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Plug-in fuel cell electric vehicles: Are they more cost-efficient than battery electric vehicles?

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***Abstract*— Plug-in fuel cell electric vehicles (PFCEVs) emerge as promising zero-emission alternatives able to combine the efficiency of the battery with a fuel cell range extender. Thus, in this work, PFCEVs composed of different battery, fuel cell, and hydrogen tank sizes were investigated and compared to battery electric vehicles (BEVs) considering the cost of the propulsion system, powertrain energy consumption, and total fuel cost. The results show that PFCEVs are promising alternatives to the BEVs, showing about 10% lower total cost even for the scenario where the hydrogen price is high, and the electricity price is low. These results can be related to the higher cost and weight of the batteries to provide long-distance ranges for the BEVs. The PFCEV sizing showed that investment cost has more impact on the total cost of the vehicle than fuel consumption, supporting the use of smaller batteries, fuel cells, and hydrogen tanks.**

Keywords— road vehicle electric propulsion, hydrogen, fuel cell range extender, passenger vehicle, fuel cell vehicles

I. Introduction

Aiming at achieving zero carbon emissions in the transportation sector two main propulsion options stand out in the current scenario: battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). Even though both types of vehicles are commercially available in the market, over 99% of the sold electric passenger cars are BEVs, mainly, due to the simpler refueling infrastructure that allows home charging, and the higher "tank to wheels" efficiency compared to the FCVs. In this regard, while the battery itself has an efficiency of about 95%, the fuel cell system can hardly reach efficiencies of over 60%. However, despite its spread commercialization compared to the FCVs, the BEVs still face challenges that limit their application, such as their limited range and long charging (refueling) time, and in particular the cost of a long-range battery. Thus, extending the BEVs range comes along with requiring heavier batteries which increases the overall vehicle consumption, apart from the cost. On the other hand, FCVs allow long-distance driving with a refueling time of a few minutes [1-3]. In this scenario, plug-in fuel cell electric passenger vehicles (PFCEVs) emerge as an attractive candidate to combine the advantages of both a BEV and an FCV. In a PFCEV, the car would have both the battery and the fuel cell system, and it would allow its operation in both modes: BEV or FCV. Since about 95% of the drivers drive less than 100 km per day in their daily routine, the PFCEV could have a smaller battery compared to the conventional BEV to fulfill this need. Meanwhile, for longer trips the vehicle would function in a FCV mode, allowing longer driving distances [4-6].

Despite its potential as an electric vehicle, PFCEVs are currently not available in the market, and most of the current research investigation is aimed at heavier vehicles such as buses and trucks [7-10]. Regarding light-passenger PFCEVs, most of the research focuses on optimizing the control system [11-13]. Recently, component sizing of light-passenger PFCEVs and their comparison with commercial vehicles were also investigated [14,15]. For instance, in an optimization study aimed at hydrogen reduction, energy savings of up to 7% were estimated compared to commercial FCVs, showing the potential of PFCEVs to reduce fuel consumption [15]. However, the investigations so far have not focused on reducing the total cost of light-passenger PFCEVs in comparison to commercial BEVs which are currently the vehicles that dominate the electric vehicle market. Therefore, in this study, we aim to evaluate and compare PFCEVs with BEVs in terms of overall energy consumption and price, taking into consideration the battery, fuel cell, and hydrogen tank size and price. Thus, the main contributions of this work are:

• Comparison of PFCEVs with BEVs in terms of the powertrain energy consumption and cost of the propulsion system (battery, fuel cell, and hydrogen tank) accounting for the components' size, weight, and price.

• Evaluation of the total cost per km for the PFCEV and BEV considering the powertrain energy consumption, and the cost of the propulsion system combined with the electricity and hydrogen price for scenarios of low and high cost of the fuels.

• Quantifying the impact of different sizes of the battery, fuel cell, and hydrogen tank on the total consumption and total cost per km for the PFCEV model.

II. System Design and Modeling

A. System Diagram

The PFCEV powertrain, as shown in the diagram in Fig 1, was designed and modeled considering the following components: the wheels, the gear, the inverter and the motor, the battery, and the fuel cell system. Thus, the vehicle can run both with electricity-only (BEV mode) or with hydrogen (FCV mode) as the driver's choice. In the FCV mode, the battery also operates, considering the control strategy previously described in [16], in which the fuel cell provides power according to the battery state of charge (SOC) level. The simulation was conducted in MATLAB and the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) was used as the drive cycle reference. The simulations started with the battery at 90% SOC,

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and all the components were modeled in an electrical steady state.

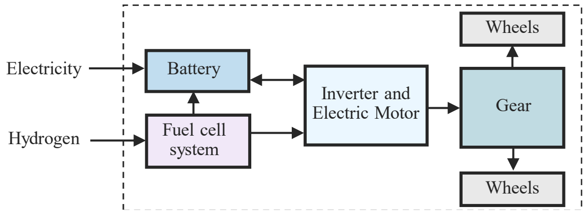

Fig. 1. System diagram for the plug-in fuel cell electric vehicle (PFCEV) considered in this model.

B. *Propulsion System*

The energy propulsion system for the PFCEV was composed of both the battery and the fuel cell system. The battery was a Li-ion battery with 3 mΩ cell resistance composed of 100 cells, as described in [17]. The nominal voltage of the battery was 380 V, and the battery capacity was considered to be in the range of 30-60 Ah. This range was selected after pre-simulations assuming that the vehicle should function in the BEV mode for distances between 50 and 100 km, following the driving range of most of the drivers as reported in [6]. For the comparison with a conventional BEV, battery capacities up to 400 Ah were also considered. To account for the weight difference among the different battery sizes, the Tesla Model S was considered and a value of 6,35 kg per kWh was assumed [18].

The fuel cell system was modeled by scaling down the fuel cell system curve from the Toyota Mirai for a maximum power of 30, 45, and 60 kW. This efficiency curve accounts for the fuel cell system composed of the fuel cell stack, the compressor, the pumps, and the converter [19]. To account for the fuel cell system weight, a fixed mass was assumed for the auxiliaries, and a value of 0.56 kg per kW (maximum power) was considered for the fuel cell stack, based on [20]. The hydrogen tank weight was considered proportional to the Toyota Mirai hydrogen tank, assuming a total capacity of 3 and 4 kg [21]. To address the propulsion system costs, a value of 300 € per kg of hydrogen capacity of the hydrogen tank was assumed, 140 € per kWh of the battery, and 36 € per kW of the fuel cell based on the information in [15]. Thus, since fuel cells are energy conversion devices and batteries are energy storage devices, the fuel cell energy storage is added separately and the fuel cell price itself is related to its maximum power. The relations of weight and prices considered in this study are summarized in Table 1 for both the PFCEV and the BEV model.

TABLE I. SIZE, WEIGHT, AND PRICE FOR THE BATTERY, FUEL CELL, AND HYDROGEN TANK USED FOR THE PFCEV AND BEV MODELS.

PFCEV			
System	**Battery**	**Fuel cell**	**H_2 Tank**
Size	30 - 60 Ah (380 V NV)	30 - 60 kW (max power)	3 e 4 kg (H_2 capacity)
Weight	6.35 kg/kWh	59 auxiliaries + 0.56 kg per kW	19 kg per kg H_2 capacity
Price	140 € per kWh	36 € per kW max power	300 € per kg H_2 capacity
BEV			
Size	120 - 400 Ah (380 V NV)	-	-
Weight	6.35 kg/kWh	-	-
Price	140 € per kWh	-	-

To calculate the average consumption the following data was considered. Most of the drivers drive less than 100 km per day in their daily routine, with an average of around 50 km per day. Trips over 200 km occur on average once a month [6]. The average driving range reported by the U.S. Department of Transportation is around 20k per year [22]. Therefore, to estimate the average consumption, we have considered that the PFCEV would drive 50 km per day for 29 days/month in the BEV mode, and 400 km one day/month in the FCV mode. Thus, the vehicle would drive 22.2 k km per year, driving 78,4% of the distance in BEV mode and 21,6% in FCV mode. This data was used to calculate the average PFCEV consumption.

To account for the total vehicle cost per km, considering initial investment, consumption, maintenance, and vehicle depreciation, the total cost of ownership,

$$TCO = \alpha \frac{IC}{tkm} + \frac{C_{o\&m}}{tkm} + P_f FI \quad (1)$$

was calculated based on [23], where α is the capital recovery factor, assuming 15 years of driving and a 0.8% interest rate based on European transportation inflation data [24]; IC is the initial investment of the propulsion system (battery, fuel cell, hydrogen tank) calculated as described in Table 1; $C_{o\&m}$ is the operation of maintenance cost assumed to be 2% of the total initial cost, and tkm the total traveled km per 15 years. The first two terms of (1) are referred to here as the total price for the propulsion system while, the third is referred to as the total consumption cost. For the consumption cost, values of 0.15 and 0.30 €/kWh were considered for the electricity price and 16 and 27 €/kg-H_2 for the hydrogen. These values were considered to represent scenarios of low and high electricity as well as hydrogen prices based on [25-28].

C. *Other powertrain components*

Besides the battery and the fuel cell system, the vehicle powertrain was also composed of the wheels, the gear, the inverter, and the electric machine. The system model was designed as follows: The wheels were modeled considering mathematical formulas for the vehicle dynamics forces: friction (aerodynamic drag), rolling resistance, and acceleration forces, as described in [29]. The vehicle parameters used are summarized in Table 2. The gear was designed as a single step with a ratio of 10 with 97% efficiency based on [30]. The inverter was a dc-ac IGBT 3-phase unit and the electric machine was an 8-pole PMSM previously described in [31,16].

TABLE II. VEHICLE MODEL PARAMETERS

Parameter (initials)	**Value (unit)**
Mass (m)	1400 + battery, fuel cell system and hydrogen tank (kg)
Air density (ρ_α)	1.225 (kg/m^3)
Aerodynamic drag coefficient (C_d)	0.3 (-)
Cross-sectional area (A_f)	2.1 (m^2)
Rolling resistance coefficient (C_r)	0.009 (-)
Gravity constant (g)	9.82 (m/s^2)
Wheel radius (r)	0.3 (m)

III. Simulation Analysis

A. Comparison with conventional BEV

The comparison of the PFCEV with the BEV was done in terms of energy consumption per km, the total investment cost, and finally, considering the total cost per km as described in (1). Thus, by first comparing in terms of energy consumption concerning range, it was found that the PFCEV consumed less energy than the BEV in the electric-only mode (BEV mode). Thus, even with the extra weight provided by the fuel cell system, the PFCEVs were found to be more efficient than the BEV in the BEV mode due to the high weight required from BEVs to achieve long-distance range. However, in the FCV mode, the vehicle consumes more energy than the BEVs due to the low efficiency of the fuel cell system compared to the battery. Nevertheless, regarding the average consumption, the PFCEVs consume less energy per km than the BEVs bigger than the 350 km range capacity since the vehicle would mostly drive in the electric-only mode, calculated as described in the previous section. Thus, it demonstrates the potential of these vehicles compared to the BEV. Fig. 2 shows the energy consumption per km in terms of vehicle driving range for both the PFCEVs and the BEVs. The different ranges for the FCV mode and PFCEV correspond to the different sizes of hydrogen tanks. The differences in consumption between the different PFCEV sizes will be discussed later.

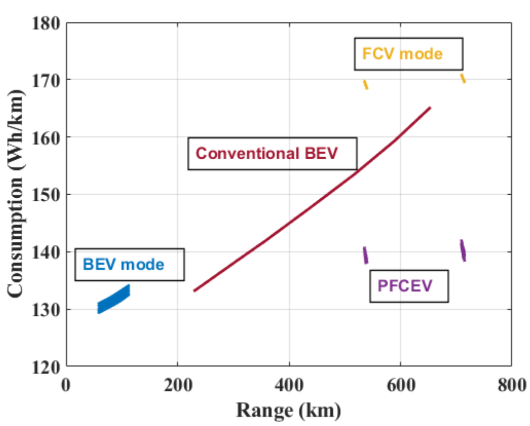

Fig. 2. Energy consumption per km versus range capacity of the vehicle for the PFCEVs (average values), along with their consumption in BEV and FCV mode as well as the values obtained for different ranges of BEVs.

Regarding the total investment considering the battery, the fuel cell system, and the hydrogen tank or just the battery for the BEVs, the PFCEVs presented lower costs for all the cases considered here compared to the BEVs with a range higher than 250 km. Thus, once more, it shows that PFCEVs are promising to be competitive with conventional BEVs. Fig. 3 shows the total investment price for the propulsion system for both vehicles versus the range capacity. The difference in the range for the PFCEVs corresponds to the different tank capacities. The sizing difference for those vehicles will be discussed later. For now, the TCO will be considered. Therefore, despite the lower price and lower energy consumption found so far for the PFCEV compared to the BEV, the difference in fuel price and other costs related to vehicle ownership should also be investigated to better evaluate the proposed scenarios, as described in the following.

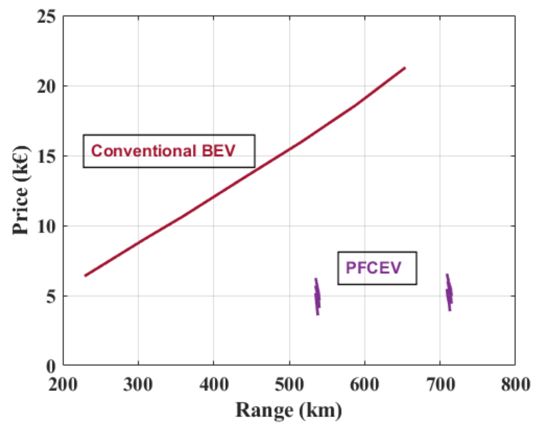

Fig. 3. Price of the investment cost for the propulsion system for the PFCEV (battery, fuel cell, and hydrogen tank) and BEV (battery) considering different range capacities.

The TCO, PFCEV, and BEV with a range capacity of around 500 km were compared. The BEV had a 300 Ah battery, and the PFCEV had a hydrogen tank of 3 kg. For this comparison, the PFCEV was composed of a 60-kW/60 Ah battery. So, it has about a 100 km range in the electric-only mode. The impact of TCO was divided into two parts, referred to the fuel consumption and propulsion system cost as previously described. The vehicles were compared in two different scenarios. The first one favors the FCV mode where the electricity price is high (0.30 €/kWh) and the hydrogen price is low (16 €/kg), and the second favors the BEV mode where the electricity price is low (0.15 €/kWh) and the hydrogen price is high (27 €/kg). In the first scenario, the total cost per km was about 40% higher for the BEV compared to the PFCEV. This result reinforces the potential of the PFCEVs to be more cost-efficient than the BEV, for the case where the hydrogen price is low. When the hydrogen price is high and the electricity is low, still the PFCEV shows a lower total cost per km, with a 10% difference in this case. This result can be related mainly to the high cost of the propulsion system for the BEV when the range capacity for this vehicle is as high as 500 km. Thus, it shows that even considering the current price fluctuation for hydrogen and electricity, the PFCEVs are promising alternatives to electric vehicles. Fig. 4 shows the results for the total cost per km for the BEV and PFCEV for the scenario where hydrogen has a low price and electricity has a high price, and Fig. 5 shows the scenario where hydrogen price is high, and electricity is low.

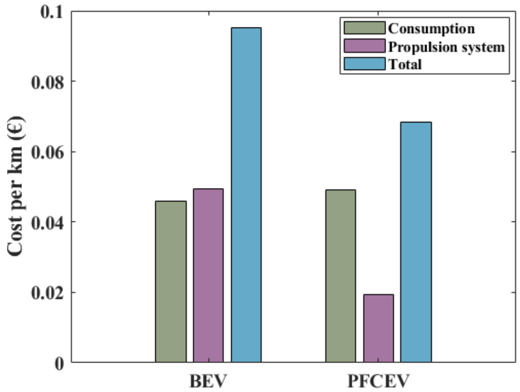

Fig. 4. Cost per km/€ for the fuel consumption, the propulsion system, and the total for the BEV and PFCEV for the scenario where hydrogen price is low and electricity price is high.

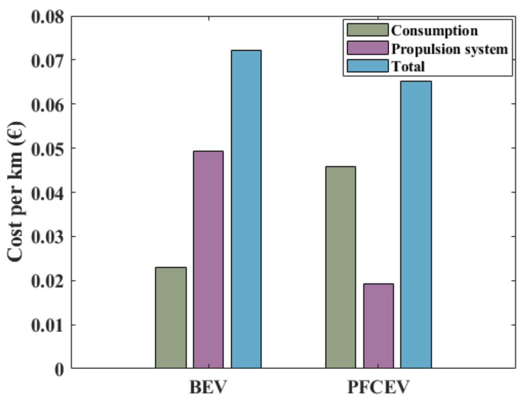

Fig. 5. Cost per km/€ for the fuel consumption, the propulsion system, and the total for the BEV and PFCEV for the scenario where hydrogen price is high and electricity price is low.

B. *PFECV battery, fuel cell, and hydrogen tank size effect*

To evaluate the impact of the battery, the fuel cell, and the hydrogen tank size for the PFCEVs, we have also considered the investment price, the energy consumption, and the total cost per km based on (1). In terms of price, the bigger the fuel cells, the battery, and the hydrogen tank, the higher the total price of the propulsion system, as shown in Fig. 6. Regarding the consumption, in the BEV mode, the PFCEVs with a bigger hydrogen tank have higher consumption than all the PFCEVs composed of smaller hydrogen tank sizes, as shown in Fig. 7. This shows that the weight impact of the hydrogen tank is higher than the weight impact of the fuel cell. Thus, smaller hydrogen tanks provide less consumption in the BEV mode, regardless of the fuel cell size. Concerning the battery size, the bigger the batteries, the higher the consumption in the BEV mode, related to the higher weight of those systems.

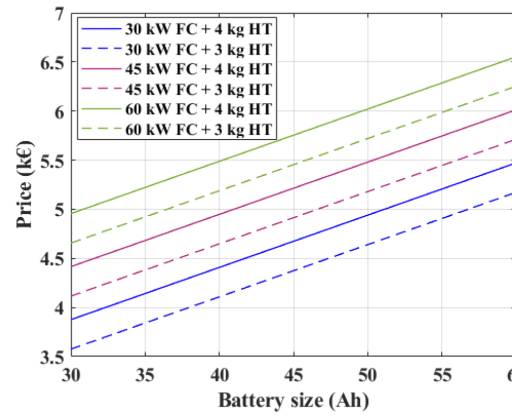

Fig. 6. Price of the investment cost for the propulsion system considering the different sizes of battery, fuel cell, and hydrogen tank.

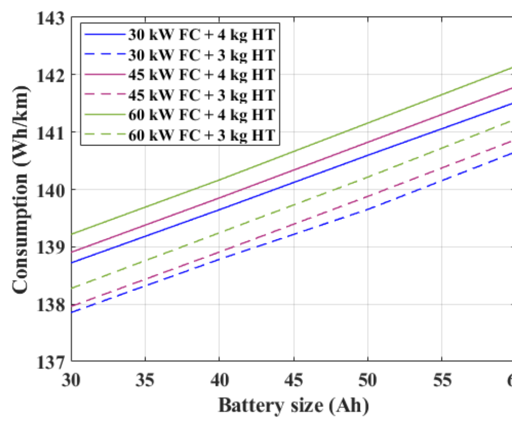

Fig. 7. Energy consumption per km in the BEV mode considering the different sizes of battery, fuel cell, and hydrogen tank.

In the FCV mode, the consumption profile changes. Even though the bigger the fuel cells, the higher the weight, the bigger fuel cells can operate at high-efficiency points, which lowers its consumption. Thus, overall, smaller fuel cells presented higher consumption, as shown in Fig. 8. Concerning the battery size and the hydrogen tank size, in the FCV mode, the bigger they are, the higher the consumption. Even though in the BEV and FCV modes, the consumption showed different profiles, when it accounts for the total cost per km, as referred to in the TCO determined using (1), the total cost of the system has a more significant impact between the different systems than the consumption itself. Therefore, when the TCO is calculated for the different systems, the profile follows the same as the one presented for the system cost shown in Fig 6. Even when it accounts for different prices of hydrogen and electricity, the profile is the same although the values of total cost change. Thus, the same profile can be shown in Fig. 9 for the case of low hydrogen price and high electricity price, and in Fig. 10 for the scenario of high hydrogen price and low electricity price. Therefore, the impact of having smaller fuel cells promotes PFCEVs with lower total cost because the total cost of the system is lower, even though their consumption in the FCV mode is higher. Further, having smaller fuel cells contributes more to reducing the cost than reducing the size of the hydrogen tank because even though they add more weight the price of having a bigger hydrogen tank adds less cost to the propulsion system than having bigger fuel cells. Regarding the battery, supporting the conclusion from the previous subsection, smaller batteries result in a lower total cost per km. Choosing between different battery sizes is related to the range capacity required for the electric-only mode. In this study, the smaller batteries provided about 60 km in the BEV mode while the bigger batteries about 100 km.

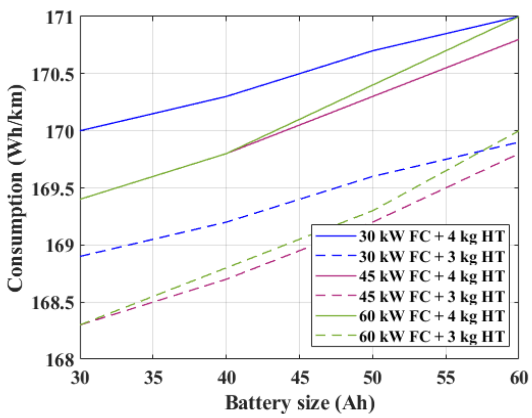

Fig. 8. Energy consumption per km in the FCV mode considering the different sizes of battery, fuel cell, and hydrogen tank.

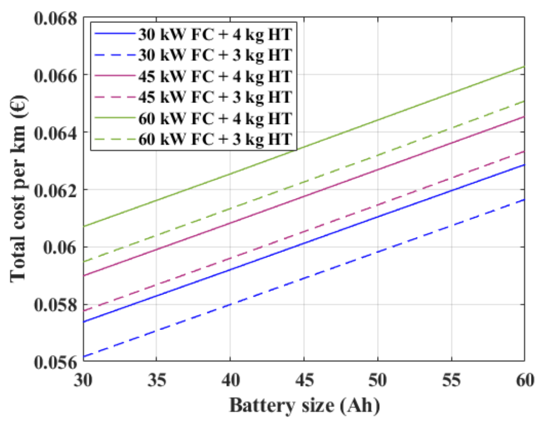

Fig. 9. Cost per km/€ for the PFCEV considering the different sizes of battery, fuel cell, and hydrogen tank, for the scenario where hydrogen price is low and electricity price is high.

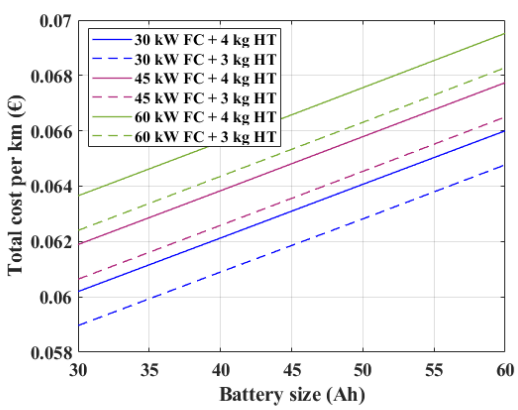

Fig. 10. Cost per km/€ for the PFCEV considering the different sizes of battery, fuel cell, and hydrogen tank, for the scenario where hydrogen price is high and electricity price is low.

IV. CONCLUSIONS

In this work, PFCEVs were shown to be promising vehicles to lower the investment price, the energy consumption, and the total cost per km compared to the BEVs. Even for the scenario where the hydrogen price is high and the electricity price is low, the PFCEVs were still shown to be more cost-efficient, with about 10% lower total cost. These results are related to the higher cost and weight of the batteries to provide long-distance ranges for the BEVs. The impact of different component sizes for the PFCEVs demonstrated that the total cost followed the same profile as the investment cost, showing that lower-cost systems have more impact on the total cost of the vehicle than fuel consumption. For future research, addressing the environmental impact of the different systems could add more understanding for the comparison of BEVs and PFCEVs as well as optimize the system sizing.

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