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Prospects and impediments for hydrogen fuel cell buses

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ABSTRACT

The number of demonstration projects with fuel cell buses has been increasing worldwide. The goal of this paper is to analyse prospects and barriers for fuel cell buses focusing on their economic-, technical-, and environmental performance. Our results show that the prices of fuel cell buses, although decreasing over time, are still about 40% higher than those of diesel buses. With the looming ban of diesel vehicles, and current limitations of battery electric vehicles, fuel cell buses could become a viable alternative in the mid-to long-term. With the requirements for a better integration of renewable energy sources in the transport system, interest in hydrogen is rising. Hydrogen produced from renewables used in fuel cell buses has the potential to save about 93% of CO_2 emissions in comparison to diesel buses. Yet, from environmental point-of-view it has to be ensured that hydrogen is produced from renewables. Currently, the major barrier, for a faster penetration of fuel cell buses are their high purchase prices, which could be significantly reduced with the increasing number of buses through technological learning.

The final conclusion is that a tougher transport policy framework is needed which fully reflects the environmental impact of different buses used.

1. Introduction

Due to the increasing greenhouse gas (GHG) emissions from the transport sector, as well as rapid urbanization, there is on-going requirement for emission and pollution reductions. To improve life quality in urban areas it is very important to reduce noise level and consumption of fossil fuels, which pose significant risks to the health. There is an urgent need to increase use of alternative fuels and alternative automotive powertrains in mobility applications [1,2]. Moreover, it is important to switch from car-oriented mobility toward more energy efficient transport practices, such as public transport.

Mass public transport is the backbone of urban mobility, especially in large cities with high population density. The average number of annual journeys per capita in countries with more than 30 million urban residents is in the range between approximately 40 (in the USA) and 250 (in Japan) [3]. This mobility need is covered by different transport modes. However, as shown in Fig. 1, bus is dominant transport mode with a 63% share. Almost 68% of bus fleets are standard buses (12-m buses) with a capacity between 75 (comfort capacity) and 100 (max. capacity) passengers, see Fig. 1.

Currently, diesel buses are the most popular and they represent 50% of all bus fleets. In addition, 22% of the buses use diesel in combination with biodiesel or some other additives. Different types of electric busses account together for about 18% of all buses, as shown in Fig. 2.

In the EU, buses are the mostly used form of public transport due to high cost-efficiency and flexibility. Buses make about 56% of all public transport journeys. They are suitable for urban, as well as for suburban and rural areas. Moreover, they have the lowest carbon footprint per passenger. Currently, there are about 900,000 buses in circulation on Europe's roads [5].

Since the evidence of climate change and local pollution is becoming more and more evident, many cities worldwide have enforced the development of city buses using alternative propulsion systems. Many of the EU's larger cities have set out ambitious targets and policy measures to stimulate a shift in the powertrain technology used in their bus fleets. Some of the measures are set on the national level (e.g. in the Netherlands all new buses procured from 2025 have to be zero-emission buses), and some on the city level (e.g. Paris, Madrid, Athens and Copenhagen committed to remove all diesel vehicles from city by 2025) [6]. In the EU, public authorities and operators of public transport services are obliged to follow the Clean Vehicles Directive (2009/33/EC) regarding energy consumption, CO_2 emissions, and other harmful emissions (NOx, NMHC and particulates) when purchasing new buses. Moreover, all

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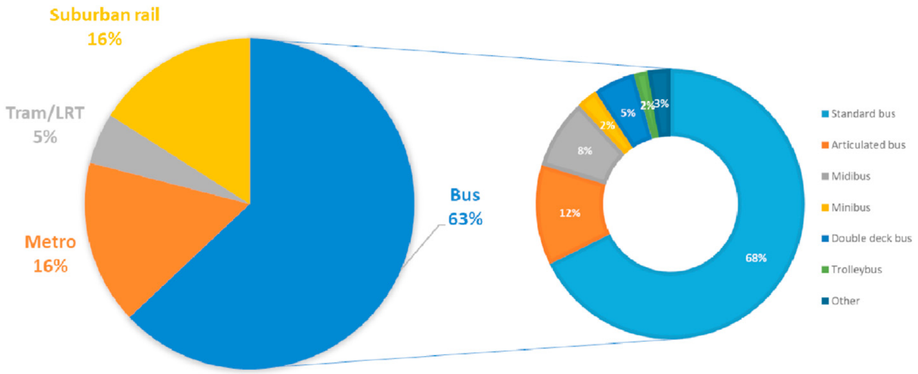

Fig. 1. Average modal distribution of all public transport journeys and share of bus fleet types (Data source [3,4]).

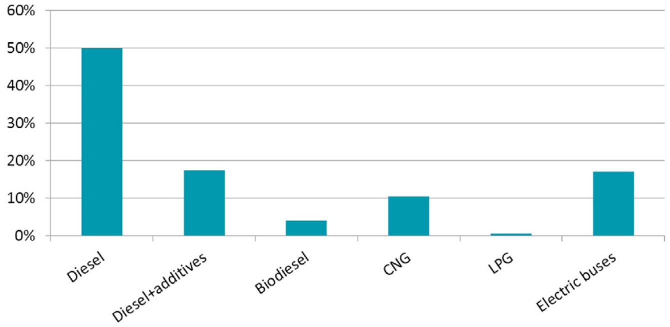

Fig. 2. Global share of bus propulsion systems (Data source [4]).

new bus models sold on the market after January 1, 2014 must meet the Euro VI standards for harmful emissions [7]. Although some improvements have been already reached with Euro VI diesel engines, currently largest expectations for the future are in the transition towards zero-emissions city buses, such as battery electric buses (BEBs) and fuel cells buses (FCBs).

In contrary to very broad portfolio of analysis related to battery electric vehicles and fuel cell passenger cars [8–11], the number of available literatures on BEBs and FCBs is limited. The interest in hydrogen-powered buses is increasing starting from the beginning of this century. Santarelli et al. [12] conducted one of the first studies on fuel cell buses already in 2003. This study evaluated emissions and economics of the FCBs. However, the capital costs used in this study were projected costs, which are below currently experienced costs of FCBs [13]. First studies on the social aspects of hydrogen FCBs have focused on general acceptance of hydrogen use as a fuel [2,14] as well as on the corresponding willingness to pay [15,16]. Later, these analyses have been extended by examining the view of FCB-implementers and users, indicating that no “show-stopper” is identified that would prevent future generations from the use of FCBs [2]. Doyle et al. [17] investigated suitability of FCB and BEB from the operator's perspective in different case studies, indicating the environmental and societal benefits of alternative buses in reduction of local pollutants and energy security concerns. In early studies, focus was at first on modification of diesel buses [18] as well as on non-hybridized FCBs in combination with hydrogen produced by steam reforming [19]. Moreover, also different sizing configurations were studied [20,21]. Ally and Pryor [22,23] conducted a life cycle assessment of FCBs assuming that hydrogen is a by-product from a crude oil refinery. Lee et al. [24] also performed the life-cycle environmental assessment of fuel cell electric school/transit buses in the United States, showing that results can vary significantly depending on duty cycles, geographical factors, hydrogen production pathways, and regional electric grids. Lajunen and Lipman [25] have evaluated the lifecycle costs and carbon dioxide emissions of different transit buses including FCBs. A well-to-wheel analysis is used by Correa et al. [26] to compare performance of different urban buses.

The value chain of green hydrogen for FCBs, considering different hydrogen delivery options, is analysed by Coleman et al. [27] based on field data derived from the 6 MW power-to-gas plant “Energiepark Mainz” and the bus demonstration project “H_2-Bus Rhein-Main”. In 2010, Bonilla and Merino [28] conducted economic assessment of FCB considering carbon credits and subsidies under rather optimistic capital cost assumptions. Cockroft and Owen [29] have accomplished cost-benefit analysis of FCBs in comparison to diesel and CNG buses in the Perth bus fleet assuming, that buses are produced under conditions of economies of scale and fully developed fuel infrastructure. A comparative energy and environmental analysis of different urban buses is conducted by Correa et al. [30] with the focus on Argentina, Brazil and Chile. Meishner and Sauer [31] have conducted technical and economic comparison of different electric bus concepts based on demonstration projects in European cities, however not considering FCBs. A comprehensive review paper on fuel cell applications in the automotive industry is conducted by Olabi et al. [32]. They have discussed the challenges related to the use of fuel cells in the transport sector considering different transport modes.

Since in various European countries, such as Austria, some of the bus fleet operators are planning to replace old diesel buses with FCBs, in the scope of this paper we have at first done a comprehensive documentation of the current demonstration projects, as well as fuel cell bus types and characteristics.

The major goal of this paper is to analyse prospects and key barriers for the increasing use of hydrogen fuel cell buses using recent data with a special focus on their economic and technical performance, as well as their environmental impact. In existing literature capital costs used are frequently assumed future costs, which are often below or above currently experienced costs of FCBs. In our analysis, total transport costs of the bus use are calculated per kilometre driven. In addition, a sensitivity analysis is conducted showing the impact of major parameters, such as travel activity, lifetime and hydrogen price. Finally, the future prospects are analysed by developing scenarios based on technological learning. This paper combines comprehensive economic and environmental analysis over the full lifecycle of bus operation, as well as static sensitivity investigations and dynamic future scenario analyses using the most recent data available. In opposite to some of the previous studies that have analysed hydrogen powered internal combustion engine buses or non-hybridized FCBs, in this paper our major focus is on hybrid fuel cell buses, which are today mostly used configuration. The results of this work are divided in three major categories: (i) documentation of the state of the art of FCBs as a background for the selection of the input parameters for further analysis, (ii) economic assessment and (iii) environmental assessment.

In the section below, we have documented at first state of the art of fuel cell buses with the special focus on demonstrations projects. In Section 3, methods used for economic and environmental assessments are described. Corresponding results of our analysis are presented and discussed in Section 4. Major conclusions are drawn at the end of the paper.

2. Hydrogen and fuel cell buses: state of the art

Hydrogen is a secondary energy carrier, like electricity, that can be produced from a range of primary energy sources, and can be used for different purposes. Currently, the mostly used hydrogen production technology is steam reforming of natural gas, due to relatively cheap hydrogen production costs [33]. However, using steam reforming of natural gas per energy kilogram of hydrogen about 10 kg of CO_2 is produced [34]. Electrolysis of water has currently minor applications but it is of special interest for the future. Larger use of renewable energy sources (RES) is considered as a pre-condition for heading towards smart and sustainable energy systems. With the increasing use of RES, hydrogen as energy storage could bring benefits to the balancing of the electricity system [35]. Using renewable or low carbon energy sources (e.g. nuclear) for electrolysis offers significantly higher emission savings than steam reformation or electrolysis powered by fossil energy carriers.

Fuel cell is best device to be used in combination with hydrogen. Fuel cells convert hydrogen and oxygen directly into electricity. In the transport sector, their major advantages comparing to internal combustion engine are better energy efficiency and significant emission reduction. On-road efficiency of fuel cell vehicles is two or three times higher comparing to internal combustion engine (ICE) vehicles. Regardless of the fuel used, fuel cells largely eliminate emission of particulates and oxides of sulphur and nitrogen, which are pollutants associated with conventional ICE. If hydrogen is produced from renewable energy sources, fuel cell vehicles are considered one of the most promising zero-emission automotive technologies in the long term.

Although hydrogen and fuel cells can be used for a broad portfolio of applications, in the mid-term they are appearing to be a suitable alternative to conventional- and battery electric large size vehicles with the need for longer driving range, such as buses. Since buses return regularly to a depot, in urban areas their use can be realized with minimal refueling infrastructure requirements. Their low or zero emissions increase their competitiveness especially with diesel-powered buses. Moreover, they avoid pollution problems specifically related to diesel buses. Due to the environmental benefits over conventional buses, urban authorities often provide subsidies and support for the demonstration of FCBs.

In the EU broad portfolio of policies and directives are directly or indirectly supporting the use of FCBs. In the next years, due to announced ban of diesel vehicles in many countries (e.g. Norway, the Netherlands, Ireland, Slovenia) as well as introduction of the zero emission zones in urban areas, interest in BEBs and FCBs is increasing.

Hydrogen FCBs have been demonstrated in real-world operations especially over the last twenty years. They can be seen as a complementary technology to BEBs. FCBs offer a zero-emission mobility solution on a wide range of routes and challenging terrains. Hydrogen and fuel cells have a particular advantage when heavier bases are required (e.g. articulated – or double decks buses) with a high daily travel needs. The long range of FCBs is a unique advantage in the zero-emission bus sector. This increase operators' flexibility and productivity. In addition, this is supported by short refueling times. FCBs can be refueled in about 7 min. Fast refueling time in combination with long driving range is very suitable for depot-based refueling. This can significantly decrease need for public refueling infrastructure what is very relevant in the early stage of FCB-deployment.

Since the first FCB was developed in 1993 by Ballard [36], their number is continuously increasing.

Currently, there are more than 2000 FCBs on the roads worldwide but majority of them is in China, see Fig. 3. Most of FCBs are operating in the scope of different demonstration projects. The rapid grow in use of FCBs in China over the last few years can be mainly attributed to a favorable policies launched by Chinese governments at various levels. For 2030 and 2050 many countries have announced ambitious targets for the deployment of fuel cell vehicles and buses, as well as development of refueling infrastructure [33].

There are three major configurations of hydrogen buses: (i) the hydrogen powered internal combustion engine bus, (ii) fuel cell bus, and (iii) the hybrid fuel cell bus. The internal combustion hydrogen bus works similar to a conventional diesel bus and is modified for the combustion of hydrogen. In early FCB-configurations, a fuel cell generates electricity, which is directly supplied to an electric motor. In this configuration, there is no mechanism to capture the kinetic energy dissipated during braking. In the meantime, all of the main fuel cell bus developers have moved to a fully hybridized mode, with the fuel cell operating in a series hybrid configuration. In these fuel cell buses, developers are still experimenting with the energy storage device, which can be batteries, ultra-capacitors, or a combination of both [1]. Currently, the mostly used FCB-configuration is hybrid design with battery. In this configuration, the fuel cell system is considered as a „range extender", which recharges the battery during the drive cycle. The batteries themselves provide the main motive power for the bus [1].

Fig. 4 illustrates three different configurations of hydrogen-powered buses.

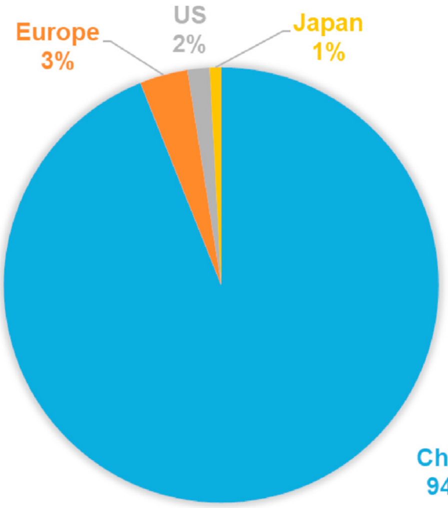

Fig. 3. Share of FCB-stock worldwide (Data source [36]).

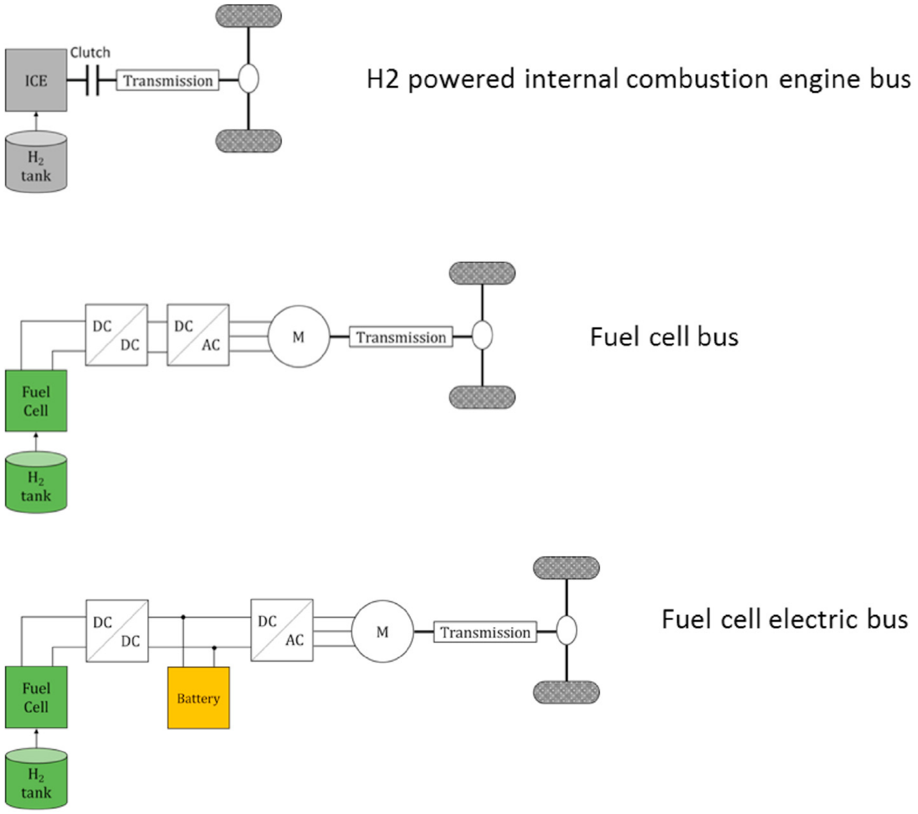

Fig. 4. Three types of hydrogen buses *(M is the electric motor).*

2.1. Survey on case studies

To support research and development of alternative bus solutions, the EU has funded a series of demonstration projects related to FCBs as well as corresponding infrastructure. The number of FCBs is continuously increasing due to such projects. The most important demonstration projects in Europe are listed in Table 1.

Over the last few years, it can be noticed increasing number of FCBs and hydrogen refueling stations. Moreover, it can be noticed increase in energy efficiency of FCBs [37,42,43], and decrease of their investment cost [44–47]. However, the hydrogen price remained on the same level.

The newest European funding project H2BUS EUROPE aims to address also this barrier by establishing a green hydrogen value chain with the goal to reduce hydrogen price to 5–7 € per kilogram [37].

Table 2 shows an overview of the major characteristics of the FCBs currently used in European cities. Most of them are standard fuel cell electric buses. With the European funding projects, more and more manufactures are stimulated to enter the FCB-market.

3. Methods

For the mostly used hybrid FCB configuration, we have conducted economic and environmental assessment using most recent input data from already on-going demonstration projects. In our sensitivity analysis, we have also considered some expectations announced for the future cost developments.

3.1. Economic assessment

The major barriers for the faster penetration of FCBs are their high costs in comparison to conventional diesel buses. In the following, we have calculated total costs of the use (TCU) of FCBs in Austria in comparison to diesel and battery electric buses, which are already in uses in many Austrian cities. Moreover, in order to understand the impact of different parameters on the total costs we have conducted sensitivity analyses.

The total costs of mobility with buses analysed are calculated considering their investment costs (IC), driven distance per year (d), their energy costs (C_E) and other operating and maintenance cost ($C_{O\&M}$):

$$TCU = \frac{IC_i \cdot \alpha}{d} + C_{E_i} + \frac{C_{O\&M_i}}{d} \quad [\notin / km] \tag{1}$$

The capital recovery factor (α) is calculated depending on the discount rate (r) over the analysed period (n):

$$\alpha = \frac{(1+r)^n \cdot r}{(1+r)^n - 1} \tag{2}$$

The energy costs C_E are dependent on the average energy consumption of the buses (E_i) and the corresponding energy (diesel, hydrogen and electricity) prices (P_{Ei}):

$$C_{E_i} = E_i \cdot P_{E_i} \quad [\notin / km] \tag{3}$$

The labour cost for the drivers, are not included in this calculation, since these costs are the same for all bus types analysed.

In our base case we have calculated with the current Austrian energy price data [52,53]. In this case we have calculated with the exemptions of registration- and value add tax. The major bus characteristics, such are energy consumption, costs, etc., are taken from literature [39,54–57]. Major input data and assumptions for our calculations are given in Table 3.

Table 1
Major demonstration projects in Europe.

Project name & duration	No. of buses	Locations	Main goal
CUTE [37] (Clean Urban Transport for Europe) 2001–2005	27	Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm, Stuttgart	- to demonstrate the reliability of FCB and their supply infrastructure in regular public transport service, with a wide range of operating conditions.
HyFLEET: CUTE [38] 2006–2009	47 (33 FCEB and 14 ICEB)	Amsterdam, Barcelona, Berlin, Hamburg, London, Luxembourg, Madrid, Perth, Peking, Reykjavik	- to ensure the continuation of the operation of the CUTE FCB fleet and extended it also to H2 powered ICEB.
CHIC [39] (Clean Hydrogen in European Cities) 2010–2016	58 (54 FCEB and 4 ICEB)	*Phase 0*: Berlin, Cologne, Hamburg, Whistler *Phase 1:* Aargau, Bolzano, London, Milan, Oslo	- to demonstrate that FCB are ready for full commercial deployment.
HIGH V.LO-CITY [40,41] 2012–2019	14	Aberdeen, Antwerp, Groningen, San Remo	- to speed up the integration of last generation FCB in public transport service.
HyTransit [42] (European Hydrogen Transit Buses in Schotland) 2013–2019	6	Aberdeen	- to operate FCB on long intercity routes in everyday public transport service.
3EMOTION [43] (Environmentally friendly Efficient Electric Motion) 2015–2022	29	Aalborg, London, Pau, Rotterdam, Versailles	- to bridge the gap between former FCB demonstration projects and the deployment on a larger scale.
MEHRLIN [44] (Models for Economic Hydrogen Refueling Infrastructure) 2016–2020	7H_2 refueling stations	Birmingham, Bolzano, Cologne, London, Rotterdam, Wuppertal	- to focus on the financial aspects of H_2 refueling stations serving FCB fleets.
JIVE [44,45] (Joint Initiative for hydrogen Vehicles across Europe) 2017–2022	139	Aberdeen, Birmingham, Bolzano, Cologne, Herning, London, Rhein-Main, Wuppertal	- to accelerate commercialization and cost reduction of FCB.
JIVE2 [44,46] 2018–2023	152	Akershus, Auxerre, Cologne, Dundee, Gatwick Airport, Gävleborg, Groningen, Pau, Reykjavik, South Holland, Toulouse, Wuppertal	- to reduce the investment cost of FCB down to 625,000 €.
H2BUS EUROPE [47] 2019–2023	600–1000	Denmark, Latvia and UK, (Norway, Sweden, Germany)	- to realize the deployment of 1000 FCB and the necessary infrastructure with competitive cost in European cities and to reach significant reduction of the investment costs.

Table 2
Overview of FCB manufacturers (Data sources [48–51].

	Van Hool bus	Evobus	Solaris	Wright bus
Bus type	Standard FCB	Standard FCB	Articulated FCB	FCB with supercapacitors
Bus length (m)	12/13	12/13	18,75	12
Fuel cell system (kW)	150	120	100	75
Battery system (kW)/	100	250	120	
Supercapacitor system (kW)				240
Hydrogen storage system	7 tanks, 350 bar	7 tanks, 350 bar	9 tanks, 350 bar	4 tanks, 350 bar
Full tank capacity (kg)	35	35	45	33

Table 3
Major input data and assumptions for the TCU calculation (2018).

	Diesel ICEB	FCB	BEB
Discount rate (r)	5%	5%	5%
Analysed period (n)	14 a	14 a	14 a
Driven distance (d)	45,000 km/a	45,000 km/a	45,000 km/a
Energy price (P_E)	0.90 €/l_{diesel}	7.50 €/kg_{H2}	0.15 €/$kWh_{electricity}$
Specific energy consumption (E)	35.0 l_{diesel}/100 km	9.0 kg_{H2}/100 km	1.27 $kWh_{electricity}$/km
O&M cost ($C_{O\&M}$)	0.27 €/km	0.24 €/km	0.20 €/km
Investment cost (IC)	250,000 €	630,000 €	370,000 €

Results of our economic analysis are documented in Section 4.

3.2. Environmental assessment

The major reason to consider replacement of diesel buses with FCBs is due to some environmental advantages. For their use in urban areas, it is huge benefit that they have zero emissions at the point of use. They are also able to reduce noise level up to 60% [57]. Moreover, they can significantly contribute to the CO_2 emission reduction depending on the hydrogen production method and primary energy sources used.

In this paper, we are making difference between ‘grey’ and ‘green’ hydrogen. The grey hydrogen is hydrogen produced by a central steam methane reformer, stored with 200 bar in gas bottle bundles and then transported on a trailer over a distance of 200 km to the hydrogen refueling station resulting in a CO_2 emission factor of 13.20 $kgCO_{2eq.}$ per kg H_2 at nozzle [2]. The green hydrogen is produced in electrolyser using electricity from renewable energy sources. For this scenario, we calculate with a CO_2 emission factor of 0.7 $kgCO_{2eq.}$ per kg H_2 at nozzle [2].

The CO_2 emission factor of electricity for BEBs strongly depends on the electricity mix which can be with a high share of fossil energy such as in Germany, or with high share of renewable energy such as in Austria. The average electricity mix of EU-28 has a CO_2 emission factor somewhere in between these two exemplary countries [58].

Table 4 gives an overview of CO_2 emission factors used for different fuel types, including well-to-tank (WTT) and tank-to-wheel (TTW) emissions. Since FCBs and BEBs have zero emissions at the point of use, the TTW emissions are only relevant for diesel buses, see also Fig. 11.

Finally, CO_2 emissions over the lifespan (n) of the buses are dependent on the level of travel activity (d), the energy intensity of the buses (E), and the carbon content (emission factor) of the energy used (f_{CO2}). The relationship between these parameters is represented mathematically by following equation:

$$CO_{2_i} = E_i \cdot d \cdot n \cdot f_{CO_{2i}} \tag{4}$$

Results of our environmental analysis are documented in the next section. Note that the focus is put on Well-to-Wheels (WTW) emission analyses. This approach differs from a Life Cycle Analysis (LCA), as it does not consider energy and emissions involved in building facilities and the vehicles, or emissions related to the end of life. WTW analysis focuses on lifetime energy use and corresponding GHG emissions.

4. Results and Discussion

The results of this work are divided in two major categories: (i) economic assessment and (ii) environmental assessment.

4.1. Economic assessment

The major barriers for the faster penetration of FCBs are their high costs in comparison to conventional diesel buses. In this paper, we have calculated total mobility costs of FCBs in Austria in comparison to diesel and battery electric buses.

For the three bus types analysed, the total cost of the bus use per km driven are depicted in Fig. 5. It is obvious that the investment costs of FCBs are far away from the possible competitiveness with diesel buses, as well as with BEBs. Beside high investment costs, FCBs have also very high fuel costs due to high hydrogen prices. Only operating and maintenance costs of the FCBs are similar to those of diesel buses and BEBs.

To estimate major impact parameters on the total costs of the bus use per km driven, we have conducted sensitivity analysis. By varying different parameters - the distance driven, hydrogen price and the lifetime of the buses - one after the other, their influence on the total cost structure is assessed.

Regarding the range of bus kilometres driven per year, there is a wide range in the literature. For example, Potkány et al. [54] calculate with a driving distance of about 72,000 km per year for the regular bus line Trnavské Mýto – Vajnory in Bratislava, Slovakia. Müller et al. [39] report about common bus ranges up to 250 km per day, e.g. in Bolzano. In Berger [57], 250 km per day is used in the minimum range scenario, resulting in about 87,500 km per year. In addition to our base case where we have calculated with 45,000 km per year, for the sensitivity analysis we have calculated with 90,000 km per year, see in Fig. 6 "variation of km". With an increasing number of km driven, the cost difference between buses analysed decreases, especially between diesel and BEBs. With "variation of life-time" a lifetime reduction from 14 years in the base case to 8 years is analysed. It can be seen, that shorter lifetime is especially unfavourable for FCBs and BEBs. Finally, the case of a lower H_2-price (5 €/kg instead of 7.5 €/kg), Fig. 6 shows that lower hydrogen price has moderate impact on the total cost of FCBs which are largely dominated by capital cost. To reach market competitiveness of FCBs it is essential to reduce their investment cost.

Table 4
CO_2 emission factors of different fuel types [2,58–60].

Fuel type	CO_2 emission factor (f_{CO2})
Diesel	3.13 $kg_{CO2eq.}/l_{diesel}$
'Grey' H_2	13.20 $kg_{CO2eq.}/kg_{H2}$
'Green' H_2	0.7 $kg_{CO2eq.}/kg_{H2}$
Electricity EU-28	0.2958 $kg_{CO2eq.}/kWh_{el.}$
Electricity Austria	0.0851 $kg_{CO2eq.}/kWh_{el.}$
Electricity Germany	0.4408 $kg_{CO2eq.}/kWh_{el.}$

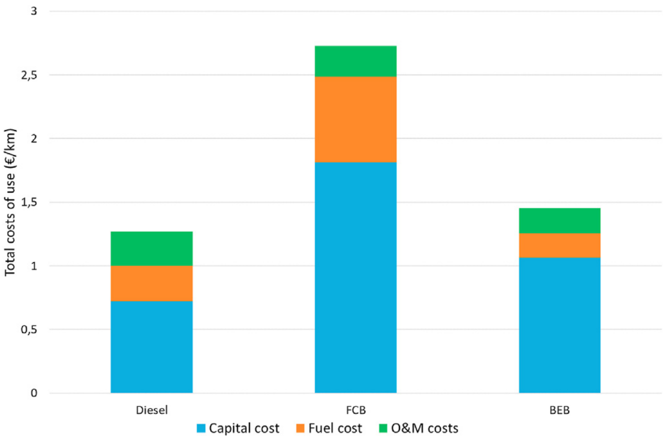

Fig. 5. Total cost of use of diesel-, fuel cell- and battery electric busses, 2018.

In addition, we have analysed the future costs in a scenario up to 2050. In this scenario it is assumed that with increasing deployment of FCBs and BEBs, their investment costs could become considerably lower due to technological learning. These scenarios for the development of the investment costs of diesel-, electric- and fuel cell buses are shown in Fig. 7.

Moreover, in this scenario, we have also calculated with a reduction in hydrogen price as shown in Fig. 8. Fig. 8 depicts the development of the fuel costs on a yearly base. As can be seen from this figure, by around 2040 the fuel costs of FCBs will be lower than those of diesel buses.

The major reason for the decrease in hydrogen costs is the assumed technological learning effect of the electrolysers. However, electricity prices are slightly increasing because of increasing costs for grid extention and the construction of new power plants. The efficiency of all technologies is increasing, but also additional energy consuming services of vehicles. At least, over the last years, most of the energy efficiency improvements on conventional cars were offset with increasing car power or additional energy services in vehicles. In this paper we have assumed, increasing CO_2 taxes on fossil energy inputs which have a clear impact on diesel and a slight impact on electricity prices.

The results of the analysis for the TCU on a yearly base up to 2050 are illustrated in Fig. 9. As can be seen from this figure already by about 2027 the total costs of BEBs can be lower than those of diesel buses and by 2050 all three bus types end up with total costs in similar ranges.

Finally, Fig. 10 shows the results of this analysis for the breakdown of the total costs into capital, fuel and O&M costs. As can be seen from this figure already by 2030 the total costs of BEBs can be lower than those of diesel busses and by 2050 all three bus types end up with costs in similar ranges.

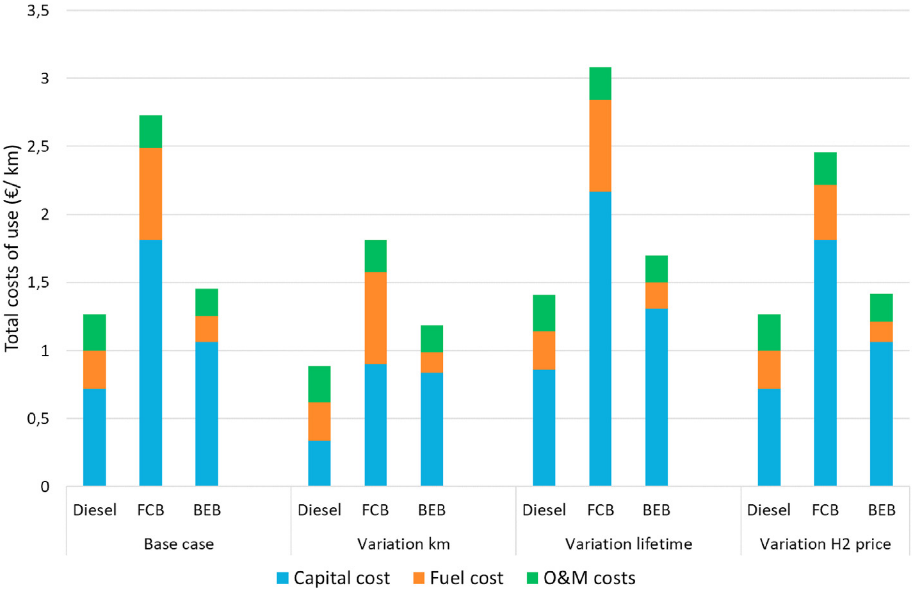

Fig. 6. Sensitivity analysis of total cost of bus use with respect to km driven, lifetime and hydrogen price, 2018.

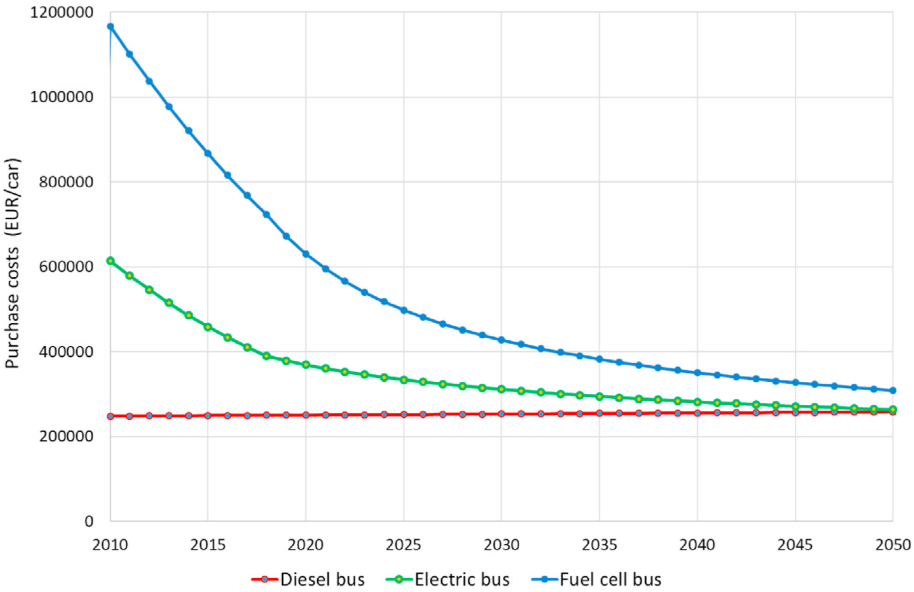

Fig. 7. Scenarios for the development of the investment costs of diesel-, electric- and fuel cell buses up to 2050 due to technological learning.

To increase use of alternative power trains in the transport sector many countries have provided different supporting measures. For example, in Austria, alternative solutions in the field of mobility management, fleets and logistics are supported within the #mission 2030 electro mobility campaign of the federal ministries BMNT (Federal Ministry for Sustainability and Tourism) and BMVIT (Federal Ministry of Transport, Innovation and Technology) with an overall budget of 93 million Euro [61]. Companies, regional authorities and associations can get the subsidies for FCBs as well as for BEB as shown in Table 5.

4.2. Environmental assessment

Although the economic analysis shows clearly that currently FCBs are not competitive with conventional diesel buses as well as with BEBs, they have some environmental advantages, which make them interesting for the future mobility system. Fig. 11 shows in comparison CO_2 emissions of standard 12 m buses. It compares diesel ICEB, FCB powered by grey and green hydrogen, and BEB powered with different electricity mixes: the average mix of the EU-28, Austrian- and German-mix.

It can be noticed that CO_2 emissions of the FCBs in combination with grey hydrogen are even higher than those of conventional diesel buses. However, with FCBs driven with green hydrogen significant emission saving can be reached. Table 6 shows an overview of the potential savings in CO_2 emissions that can be achieved by operating the alternative bus solutions instead of conventional diesel ICEB.

In this context, it is important to discuss the issue of “green” hydrogen. Oft FCBs and BEBs are considered as environmentally

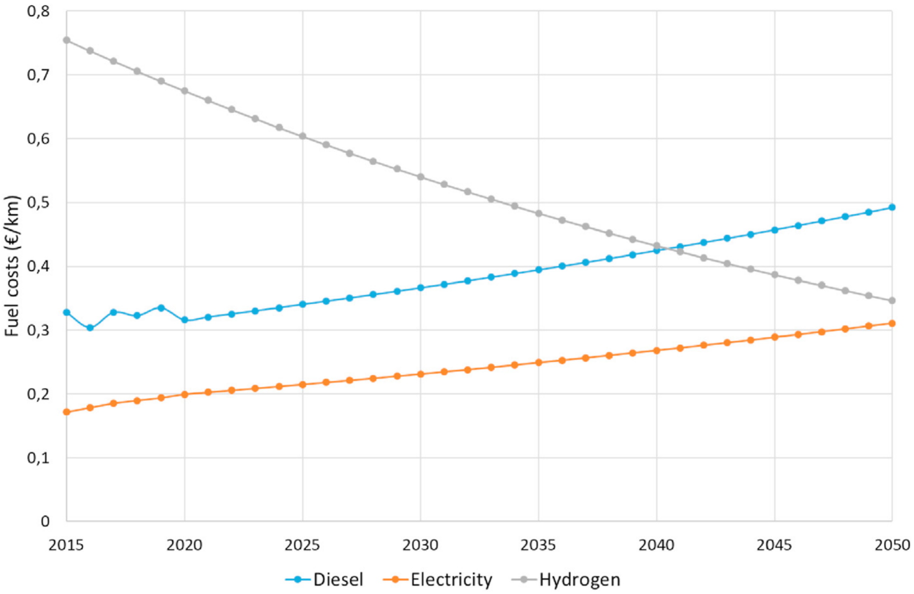

Fig. 8. Scenarios for the development of the fuel costs of diesel-, electric- and fuel cell buses up to 2050.

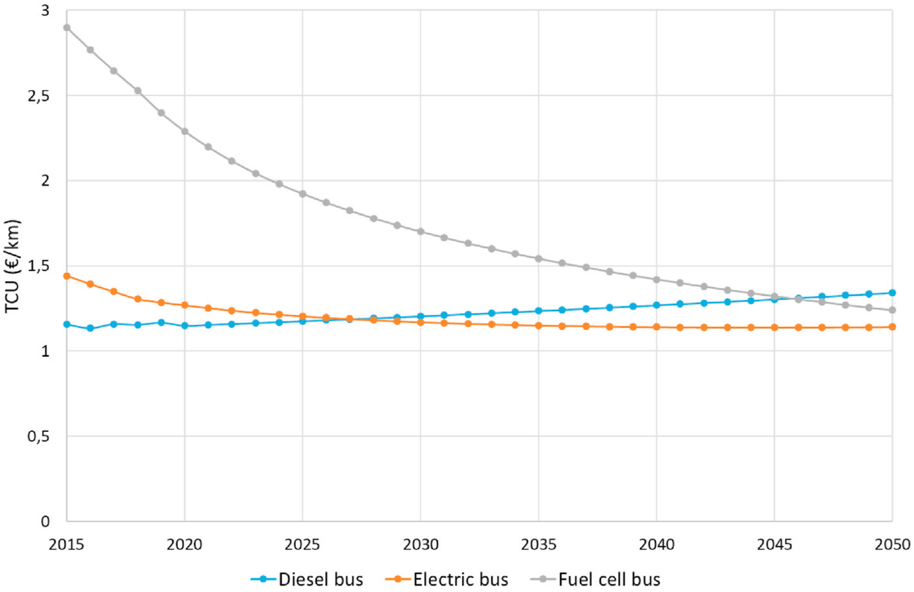

Fig. 9. Scenario for the development of the TCU of diesel-, electric- and fuel cell buses up to 2050 due to technological learning and decreasing hydrogen costs.

friendly technology. However, their environmental impact is very dependent on the primary energy sources used for electricity generation and hydrogen production. The full environmental benefits of these alternative buses could be reached only in combination with energy carriers produced from renewable or low carbon energy sources. Hence, it is obvious that use of FCBs make sense just in combination with hydrogen production from renewable energy sources. In this analysis the emissions caused during for bus manufacturing and maintenance are not included, due to very limited data sources. However, emissions caused during fuel production and bus operation have an overwhelmingly impact on the total emissions of the buses [2].

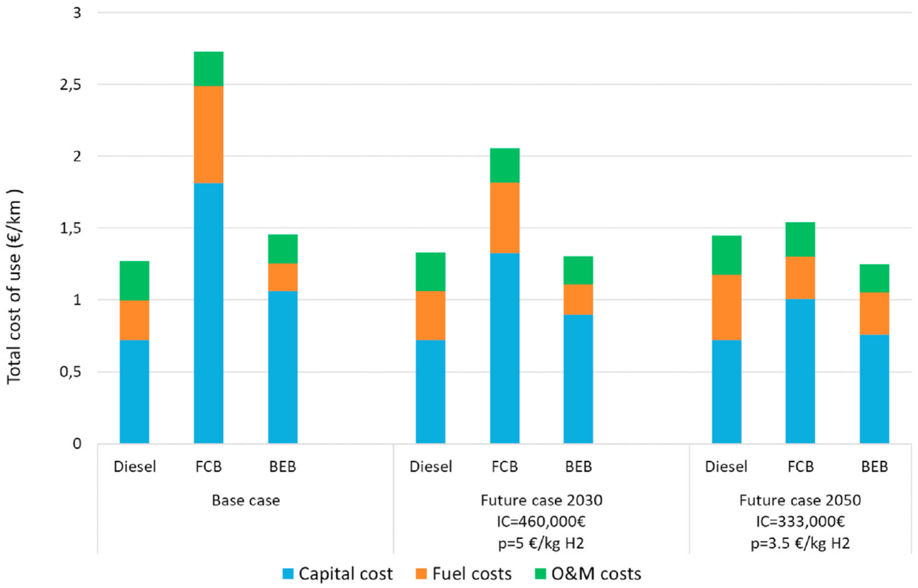

Fig. 10. Scenario for the breakdown of the total costs of diesel-, electric- and fuel cell buses in 2030 and 2050 due to technological learning and decreasing hydrogen costs.

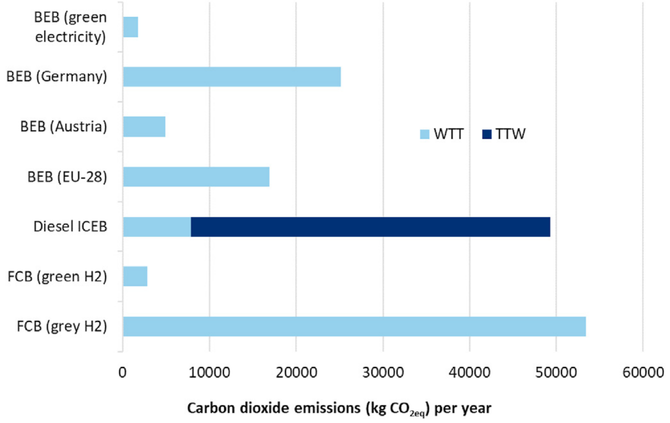

Fig. 11. WTT and TTW carbon dioxide emissions of different standard 12 m buses with 45,000 km driven per year.

Table 5
Subsidies for electric buses - battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV) - in Austria [62].

Vehicle class	Subsidy amount per vehicle
Class M3, up to 39 passengers	40,000 €
Class M3, 39 to 120 passengers	60,000 €
Class M3, more than 120 passengers	100,000 €

5. Conclusions

To cope with the increasing emissions from the transport sector it is necessary to increase use of alternative automotive technologies with zero or low carbon emissions. Zero-emissions alternatives are of special interest for polluted urban areas.

Public bus transport is currently mostly covered with diesel buses. Although theses buses have been significantly improved over time, they should be in the long-term replaced with more environmentally friendly buses such as FCBs and BEBs. However, these alternative solutions are still not economically competitive on the market, especially FCBs. Currently, FCBs are mostly used in different pilot and demonstration projects. Their total number is very low but increasing.

Although, FCBs are still immature technology they have significant potential for the emissions reduction in comparison to diesel buses if they are using green hydrogen up to 93%. From the environmental point of view, it is of absolutely highest priority to ensure by credible measures that the hydrogen is produced from renewable energy sources. Moreover, FCBs can reduce noise level and local pollution.

In the short-and mid-term BEBs are a more suitable alternative to conventional diesel buses in urban areas. However, in the long-term, especially when longer driving range is required, FCBs will be of interest.

The major barriers for their faster penetration are especially high investment costs of FCBs, which are currently about 40% higher than those of diesel buses. In the future, this could be reduced by harvesting technological learning effects. It can be expected that technological learning and economies-of-scale will

Table 6
Savings in CO_2 emissions during the operation of FCB and BEB compared to diesel ICEB.

Bus type	Savings in GHG emissions compared to diesel ICEB during the operation
FCB with ‘green’ H_2	93%
BEB with electricity from EU-28	59%
BEB with electricity from Austria	88%
BEB with electricity from Germany	39%

bring down the costs of the FCBs, as well as hydrogen costs. Already by about 2027 the total costs of BEBs can be lower than those of diesel buses and by 2050 total costs of all bus technologies analysed could be in a similar range. Currently, due to high purchase prices of the FCBs, impact of hydrogen prices on total mobility costs is relatively low.

For the broader use of FCBs it will be also necessary to make investments in infrastructure including hydrogen production, distribution and refueling stations. To encourage investment in hydrogen and fuel cells it is very important to have clear and stabile policy goals as well as corresponding policy framework. It would be very important to introduce CO_2 based taxes that reflect costs associated environmental damage caused by mobility.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

BEB	battery electric bus
CO_2	carbon dioxide
FCB	fuel cells bus
FCEB	fuel cells electric bus
GHG	greenhouse gas
H_2	hydrogen
ICE	internal combustion engine
ICEB	internal combustion engine bus
M	electric motor
TTW	Tank to Wheel
WTT	Well to Tank
WTW	Well-to-Wheel

Credit author statement

Conceptualization: Ajanovic and Haas Methodology: Ajanovic and Haas Formal analysis: Ajanovic, Glatt and Haas Writing - Review & Editing: Ajanovic and Haas Visualization: Ajanovic; Glatt Project administration: Ajanovic, Glatt Funding acquisition: Ajanovic

References

[1] Zivanovic, Z., Perspectives of application of fuel cell electric buses – some experiences from their operation. Mobil Veh Mech. DOI: 10.24874/mvm.2017.43.02.05. 2017.

[2] Lozanovski A, Whitehouse N, Ko N, Whitehouse S. Sustainability assessment of fuel cell buses in public transport. Sustainability 2018;10(5). https://doi.org/10.3390/su10051480. 2018. 1480.

[3] UITP. Statistics brief. Urban public transport in the 21st century. 2017. accessed on 29 February 2020, http://www.uitp.org/urban-public-transport-21st-century.

[4] UITP. Statistics brief. Global bus survey. 2019. accessed on 29 February 2020, www.uitp.org/global-bus-survey-2019.

[5] ACEA. Fact sheet. What are buses?. 2017. accessed on 6 January 2020, https://www.acea.be/publications/article/fact-sheet-buses.

[6] Elementenergy. Commercialisation of hydrogen fuel cell buses. Discussion paper. October. 2017. http://www.element-energy.co.uk/wordpress/wp-content/uploads/2018/01/FC-bus-commercialisation-White-Paper_October-2017.pdf.

[7] feeets Clean. Celan buses – experience with fuel and technology options. February 2014. www.claen-fleets.eu.

[8] Ajanovic A, Haas R. Economic and environmental prospects for battery electric- and fuel cell vehicles: a review. Fuel Cell 2019;19(5):515–29. https://doi.org/10.1002/fuce.201800171.

[9] Pollet BG, Kocha SS, Staffell I. Current status of automotive fuel cells for sustainable transport. Current Opinion in Electrochemistry August 2019;16:90–5. https://doi.org/10.1016/j.coelec.2019.04.021.

[10] Manoharan Y, Hosseini SE, Butler B, Alzhahrani H, Fou Senior BT, Ashuri T, Krohn J. Hydrogen fuel cell vehicles; current status and future prospect. Appl Sci 2019;9:2296. https://doi.org/10.3390/app9112296.

[11] Smaragdakis S Kamenopoulos, Tsoutsos T. How risky is the introduction of fuel cell electric vehicles in a mediterranean town? Int J Hydrogen Energy 10 July 2020;45(35):18075–88.

[12] Santarelli M, Cali M, Bertonasco A. Different fuelling technologies for urban transport bus service in an Italian big town: economic, environmental and social considerations. *Energy Convers* Manag 2003;44:2353–70.

[13] Stempien JP, Chan SH. Comparative study of fuel cell, battery and hybrid buses for renewable energy constrained areas. J Power Sources 2017;340:347–55.

[14] O'Garra T, Mourato S, Pearson P. Analysing awareness and acceptability of hydrogen vehicles: a London case study. Int J Hydrogen Energy 2005;30:649–59.

[15] Bigerna S, Polinori P. Willingness to pay and public acceptance for hydrogen buses: a case study of perugia. Sustainability 2015;7:13270–89.

[16] O'Garra T, Mourato S, Garrity L, Schmidt P, Beerenwinkel A, Altmann M, Hart D, Graesel C, Whitehouse S. Is the public willing to pay for hydrogen buses? A comparative study of preferences in four cities. Energy Pol 2007;35:3630–42.

[17] Doyle D, Harris A, Chege S, Douglas L, Early J, Best R. Hydrogen fuel cell buses: modelling and analysing suitability from an operational and environmental perspective. *WCX SAE* world congress experience. 2020. ISSN: 0148-7191. e-ISSN: 2688-3627, https://www.sae.org/publications/technical-papers/content/2020-01-1172/.

[18] Vandenborre H, Sierens R. Greenbus: a hydrogen fuelled city bus. Int J Hydrogen Energy 1996;21(6):521–4.

[19] Frey HC, Rouphail NM, Zhai H, Farias TL, Goncalves GA. Comparing realword fuel consumption for diesel- and hydrogen-fueled transit buses and implication for emissions. Transport Res Part D 2007;12:281–91.

[20] Wang Y, Moura SJ, Advani SG, Prasad AK. Optimization of powerplant component size on board a fuel cell/battery hybrid bus for fuel economy and system durability. Int J Hydrogen Energy 5 July 2019;44(33):18283–92. https://www.sciencedirect.com/science/article/abs/pii/S0360319919320476.

[21] Yogesha SA, Brahmbhatt S, Raja M, Arikapudi S, Bhut B, Jaikumar V. Development of hydrogen fuel cell bus technology for urban transport in India. *SAE technical paper* 2019-26-0092. 2019. https://doi.org/10.4271/2019-26-0092.

[22] Ally J, Pryor T. Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems. J Power Sources 2007;170:401–11.

[23] Ally J. Life cycle assessment (LCA) of the hydrogen fuel cell, natural gas, and diesel bus transportation systems in western Australia. Perth: Murdoch University; 2008.

[24] Lee DY, Elgowainy A, Vijayagopal R. Well-to-wheel environmental implications of fuel economy targets for hydrogen fuel cell electric buses in the United States. Energy Pol May 2019;128:565–83. https://doi.org/10.1016/j.enpol.2019.01.021.

[25] Lajunen A, Lipman T. Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. Energy 2016;106:329–42. https://doi.org/10.1016/j.energy.2016.03.075.

[26] Correa G, Muñoz P, Falaguerra T, Rodriguez CR. Performance comparison of conventional, hybrid, hydrogen and electric urban buses using well to wheel analysis. Energy 2017;141:537–49. https://doi.org/10.1016/j.energy.2017.09.066.

[27] Coleman D, Kopp M, Wagner T, Scheppat B. The value chain of green hydrogen for fuel cell buses – a case study for the Rhine-Main area in Germany. Int J Hydrogen Energy 14 February 2020;45(Issue 8):5122–33. https://doi.org/10.1016/j.ijhydene.2019.06.163.

[28] Bonilla O, Merino DN. Economics of a hydrogen bus transportation system: case study using an after tax analysis model. Eng Manag J 2010;22(3):34–44.

[29] Cockroft C, Owen A. Hydrogen fuel cell buses: an economic assessment. 2008. https://www.researchgate.net/publication/228835447_Hydrogen_Fuel_Cell_Buses_an_Economic_Assessment.

[30] Correa G, Muñoz PM, Rodriguez CR. A comparative energy and environmental analysis of a diesel, hybrid, hydrogen and electric urban bus. Energy 15 November 2019;187:115906. https://doi.org/10.1016/j.energy.2019.115906.

[31] Meishner F, Sauer DU. Technical and economic comparison of different electric bus concepts based on actual demonstrations in European cities. IET Electr Syst Transp 2020. https://doi.org/10.1049/iet-est.2019.0014.

[32] Olabi AG, Wilberforce T, Abdelkareem MA. Fuel cell application in the automotive industry and future perspective. Energy 2021;214:118955. https://doi.org/10.1016/j.energy.2020.118955.

[33] Ajanovic A, Haas R. Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. Int J Hydrogen Energy 2020. https://doi.org/10.1016/j.ijhydene.2020.03.122. Available online 7 April.

[34] IEA. The future of hydrogen: seizing today's opportunities. International

Energy Agency; June 2019.

[35] Ajanovic A, Hiesl A, Haas R. On the role of storage for electricity in smart energy systems. Energy 2000;1:117473. https://doi.org/10.1016/j.energy.2020.117473. June 2020.

[36] Deloitte. Fueling the future of mobility-Hydrogen and fuel cell solutions for transportation. Financial advisory. Deloitte China. 2020. https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf.

[37] IEA – International Energy Agency. Clean urban transport for Europe (CUTE) – hydrogen and fuel cell buses. 2019. accessed on 21 February 2020, https://www.iea.org/policies/3735-clean-urban-transport-for-europe-cute-hydrogen-and-fuel-cell-buses.

[38] Eltis: HyFLEET. CUTE is the world's largest hydrogen bus demonstration and research project. 2009. accessed on 21 February 2020, https://www.eltis.org/discover/case-studies/hyfleetcute-worlds-largest-hydrogen-bus-demonstration-and-research-project.

[39] Müller K., Schnitzler F., Lozanovski A., Skiker S., Ojakovoh M. Clean hydrogen in European cities, FCH JU (2017), D 5.3 – CHIC final report.

[40] Hyvlocity: Project summary, available online: http://highvlocity.eu/2012/about/project-summary/(accessed on 21 February 2020).

[41] FCH JU: Trial and deployment of fuel cell applications – transport, project posters, PRD 2019 panel, available online: https://www.fch.europa.eu/sites/default/files/Panel%201.pdf (ac-cessed on 21 February 2020).

[42] European Commission: European Hydrogen Transit Buses in Scotland, available online: https://cordis.europa.eu/project/id/303467/reporting (accessed on 5 March 2021).

[43] 3EMOTION: Environmentally friendly Efficient Electric Motion, available online: https://3emotion.eu/about-project (accessed on 6 January 2020).

[44] FCH JU: Towards clean public transport, leaflet about JIVE/JIVE2/MEHRLIN, available online: https://www.fuelcellbuses.eu/sites/default/files/documents/Leaflet_JIVE%20JIVE2%20MEHRLIN.pdf (accessed on 21 February 2020).

[45] European Commission: Joint Initiative for hydrogen Vehicles across Europe, available online: https://cordis.europa.eu/project/id/735582/de (accessed on 5 March 2021).

[46] European Commission: Joint Initiative for hydrogen Vehicles across Europe 2, available online: https://cordis.europa.eu/project/id/779563/de (accessed on 5 March 2021).

[47] Fuel Cell Electric Buses: H2Bus Europe, available online: https://www.fuelcellbuses.eu/projects/h2bus-europe (accessed on 6 January 2020).

[48] H2BUS. Leading players enabling true zero-emission hydrogen solution for public trans-portation. press release; 3 June 2019. accessed on 21 February 2020, http://h2bus.eu/onewebmedia/H2Bus.pdf.

[49] Fuel Cell Electric Buses Knowledge base. https://www.fuelcellbuses.eu/.

[50] Köln Regionalverkehr. Datenblatt A330 FCBrennstoffzellen-hybridbus der Regionalverkehr köln GmbH. 2018. accessed on 5 January 2020, https://www.rvk.de/fileadmin/images/Null_Emissio/2018_Datenblatt_Van_Hool.pdf.

[51] Solaris: zero emissions powertrains, product catalogue 2019/2020. October 2019.

[52] BMNT. Aktuelle treibstoffpreise. 2019. accessed on 24-11-2019, https://www.bmnt.gv.at/energie-bergbau/energiepreise/aktuelle-treibstoffpreise-europro-liter.html.

[53] Energie Oesterreichs. Daten und Fakten zum Strompreis in Österreich. 2019. accessed on 27 January 2020, https://oesterreichsenergie.at/daten-fakten-zum-strompreis.html.

[54] Potkány M, Hlatká M, Debnár M, Hanzl J. Comparison of the lifecycle cost structure of electric and diesel buses. Naše more 2018;65(4):270–5. https://doi.org/10.17818/NM/2018/4SI.20.

[55] Consulting Grütter. Förderung von Hybrid- und Elektrobussen Schlussbericht. February 2015.

[56] Stempien JP, Chan SH. Comparative study of fuel cell, battery and hybrid buses for re-newable energy constrained areas. J Power Sources 2017;340:347–55. https://doi.org/10.1016/j.jpowsour.2016.11.089.

[57] Berger R. Fuel cells and hydrogen applications for regions and cities vol 1 - consoli-dated technology introduction dossiers. FCH2 JU; September 2017.

[58] EEA. CO2 emission intensity. 2018. accessed on 24 February 2020, https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-5#tab-based-on-data.

[59] Umweltpakt Bayern: excel-Tabelle zur Berechnung der CO2-Äquivalent-Emissionen (CO2-Rechner). 2018. accessed on 24 February 2020, https://www.umweltpakt.bayern.de/energie_klima/fachwissen/217/berechnung-co2-emissionen.

[60] Ajanovic A, Haas R. On the environmental benignity of electric vehicles. J Sustain Dev Energy Water Environ Syst 2019;7(3):416–31. https://doi.org/10.13044/j.sdewes.d6.0252.

[61] BMNT and BMVIT. Faktenblatt "#mission2030 E-Mobilitätsoffensive. 2019. available online: https://www.bmvit.gv.at/dam/jcr:354ccac1-b2ec-4c1a-81bb-0e9dab1d6f9e/emoboffensive.pdf.

[62] Kommunalkredit Public Consulting: informationsblatt E-Mobilitätsmanagement, E-Flotten und E-Logistik. 2019. https://www.umweltfoerderung.at/fileadmin/user_upload/media/umwelt-foerderung/Dokumente_Betriebe/Fahrzeuge__Mobilitaet__Verkehr/UFI_Standardfall_Infoblatt_E-Mob.pdf.