Comparative analysis of fuel cell and electric public for transport busses

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Abstract. Current public transport systems have been in desperate need of modernization in the past decade. The pressing issue of climate change, alongside the ever-increasing strictness of emission standards, have guided public transport operators towards the use of alternative propulsion vehicles. The most popular option to conventional powered public transport vehicles have been BEBs (Battery Electric Busses). However, in the past years, FCEBs (Fuel Cell Electric Busses) have gained massive ground in this sector. The following paper aims to shed a light on the advantages and disadvantages of both technologies, in order to determine whether or not FCEBs represent a viable solution for the future.

1. Introduction

At this moment in time, humanity finds itself at a turning point in respect to dealing with one of the most critical challenges in its history. Pollution has become an extremely destructive consequence of the rapid pace of development and the continuous process of technical evolution found in all areas of activity. Unfortunately, society has developed in a direction deeply based on consumption and swift evolution, neglecting its efficiency in terms of energy management. This has put mankind on a collision course with disastrous long-term consequences for the environment so vital to our evolution.

One of the most viable resolutions to this problem, generated partly by the transport sector, is the implementation of widespread public transport alongside imposing traffic restrictions. In order to facilitate the adoption of public transport as a primary transport solution, several modern and sustainable transport vehicles must be endorsed as viable alternatives to personal transport vehicles.

Sustainability in the transport sector has become one of the biggest challenges on a European level, in the light of current environmental challenges. The paramount measures applied in these areas have been the introduction of stricter emissions regulations and the perpetual renewal of transport fleets all over the EU. The main sustainable options in regard to sustainable bus transport, have been BEBs (Battery Electric Busses) and FCEBs (Fuel Cell Electric Busses). Both technical solutions are based on the use of electrical energy as means of propulsion.

The fundamental difference between these classes of vehicles, is the means by which they store electrical energy. Both types use batteries in order to manage and contain the voltage necessary for propulsion, however, FCEBs use fuel cells as an energy buffer, reducing the strain of the battery, used mainly for power delivery. This feature make FCEBs less vulnerable to battery deterioration, drastically reducing the cost of operation.

Battery powered busses have long been in use and currently represent the main solution for sustainable urban transport. The main differentiating factors between this kind of transport solutions are the chemistry of the batteries, charging power, battery capacity and range. The main type of battery used in the energy storage of battery electric busses, are Lithium-based (LFP, NMC, LTO). The chemical configuration of the batteries, dictate in turn, the range and energy consumption of BEBs. The average range of such busses varies around 150 km to 300 km depending on the size of the battery pack. The average energy consumption of such vehicles is of 1.3 kWh/km, depending on environment conditions, as well as vehicle load and usage rates. These known parameters, make BEBs, an obvious alternative to conventional fuel public transport busses [1].

Given the fact that BEBs were adopted on a large scale and in a relatively short time window, limited progress was made in the development of new battery technologies. This has led to a few shortcomings regarding the long-term operation of such busses. BEBs offer the possibility of drastically reducing local emissions and sound pollution at the cost of a difficult and complex recycling process. This significant disadvantage can be overcome by using an alternative way of buffering the energy needed for electric propulsion [2].

In this regard, hydrogen takes center stage, being one of the most efficient energy carriers available at the moment. It can be obtained by various means and can be used to store the required energy for long range operation of electric motors, by means of fuel cell usage. Presently, the most common methods of obtaining hydrogen, are steam reforming of natural gas and electrolysis. Both means present their own advantages and disadvantages, electrolysis being the more sustainable method of the two [3].

Fuel cells represent constructions capable of transforming hydrogen and oxygen into electricity, utilized to power tractive systems. They possess superior energy efficiency and emissions reduction capabilities. Having this transformation at hand, offers FCEBs the possibility to travel longer distances compared to conventional BEBs. In this way, energy storage is offset into specially designed tanks, capable of storing adequate amounts of hydrogen for extended ranges of operation [4].

There are several types of fuel cells available to the market, each presenting a series of advantages and disadvantages. The most used type of fuel cell is the Proton Exchange type (PEM). It uses a solid type of electrolyte in the form of an exchange membrane. PEM fuel cells operate in a narrow temperature range of 80-100 ºC and are capable of developing powers up to 100kW with an efficiency of around 40-60 %. This type of fuel cell has found broad use in the mobility industry, as it has a reduced startup time, alongside small packaging, and reduced weight. However, PEM fuel cells manifest a high sensitivity to humidity or dryness, as well as being influenced by water salinity and environment temperature. Other types of fuel cell technologies are: Alkaline (AFC), Phosphoric acid (PAFC), Molten carbonate (MCFC) and Solid oxide (SOFC). However, these types of fuel cells are not normally found in mobility applications, due to long start times and high costs of production and operation.[5] [6] [7].

In the elaboration of this paper, two main solutions of alternative public transport were modeled. The baseline is a completely electric bus, equipped with a Li-Ion battery pack and two hub-mounted electric machines. The fuel cell variant is also equipped with a smaller battery used for power delivery, in addition to a PEM fuel cell. This paper aims to highlight the key differences between these solutions, as well as to compare the way in which improvements to fuel cell technologies can help adopt this type of vehicle as a backbone of sustainable transport systems.

2. Material and Method

The purpose of this paper is to illustrate the differences in functionality of two buses that are similar in terms of construction but different in terms of energy management. In order to perform this analysis, AVL Cruise M, developed by AVL List GmbH has been used.

In order to perform the analysis, two vehicles produced by Solaris were modelled using AVL Cruise M. Solaris has developed and built a versatile public transport platform, found in multiple construction variants, the construction solution chosen being Urbino 12, a bus found in both fully electric and fuel cell versions. Given the high degree of similarity between these vehicles, the focus of this paper will be to illustrate the functional differences, the structural part of the models being fundamentally similar. Of interest will be the way in which the range of these buses evolves, once they are subjected to identical test cycles. Before the actual modeling stage, it is important to define the various structural and functional characteristics of the vehicles considered. The data can be found in table 1.

Table 1. Constructive characteristics of the Solaris Urbino 12 busses [8]

Model			
Urbino 12 Electric		**Urbino 12 Fuel Cell**	
Kerb mass	13790 Kg	**Kerb mass**	11032 Kg
Maximum authorized mass	19000 Kg	**Maximum authorized mass**	19000 Kg
Length	12000 mm	**Length**	12000 mm
Width	2550 mm	**Width**	2550 mm
Frontal area	1.97 m^2	**Frontal area**	1.97 m^2
Friction coefficient	0.8	**Friction coefficient**	0.8
Battery power	350 kW	**Battery power**	100 kW
Motor	2 x ZF AVE 130	**Motor**	2 x ZF AVE 130
Motor power	2 x 150 kW	**Motor power**	2 x 150 kW
Fuel cell	-	**Fuel cell**	Ballard HD 60
Range	100 Km	**Range**	350 Km
Tank capacity	-	**Tank capacity**	28 – 37.5 kg H_2

The modelling process contained a series of parametrization processes. The models have a modular construction, every functional element of a BEV and FCEV being represented by a dedicated module. In order to obtain valid results, all components were modelled to the specifications published by the manufacturer. The electric model is composed of a battery pack, an ensemble of 2 ZF AVE 130 hub-mounted electric motors, a consumer module and a control functions subsystem. In addition to the components listed previously, the fuel cell variant of the Urbino 12 is equipped with a Ballard HD60 fuel cell.

The battery pack was configured having as reference the output power, voltage and current, in order to be as accurate as possible. The tractive system is composed of 2 electric motors, modelled after the real machines used by Solaris and manufactured by ZF. Each motor develops a peak power of 250 kW and a nominal voltage of 650V with a maximum current of 340A [9]. The control functions subsystem contains algorithms used for controlling each engine, as well as the calculation functions of range and performance of the vehicle. The functions used for implementing the test cycle, are also contained in this subsystem. The fuel cell model contains the Ballard HD60 fuel cell, as well as a dedicated function that controls the energy flow between the battery and the fuel cell.

The WLTC cycle has been chosen as the test cycle, being included in the AVL suite. This profile contains speeds close to those with which an urban bus would travel integrating the lower and upper limits between which the speed of the modeled vehicle must be located. In addition to these limits, the actual travel speed is included, along with gear shift points (if applicable).

In order to validate both models, their dynamic performance, energy consumption, battery state of charge and range were observed. Following the simulation, both models obtained performances similar to those declared by the manufacturer. The models can be observed in figure 1 and 2.

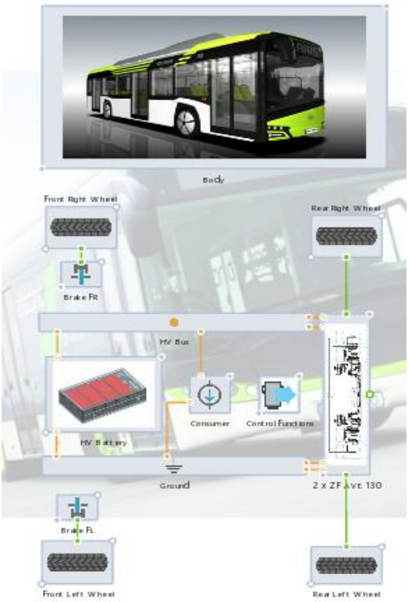

Figure 1. Urbino 12 Electric model

Figure 2. Urbino 12 Fuel Cell model

3. Results and Discussions

The first criterion analysed in case of the electric model, is the evolution of the range in relation to the travel speeds imposed by the test cycle. The results obtained are in line with the actual values provided by the manufacturers. At the end of the test cycle, a remaining range of 77.82 km was obtained. Considering the distance covered of 23.02 km, a total range of 100.84 km would be obtained, a value extremely close to range of 100 km declared by the manufacturer. However, range is influenced by a multitude of factors, its value varying depending on the environment temperature, the driving regime, the amount of energy recovered being also extremely important in defining the range of transport. The evolution of range in case of the electric model can be seen in figure 3.

The second metric analysed is the energy consumption of the vehicle. Following the simulation, an average consumption of 185.6 kWh/100km was obtained. This translates into 1.8 kWh/km, a value situated in the interval of 1-2 kWh/km declared by the manufacturer [10]. The evolution of energy consumption over the test cycle can be seen in figure 4.

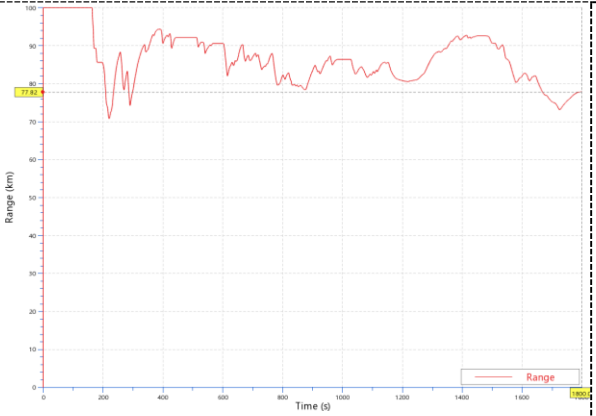

Figure 3. Evolution of range – Urbino 12 Electric

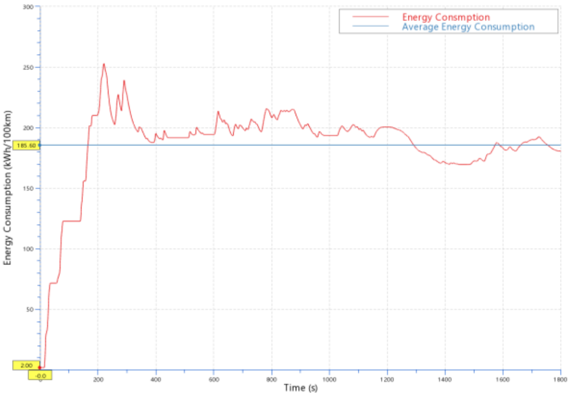

Figure 4. Battery energy consumption and average battery energy consumption – Urbino 12 Electric

In case of the fuel cell model, 5 different simulation cases were defined. Given the fact that PEM fuel cells are highly complex devices, their performance is affected by many variables. In order to showcase the improvement potential of this technology, 5 different simulation cases were created, the differentiating factor being catalyst layer thickness (measured in cm). The catalyst layer thickness is crucial as it represents the place where the electrochemical reactions associated to the generation of electricity take place. The thickness of this layer has a significant influence on the efficiency of the fuel cell. This influence is outlined through the simulation cases shown in table 2.

The first parameters analysed in the fuel cell model simulation were range and energy consumption. The results obtained after the electric model simulation, serve as a baseline for comparison. The evolution of these factors can be seen in figures 5 and 6. The data is presented in table 2.

Figure 5. Evolution of range – Urbino 12 Fuel Cell

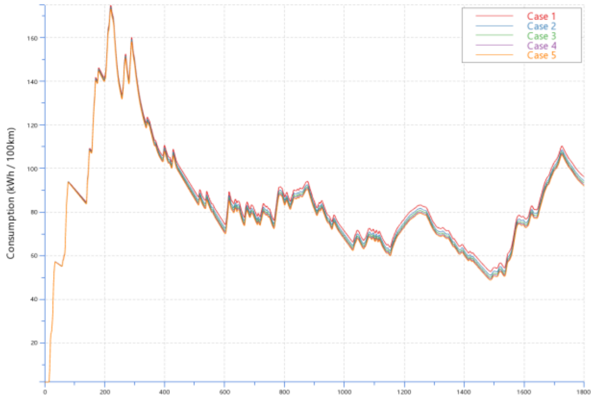

Figure 6. Battery energy consumption– Urbino 12 Fuel Cell

Table 2. Fuel cell model simulation results

	Simulation case				
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Catalyst layer thickness (cm)	0.001	0.002	0.003	0.004	0.005
Remaining range (km)	295.74	302.03	305.63	308.26	310.40
Average battery energy consumption (kWh/100km)	86.63	85.24	84.42	83.83	83.35

The best way to compare these types of vehicles, is to take into consideration their overall energy consumption. In case of the BEBs, the only energy source is the battery, the overall energy consumption being identical to the battery energy consumption.

In case of the FCEBs on the other hand, there are two sources from which energy can be consumed: the battery pack and the fuel cell. The battery pack energy consumption is calculated by the software and can be seen in figure 6. However, the overall energy consumption of the vehicle represents a sum of the energy drawn from the battery and the energy resulted from the hydrogen mass reacted in the fuel cell. The hydrogen mass reacted can be seen in figure 7. The difference in the reacted hydrogen mass determined by the efficiency of the fuel cell. The difference in efficiency is determined by the catalyst layer thickness. The efficiency of the fuel cell in each case can be seen in figure 8.

Given the fact that 1 kg of hydrogen has the equivalent of 33.6 kWh, and the reacted mass can be extracted from the software, the overall energy consumption can be determined [12]. The data can be seen in table 3.

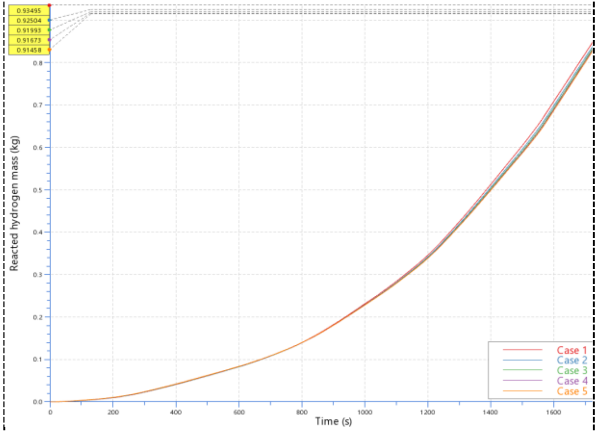

Figure 7. Reacted hydrogen mass – Urbino 12 Fuel Cell

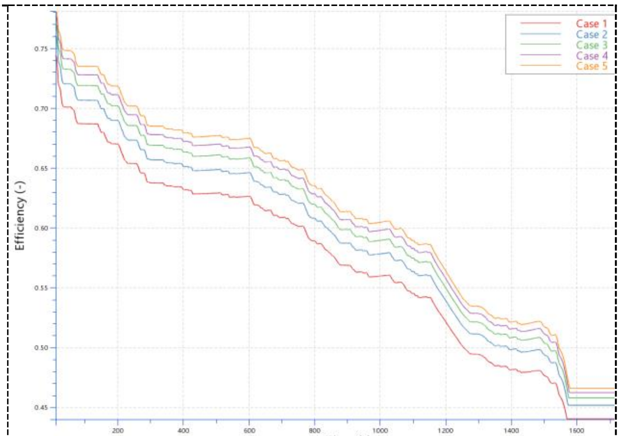

Figure 8. Fuel cell efficiency – Urbino 12 Fuel Cell

Table 3. Overall energy consumption

Distance travelled (km)	23.02				
Baseline - Urbino 12 Electric model					
Energy consumption (kWh/km)	1.8				
Total energy consumption (kWh)	41.436				
	Simulation case				
	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Fuel cell efficiency (%)	56	58	59	60.2	60.8
Average battery energy consumption (kWh/100km)	86.63	85.24	84.42	83.83	83.35
Hydrogen mass reacted (kg)	0.934	0.925	0.919	0.916	0.914
Energy resulted from the hydrogen mass reacted (kWh)	31.38	31.08	30.87	30.77	30.71
Total energy consumption (kWh)	51.17	50.70	50.29	50.06	49.88

4. Conclusions

In view of the aspects mentioned in this paper, as well as the data provided following the comparative analysis of the two solutions proposed the following can be concluded:

- Vehicles equipped with fuel cells offer a longer battery life, by their ability to keep their state of charge at a set threshold, the batteries being capable of going through fewer full charge cycles. The sustainability of fuel cell vehicles stems from their ability to use a variety of energy storage devices, having the ability of extending the life of their battery packs. At the same time, replacing battery packs and fuel cells involves lower costs than electric vehicles. Vehicles with fuel cells are able to offer significantly more range than electric vehicles, using smaller battery packs with higher efficiency

- The range offered by fully electric solutions is much more vulnerable, being directly affected by the driving regime, the environmental conditions, as well as the surfaces on which the vehicle travel. In the case of fuel cell solutions, the evolution of range is far more predictable in terms of monitoring hydrogen consumption, the estimates being closer to real values.
- Following the simulations, the total energy consumption in case of the FCEB, was always higher than the consumption obtained following the BEB simulation. The lowest value of consumption obtained in the case of the fuel cell model is still higher by 8.45 kWh than the baseline value set by the electric model. However, due to the progress in terms of fuel cell manufacturing and technology, this difference can be soon overcome.
- The peak efficiency of the fuel cell contained in the models was of 60.8%, the lowest value being of 56%. The peak hydrogen mass reacted was registered in case number 1 as opposed to case number 5 which manifested the lowest amount of hydrogen reacted. Analysing the battery energy consumption in corelation with the hydrogen consumption, it can be stated that in the event of a significant improvement of fuel cell efficiency, the overall energy consumption of such vehicles cand be drastically reduced to a level that competes with or surpasses fully battery powered vehicles.

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