Energy Efficiency Assesment of Sustainable Public Transport Solutions: a Comparative Analysis Fuel Cell vs Battery in Real Life Scenarios

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***Abstract*— Given the current paradigm in the field of sustainable mobility, an urgent need to modernize public transport systems, has become undoubtably vital. The increasing concerns regarding climate change and the tightening of emissions standards, have directed public transport operators towards the large-scale adoption of alternative propulsion vehicles. The most notable option in this area are Battery Electric Buses (BEBs), a mean of transport that has gained tremendous popularity in the past decade. However, Fuel Cell Electric Buses (FCEBs) emerged as a prospective option in this sector. The aim of this paper is to provide a thorough assessment between these alternative transport solutions, with the ultimate goal of determining the energy efficiency of both BEBs and FCEBs.**

Keywords— Battery Electric Buses, Fuel Cell Electric Buses, energy efficiency, comparative study

I. Introduction

Humanity is currently at a pivotal juncture in addressing one of its greatest challenges throughout history. Pollution has emerged as a highly destructive consequence of accelerated industrialization and ongoing technological advancements in all sectors. Unfortunately, society has prioritized consumption and accelerated development at the expense of energy efficiency. This has set humanity on a perilous course with crucially important long-term environmental consequences for our evolution.

The pervasive implementation of public transportation coupled with traffic restrictions is a viable solution to this issue, which is partially driven by the transportation sector. To encourage the use of public transportation as the primary mode of transportation, various modern and environmentally friendly vehicles must be promoted as viable alternatives to private automobiles.

Within the context of contemporary environmental challenges, sustainability in the transportation sector has emerged as one of Europe's most pressing concerns. Stricter emission regulations and continuous public transport fleet alterations have been the primary measures taken throughout the EU. Battery Electric Buses (BEBs) and Fuel Cell Electric Buses (FCEBs) are the main options in the field of sustainable bus transportation. Both utilize electrical energy as a means of propulsion, the main difference between them, being the way in which they store energy. While both varieties rely on batteries for managing and storing the voltage required for propulsion, FCEBs use hydrogen as an energy buffer, thereby reducing the battery's workload for energy storage and power delivery. This characteristic makes FCEBs less susceptible to battery degradation and significantly reduces operational costs.

Battery powered electric busses have been in use for a long time and are presently the primary sustainable urban transportation option. These solutions are distinguished by their battery chemistry, charging power, battery capacity, and range. BEBs typically utilize lithium-based batteries (LFP, NMC, LTO) for energy storage. The range and energy consumption of these vehicles are determined by the composition of their batteries. Depending on the capacity of the battery pack, BEBs have a typical range of 150 to 300 kilometers. Variable based on environmental conditions, vehicle load, and utilization rates, the average energy consumption is approximately 1.3 kilowatt hour per km. BEBs

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are a distinct alternative to conventional fuel-powered public transportation buses due to these known parameters [1].

However, limited progress has been made in developing new battery technologies as a result of the widespread adoption of BEBs within a relatively brief period of time. This has led to certain disadvantages in the long-term operation of these vehicles. BEBs have the potential to reduce local emissions and noise pollution, but their recycling process is complex and difficult. Implementing a different method for storing the energy required for electric propulsion can mitigate this significant disadvantage [2].

Hydrogen emerges as a key factor in this context, as one of the most efficient energy carriers currently available. It can be obtained through a variety of methods and used to store the energy required for long-distance electric motor operation through the utilization of fuel cells. Currently, the most prevalent methods for obtaining hydrogen are steam reformation of natural gas and electrolysis, with the latter being the more environmentally friendly choice [3].

Fuel cells are devices that convert hydrogen and oxygen into electricity for use in propulsion systems. They provide exceptional energy efficiency and emission reduction capabilities. This modification enables FCEBs to travel greater distances than conventional BEBs. Specially designed containers capable of storing sufficient quantities of hydrogen for extended operation ranges are used to store energy [4].

There are numerous varieties of fuel cells on the market, each with their own advantages and disadvantages. Proton Exchange Membrane (PEM) fuel cells, which use a solid electrolyte in the form of an exchange membrane, are the most common variety. PEM fuel cells operate within a limited temperature range of 80-100 degrees Celsius and are capable of producing up to 100 kilowatts of power at an efficiency of 40-60 percent. Due to their quick startup time, small dimensions, and reduced weight, they have found widespread use in the mobility industry. PEM fuel cells are however sensitive to moisture, dehydration, water salinity, and ambient temperature. Other fuel cell technologies include Alkaline (AFC), Phosphoric Acid (PAFC), Molten Carbonate (MCFC), and Solid Oxide (SOFC), but these are utilized less frequently in mobility applications due to their lengthier startup times and higher production and operational costs [5] – [7],[10].

This paper examines two primary alternatives to conventional public transportation. The baseline solution is a completely electric bus with two hub-mounted electric motors and a Li-Ion battery pack. In addition to a PEM fuel cell, the fuel cell variant also incorporates a smaller battery for power delivery. The purpose of this paper is to emphasize the key distinctions in terms of energy efficiency between these solutions and to demonstrate how advancements in fuel cell technologies can facilitate the adoption of these vehicles as the backbone of sustainable transportation systems.

II. Material and Method

The purpose of this paper is to illustrate the functional differences between two buses that are similar in construction but have differing energy management. AVL Cruise M, a simulation software created by AVL List GmbH, was utilized for this analysis.

To execute the analysis, two vehicles were modeled using AVL Cruise M. Solaris has designed and constructed a flexible public transportation platform with multiple construction variants, with the selected construction solution being the Urbino 12 bus, which is available in both fully electric and fuel cell versions. Due to the high degree of similarity between these vehicles, the emphasis of this paper will be on illustrating the functional distinctions, as the structural components of the models are essentially similar. Prior to the modeling phase, it was essential to define the structural and functional characteristics of the vehicles under consideration. The parameters can be seen in Table I.

The modeling procedure included a number of parameterization steps. Each functional component of a BEV and FCEV is represented by a dedicated module in the models' modular construction. To acquire valid results, all components were modeled according to the manufacturer's published specifications. The electric model consists of a battery cell, a group of two ZF AVE 130 hub-mounted electric motors, a consumer module, and a subsystem for control functions. In addition to the previously enumerated components, the Urbino 12 fuel cell variant is equipped with a Ballard HD60 fuel cell.

To ensure maximum precision, the battery pack was configured using the output power, voltage, and current as references. The tractive system consists of two ZF-manufactured electric motors modeled after the actual machinery used by Solaris. Each motor generates 250 kilowatts of peak power, 650 Volts of nominal voltage, and 340 Amperes of maximum current [9]. The control functions subsystem contains the algorithms used to control each engine, as well as the vehicle's range and performance calculation functions. Also contained within this subsystem are the functions used to implement the test cycle. The fuel cell model consists of a Ballard HD60 fuel cell and a function that regulates the energy transfer between the battery and the fuel cell. The models are depicted in Fig. 1.

TABLE I. CONSTRUCTIVE CHARACTERISTICS OF THE URBINO 12 BUSSES [8]

Bus characteristic	Bus type	
	Urbino 12 Electric	***Urbino 12 Fuel Cell***
Kerb mass	13790 Kg	11032 Kg
Maximum authorized mass	19000 Kg	19000 Kg
Length	12000 mm	12000 mm
Width	2550 mm	2550 mm
Frontal area	1.97 m^2	1.97 m^2
Friction coefficient	0.8	0.8
Battery power	350 kW	100 kW
Motor	2 x ZF AVE 130	2 x ZF AVE 130
Motor power	2 x 150 kW	2 x 150 kW
Fuel Cell	-	Ballard HD 60
Range	100 Km	350 Km

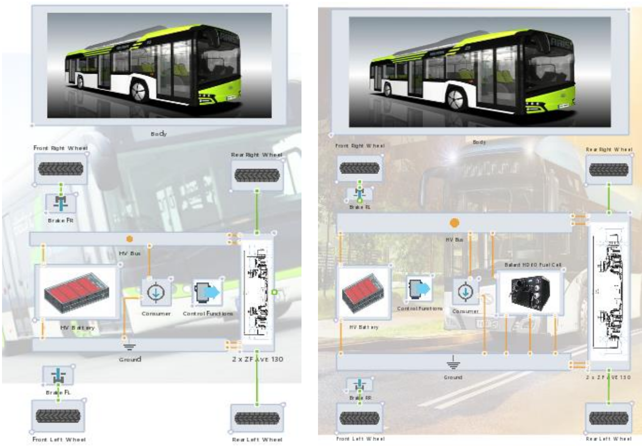

Fig. 1. Urbino 12 Electric (left) and Urbino 12 Fuel Cell (right) models

The results obtained following the simulations, were generated by using real data collected from the electric busses in use in the city of Cluj-Napoca. The data collected from the busses contain information regarding the GPS position of the bus, vehicle velocity, time and date, as well as other parameters such as brake lining usage, total energy charged and discharged.

The simulation data was collected using a CANedge 2 device capable of data collection via the OBD (On Board Diagnostics) connector of the bus using an adapter supplied by the equipment manufacturer. The device and adapter are depicted in Fig. 2.

The data could be collected on-site (using a memory card) or via an API (Application Programming Interface) that was implemented to capture a greater quantity of data. The obtained data was then processed in Microsoft Excel and imported into AVL Cruise M.

Throughout an entire weekday, the sequences used in the simulations were collected on the same bus. Thus, conclusive data regarding the driving profile, vehicle velocity, and vehicle position could be utilized to recreate the bus's behavior under real-world conditions.

Fig. 2. CANedge2 device used for bus data collection

Three driving cycles were generated using data on time and vehicle speed. The most significant time periods in Cluj-Napoca were the prime hours. The morning congestion hour begins when the majority of the population commutes to work or school. The first traveling cycle considered has a duration between 07:30 and 08:30. This time period will be referred to as "morning rush hour" throughout the publication. The interval between 16:20 and 17:30 will be referred to as "afternoon rush hour" throughout the entire publication. The population is commuting from their workplaces or schools to their residences during this time period. The last period considered is the interval between 21:00 and 22:00, which will be referred to as "evening rush hour" throughout the publication. The population travels towards the city center for a variety of activities.

Fig. 3 shows the expression of the three generated driving cycles.

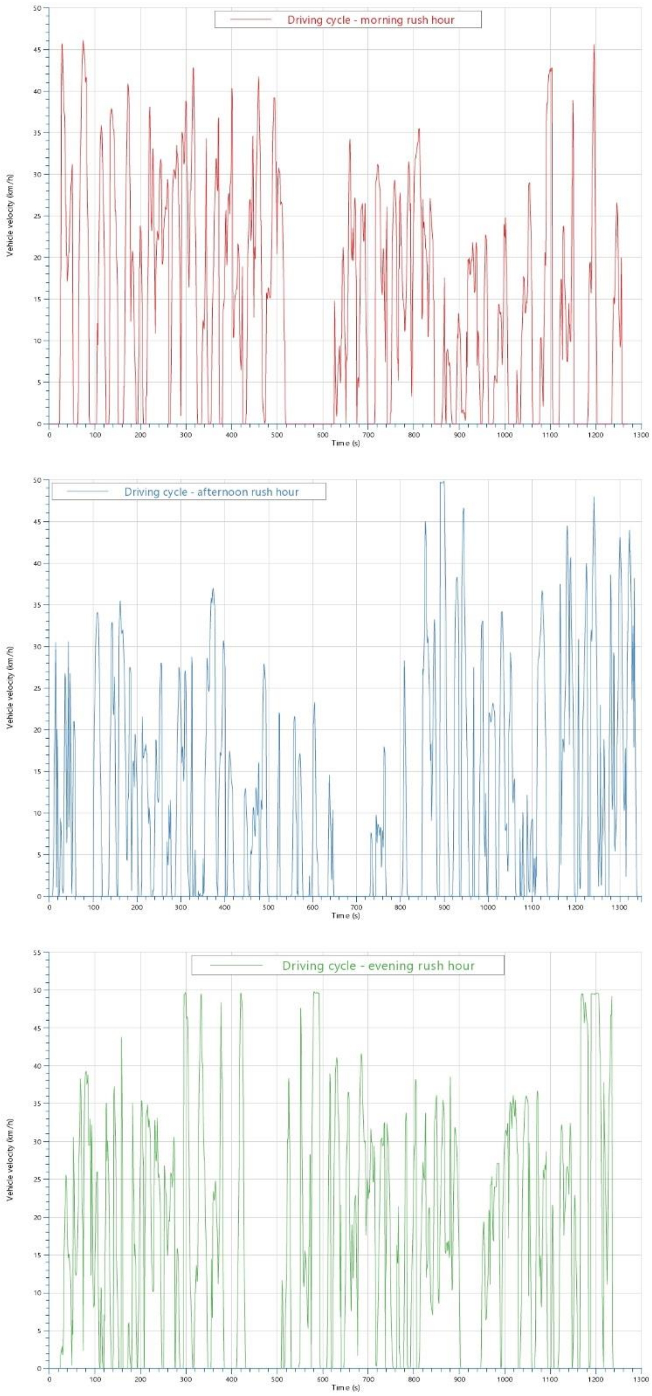

Fig. 3. Simulated driving cycles – morning rush hour (top), afternoon rush hour (middle), evening rush hour (bottom)

The selected intervals were chosen in order to provide a comprehensive perspective of the behavior of the electric buses under the heaviest load throughout the day. After establishing a correlation between real data and simulation, the fuel cell model will endure identical driving cycles in order to compare the theoretical performance of such vehicles to that of their electric counterparts.

The cycles describe the time-relative evolution of the vehicle velocity, throughout a two-way trip between the extremes of the defined transport line. This aspect allows the study of the vehicle behavior heading towards the city center, as well as the behavior of the vehicle, returning to a less agglomerated part of the city.

An important mention is the fact that the depicted cycles may depend on the driver profile, as well as the exterior temperature and ridership patterns. The results presented in this paper have a strong base in reality, however the obtained results may vary depending on a series of factors mentioned previously.

III. Results

In case of the electric bus model, the first analyzed metric was the SoC (State of Charge) at the end of the cycle. This analysis offers the possibility of correlating the simulation results with the real data. The evolution of the SoC in each of the three driving cycles can be observed in Fig. 4. The data is presented in Table II.

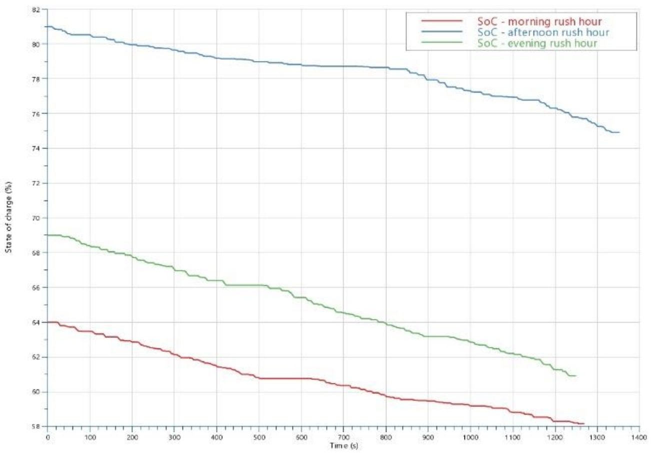

Fig. 4. Electric Bus model - State of Charge evolution

TABLE II. Electric Bus model - State of Charge evolution

SoC evolution		State of Charge [%]	
		Real value	*Simulated value*
Morning rush hour	Initial value	64	64
	End of cycle value	57	58
Afternoon rush hour	Initial value	81	81
	End of cycle value	77	75
Evening rush hour	Initial value	69	69
	End of cycle value	62	61

The data reveals the fact that the model is close to the real bus in terms of modulating its energy consumption relative to the driving cycle. However, one worthy mention is the fact that the SoC is heavily influenced by the use of auxiliary systems, such as air conditioning and interior heating. The acceleration patterns presented in the driving cycles are also more aggressive than the modelled components can compensate for. The driving cycles include each stop on the route, as well as potential stops caused by heavy traffic, in areas in which the dedicated bus lanes merge with regular lanes. Another aspect that is worthy of mention, is the great differences between the cycle's average speeds. The data regarding this aspect is presented in Table III.

TABLE III. Driving cycles average vehicle velocity

Average velocities	Vehicle velocity [km/h]
Morning rush hour	13.48
Afternoon rush hour	11.03
Evening rush hour	16.42

The illustrated differences between the average speeds indicate the traffic patterns in which the bus must function, thus greatly influencing the energy consumption. The evolution of the energy consumption of the electric bus is shown in Fig. 5. The model obtained similar energy consumption to the real bus, however, in the modelling of the electric bus, the route elevation changes, and auxiliary systems were not taken into account. The comparison is shown in Table IV.

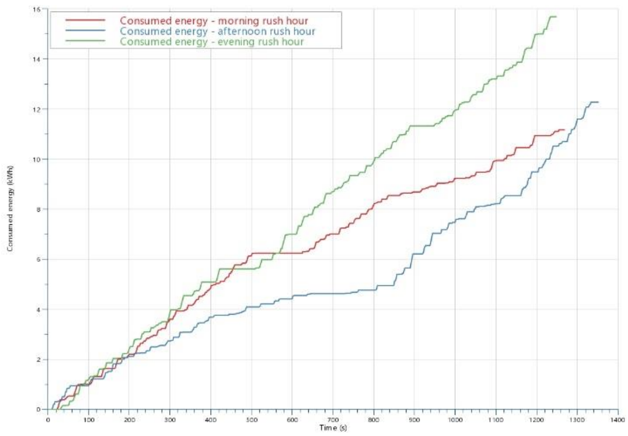

Fig. 5. Electric Bus model – Consumed energy evolution

TABLE IV. Electric Bus model – Consumed energy

Consumed energy	Energy [kWh]	
	Real value	*Simulated value*
Morning rush hour	13.513	11.175
Afternoon rush hour	13.177	12.281
Evening rush hour	17.286	15.686

A limited discrepancy between the simulated and real consumption values is evident. The main factor in the differences obtained is the lack of compensation for the route elevation and configuration, the present simulation being a cycle drive in ideal conditions. Another factor that contributes to the observed differences is the discharge profile of the batteries, the management of the discharge protocol proving to be difficult to model fully accurately.

The final analyzed metric in case of the electric bus model, is the energy consumption profile. The values obtained are slightly higher in the case of the simulation, as opposed to the real data collected. The energy consumption profile can be observed in Fig. 6. The data is presented in table V.

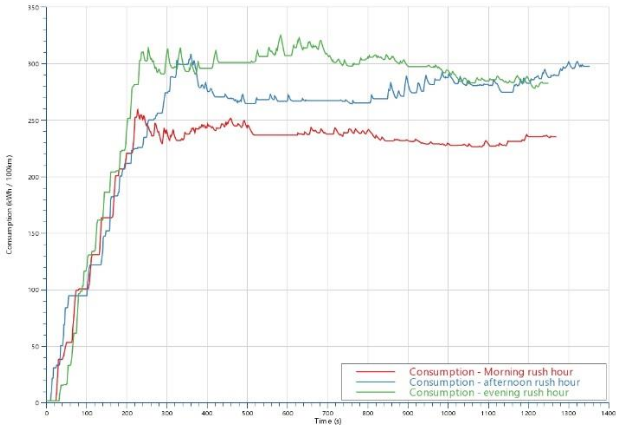

Fig. 6. Electric Bus model – Energy consumption evolution

TABLE V. ELECTRIC BUS MODEL – AVERAGE ENERGY CONSUMPTION

Average energy consumption	**Energy consumption [kWh/km]**	
	Real value	***Simulated value***
Morning rush hour	2.31	2.15
Afternoon rush hour	2.63	2.50
Evening rush hour	2.81	2.67

The consumption obtained from real data and simulation results, will serve as the baseline for the comparison in this paper. Given the fact that the simulated results are generally close to those obtained in real use, with the use of the same modelling techniques, the fuel cell bus model will be able to offer an insight into the energetic efficiency patterns of one such vehicle.

The most effective way to compare these vehicle varieties is by analyzing their total energy consumption. In the case of BEBs, the primary energy source is the battery pack, and the total energy consumption is equal to that of the energy drawn from the battery. There are two energy sources accessible for consumption in FCEBs: the battery pack and the fuel cell. The software computes the energy consumption of the battery charge. However, the vehicle's total energy consumption equals the sum of the energy extracted from the battery and the energy produced by the reaction of hydrogen mass in the fuel cell. The reacted hydrogen mass is depicted in Fig. 7.

TABLE VI. FUEL CELL BUS MODEL – REACTED HYDROGEN MASS

Reacted hydrogen mass	**Hydrogen mass [kg]**
Morning rush hour	0.381
Afternoon rush hour	0.361
Evening rush hour	0.502

The various SoC points at the outset of each drive cycle are one of the reference points in the considered drive cycles. To accurately compare these types of vehicles, the fuel cell model was configured with a serial topology to ascertain the powertrain's function by consuming hydrogen. The details are presented in Table VI.

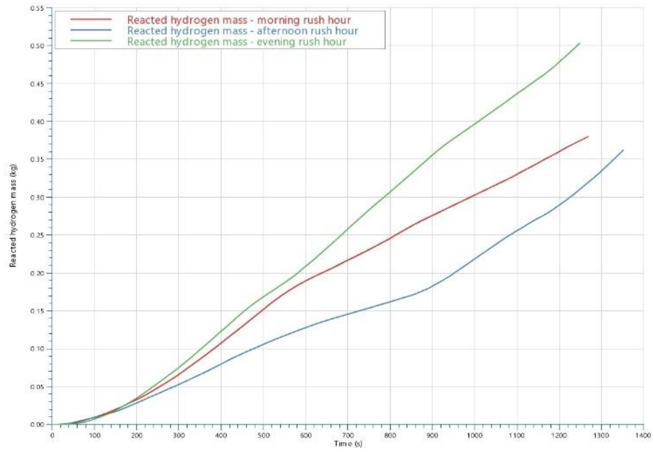

Fig. 7. Fuel Cell Bus model – Reacted hydrogen mass evolution

Given that 1 kilogram of hydrogen is equivalent to 33.6 kilowatt-hours and that the software can derive the mass of reactants, it is possible to calculate the total energy consumption [11]. The conversion is shown in Table VII.

TABLE VII. FUEL CELL BUS MODEL – HYDROGEN MASS TO ENERGY CONVERSION

Hydrogen mass to energy conversion	**Conversion**	
	Hydrogen mass [kg]	***Energy [kWh]***
Morning rush hour	0.381	12.801
Afternoon rush hour	0.361	12.129
Evening rush hour	0.502	16.867

The differences between the energy consumption in the case of the electric model and the fuel cell model, are due to the way the model manages energy efficiency. These differences are easily observed in Fig. 8 and Fig. 9, by overlapping the electrical energy consumption curves of the electric model, with the demanded hydrogen mass flow in the fuel cell model.

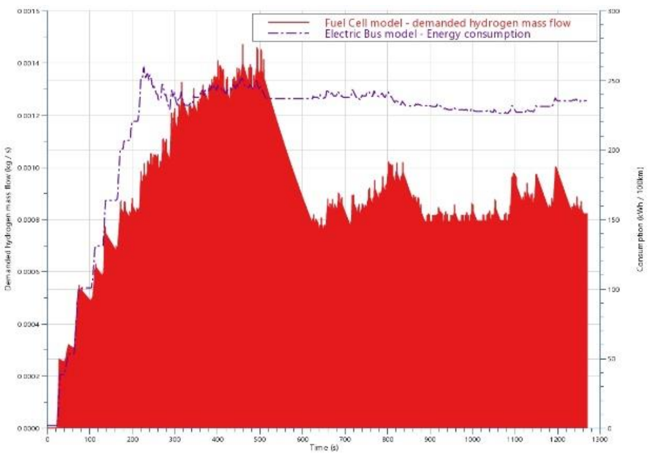

Fig. 8. Comparison – Demanded hidrogen mass flow vs Energy consumption – Morning rush hour

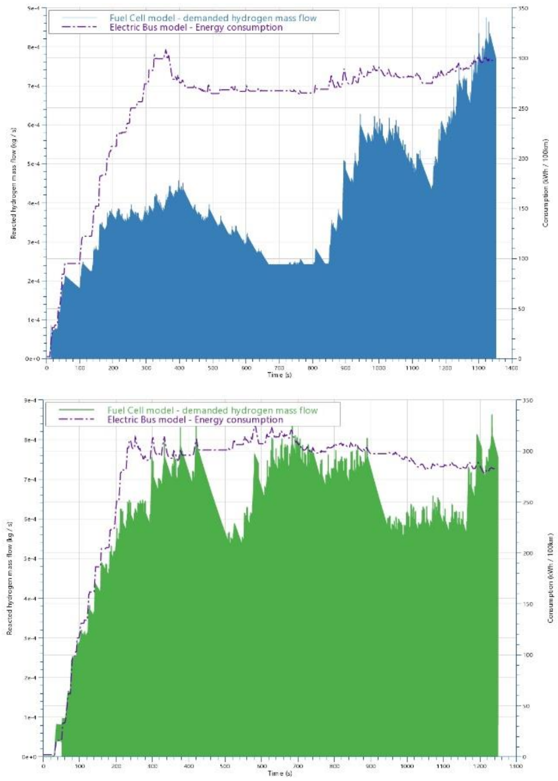

Fig. 9. Comparison – Demanded hidrogen mass flow vs Energy consumption – Afternoon rush hour (top), Evening rush hour (bottom)

IV. CONCLUSIONS

On the basis of the aspects discussed in this paper and the data provided following a comparative analysis of the two proposed solutions, the following can be determined:

• Following the simulations, a series of comprehensive results were discovered. The final comparison is shown in Fig 10. The obtained results are applicable on the current model and do not reflect a general vehicle behavior in neither of the simulated models.

• The fuel cell model has obtained a slightly larger overall energy consumption in the morning and evening rush hour scenarios, however, it has obtained marginally better results in the case of the afternoon rush hour scenario. The impulse-based architecture of the driving cycles, impose a severe strain on the powertrains of both models, resulting in higher energy consumptions, compared to the theoretical data disseminated by the bus manufacturer. However, the cycles imposed in the simulations are based on real life exploitation patterns and reflect the considerable effort on which these vehicles are subjected to during their use.

• Considering the results, and the fact that fuel cell vehicles generally have a longer battery life due to their ability to maintain their state of charge at a predetermined level, thereby requiring fewer full charge cycles, we can conclude the sustainability factor of fuel cell vehicles based on their ability to utilize a variety of energy storage means, thereby extending the lifespan of their battery packs. Moreover, replacing fuel cells is less expensive than entire battery packs in the case of electric vehicles. Using smaller, more efficient battery systems, fuel cell-powered vehicles are able to provide significantly greater exploitation range than electric vehicles.

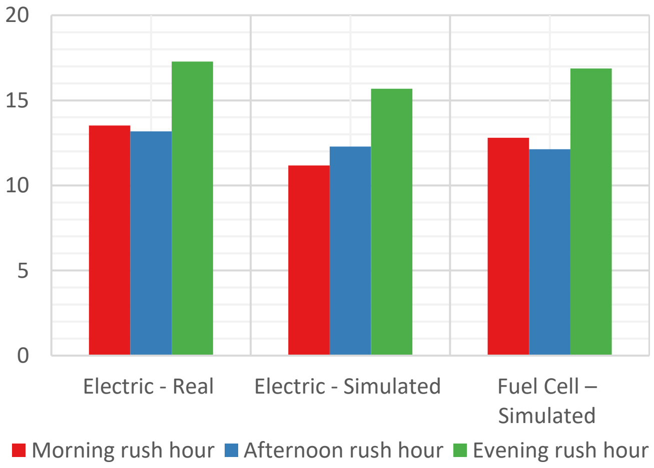

Fig. 10. Final energy efficiency analysis

• The range provided by completely electric solutions is significantly more susceptible, as it is directly impacted by driving style, environmental conditions, and road surface. In the case of fuel cell solutions, the evolution of range is significantly more predictable in terms of monitoring hydrogen consumption, with estimates that are closer to actual values.

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