In 2013, TfL purchased three more hydrogen fuel cell buses and expanded the fleet to eight buses (Ballard, 2016). Subsequently, in 2015, TfL again added 2 more fuel cell buses to its fleet (Van Hool). In May 2019, Transport for London ordered other 20 double-decker hydrogen fuel cell buses to expand its zero-emission bus fleet. 20 hydrogen fuel cell buses were put into service in 2020 on Routes 245, 7 and N7 213. It is planned that all buses used in London's urban traffic will be zero emission by 2030.

Currently, TfL uses 3 types of buses (Rosen, 2016):

- FCEV (StreetDeck Fuel Cell Electric Vehicle (FCEV) premiered at Euro Bus Expo): electric motor power: 200 kW; loading capacity: 85 passengers; range: average 350 km, up to 500 km; charging time 5-10 minutes.
- BEV: electric motor power: 200 kW; battery capacity: 382 kWh; loading capacity: 84 passengers; range: ~ 250 km; 4-5h charging time.
- ICEV: ICE engine power: 320 kW; loading capacity: 120 passengers; range > 300 km; charging time approx. 5 minutes (Ezzat and Dincer, 2018, Turoń, 2020).

3. Cost analysis of the use of hydrogen fueled buses

The subject of financial analysis for any investor is the actual cash inflows and outflows associated with the investment. The decision to purchase a bus fleet should take into account the following financial costs (Eko-Efekt Sp. z o.o., 2019; Gromadzki, 2021; Mroskowiak and Witosz, 2021):

- investment costs for rolling stock and for the technical infrastructure of operation and supply,
- fuel and electricity purchase costs, resulting from the planned work of transport for particular types of vehicles,
- vehicle maintenance costs,
- costs for external emissions such as pollutants, greenhouse gases and noise,
- vehicle insurance costs.

Cost-benefit analyses of the use of zero-emission buses carried out by transport companies have shown that the purchase of hydrogen buses may be possible, but there is currently no infrastructure for hydrogen vehicles in Poland (Gromadzki, 2021; Mroskowiak and Witosz, 2021). The market price of hydrogen is EUR 9.50. It is approximately PLN 40-45 per kg. A public transport bus uses about 8 kg of hydrogen per 100 km, so the cost of driving 100 km would currently be 320 PLN. The cost of purchasing the bus is about 4 million PLN, and the cost of building a hydrogen station is estimated at 4-6 million PLN (Mroskowiak and Witosz, 2021).

Figure 5 presents the TCO (total cost of ownership) breakdown for the three types of buses operated by TfL (Rosen and Koohi-Fayegh, 2016). The TCO value includes both the purchase cost and the operating costs of individual types of buses. As can be seen from the table below, purchase cost and fuel cost are the main components of the TCO of fuel cell buses. This is due to the high purchase prices of buses as well as the high price of hydrogen (higher than for ICEV buses with conventional drive and BEV – electric drives). The costs of insuring fuel cell buses are also high. However, it is estimated (Rosen and Koohi-Fayegh, 2016) that these costs will soon fall as the prices of fuel cell systems and hydrogen fall. An additional element is road tax, the amount of which depends on exhaust emissions. All three types of buses pay road taxes, but for ICE vehicles, these are much higher due to their high emissions.

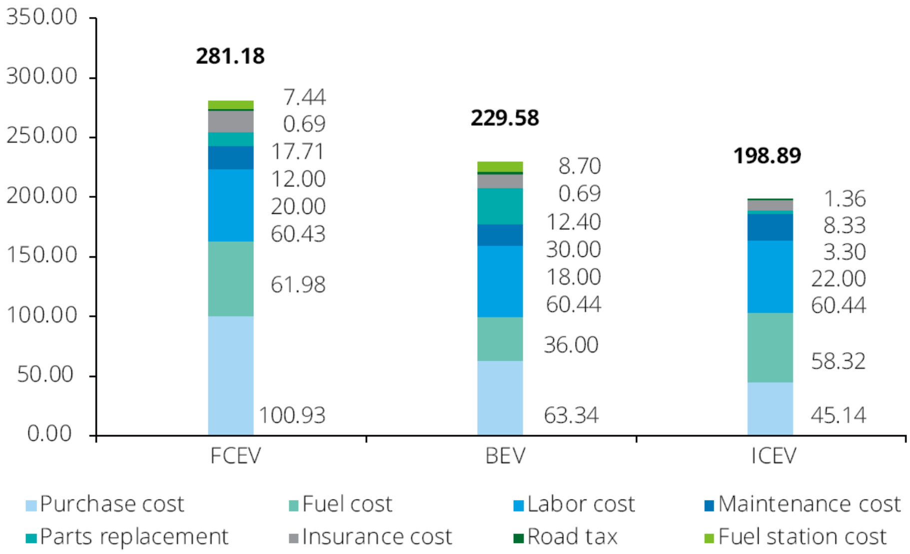

Figure 5. Summary of TCO (Total Cost of Ownership) for the three types of buses operated by TfL. Adopted from Rosen and Koohi-Fayegh, 2016.

Figure 6 shows the estimated total cost of ownership (TCO) of fuel cell buses over the next 10 years. It is estimated that the total cost of ownership of fuel cell buses will be lower than that of battery buses and ICE buses from 2024 (Rosen and Koohi-Fayegh, 2016).

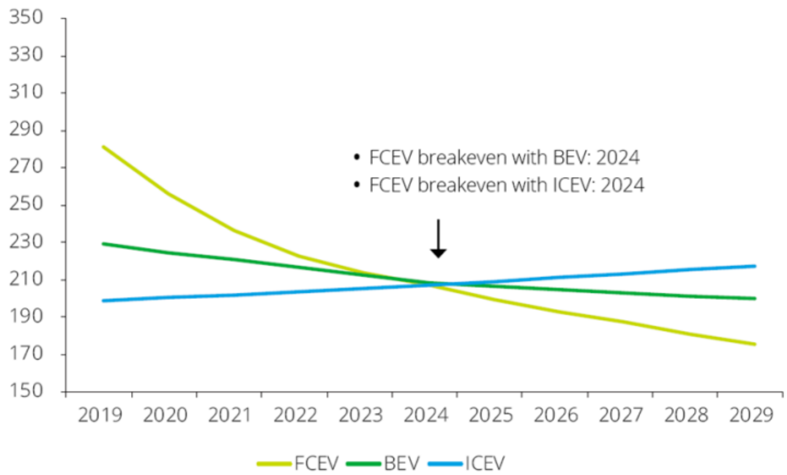

Figure 6. Estimated Total Cost of Ownership (TCO) of FCEV buses over the next 10 years. Adopted from Rosen and Koohi-Fayegh, 2016.

4. Conclusions

Although the total cost of ownership of fuel cell buses (FCEV) today is higher than that of electrically powered buses (BEV) and conventionally powered buses (ICE), there are intangible benefits to using fuel cell technology in city transit. First, the fuel cell buses meet the London Council's emission standards. In April 2019, London began implementing an "Ultra Low Emission Zone" ("ULEZ"). Vehicles exceeding the emission standard are charged an additional ULEZ fee. The zone is expected to be expanded to include larger vehicles such as buses, coaches and trucks. The introduction of ULEZ is one of the steps to meet the goals of reducing carbon dioxide emissions in London. In the foreseeable future, city authorities will introduce increasingly stringent restrictions on emissions from public transport vehicles, which will make the total cost of ownership of conventional ICE vehicles much higher, and green vehicles such as BEV and FCEV will become the standard in public transport.

Acknowledgements

This paper was financed from the resources of the Silesian University of Technology, project no. 13/010/BK_22/0065.

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