Techno Economic feasibility study on Fuel Cell and Battery Electric Buses – Austria

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Abstract: The objective of this study is to evaluate and compare the carbon footprint and economic impact of the fuel cell electric buses (FCEB) and battery electric buses (BEB) that are to be deployed to replace the existing diesel bus fleet in the city of Graz, Austria. These buses have zero tailpipe emissions, but the production of fuel and bus components generate significant emissions. Secondary literature research, life cycle assessment (LCA), and total cost of ownership (TCO) are the methods employed in this study. Parameters benchmarked during the literature research are the inputs to estimate the LCA and TCO. It is found that the FECBs produce the lowest emissions only when operated on renewable electricity. BEBs suffer from problems of daily range during summers and winters. Hence, the possibility of implementing a mixed fleet of BEBs and FCEBs is considered as it solves the conundrum of range and costs.

Keywords: Global greenhouse gas emissions, battery electric bus, fuel cell electric bus, life cycle assessment, total cost of ownership.

1 Introduction

Transformation towards a cleaner energy is an important agenda on the United Nations sustainable development goals [1]. Clean energy is especially important in the mobility sector in the transformation in Austria, as transport has been the most polluting sector in the last decade [2]. Austria aims to transition towards zero emission public transport technologies by 2030 [3]. It is necessary to reduce 7 Mt CO_2-eq of global greenhouse gas emissions (GHG) in Austria to achieve the 2030 target [2]. Diesel buses used for public transportation are major contributors to global greenhouse gas (GHG) emissions in Austria. A project named *move2zero* aims to completely decarbonize the public transport system in the city of Graz, Austria [4]. In this study, feasibility of employing alternate zero emission buses in the city of Graz (which has a public transport fleet of 162 diesel buses) has been explored. 97 of the buses are 18 m articulated buses and 65 are 12 m solo buses. The alternate zero emission bus technologies considered are battery electric buses (BEBs) and fuel cell electric buses (FCEBs). Major drawbacks of the BEBs include the short range (<200 km), seasonally increased energy requirements (for heating and cooling), and long recharging period. 45 % of the routes in Graz have a daily range of more than 200 km. BEBs do not suffice operating in this high mileage requirement everyday throughout the year. FCEBs have a higher range (>350 km), energy sufficiency during different seasons, and lower refuelling period. But FCEBs are still technologically maturing and have high costs [5]. Hence, a scenario of a mixed/heterogenous fleet of BEBs and FCEBs have also been considered in order to meet the needs of the diverse topology of the routes by taking advantage of the benefits of both technologies. The objective of this study is to compare the carbon footprint of fuel cell dominant electric buses (FCEBs) and battery dominant electric buses (BEBs), to choose the best available option from both environmental and economic perspective.

2 Methodology

The methods employed in this study are market research, life cycle assessment (LCA), and total cost of ownership (TCO). LCA helps to analyse the impact of emissions of the buses from cradle to grave. TCO evaluates capital and operational expenditure of the buses for a comprehensive economic assessment.

2.1 Market research

Market research is carried out in the form of secondary literature research to analyse the state of the art of the buses and identify the FCEB and BEB manufacturers that are likely to be deployed in the city of Graz. Hence, the following important parameters related to the performance and configuration of the buses have been identified: range (km), overall bus lengths, passenger capacities, battery power (kW), battery capacity (kWh), battery type, fuel cell power (kW), energy storage type, energy storage power capacity (kWh), hydrogen (H_2) storage pressure (bar), number of hydrogen cylinders, hydrogen storage capacity (kg) and other vehicle components [6, 7]. This data from the market research forms the input basis for LCA and TCO.

2.2 Life cycle assessment

LCA, a tool used for environmental impact assessment is employed in this study to assess the carbon footprint of the buses from cradle to grave. First, well to wheels (WTW) assessment is used to estimate the emissions related to fuel production, distribution, and use:

1. Well-to-Tank (WTT)
   WTT phase consist of emissions during gaseous H_2 production and delivery to the hydrogen re-fuelling station (HRS) to fuel the FCEBs. For BEBs, the emissions during electricity generation for charging is considered.
2. Tank-to-Wheel (TTW)
   TTW assesses the emissions during the operation from the point of refuelling/recharging. Although for both FCEBs and BEBs, the GHG emissions during the operation is close to zero but there is a significant impact in the manufacturing of the buses and their components.
3. Well-to-Wheels (WTW)
   WTW involves combining emissions from WTT and TTW phases to estimate the carbon footprint of the fuel used for the buses.

Next step consists of adding the manufacturing and recycling GHG emissions of all the bus components to estimate the lifetime emissions of the buses from cradle to grave. The software used for LCA is GREET. Different pathways have been modified according to the specific case scenarios to estimate the total GHG emissions. The buses are assumed to be manufactured and assembled in Europe (EU). Hence pathways in the GREET model have been modified accordingly. The buses are then delivered for operation in Graz, Austria and the pathways have been modified in the GREET model to suit the local needs. The functional unit used is g CO_2-eq / km for WTW emissions. While lifetime fleet emissions use kt CO_2-eq / lifetime mileage.

2.3 Total cost of ownership

TCO (€ / km) is used to estimate the capital and operational expenditure of the buses. "*Total cost of ownership represents a philosophy which aims at understanding the total cost of a purchase from a particular supplier*" [8]. The approach of TCO evaluates the initial purchase investments and analyses the lifetime maintenance and operating costs:

$$TCO = \frac{V + F + K + D + I + M + S + B - R}{lifetime\ mileage}$$

Table 1: Explanation of the terms used in the TCO formula.

Symbols	Description
V	Cost of one bus (€)
F	Fuel cost over the lifetime of one bus (€ / kWh) or (€ / kg H_2)
K	Powertrain (battery/fuel cell stack) replacements cost (€)
D	Drive train maintenance cost per year per bus (€)
I	Refueling/recharging infrastructure costs (€)
M	Infrastructure maintenance cost per year (€)
S	Slow charging slot (€ / slot)
B	Fast charging slot (€ / slot)
R	Re-sale value of the bus (€)

3 Boundary Conditions

In this section, the boundary conditions pertaining to the FCEBs and BEBs have been detailed. The boundary conditions consist of the input for the LCA: electricity generation mixes, configuration of the buses, and operation of the buses.

Carbon intensity of the electricity grid has a positive correlation with the GHG emissions [9, 10].The required electricity has a significant impact on the fuel cell and battery production, raw material extraction, and assembly of the buses. The buses are manufactured in Europe. Therefore, an average EU electricity generation mix input has been used in the GREET model. These changes apply to the pathways and scenarios concerned with the manufacturing, production, and assembly of the buses. The BEBs operate on electricity and the FCEBs use gaseous hydrogen as the fuel. Electrolysis produces the purest form of hydrogen when compared to hydrogen extracted from hydrocarbon fuels [11]. The gaseous hydrogen in this study is produced through electrolysis as planned in the city of Graz, Austria. It is an energy consuming process consisting of the sub steps electrolysis, compression, storage, and transportation, which have significant environmental impacts. Hence electricity mix is an important indicator of carbon intensity during the WTT phase where the buses are recharged/refuelled.

European electricity generation mix has a carbon intensity of 270 g CO_2-eq / kWh in the year 2020. This is because of the combined contribution of 34% of electricity generation from natural gas and coal in Europe [12]. Whereas for the year 2030, a highly ambitious scenario for EU has been assumed where the fossil fuel share has been cut down to 4.5%, significantly decreasing the carbon intensity of the electric grid to 62.71 g CO_2-eq / kWh [13]. Austria's electricity has a low carbon intensity of 130 g CO_2-eq / kWh because of the high share of hydro power generating more than 60% of the electricity [12]. There is also a separate scenario developed for the year 2020 considering only the available renewable energy mix (consisting of hydro, wind, and solar power plants) for the generation of electricity in Austria at 19.87 g CO_2-eq / kWh [14]. Since Austria plans to produce electricity only through renewable energy power plants in 2030, the carbon intensity is even lower at 10.41 g CO_2-eq / kWh [3]. A lower carbon intensity in 2030 is also due to the assumption of technological maturity in each power plant, decreasing the overall carbon footprint compared to the year 2020.

Carbon intensity of the electricity mixes from the EU and Austria have a positive correlation with the GHG emissions during manufacturing and operation of the buses respectively. Table 2 shows the configuration of the buses that are considered as a possible replacement for the diesel bus fleet.

Table 2: Configuration and operational capacity of the benchmarked FCEBs and BEBs.

Manufacturer	**Solaris Urbino 12 Hydrogen (FCEB 12m)**	**Solaris Urbino 12 Electric (BEB 12m)**	**Solaris 18 m Hydrogen (FCEB 18m)**	**Solaris 18 m Electric (BEB 18m)**
Overall length [m]	12	12	18	18
Passenger capacity [no.]	80	80	120	120
Motor rater power [kW]	220	250	250	250
Fuel cell manufacturer	Ballard	-	Ballard	-
Fuel cell system power [kW]	70	-	150	-
Hydrogen cylinders (@350 bar) [no.]	5	-	5	-
Hydrogen storage capacity [kg]	37.5	-	40	-
Battery type	Li-ion NMC	Li-ion NMC	Li-ion NMC	Li-ion NMC
Battery capacity [kWh]	30	395	60	550
Refueling time	apprx 12 min	apprx 8 hours	apprx 15 min	apprx 11 hours
Range [km]	up to 350	apprx 200	up to 325	apprx 250
Fuel/energy consumption	8 kg H_2 / 100 km	220 kWh / 100 km	9.5 kg H_2 / 100 km	256 kWh / 100 km
Source	[15]	[15]	[16]	[16]

The bus manufacturing company Solaris has variants in both fuel cell dominant (FCEBs) and battery dominant electric buses (BEBs). The powertrain of an FCEB consists of a powerful fuel cell along with a small Li-ion battery pack coupled to the motor. Whereas the BEBs run solely on a larger Li-ion battery pack. The articulated 18 m buses along with the solo 12 m buses in both the variants have been considered. Both variants of FCEBs and BEBs are assumed to use regenerative break technology which recuperates 20% of total energy. Electrolyser efficiency of 65% is considered for the year 2020, while it is 80% for the year 2030 due to technological maturity [17].

4 Results and discussion

This section is divided into four parts. The first consists of comparison of GHG emissions between variants of FCEBs and BEBs operating on average Austrian electricity and solely on renewable electricity. The second section contains analysis of whether the considered variants suffice the daily range under different seasonal operating conditions. The third consists of the comparison of lifetime GHG emissions for different bus fleets for the years 2020 and 2030. And the final section comprises the TCO considering different bus fleet scenarios for the years 2020 and 2030.

4.1 GHG emission comparison

FCEBs and BEBs have negligible tail-pipe emissions unlike diesel buses. Significant GHG emissions are produced during the WTT and manufacturing phases. Figure 1 shows the GHG emissions (in g CO_2-eq / km) for 12 and 18 m variants of FCEBs and BEBs.

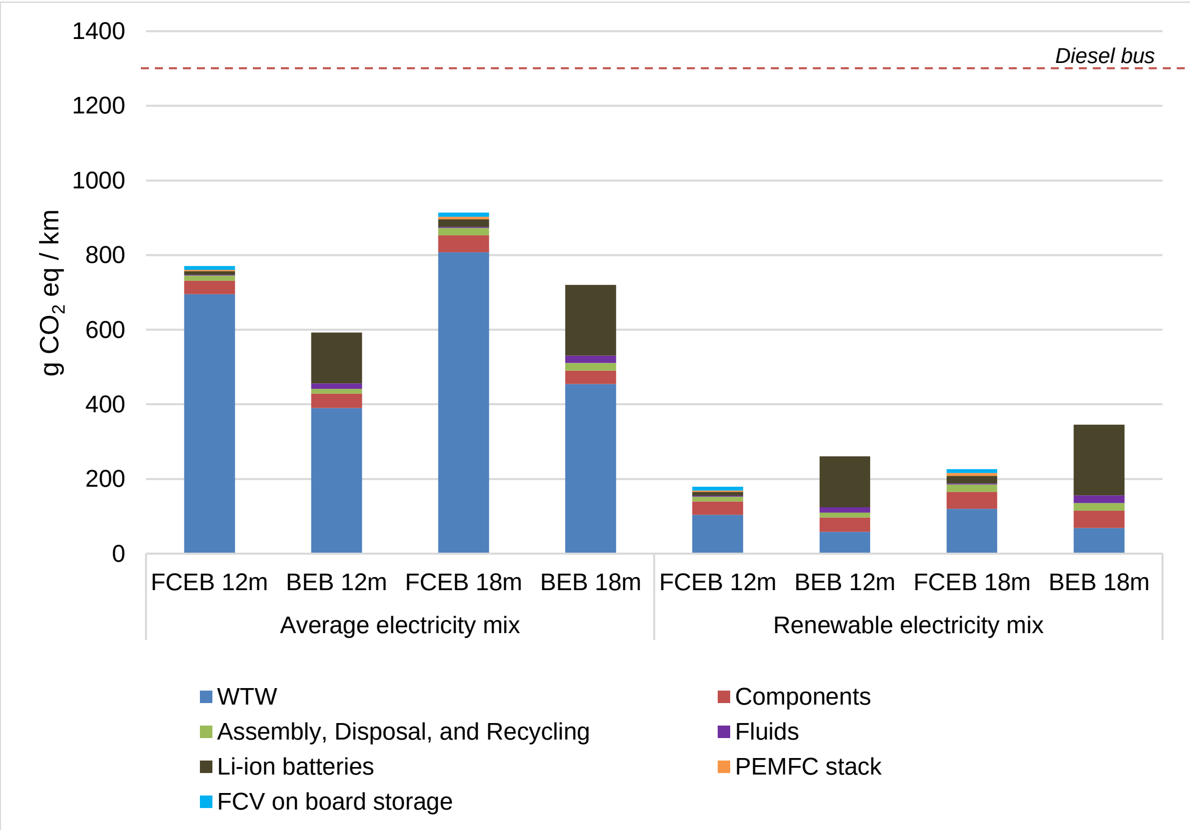

Figure 1:Comparison of GHG emissions of FCEB vs BEB variants.

The first four columns represent emissions from the buses operating on the average electricity mix in Austria. The next four are buses operating on renewable electricity mix in Austria. Since gaseous H_2 production is intensive, the WTT phase for FCEBs has high GHG emissions compared to the BEBs which only require electricity for recharging. All the buses have similar components like chassis, bus body parts, etc manufactured in Europe. Hence, there is only a proportional increase in emissions for components of 18 m buses as they need more material. The Li-ion battery stack has significantly higher GHG emissions than the fuel cell stack. Therefore, buses operating on average electricity mix produce emissions comparable to what a diesel bus produces on an average at 1,300 g CO2-eq / km. However, using renewable electricity mix for operation significantly decreases the emissions. The emissions regarding recycling of batteries and fuel cells are not included due to lack of consistent data.

4.2 Range and seasonal requirements

One of the major obstacles for the utilization of BEBs is the range. Graz has more than 45% routes which have a daily operation range of above 200 km [18]. There are currently 162 diesel buses in the fleet. 97 of which are articulated 18 m buses which are assigned for most of the short daily routes up to 200 km. While 65 buses (12 m) operate on the longer daily routes of more than 200 km. Since some of the longer routes are more than 250 km, the BEBs do not suffice on a normal operating condition using overnight charging station (ONC). This becomes a bigger obstacle when considering seasonal operation during summers and winters, as the range of BEBs at one full recharge decreases significantly. This is due to the high energy consumption for heating, ventilation, and air-conditioning (HVAC) systems inside the buses. As seen in figure 2, BEBs fall short of the 200 km mark but the FCEBs perform sufficiently in most of these routes along with the advantage of having a shorter refuelling period.

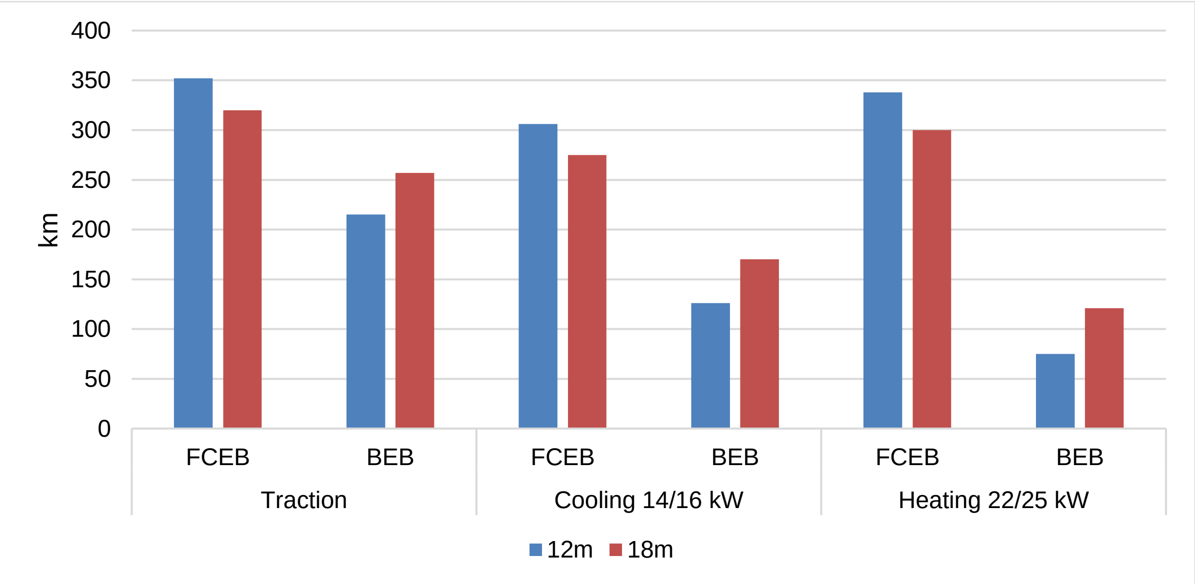

Figure 2: Mileage comparison of FCEB and BEB variants during different seasons.

It becomes necessary to add an extra fleet of 12 m BEBs to the BEB fleet operating on ONCs to cover the daily routes ranging above 200 km. Otherwise, opportunity charging station (OPC) must be implemented in the infrastructure which have higher costs. Hence, a heterogenous/mixed fleet has been taken into consideration. While the 18 m BEB fleet (97 buses) is used for daily routes below 200 km, 12 m FCEB fleet (65 buses) is used for routes above 200 km. The operating consequences in case of OPCs regarding required number of strategic charging stations within the city center, adaptions of operating schedules and associated risks have not been considered in this analysis.

4.3 Fleet lifetime emissions

The lifetime fleet emissions have been estimated considering various scenarios: homogenous FCEB fleet (162 buses), homogenous BEB fleet (227 buses), and a heterogenous/mixed fleet (97 of – 18 m BEBs and 65 of - 12 m FCEBs). Figure 3 shows the lifetime emissions (in kt CO_2-eq) of the bus fleet at an average lifetime mileage of 800,000 km for 15 years. The figure depicts a sensitivity analysis of lifetime emissions for the years 2020 and 2030 for different scenarios of homogenous BEB, FCEB fleets, and a heterogenous fleet. Emissions are estimated for operation considering both the average and renewable electricity mixes for 2020. Whereas for the year 2030, the electricity mix for operation is solely from renewable energy [3].

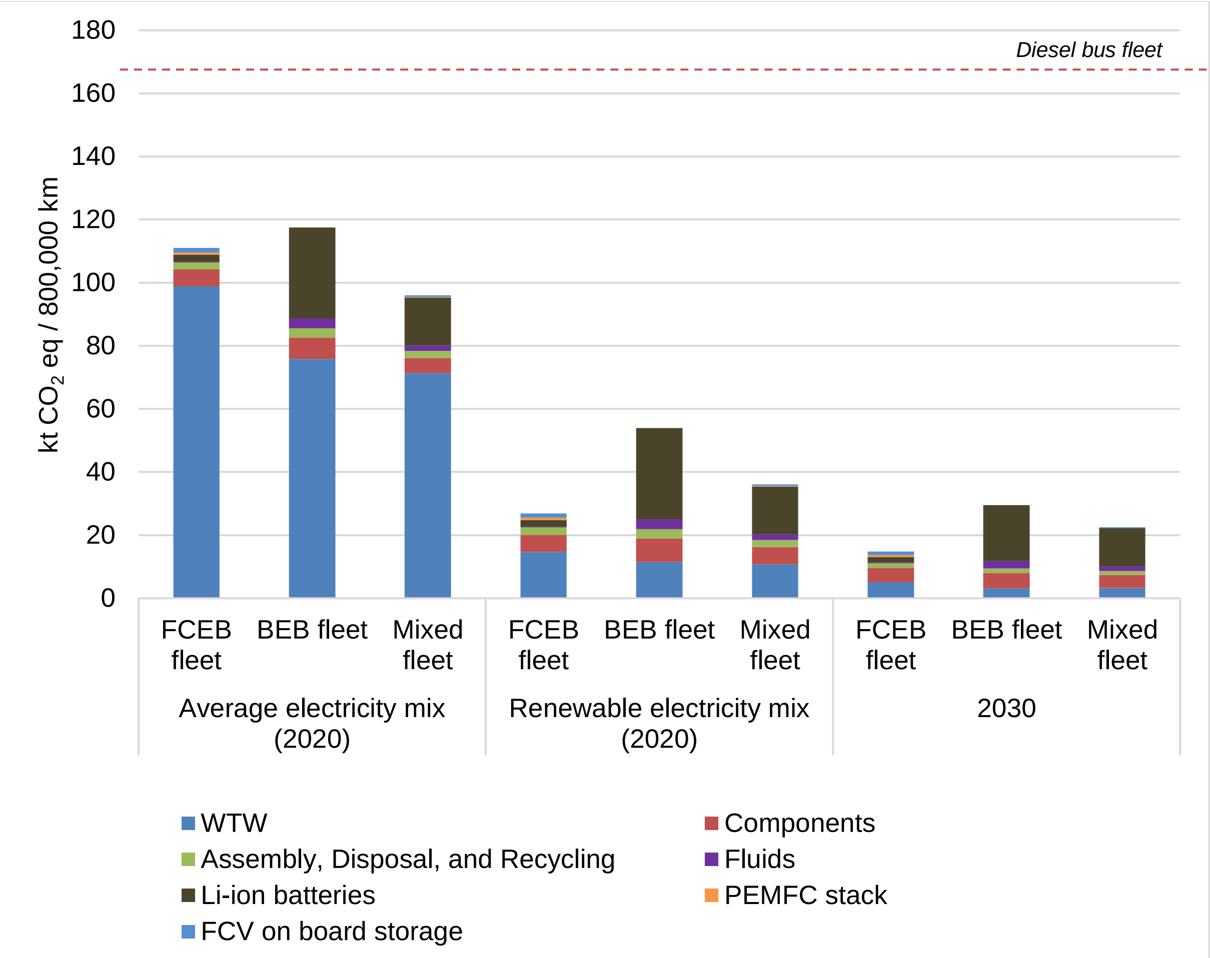

Figure 3: Lifetime GHG emissions comparison for differrent bus fleet scenarios.

A diesel bus fleet consisting of 162 buses produces approximately 166 kt CO_2-eq of GHG emissions. Both homogenous and heterogenous fleets being refuelled using the average electricity mix produce considerable amounts of emissions but emit significantly less GHGs when operated on renewable electricity. A heterogenous/mixed fleet has lower emissions than a BEB fleet when both the fleets are refuelled/recharged by renewable electricity. FCEB fleet refuelled by green gaseous H_2 leads to the least lifetime emissions.

4.4 Total cost of ownership

The TCO of BEBs using OPCs is higher than BEBs operating on ONCs because fast charging requires implementation of OPC slots which are more expensive and have higher electricity prices (0.4 Euro / kWh) compared to the fleet charged only using ONC. The homogenous FCEB fleet has a higher TCO compared to the BEB fleet because of high fuel and infrastructure costs. Although the heterogenous fleet of BEBs and FCEBs has a high initial infrastructure investment cost, it has a slightly lower TCO compared to the other scenarios because of not needing OPCs, lower electricity prices for recharging (0.1 € / kWh), and not requiring an extra BEB fleet. Figure 4 shows the TCO calculated considering the lifetime of the bus for different scenarios which include the homogenous fleet of BEBs operating on ONCs (227 buses) and OPC (162 buses), FCEB fleet being refuelled at HRS, and a heterogenous fleet where 97 - 18 m BEBs are charged at the ONCs and 65 - 12 m FCEBs are refuelled at HRS.

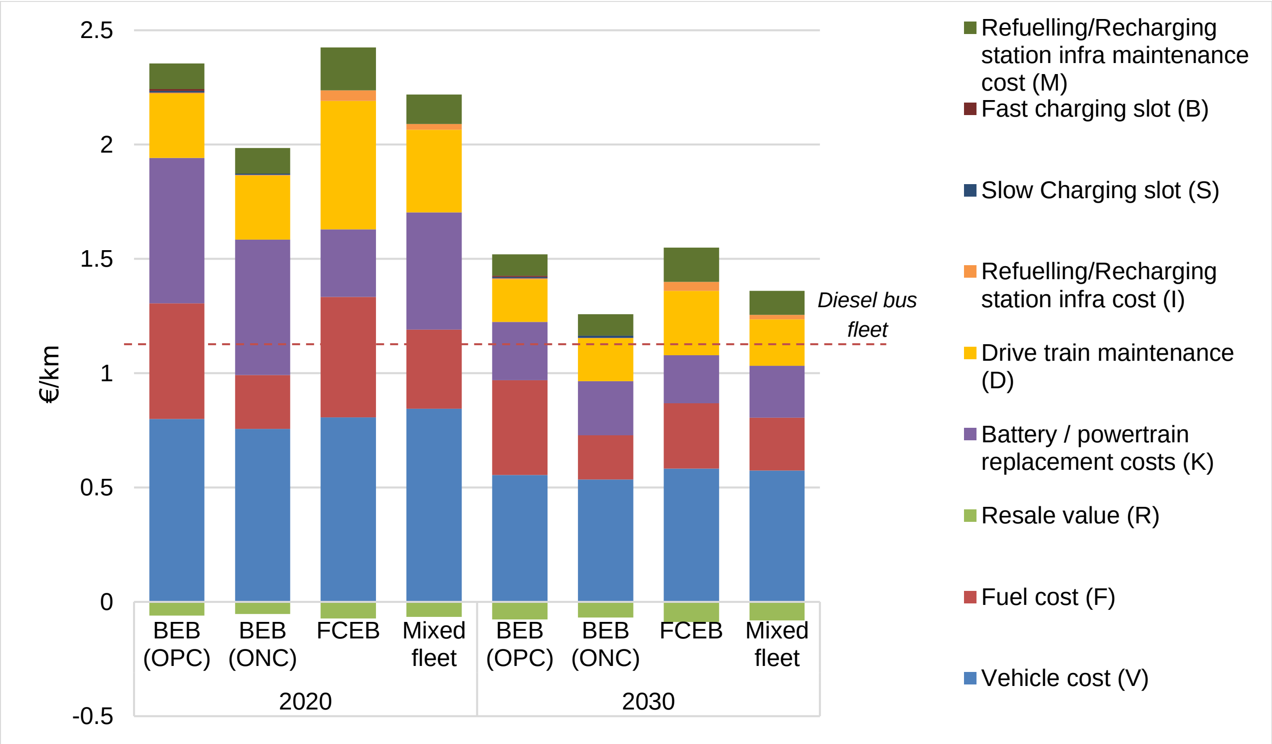

Figure 4: Comparison of TCO for different bus fleet scenarios.

5 Conclusion

This study has provided valuable information about the carbon footprint, mileage, and costs of the FCEBs and BEBs that are to be deployed in Graz, Austria. The results portray that carbon intensity of the electricity mix has a significant impact on the manufacturing and operation of both technologies. When operated on average Austrian electricity mix (year 2020), lifetime emission reduction potential of the BEB fleet (ONC), FCEB fleet, and the mixed fleet are 46 kt CO_2-eq, 56 kt CO_2-eq, and 70 kt CO_2-eq respectively. Electricity used during the WTT phase and production/assembly of the Li-ion batteries are the key contributors to the BEB emissions.

The primary contributor to the FCEB's emissions is gaseous H_2 production since it is an energy-intensive process. However, when operated solely on renewable electricity, lifetime emission reduction potential of the BEB fleet (ONC), FCEB fleet, and the mixed fleet are 111 kt CO_2-eq, 138 kt CO_2-eq, and 132 kt CO_2-eq respectively. The WTT phase for both BEBs and FCEBs initiates an emission reduction of 86% and 80% respectively. Nevertheless, the emissions from Li-ion batteries remain constant since there is no change in the electricity mix for manufacturing of the buses taking place in the EU. The drastic changes can be observed in the models simulated for the year 2030 due the lower carbon intensity of electricity both in Austria and in Europe.

TCO for different scenarios of BEB fleet (OPC), BEB fleet (ONC), FCEB fleet, and mixed fleet is 2.29 € / km, 1.93 € / km, 2.35 € / km, and 2.15 € / km respectively per bus. Fast-charging slots for BEBs (OPC) along with the higher electricity price of recharging at 0.4 € / kWh results in a high TCO. FCEBs have high initial investment and fuel costs, BEBs operating on ONCs have the lowest TCO.

In conclusion, the BEBs do not suffice the daily mileage and the Li-ion batteries used in BEBs produce high emissions but are technologically mature and cost effective. FCEBs suffice the daily mileage and produce lower emissions, but they are still in the technological maturity phase with high investment costs for buses and the associated refuelling infrastructure. The fuel cell stack used in the powertrains of FCEBs has a very high degree of recyclability whereas Li-ion batteries have a low degree of recyclability [5]. A possible solution to fulfil mileage and costs, while maintaining a high emission reduction, is to use a heterogenous/mixed fleet of BEBs and FCEBs. A mixed fleet has a median TCO and the daily range requirement for routes above 200 km can be satisfied using the 12 m FCEB fleet. Implementation of BEBs do not require major infrastructural changes when compared to FCEBs.

For emissions reduction, it is crucial that the electricity used to operate the buses comes from renewable sources. Excess electricity from the volatile renewable energy can be converted and stored as hydrogen. The batteries from the buses that have reached the end of life can also be used as secondary storage devices to store the excess electricity. However, more research is needed concerning recycling emissions of batteries and fuel cells. The LCA and TCO results provide a holistic insight about lifetime emissions and costs associated with alternate zero emission buses considered in this study. In addition, more in-depth and comprehensive analysis of individual bus routes would be necessary to support the transformation towards the public transport decarbonisation.

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