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*Jędrzej MATLA*
*Andrzej KAŹMIERCZAK*
*Michał GRZEBYK*
*Tomasz HARDY*

**Combustion Engines**
**Polish Scientific Society of Combustion Engines**

# The study of hydrogen consumption in 12-meter fuel cell electric urban buses

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*The fuel consumption aspect of fuel cell electric buses (FCEBs) in urban transportation is a significant research and economic issue. Following article presents the results of hydrogen consumption studies for a fleet of 12-meter FCEB under real life operating conditions in a Polish public transport company on selected routes and evaluates their operational suitability. The analysis includes factors such as the impact of weather conditions, number of stops, elevation gain, and average slope of the route. The article also discusses the challenges associated with implementing hydrogen technology in public transport and the future development prospects for this sector. The results obtained were compared with other studies in this research area.*

Key words: *hydrogen consumption, hydrogen bus, FCEV, fuel cell, urban conditions*



## 1. Introduction

Key aspects regarding the vehicles used in the fleets of urban public transport companies are related to their purchase cost, quality, service costs, ergonomics, or reliability. As practice shows, a significant part of the cost of service is fuel consumption, so this is the primary factor for assessing the operational suitability of a given bus [2].

The transformation of fleets of urban public transport companies is a key challenge for both the Polish and European economies. Road transport is responsible for about 24% of total greenhouse gas emissions in the European Union [11], making it a crucial area of development. Moreover, bearing in mind the increased demand and limited supply of petroleum resources, as well as the geopolitical situation, it can be concluded that these are the factors that define strategic action for the development of low emission technologies. One of the main goals of the European Union is to popularize alternative fuels and the transportation means that use them to increase energy independence. Hydrogen, as the fuel of the future, is playing an increasingly important role in the decarbonization of public transportation. Fuel cell powered city buses offers zero emissions (except for water vapors) and significant noise reduction, which translates into environmental and health benefits especially in crowded European cities. In addition, the development of this technology could make a significant contribution to reducing fossil fuel imports in the future.

A key advantage of hydrogen buses is their larger range compared to electric buses powered solely by batteries. What is more, the tanks of FCEVs can be filled with hydrogen in just a few minutes, a time similar to refuel conventional vehicles [14].

## 2. Legal background

Since the research presented in this article was performed entirely in Poland, the legal aspects refers precisely to the regulations in force in this country and in the European Union. The Act on Electromobility and Alternative Fuels and the "Polish Hydrogen Strategy to 2030 (with a perspective to 2040)" are two main documents defining legislative framework in Poland that presupposes a comprehensive development of the country hydrogen network [21, 28]. They regulate, in particular, the deployment of vehicle charging infrastructure, CNG refueling, and the possession of zero emission vehicles in the fleets of companies providing public services.

In order to implement the hydrogen economy, the Hydrogen Strategy identifies priority areas for state intervention. These include building a minimum of 32 publicly accessible refueling stations and related infrastructure, developing low carbon hydrogen production technologies (primarily through RES electrolysis), enhancing national industrial competences and expanding the use of hydrogen in industry, transportation, and energy sectors. The plan calls for the creation of a national production capacity for hydrogen powered vehicles, the deployment of hydrogen fleets in urban areas, and the promotion of pilot projects in the field of public transportation. The strategy also emphasizes the creation of at least five regional "hydrogen valleys" as integrated ecosystems linking hydrogen production, storage, distribution and utilization in order to enable the creation of a coherent hydrogen market on a national scale.

The 2020 "European Hydrogen Strategy" and the European Green Deal both state that hydrogen will be crucial in the process of reaching climate neutrality by 2050 [3, 4]. The "Fit for 55" package, which includes the RED III Directive, AFIR, ETS, and new vehicle emission standards, among other measures, establishes aggressive goals for deploying alternative fuels and boosting the contribution of RES [7, 18, 26]. In the area of the market for decarbonized gases, significant is also the proposed directive on renewable gases, including hydrogen, which will set rules for their certification and integration into the energy market. In addition to promoting investments in hydrogen technologies, the new rules are meant to guarantee that these technologies adhere to sustainable development principles. A significant factor that might accelerate the commercialization of hydrogen in the transportation industry is the establishment of consistent, transparent and uniform regulations throughout the whole European Union.

## 3. Fuel consumption measurement methods

For many years, the fuel consumption of buses was measured by empirical methods on the basis of refueling to full before and after completing a route and comparing this difference with the distance traveled [1]. This method, despite its simplicity, does not provided a true picture of the vehicle operation in urban conditions, where acceleration and braking cycles in combination with load variability play an important role [16]. With advances in technology and the introduction of legislative requirements, it has become necessary to implement more precise and repeatable methods of fuel consumption measurement in buses.

In the European Union, the most important legal act regulating the measurement of fuel consumption and emissions in trucks and buses is Regulation (EU) 2017/2400 [25], which makes the use of the VECTO simulation tool mandatory, which from January 1, 2019 applies, amongst others, to new models of buses for passenger transport exceeding total mass of 5 tons. VECTO is not a classic road test, but a software tool that, using actual vehicsle technical data (e.g. weight, drivetrain type, rolling resistance, engine parameters), simulates fuel consumption and $CO_2$ emissions over standard driving cycles. For city buses, the so called "Urban Bus" cycle is typically used, which takes into account frequent stops, low speeds and varying loads characteristic of urban traffic.

The Standardized On-Road Test cycles are becoming increasingly important in the practice of evaluating fuel consumption in city and intercity buses [19]. These tests, while not part of the formal approval procedure in the European Union, are a widely accepted industry standard, used primarily to compare fuel consumption between different bus models under real world conditions. SORT is a set of three differentiated driving cycles designed to reflect typical operational profiles of buses in a variety of operating conditions, from city driving to intercity conditions. As a result, SORT test results provide more useful data for operators and decision makers who want to compare the fuel efficiency of competing bus models under similar operating conditions. The SORT tests include three driving scenarios:

SORT 1 – simulates urban driving with a very high frequency of stops and starts. Typical for densely built-up areas of central cities;

SORT 2 – corresponds to suburban conditions, with fewer stops and higher average speed;

SORT 3 – replicates intercity or expressway driving conditions, with infrequent stops and relatively high travel speeds.

Each of the SORT cycles is implemented with certain parameters: number of stops, stopping time, section length, average and maximum speeds, as well as vehicle weight (with simulated passenger load). Measurement of fuel consumption is carried out using precision measuring devices mounted on the vehicle [13]. An important element is the maintenance of consistent test conditions, which makes it possible to obtain results that are comparable regardless of location or operator.

The development of alternative propulsion systems, such as hybrid, electric and gas powered buses, has forced schange in the approach to measuring fuel consumption. In the case of hybrids, both conventional fuel consumption and electricity consumption are taken into account [17, 20]. VECTO and type approval procedures often take into account the so called fuel energy equivalent, converting fossil fuel to electric energy equivalent, which allows comparison of vehicles with different power sources. In such case energy consumption is expressed in kWh per 100 km. For conventional diesel fuel its gravimetric density is 12.2 kWh/kg while for gaseous hydrogen pressurized to 350 bar it is 33.3 kWh/kg [23].

## 4. Hydrogen refueling infrastructures

At the moment, there are 8 publicly accessible hydrogen refueling stations in Poland, operated by two operators: Orlen S.A. and PAK-PCE Stacje H2 Sp. z o.o. (see Fig. 1).

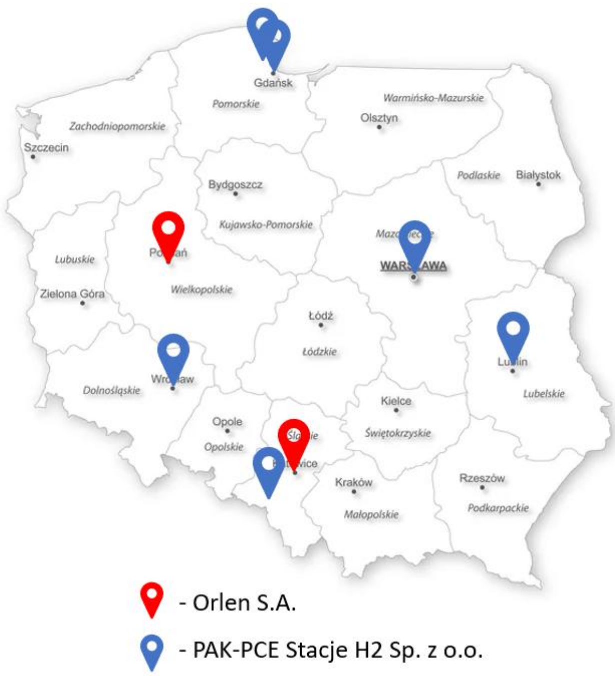


Fig. 1. Publicly accessible hydrogen refueling stations in Poland [12,22]

As a rule, the use of these stations requires appropriate precautions, but hydrogen refueling itself is quite similar to pouring CNG and does not require any additional authorizations. The process of filling a hydrogen tank usually takes from a few to several minutes. For buses, the applicable sstandard is the so called H35, indicating a maximum pressure of 350 bar and a maximum filling rate of 120 g/s. These values are defined by the SAE J2601 standard in force throughout the European Union [24].

In the case of the research presented in this paper, since no publicly available hydrogen refueling station was available in the region, the refueling of buses tanks was carried out using a so called mobile refueling station (see Fig. 2).

Due to its construction and the lack of a hydrogen pressurization system, the maximum refueling pressure was limited to 200 bar only, which in practice resulted in a limitation of the maximum range of the vehicles.


Fig. 2. Mobile hydrogen refueling station

## 5. Scope of research

### 5.1. Fleet

The classification of buses by size is a conventional classification that usually refers to their length [15]. According to one of the accepted classifications, the following types of buses are distinguished: MINI (up to 7.5 m), MIDI (7.5 to 10.5 m), MAXI (10.5 to 13 m) and MEGA (over 13 m). Now all FCEBs in Poland are classified as MAXI.

The research subject was the fleet of fourteen Solaris Urbino 12 Hydrogen buses (see Fig. 3) serving urban bus routes within the city public transportation company. Selected parameters of tested vehicles are presented in Table 1.

Table 1. Selected parameters of tested bus model [5]

| Model | Solaris Urbino 12 Hydrogen |
|---|---|
| Length [mm] | 12,000 |
| Width [mm] | 2550 |
| Height [mm] | 3000 |
| Gross mass [kg] | 19,200 |
| Fuel cell power [kW] | 70 |
| Traction battery [kWh] | 30.47 |
| Electric motor power [kW] | 2 × 125 |
| Hydrogen tank capacity [kg] | 37.5 (5 × 312 L) |
| Hydrogen tank max. pressure at 15°C [bar] | 350 |
| Heating system | AC with $CO_2$ heat pump |
| Max. range [km] | 350 |


Fig. 3. Tested bus model – Solaris Urbino 12 Hydrogen

### 5.2. Routes

The evaluation of hydrogen consumption under operating conditions was carried out for three bus lines on which the selected buses operated during February of 2025. The trips were performed from Monday to Friday during daytime.

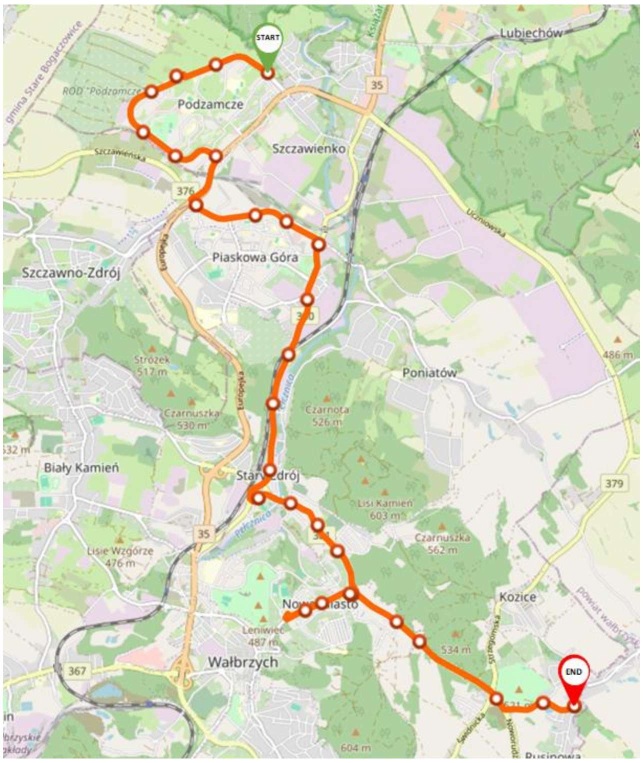


Fig. 4. Course of route 1


Fig. 5. Profile of route 1

Table 2. Route 1 parameters

| Parameter | Value |
|---|---|
| Length [km] | 15.6 |
| Number of stops [-] | 28 |
| Elevation gain [m] | 113 |
| Total climb [m] | 217 |
| Total descent [m] | 126 |
| Avg. slope [%] | 0.72 |

The first route is the longest of the routes considered, with a one way length of 15.6 kilometers. At the same time, it is the route with the smallest number of stops equal to 28. The average slope of the route is 0.72%, which ranks it in the middle of the other routes in this regard.

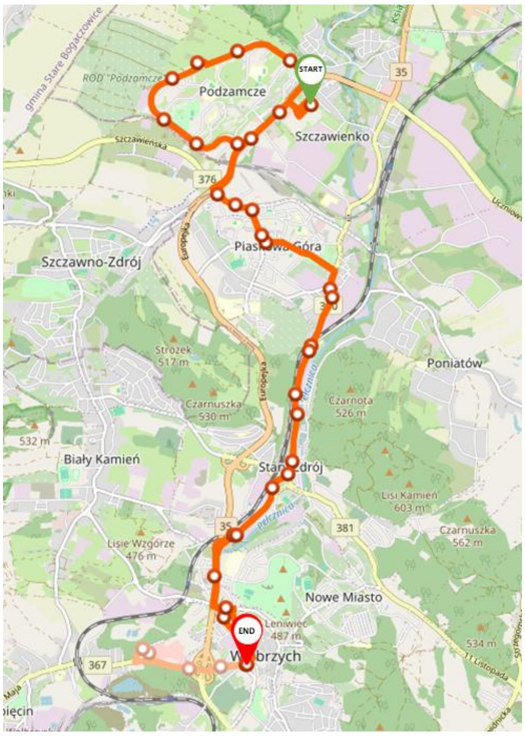


Fig. 6. Course of route 2


Fig. 7. Profile of route 2

Table 3. Route 2 parameters

| Parameter | Value |
|---|---|
| Length [km] | 13.7 |
| Number of stops [-] | 33 |
| Elevation gain [m] | 73 |
| Total climb [m] | 128 |
| Total descent [m] | 60 |
| Avg. slope [%] | 0.53 |

Route number two is the shortest among all analyzed routes, with a length of 13.7 kilometers. It is also the route with the smallest average slope of 0.53% and the lowest elevation of 73 meters. Moreover, the total climb of 128 meters is significantly less from the others by means of approx. 100 m. The number of stops on the route is 33, placing it in the mid-range when compared to the other options.

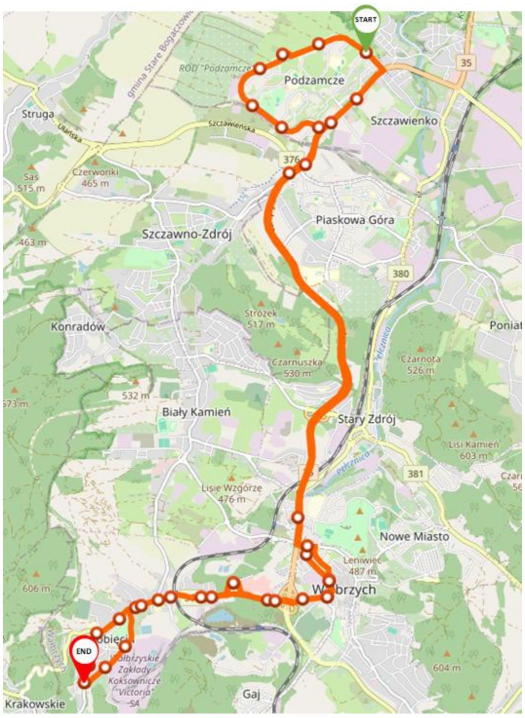


Fig. 8. Course of route 3


Fig. 9. Profile of route 3

Table 4. Route 3 parameters

| Parameter | Value |
|---|---|
| Length [km] | 14.4 |
| Number of stops [-] | 36 |
| Elevation gain [m] | 130 |
| Total climb [m] | 231 |
| Total descent [m] | 102 |
| Avg. slope [%] | 0.90 |

The third route under consideration is characterized by the highest number of stops of 36 and the highest elevation of 130 meters. Its distance is 14.4 kilometers, and the average gradient is 0.90%. Noteworthy, this route features the longest stretch without stops measuring approximately 5 kilometers. The profile of this route is characterized by the smoothest elevation changes along its entire course.

### 5.3. Weather conditions

In the operation of FCEBs ambient temperature plays an important role in both the efficiency of the fuel cell system and the energy requirements of onboard systems. It has a particularly noticeable impact during transitional periods, when atmospheric conditions change noticeably. During the period under review (February), outdoor temperatures remained below zero typically for the winter.

The fuel cell in most FCEBs models operates optimally in the temperature range of 60–80°C. During winter months, such as February, low ambient temperature increases the time required to reach its operating value. Until internal conditions stabilize, the system operates with reduced efficiency, resulting in increased instantaneous fuel consumption. Low temperature operation can also affect the hydrogen management system, including the moisture condition of the proton membrane, whose excessive dehydration or condensation can limit the efficiency of chemical conversion [27].

For research purposes, archival data from the Institute of Meteorology and Water Management for the monitoring station located in Szczawno-Zdrój was used [6].

## 5. Results and discussion

Due to the number of vehicles tested amounting to 14 units, data of hydrogen consumption was collected on the basis of readings from the onboard system. Presented results refer to hydrogen consumption in February, as the month with the most relevant experimental data. The results of considerations are presented in table number 5.

Table 5. Average hydrogen consumption in February

| Parameter | Route 1 | Route 2 | Route 3 |
|---|---|---|---|
| Length [km] | 15.6 | 13.7 | 14.4 |
| Number of stops [-] | 28 | 33 | 36 |
| Elevation gain [m] | 113 | 73 | 130 |
| Total climb [m] | 217 | 128 | 231 |
| Total descent [m] | 126 | 60 | 102 |
| Avg. slope [%] | 0.72 | 0.53 | 0,90 |
| Total distance [km] | 3199 | 4831 | 6037 |
| Total $H_2$ [kg] | 284.63 | 424.13 | 549.75 |
| Avg. $H_2$ consumption [kg/100 km] | 8.90 | 8.78 | 9.11 |

The green color indicates the parameters that favor the lowest fuel consumption, while the red color indicates the parameters that are least desirable in this sense. Yellow color indicates the values that are in between. The lowest average hydrogen consumption (8.78 kg/100 km) was observed for route number 2, which features the lowest elevation gain, average slope and total climb. It is also the shortest route among those considered . As the study showed, an increase in the number of stops correlates with increased fuel consumption, which suggests that this is a factor that has a direct impact on this parameter. The same applies to elevation gain and total climb, which was to be expected given the conversion of kinetic into potential energy. The highest hydrogen demand was recorded for the route 3 with the highest elevation gain, total climb and average slope. It was also the route with the most amount of stops.

Figure 10 shows the average daily fuel consumption for the three routes investigated in relation to the average daily ambient temperature.

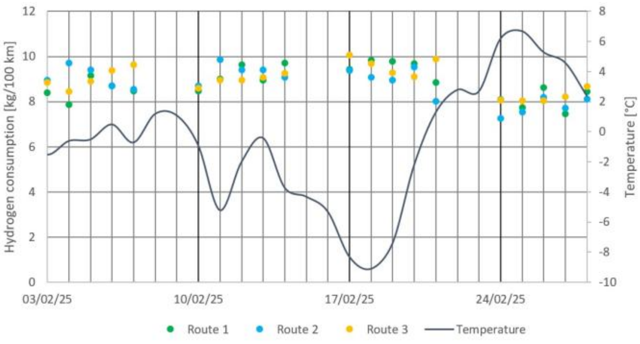


Fig. 10. Average fuel consumption in relation to temperature

The temperature remained mainly below zero for the first three weeks of research with a noticeable drop in third week, however despite the evident drop in temperature, there was no significant change in hydrogen consumption. In the final fourth week there an increase in temperature was observed, which correlated with a noticeable reduction in fuel consumption during this time. The most likely reason for this is the changing energy demand from auxiliary systems, in particular the heating and ventilation system. In February, at low temperatures, the heating of the passenger compartment is one of the main energy loads. FCEBs, unlike internal combustion vehicles, do not produce a large amount of waste heat, so all heating energy must be supplied from the battery or from auxiliary heating systems.

As spring time approaches, the demand for heating gradually decreases, which should result in a reduction in the energy load on the propulsion system. In addition, there is still no significant use of air conditioning during this period, which means that the onboard systems do not generate significant additional energy losses. With these arguments in mind, it makes sense to carry out further research in this area for the following months. In March and April, when the average outside temperatures start to rise, the cell should reach its operating temperature faster and its operation becomes more stable. Thus, the influence of weather conditions on the energy generation process should decrease. This means that less energy is used to warm up the system to a ready state, and the process of converting hydrogen into electricity itself is carried out with higher efficiency.

Finally, the results of the study were compared with those obtained by other research teams as can be seen in Table 6. The results obtained do not differ significantly from the others, which proves that the methodology used is correct and can be applied in further studies.

Table 6. Results of comparable studies [8–10]

| Location | Date | Bus model | Avg. $H_2$ consumption [kg/100 km] |
|---|---|---|---|
| Bolzano, Italy | 2021 16 months | Mercedes Citaro O530 | 9.31 |
| | | Solaris Urbino 12 Hydrogen | 10.07 |
| California, USA | 2013 14 months | Van Hool A300L FC | 9.74 |
| 9 cities in Europe | 2017 72 months | Mercedes Citaro O530 | 9.00 |

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## Nomenclature

| | |
|---|---|
| AC | air conditioning |
| AFIR | alternative fuel infrastructure regulation |
| CNG | compressed natural gas |
| ETS | emissions trading system |
| EU | European Union |
| FCEB | fuel cell electric bus |
| FCEV | fuel cell electric vehicle |
| RED | renewable energy directive |
| RES | renewable energy sources |
| SORT | standardized on road test |
| VECTO | vehicle energy consumption calculation tool |

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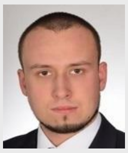
Jędrzej Matla, MEng. – PhD student, Wrocław University of Science and Technology.
e-mail: *jedrzej.matla@pwr.edu.pl*



Prof. Andrzej R. Kaźmierczak, DSc., DEng. – Faculty of Mechanical Engineering, Wrocław University of Science and Technology
e-mail: *andrzej.kazmierczak@pwr.edu.pl*

Michał Grzebyk, MEng. – PhD student, Wrocław University of Science and Technology.
e-mail: *michal.grzebyk@pwr.edu.pl*

Tomasz Hardy, DSc., DEng. – Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology
e-mail: *tomasz.hardy@pwr.edu.pl*