Comparison Between Different Hydrogen Fuelled Powertrains for Urban Busses

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Abstract: In the compelling need for the decarbonization of the transport sector, hydrogen could play a crucial role, especially in heavy duty applications where the limited specific energy of chemical batteries can significantly reduce either the payload or the operative range. Moreover, the possibility to use Hydrogen not only within Fuel Cells (FCs) systems but also as a fuel in Internal Combustion Engines (ICEs) makes it even more attractive for future sustainable transport systems. In such a framework, this work aims to compare, through numerical simulation, different hydrogen powertrain configurations designed for an urban bus application. In particular, a series hybrid architecture was chosen as a reference considering three different technologies for its Auxiliary Power Unit: two internal combustion engines fuelled with Diesel and Hydrogen respectively, and a Fuel Cell featuring almost the same power level of the internal combustion engines. The study was carried out in real world driving condition and it showed the benefits of both hydrogen powertrains on the vehicle fuel economy. Finally, in order to provide a more comprehensive overview, an analysis of the Total Cost of Ownership (TCO) was performed demonstrating that the H2-engine could achieve a significant improvement of the powertrain efficiency with investments and operating costs closer to the Diesel configuration.

Keywords: Hydrogen fuelled powertrains; Total Cost of Ownership; Urban bus

1. Introduction

Nowadays the decarbonization of the human activities represents one of the most important topics in the agenda of the European Commission in order to limit the climate changes related to the Green-House-Gas (GHG) effect [1]. Among the other, the transportation sector is particularly under the microscope of the governments since it is currently responsible for about 25% of the total CO_2 emissions and it has shown a constantly increasing trend in the past 25 years [2]. In such a framework, the powertrain electrification may represent one of the most promising solutions not only to decarbonize the transportation sector, but also to improve the air quality in highly congested urban areas. However, it may not be suitable for heavy duty applications whose range requirements may be quite challenging for current state-of-the art electrochemical batteries. As an alternative, new policies, such as the European Green Deal, should also promote the development and the production of sustainable alternative fuels capable to achieve a zero impact in their entire life cycle [3]. Among them, hydrogen has recently become a highly attractive solution, since it could be produced from renewable energy sources [4] and it can be used in both Fuel Cell (FC) Systems and Internal Combustion Engines (ICEs).

Moreover, beside the environmental aspects, from the customer perspective, the next powertrain generation should be comparable in terms of costs with conventional propulsion systems without relying on public subsidies. From this perspective, Battery Electric Vehicles (BEVs) may benefit of low operational costs thanks to their high conversion efficiency and to their low maintenance costs [5]. On the contrary, despite a strong reduction was observed in the last years [6], the still high cost of Li-Ion Batteries may result in a significantly higher initial investment in comparison with other propulsion systems.

In such a framework powertrain hybridization may represent a valuable alternative to limit the cost of the Energy Storage System (ESS), since the presence of an additional power unit allows reducing the size of the battery for the same vehicle range. Moreover, the integration of either a Fuel Cell (FC) or of a H_2-ICE avoids the local production of any GHG emission. Unfortunately, the economical convenience of hydrogen powertrain strongly depends on the fuel cost, which significantly changes according to the production technology, and it is currently significantly higher than Diesel and Gasoline [7].

Focusing on FC technology, the limited production volumes as well as the need of precious materials for some of its components may still result in a quite high capital investment, especially in a short time scenario [8]. Furthermore, the high FC efficiency may be affected by several operating parameters, such as sudden load changes, or frequent switch on/off events, which can increase the hydrogen consumption.

On the other hand the use of H_2 in ICEs could represent a valuable solution thanks to the limited number of hardware changes required to run an engine with such a fuel and to the availability of well-establish production processes [9,10]. The main drawbacks of a hydrogen engine may be represented by its relatively low energy conversion efficiency compared to FC, corresponding to a higher fuel expenditure, and to the possible generation of criteria pollutant emissions (such as Nitrogen Oxides) which may require tailored aftertreatment devices [11].

In such a framework, the definition of the optimal powertrain solution cannot be unique, but it strongly depends on the specific application [12]. Public transportation is one of the sectors with the higher penetration of Battery & FC propulsion systems, thanks to the peculiarities of its mission profiles (e.g. charging/fuelling infrastructure availability, well-known route) and to the public funding programs which may result in a short-time economic sustainability [13,14]. Recently, a comprehensive analysis of different powertrain solutions for urban busses has shown that electrified powertrains are the most suitable option for the 12m urban bus class [15].

Therefore, the present paper aims to perform, through numerical simulations, a comparison among 5 different propulsion systems suitable for a 12m urban bus. The study will not only consider the vehicle energy consumption of each configuration in real world driving conditions, but it will also analyse its Total Cost of Ownership (TCO). The analysis will cover a wide range of powertrain solutions, ranging from a conventional Diesel ICE, taken as a reference, to a full electric configuration. The intermediate electrification levels feature a series hybrid architecture, in which different technologies for the Auxiliary Power Unit (APU) will be considered. In particular, the benefits of both a Fuel Cell and H_2-ICE will be assessed with respect to a downsized version of the reference Diesel Engine.

The paper will be organized as follows: in Section 2 the case study will be presented with a short overview on the features of the vehicle and of the mission profiles. Afterwards, Section 3 will focus on the methodologies used to create the virtual test rig of the vehicle and to perform the TCO study. Then, in Section 4, the main findings of the study will be presented. First, the energy consumption of each powertrain configuration over different driving cycles will be assessed (Section 4.1). Afterwards, the results of the TCO will be discussed (Section 4.2). Finally, the main conclusions and findings of the research activities will be presented.

2. Case study

In the present paper, a 12m urban bus, the main specification of which are reported in Table 1, was considered as a test case.

Table 1: Main Specifications of the Tested Vehicle

Mass	12 tons
Road Load @ 50 km/h	16 kW
Road Load @ 80 km/h	43 kW
Road Load @ 100 km/h	74 kW

Concerning the powertrain, the configurations listed in Table 2 were taken into account.

Table 2: Powertrain Configurations

Conf. ID	Architecture	APU
1	Conventional	-
2	Series Hybrid	Diesel ICE
3		H2 ICE
4		Fuel Cell
5	Pure Electric	-

The first powertrain configuration, which was taken as a reference for this analysis, is a conventional powertrain equipped with a Heavy-Duty Diesel Engine. Moving to the hybrid configurations, they all feature a series architecture where the main power actuator is a Permanent Magnet Electric Motor capable to deliver a maximum power of 200 [kW], and the reversible EES is a Li-Ion Battery with a total installed energy of about 20 [kWh], whose cell specifications are reported in Table 3

Table 3: Battery Cell Features

Technology	LiFePO	-
Nominal Capacity	33	Ah
Specific Energy	120	Wh/kg
Nominal Voltage	3,6	V
Max Current	500	A
Arrangement	85s2p	-

Focusing on the APU, the reference engine was downsized to a rated power of about 100 kW. As far as the H_2 ICE is concerned, a power unit obtained by modifying the Diesel engine has been considered, choosing the solution that minimizes the cost and the level of complexity [16,17]. It features a PFI (Port Fuel Injection) system, coupled with the original diesel combustion chamber design, featuring a centrally mounted spark plug, replacing the original diesel injector. More details on the whole combustion and fuel injection systems are given in [18].

For the Fuel Cell Electric Vehicle (FCEV) the same power level of both H_2 and Diesel engines has been considered, rescaling a real FC system to obtain a power of about 100 kW. A DC/DC converter was also integrated to couple the FC with the high voltage board net of the electrified powertrain. The energy consumption of the FC ancillaries (such as the air compressor and the humidifier) were also included in the study in order to achieve the correct Balance of Plant (BOP).

Finally, the pure electric bus uses the same EM of the hybrid powertrains, while the battery was scaled up to achieve the same daily range of the other configurations (about 250 km).

The simulations were carried out on 3 different mission profiles, representative of a typical urban bus operation. Their specifications are listed in Table 4.

Table 4: Main Features of the considered mission profiles.

	Braunschweig	***Gillingham***	***MLTB***
Duration [s]	1740	2875	2281
Distance [km]	10.9	16.6	9.0
Avg. Speed [km/h]	22.5	20.8	14.2
Max Speed [km/h]	58.2	59.9	48.7
Avg. Acc. [m/s²]	0.2	0.2	0.2
Max Acc. [m/s²]	2.4	2.3	1.5
Stop Phases [%]	22.4	21.7	26.7
Constant Speed Driving [%]	16.1	12.2	6.4
Acceleration [%]	35.3	33.5	39.2
Deceleration [%]	26.2	32.5	27.7
Spec. Energy Demand [kWh/km]	0.90	1.05	0.94

The Braunschweig is an urban driving cycle, frequently employed in various research projects or equipment certification programs [19]. The MLTB cycle was developed by UK transport authorities in 1996 to verify the compliance of new vehicles with emissions and fuel economy standards [20]. Finally, the Gillingham Uphill, obtained from GPS acquisitions, features high elevation changes, to test also challenging driving conditions [16].

3. Methodology

The virtual test rig of the bus was developed in the GT-Suite environment [21] applying a "quasi-static" approach [22]. The models of the ICEs and of the EM relies on performance maps, experimentally measured under steady-state conditions, or computed from 1D-3D/CFD simulations depending on the considered configuration, while the battery dynamics were reproduced through a Thevenin's equivalent circuit.

Focusing on the H_2-ICE model, the engine operating maps for the selected combustion system configuration were obtained by means of a synergetic 0/1/3D-CFD approach previously developed by the authors [18]. At first a 3D-CFD numerical setup, based on a detailed chemistry scheme for both hydrogen combustion and NOx emission predictions, was implemented to obtain the reference results for calibrating a predictive combustion model in 1D-CFD environment. Afterwards, the latter simulation platform was used to optimize the main engine operating parameters (such as air/fuel ratio, boost level and spark timing) to maximize its thermal efficiency, achieving a peak of about 41%, while ensuring, at the same time, NOx emission below the current EU6 limit for HD applications. Figure 1 presents the engine efficiency map for the considered combustion system.

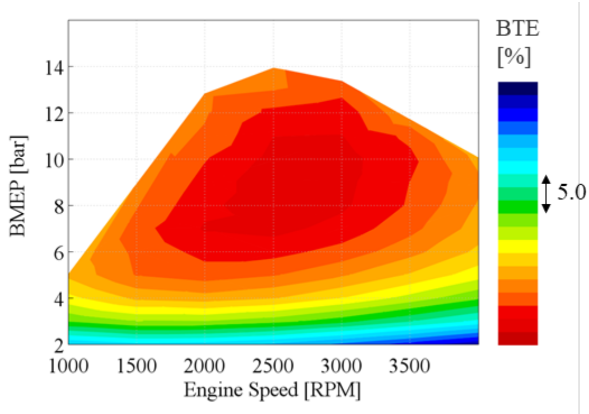


Figure 1: Normalized efficiency map of the H_2-ICE integrated in the APU.

For the Fuel Cell, a 1D CFD model was created and calibrated against a set of steady-state experimental data to properly reproduce the sensitivity of the FC polarization curve to the main operating parameters of the plant. Figure 2 proves the robustness of the developed models showing a more than satisfactory agreement between the simulation results (blue line) and the measurements (black line) in an operating condition not considered during the calibration process.

Finally, all the ancillaries needed to guarantee the FC operation were integrated in the model, considering both the air and the hydrogen supply systems. A compressor was needed to overcome the pressure losses inside the system on the air side and to ensure the correct excess of air at the anode.

Furthermore, a humidifier was needed too, to control the water content and the humidification, avoiding the degradation of the membrane. A recirculation pump was then integrated for the hydrogen, to mix the humid hydrogen exiting the cathode with the dry one coming from the tank storage and feed the FC anode.

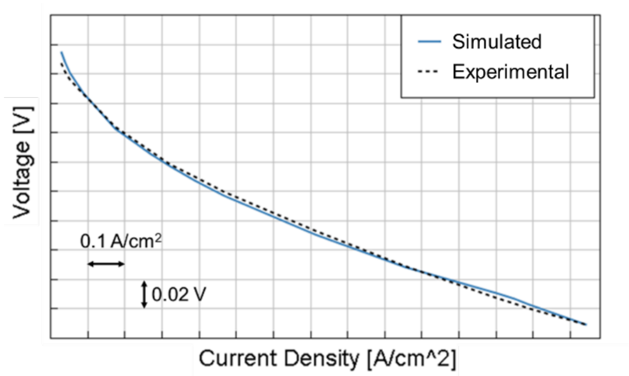


Figure 2: Comparison between the simulated polarization curve and the experimental measurements.

All the hybrid architectures require the definition of a suitable Energy Management System (EMS) [23] capable to split for each instant of time the driver power request among the available actuators. Since the optimization of the EMS is out of the scope of this study, for series hybrid configurations the same rule-based control strategy already designed in [16,24] was selected. Such a powertrain controller can achieve the charge sustaining operations by adjusting the power output of the APU according to the actual status of the vehicle and aims at minimizing the energy consumption of the vehicle keeping the operating conditions of the APU within its highest efficiency region.

3.2 Fuel Cell Efficiency Degradation

Differently from the ICE whose performance do not show any significant degradations with respect to lifetime, several studies [25,26] showed that, for a Fuel Cell, the higher the number of operating hours, the lower the system efficiency. Therefore, such a behaviour may significantly reduce the gap between the energy consumption of FCs and ICEs, and it should be included in the TCO analyses especially in the case of heavy-duty applications which typically features a long operating life.

The degradation of the Fuel Cell performance can be observed in steady state conditions, but it is more relevant in highly dynamic conditions such as for automotive applications, where load changes, Start & Stop (S&S) cycles, and cold starts events are quite frequent.

Since experimental data in aged conditions were not available in this study, a simplified approach for the lifetime prediction of the FC performance is proposed. It relies on the methodology already presented in [26] whose mathematical formulation was modified in order to include the effects of higher load operations on the degradation phenomena observed in [27].

$$\Delta V = \sum_{i}^{ChLvs} \Delta V_{ss,i} \cdot t + \Delta V_{LC} \cdot n_1 + \Delta V_{st} \cdot n_2 \qquad \text{Eq. 1}$$

In Eq. 1 a correction coefficient on the Fuel Cell Voltage ΔV is proposed to model the impact of:

- **Load Levels:** $\boldsymbol{\Delta V_{ss,i} \cdot t}$, where $\Delta V_{ss,i}$ is the voltage decay for each power level [V/h], and t is the corresponding resident time [h];
- **Load Changes:** $\boldsymbol{\Delta V_{LC} \cdot n_1}$**,** where ΔV_{LC} is the voltage decay for each load change [V] and n_1 is the corresponding load change frequency [1/h];
- **Switching Cycles:** $\boldsymbol{\Delta V_{st} \cdot n_2}$**,** where ΔV_{st} is the voltage decay per on/off switching cycle [V] and n_2 is the corresponding event frequency [1/h].

The proposed methodology leads to the degradation factors reported in Table 5 for the mission profiles analysed in this study.

Table 5: Degradation Factors on the considered driving cycles

Driving Cycle	***Degradation Factor [μV/h]***
Braunschweig	23.1
Gillingham	21.5
MLTB	13.6

These results are in good agreement with the values already presented in [26] for a similar PEMFC system. Moreover, the MLTB shows significantly lower penalties since the FC is working for long periods at low loads and with few load changes during the cycle.

The degradation factor allows calculating the actual efficiency of the Fuel Cell (see Eq. 2) which can be considered proportional to the voltage as follows:

$$\eta_{FC} = \frac{V_{cell} - \Delta V}{V_{th}} \qquad \text{Eq. 2}$$

where:

- η_{FC} is the actual Fuel Cell efficiency;
- V_{cell} is the nominal FC voltage;
- ΔV is the degradation factor;
- V_{th} is theoretical FC voltage.

The V_{th} is almost constant, since it only shows a light dependence on both operating temperature and pressure. Given a certain voltage decay and an expected lifetime of the system, the new efficiency can then be easily calculated.

Finally, the Fuel Cell system efficiency can be estimated through Eq. 3:

$$\eta_{FCS} = \eta_{FC} \cdot \eta_{aux} \cdot \eta_{DC/DC} \qquad \text{Eq. 3}$$

where $\eta_{DC/DC}$ is the efficiency of the DC/DC converter and η_{aux} the ratio between the power of the auxiliaries and the FC output power. This ratio is assumed to increase over time during the lifetime of the Fuel Cell: as a matter of fact, for a constant power request, the degradation of the FC voltage requires an increase of the current, which results in a higher mass flow rate for both hydrogen and oxygen. A constant rate of 0.5% for 1000 [h] was empirically assumed in this study.

With this simplified approach, the degradation of the Fuel Cell performance leads to an efficiency decrease of about 15% and 25% at 200'000 km and 350'000 km respectively, as shown in Figure 3.

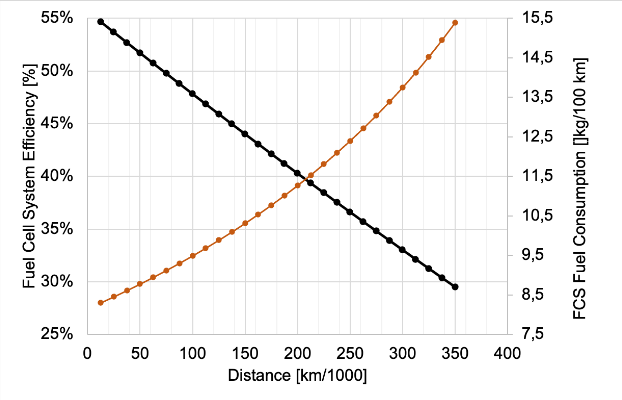


Figure 3: Reduction of the FC efficiency and increase of fuel consumption as a function of the travelled distance.

Finally, based on the actual system efficiency η_{FCS}, the actual hydrogen consumption $H_{2,FC}$ was calculated through Eq. 4 as a function of the nominal hydrogen consumption $H_{2,FC,0}$ and of the nominal system efficiency $\eta_{FCS,0}$.

$$H_{2,FC} = \frac{H_{2,FC,0}\eta_{FCS,0}}{\eta_{FCS}} \qquad \text{Eq. 4}$$

3.3 Total Cost of Ownership (TCO)

Before analyzing all the contributions included in the TCO, it is worth mentioning the main assumptions of the study.

Foremost, based on data reported in literature [16], an expected travelled distance of about 700'000 km was considered for the 12m bus. Such a distance was reached through repetitions of the considered elementary driving cycles. Moreover, when the target distance is reached, the residual value of the vehicle is assumed to be zero.

From the time-perspective, a horizon of about 10 years was chosen, considering cost forecasts for year 2030.

Moving toward the cost assessment, two main contributions can be identified. The former, which includes the investments for the glider, for the powertrain and for the storage, is the CAPital EXpenditure (CAPEX). The latter is the OPerational EXpenditures (OPEX) which accounts for fuel, repair, and maintenance costs.

CAPEX

The vehicle glider is shared among the proposed architecture and its cost was derived from a previous work of the authors [16], which also provide values for the Internal Combustion Engine. An additional penalty was also introduced for the Hydrogen conversion [28].

On the contrary, for the electric drive, values derived from an extensive literature review were assumed [6].

Similar approaches were used for the hydrogen pressurized tank, for which several studies set a cost ranging between 500-700 [€/kg] [8,28] and for the chemical battery. As already mentioned in the paper introduction, for this subsystem a significantly cost reduction was observed in the last years [6] and, according to literature [29], a value of about 100 [€/kWh] seems to be reasonable for 2030. Furthermore, a swap of the battery pack can be expected after about 1800 operating cycles [8]. Indeed, an urban bas may represent a quite demanding application for Li-Ion batteries because of the high number of depth discharge cycles which can shorten the battery life.

Finally, the cost of the Fuel Cell seems to be one of the most critical to estimate since, depending on the future market penetration, it could oscillate in a very wide range [7]. Thus, similarly to, a base scenario featuring a niche market penetration was considered, assuming a production of 2500 units per OEM per year. In addition, the significant degradation of the FC performance (see Figure 3) will force a swap of the stack at about 350'000 km when the efficiency drops below 30%. The assumptions regarding the powertrain are summarized in Table 6.

Table 6: Summary of the CAPEX costs assumed for the Reference scenario.

	Cost	*Reference*
Diesel ICE	30	[28]
H_2-ICE	40	-
Fuel Cell System [€/kW]	280	[8]
Electric Drives [€/kW]	8	[28]
Power Electronics [€/kW]	10	-
Battery [€/kWh]	100	[29]
700 bar Hydrogen Tank [€/kg]	500	[8] [28]

OPEX

Fuel Cost

A reliable forecast of the H_2 cost can also be quite difficult. Several sources indicate that in 2023 the prize of green hydrogen will range between 3-7 €/kg. A mean value of 5 €/kg was chosen for the reference scenario, but additional sensitivity analyses will be performed on this parameter.

For BEVs the recharging cost may significantly change depending on the evolution of the energy market [30], especially when fast charge is considered. Values between 0.15 and 0.6 €/kWh were observed in [30,31], but significant variations may occur thanks to either the higher share of renewable energy sources or to the increase of the demands. Therefore, for this parameter a value of 0.26 €/kWh was considered.

Finally, for the Diesel, the cost was set to about 1.6 €/l, because of the increase expected in the upcoming years.

A summary of the OPEX contributions is reported in Table 7.

Table 7: Summary of the OPEX Costs assumed for the Reference Scenario.

	Cost	Reference
H_2 Cost [€/kg]	5	[8]
Diesel Cost [€/L]	1.6	-
Electricity [€/kWh]	0.26	[8]

Repair and Maintenance

When considering Internal Combustion Engines, the maintenance cost was considered independent on powertrain architecture. The complexity of hybrid architecture may introduce additional contributions, but, at the same time, could reduce the wear of other components (e.g.: friction brakes).

4. Results and Discussion

4.1 Assessment of the Energy Consumption

The virtual test rig developed for the 12m bus was used to assess the energy consumption of each powertrain configuration on the selected mission profiles.

A preliminary analysis was performed among the hybrid architectures in order to prove their capability to achieve the charge sustaining conditions which is necessary to perform a fair comparison with the other powertrain configurations. The results collected on the Braunschweig driving cycle and reported in Figure 4 prove the capability of the powertrain control strategy to achieve the battery charge balance with all the different APU technologies.

Moving to the analysis of the energy consumption, Figure 5 shows the results collected for each powertrain configuration. As expected, the conventional Diesel Engine features the highest energy consumption for all the considered driving cycles (black bars), while the powertrain hybridization (green bars) introduces an improvement of about 8%, on average. Nevertheless, the benefit is significantly lower (about 4%) on the Ghillingam driving cycle, since the high load request allows even the conventional powertrain to keep the engine within its highest efficiency region without the need of exploiting the powertrain hybridization.

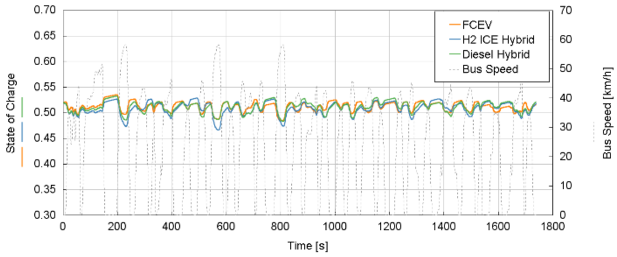


Figure 4: Comparison of the SOC trajectory of the hybrid powertrain configurations on the Braunschweig driving cycle.

The comparison between the Diesel (green bars) and the Hydrogen APUs (blue bars) highlighted that both engine technologies are able to achieve similar efficiency levels. The use of a Fuel Cell (orange bars), on the contrary, enables a huge step forward resulting in an average -30% of the energy consumption.

Nevertheless, from the Tank-to-Wheel (T2W) perspective, the best solution is a pure electric powertrain (yellow bars) which is able to achieve the minimum energy consumption in all the analysed driving scenarios.

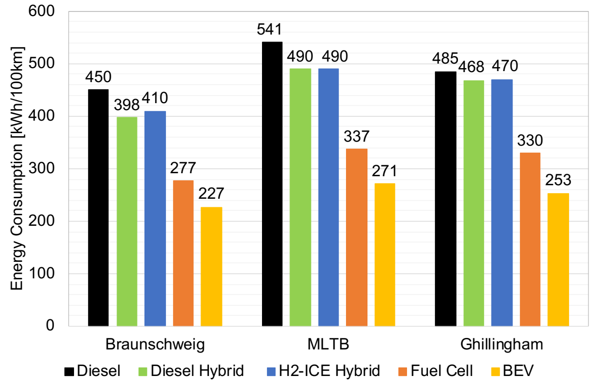


Figure 5: Comparison of the energy consumption of the proposed powertrain configurations on the considered driving cycles.

4.2 TCO Results

In the following section the TCO of the proposed powertrain architectures will be presented over the three driving cycles. The comparison will be performed with the reference cost scenario described in the previous section of the paper. Finally, two sensitivity analyses will be performed on the FC and on the hydrogen costs.

Base Scenario

The analysis of Figure 6 where the TCO is reported for all the considered driving scenarios shows that the Diesel Hybrid Electric Vehicle (HEV) represents the most convenient solution, achieving a specific cost about 0.04 €/km lower, on average, than the reference conventional powertrain.

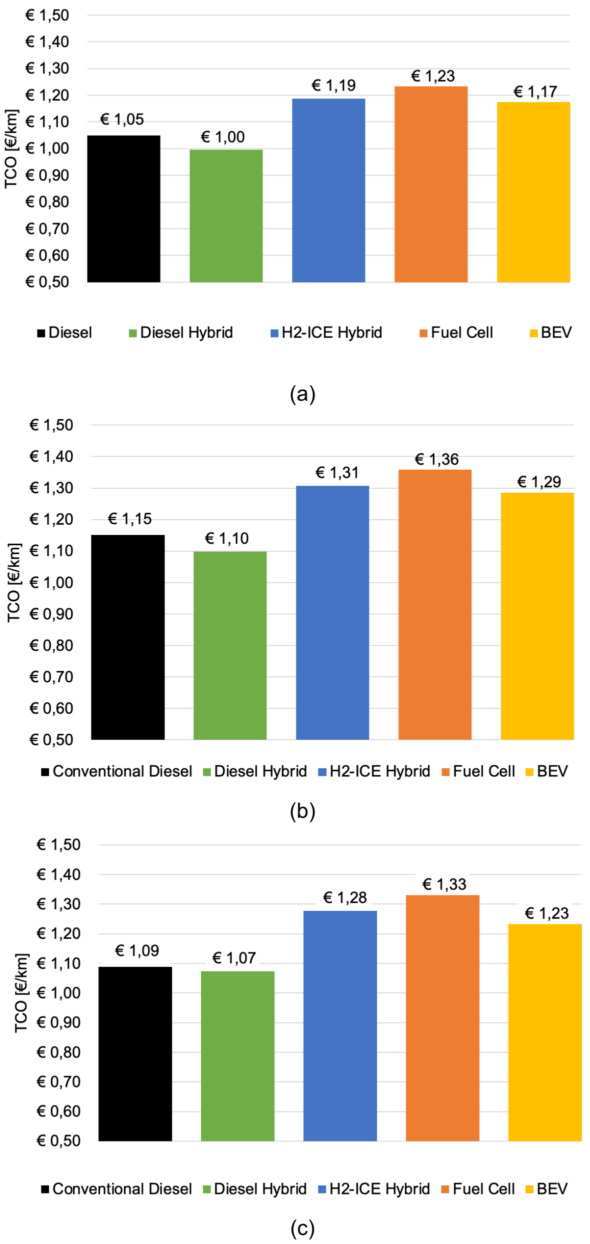


Figure 6: TCO of the proposed powertrain architectures over different driving cycles. (a): Braunscheweig - (b): MLTB - (c): Ghillingham.

The higher fuel economy and the lower cost of the downsized engine, indeed, allow overcompensating the investment for the powertrain hybridization which, in this case, is quite limited, thanks to the small battery size (about 20 kWh). Among the different tail-pipe carbon-free architectures, the BEV achieves the lower TCO thanks to its significantly higher efficiency and to its lower maintenance cost. The H_2-ICE, on the contrary, despite a competitive CAPEX, suffers of higher fuel consumption and higher fuel cost. Finally, as far as the Fuel Cell system is concerned, Figure 6 highlights a further increase of the TCO caused by the higher investment for the APU.

These trends seem to be quite homogeneous among the driving cycles, as demonstrated by the comparison of Figure 6.a,b and c.

Sensitivity Analyses

In Section 3.3 both the Fuel Cell and the Hydrogen costs were identified as one of the most difficult parameters to forecast since they can be affected by many factors such as market penetration or production technology. Therefore, two sensitivity analyses were performed on these parameters in order to assess their impact on the TCO of the proposed powertrain architectures. This study was performed on the Braunschweig driving cycle.

Fuel Cell Cost

Similarly to other new technologies, the cost of a Fuel Cell can be strongly influenced by market penetration as demonstrated by Roland Berger [8] which forecasted a huge variability of the system cost moving from niche to mass market applications (see Table 8)

Table 8: Evolution of the Fuel Cell Cost depending on the market penetration [8]

	€/kW
Niche (Base Scenario 2500 p. OEM)	280
Rather Niche (5000 p. OEM)	155
Rather Mass (25000 p. OEM)	100
Mass Market (75000 p. OEM)	55

Figure 7, where the results of the sensitivity analyses are reported, shows that a huge drop in TCO could be achieved with a *rather niche* market penetration, since the system cost would be half of the value predicted for the reference (*niche*) scenario. This almost completely closes the gap with respect to H_2-ICE, while a further increase to *rather mass production* would allow reaching the TCO of the Battery Electric Vehicle.

The achievement of the mass production, on the contrary, would not produce a significant benefit on the TCO since the hydrogen cost would become the dominant parameter.

To limit the impact of the fuel, it is much more important to limit the degradation of the Fuel Cell performance, which strongly affects the energy consumption over the whole vehicle lifetime.

According to the degradation model used, besides the improvements of both the membrane and catalyst technologies, a powertrain control strategy capable to include the degradation phenomena could significantly reduce the FC fuel economy.

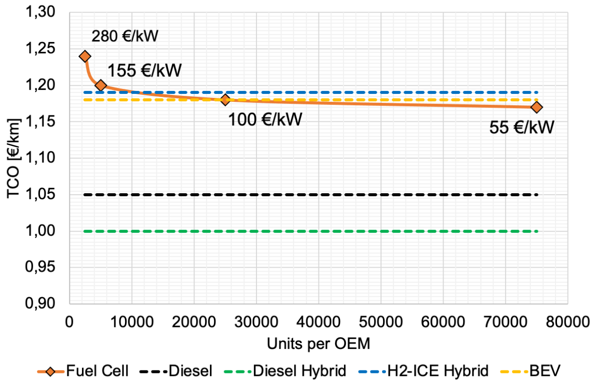


Figure 7: TCO sensitivity analysis on the Fuel Cell cost.

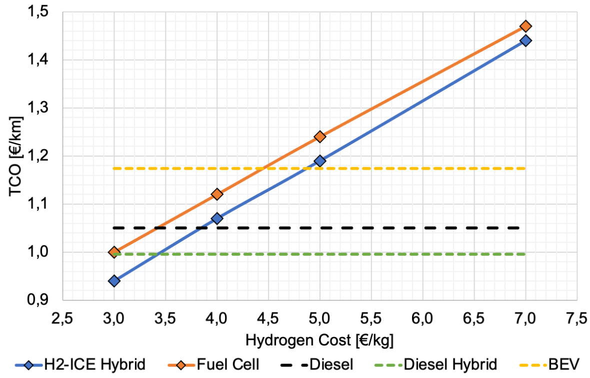
Hydrogen Price Sensitivity

The World Energy Council predicts that, starting from the actual average value of 5 €/kg, the hydrogen price may drop down to 3 €/kg in the upcoming years. From the TCO perspective such a reduction could be very beneficial, allowing the hydrogen powertrains to achieve the cost levels of the Diesel ones. Moreover, if a rather-niche market penetration is considered (see Figure8.b), with a hydrogen price of 3 €/kg the Fuel Cell becomes economically convenient with respect to H_2-ICE

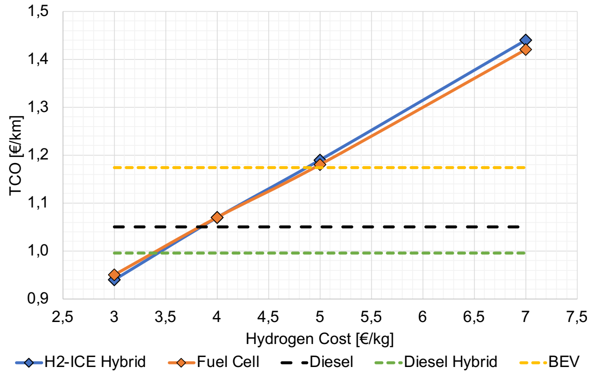
Nevertheless, such a low fuel price would require a very low cost of the electricity, whose achievement could be quite difficult, even with a strong exploitation of renewable energy sources. As an example, considering an efficiency of 80% for the electrolysis process, the electricity cost should be lower than 0.07 €/kg, even if the costs of the electrolyzer, of the water and of the compression power is neglected.

5. Conclusions

In the present paper a comparison among different powertrain solutions for a 12m urban bus was performed. The study analyzed, through numerical simulations, both the energy consumption and the Total Cost of Ownership of each architecture in different driving scenarios. A virtual test rig for each powertrain configuration was developed and a simplified methodology for the degradation of the fuel cell performance was introduced to consider the H_2 consumption penalty during the lifetime. Finally, two sensitivity analyses on the cost of the Fuel Cell system and on the hydrogen prize cost were performed, since they represent the most difficult parameters to be forecasted.



(a)



(b)

Figure 8: TCO sensitivity analysis on the hydrogen cost. (a): Fuel Cell Cost: 280 [€/kW] – (b): Fuel Cell Cost: 100 [€/kW]

The numerical simulations highlighted the minimum energy consumption for the BEV but the minimum TCO for the Diesel HEV thanks to the lower fuel cost. As a matter of fact, the H_2 could achieve almost the same efficiency, but with a significantly more expensive fuel. Among the hydrogen solutions, the Fuel Cell achieved the best energy consumption, thanks to its higher efficiency, but not the lowest TCO which was obtained with the H_2-ICE. The FC system would require a cost of 155-100 €/kW to be competitive with the H_2-ICE and BEV, respectively.

Hydrogen as fuel could be economically competitive if its price could reach a value of about 3.5 €/kg, which would require very low electricity price and a huge exploitation of renewable energy sources.

5. Acknowledgement

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8. Glossary

APU	Auxiliary Power Unit
BEV	Battery Electric Vehicle
BOP	Balance Of Plant
BSFC	Brake Specific Fuel Consumption
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamic
DC	Direct Current
EM	Electric Motor
ESS	Energy Storage System
FC	Fuel Cell
GHG	Green House Gases
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
NOx	Nitrogen Oxides
OPEX	Operational Expenditure
PEMFC	Proton Exchange Membrane Fuel Cell
PFI	Port Fuel Injection
SOC	State Of Charge
T2W	Tank to Wheel
TCO	Total Cost of Ownership
WOT	Wide Open Throttle