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A Novel Optimal Power Control for a City Transit Hybrid Bus Equipped with a Partitioned Hydrogen Fuel Cell Stack

Gino D'Ovidio *, Antonio Ometto * and Carlo Villante *

CITraMS—Center for Transportation and Sustainable Mobility, University of L'Aquila, 67100 L'Aquila, AQ, Italy

* Correspondence: gino.dovidio@univaq.it (G.D.); antonio.ometto@univaq.it (A.O.); carlo.villante@univaq.it (C.V.)

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Abstract: The development of more sustainable and zero-emissions collective transport solutions could play a very important measure in the near future within smart city policies. This paper tries to give a contribution to this aim, proposing a novel approach to fuel cell vehicle design and operation. Traditional difficulties experienced in fuel cell transient operation are, in fact, normally solved in conventional vehicle prototypes, through the hybridization of the propulsion system and with the complete fulfillment of transients in road energy demand through a high-capacity onboard energy storage device. This makes it normally necessary to use Li-ion battery solutions, accepting their restrictions in terms of weight, costs, energy losses, limited lifetime, and environmental constraints. The proposed solution, instead, introduces a partitioning of the hydrogen fuel cell (FC) and novel optimal power control strategy, with the aim of limiting the capacity of the energy storage, still avoiding FC transient operation. The limited capacity of the resulting energy storage systems which, instead, has to answer higher power requests, makes it possible to consider the utilization of a high-speed flywheel energy storage system (FESS) in place of high energy density Li-ion batteries. The proposed control strategy was validated by vehicle simulations based on a modular and parametric model; input data were acquired experimentally on an operating electric bus in real traffic conditions over an urban bus line. Simulation results highlight that the proposed control strategy makes it possible to obtain an overall power output for the FC stacks which better follows road power demands, and a relevant downsizing of the FESS device.

Keywords: urban transit bus; hybrid power unit; partitioned hydrogen fuel cell; flywheel energy storage system

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1. Introduction

The transport sector accounts for about 30% of world energy demands, this being still mainly fulfilled by fossil oil-derived fuels, generating more than 30% of total GHG emissions. Urban transport, in particular, is responsible for about a quarter of total CO_2 emissions from transportation. Regarding local aspects, the impact reduction of transport on pollution in urban areas is no longer delayable, generating unacceptable health, and social, as well as economic, costs for the community. The EU Commission therefore adopted an ambitious roadmap consisting of a series of concrete initiatives for the next decade to build a competitive transport system able to cut carbon emissions by 60% by 2050, removing conventionally-fueled vehicles from the cities [1–3]. More generally worldwide, the EU and UN actions aim at improving the energy efficiency performance of vehicles and encouraging the development of more specialized road passenger vehicles based on the use of alternative fuels propulsion systems.

Within this strategy, buses may play a crucial role, representing the most common vehicle used for urban passenger transport. The introduction of new green technologies in this urban public transport sector is therefore expected to substantially contribute to air pollution reduction. It is estimated that cleaner buses alone would account for 20% of traffic emission reduction in urban areas. Collective transport means should therefore be designed and employed to minimize their environmental impact.

To reach this aim, however, a number of aspects must be taken into account, coping both with user expectations, in terms of number and frequency of vehicle stops, and with the energetic and economic balances of the service offered. For each given service, there are, in fact, a number of possible options to be compared, varying in terms of vehicle size, payload, powertrain type, control strategies, fuel used, etc. [4–7]. Limiting the attention to on-road transport means that full electric propulsion is certainly one of the most promising options, but is competing with a number of different alternatives in terms of vehicle powertrain [8–14], including hybrid configurations (using a combination of onboard energy sources), and/or alternative fuels, both based on renewable or fossil sources [8–14].

At present, the fleets of buses operating in large cities are mostly made up of vehicles with old and highly polluting diesel motorizations. Seeking alternatives to diesel motorization is crucial for reaching the emissions reduction in mass urban transport. Electric propulsion is certainly the most promising alternative, since it may lead to zero local pollutant emissions, but battery electric vehicles (BEVs) still present substantial limitations, both in terms of lifecycle environmental impact (for example in terms of battery end-of-life), and in terms of vehicle performances (charging times, heavy weight, short battery lifetime) [15–18].

Within this context, the more interesting solution would be certainly producing electricity on board from a chemical fuel source. To this aim, hydrogen (through fuel cell) would be certainly the most environmentally compatible solution for trying to overcome BEV limitations while still having zero local emissions. However, years of previous studies showed that direct fuel cell propulsion would not be a near-future option, as fuel cell is inadequate to follow highly transient road power demands. Fuel cell should therefore be, as much as possible, operated steadily, hybridizing the vehicle through an onboard electric energy storage device (HFCVs) [19].

In summary, the authors' opinion is that limiting the attention to urban buses, BEVs, and HFCVs provide the most promising alternatives: the choice of the best solution is also affected by the path used in electricity or hydrogen production (e.g., fossil fuel reformulation or water electrolysis in the case of hydrogen), so it may vary locally and during time, as far as renewables share increases in electric energy production. In any case, both systems guarantee a substantial bettering with respect to conventional vehicles, making it locally possible not to generate any pollutant emission [20–24].

Within this context, this paper tries to give a contribution proposing a novel approach to HFCVs vehicle design and operation. Traditional difficulties experienced in fuel cell transient operation are, in fact, normally solved in conventional vehicle prototypes, through the hybridization of the propulsion system and with the complete fulfillment of transients in road energy demand through a high-capacity onboard energy storage device. This makes it normally necessary to use Li-ion battery solutions, accepting their restrictions in terms of weight, costs, energy losses, limited lifetime, and environmental constraints.

The proposed solution, instead, introduces a partitioning of the hydrogen fuel cell (FC) and novel optimal power control strategy with the aim of limiting the capacity of the energy storage, still avoiding FC transient operation. The limited capacity of the resulting energy storage systems which, instead, have to answer higher power requests, makes it possible to consider the utilization of high-speed flywheel energy storage system (FESS) in place of high energy density Li-ion batteries [25–29].

The FESS, a flywheel connected to an electrical motor–generator, is a device able to store electric energy on board with high efficiency, fast dynamic response, long cycle life, no charge/discharge limits, and no chemical pollution. High-speed FESSs (up to 80,000 rpm) with composite material rotors are mainly used to increase the energy density; in order to reduce energy losses, they require magnetic bearings to avoid mechanical friction, and vacuum vessels to reduce air drag. The present high price is expected to drop in the near future due to mass production, and the FESS could become competitive with respect to devices that use other energy storage technologies [20–24]. The functional coupling of FC and high-speed FESS allows a high efficiency and zero-emission hybrid power units (HPUs) to be realized, suitable for urban electrical traction applications. A novel HPU consisting of a hydrogen FC and a set of high-speed FESSs was already studied and proposed by the authors for small-sized city buses [30–34] and city light trains [35].

The proposed control strategy was validated by vehicle simulations based on a modular and parametric model; input data were acquired experimentally on an operating electric bus in real traffic conditions over an urban bus line. Simulation results highlight that the proposed control strategy makes it possible to obtain an overall power output for the FC stacks which better follows road power demands, and a relevant downsizing of the FESS device.

In detail, the paper is organized as follows: Section 2 illustrates the system definition, the proposed hybrid power configuration, and the control strategy. In Section 3, the models of the vehicle and the powertrain components are described. Then, in Section 4, the case study is presented in terms of vehicle specifications, drive cycle, and path topography. Section 5 reports simulation results of system behavior of the proposed innovative configuration, which are then compared with a benchmark vehicle in Section 6. Finally, conclusions are summarized in Section 7.

2. System Definition

A simplified general scheme of the proposed vehicle architecture is shown in Figure 1; it consists of a middle-sized urban transit bus for passenger transport. The electrical motor is mechanically connected to the rear axle of traction by means of a speed reducer.

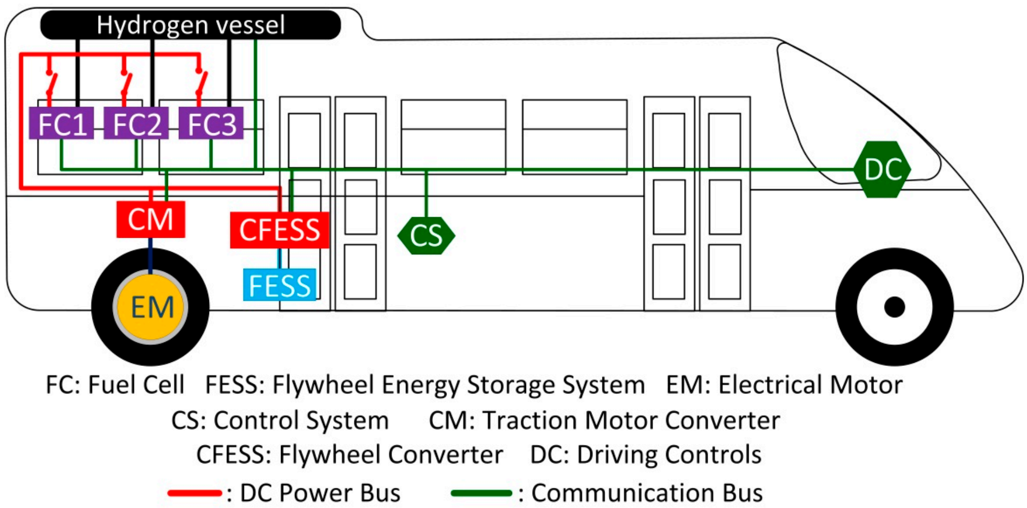

Figure 1. Powertrain scheme of transit bus.

The proposed powertrain unit uses an electric traction motor (EM) fed by a hybrid power unit (HPU) consisting of an FC stack and a bench of FESSs. In Figure 1, FESS modules are represented as a single group, since they are managed together as a whole.

The proposed solution is innovative with respect to the state of the art. Conventional solutions, in fact, are based on two different approaches.

- The former uses a dynamically operated FC stack, accepting a low mean system efficiency: the FC stack, in fact, has an efficiency curve which is highly dependent on its load factor and presents a limited operating range around its highest efficiency point. Moreover, if FC operating conditions are rapidly and relevantly changed, to follow the variable load power, the average system efficiency could be much lower than the measured one in quasi-steady state operation conditions.

- The second approach is based on a hybrid system with a fixed-point-operated FC stack to cover the mean load power and a high-capacity energy storage system (ESS) (usually made of Li-ion batteries) to cover the dynamic load power. This approach allows the FC to be operated around its best efficiency point and to be designed for the mean value of the traction power. This latter consideration is only valid if the power system is designed for a given application. In real conditions, since a vehicle may be used on completely different paths, this approach normally leads to a relevant over-sizing of the rated power of the FC and/or of the ESS, also affecting the system fuel consumption.

The novel solution, here proposed, is somehow intermediate between these two approaches and is based on the splitting of the FC stack in a number of independently on/off operated units; it allows the dynamic power to be better followed, and so optimizes the energy efficiency and the reducing energy requirements of the ESS; this also makes it possible to replace Li-ion batteries with higher-efficiency and more environmentally-friendly FESSs.

The traction motor and the FESSs are connected to the DC power bus (continuous red line) by means of converters (CM and CFESS) to manage the power flows as required by the master control system (CS) via the communication bus (green line).

Due to the FC's slow dynamic response, the master controller imposes a constant operating point for each FC stack so that the FESS handles the load variations with the aim to:

- Provide power when the load power is higher than the FC power.
- Recover when the FC power is higher than the load power, and during the regenerative electrical braking.

The schematic of the hybrid powertrain and the reference directions of the power flows are shown in Figure 2.

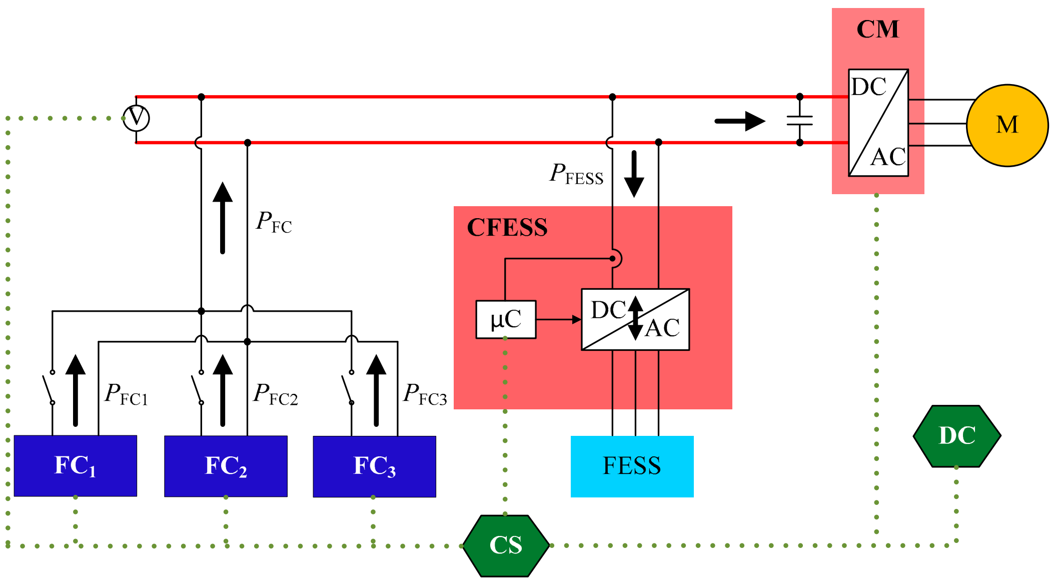

Figure 2. Schematic of the hybrid powertrain.

3. System Model

Mathematical models were developed and used in a numerical simulator in order to evaluate the performance of the proposed transit bus and its components by varying system parameters.

A dynamic systems modeler and simulator in a Matlab-Simulink environment [36–38] was used to carry out a parametric model of the system, which was able to evaluate the performance of the vehicle moving over a given path. A synthetic sketch of the model is reported in Figure 3.

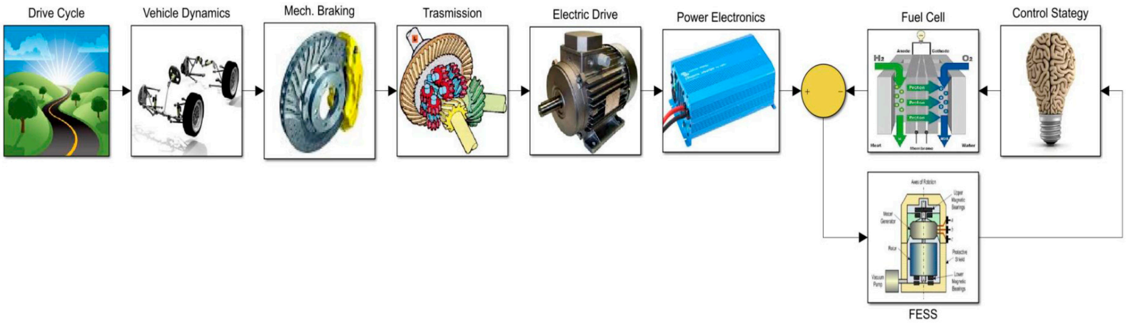

Figure 3. Sketch of the mathematical model of the system.

Here, the model is only briefly described with comments on its main features. For full detail on its characteristics, please refer to other papers by the same authors [36–39].

The implemented model calculates the traction power requirement by starting from the road characteristics and vehicle parameters (features and load factor). Each component of the powertrain was modelled separately and validated by means of experimental data from literature.

The simulator is based on the well-known differential equation of motion:

$$\sum F(t) = m \cdot a(t) \tag{1}$$

The summation of the forces can be split into the traction thrust $T(v(t))$ and the summation of the resistances to the vehicle motion $\Sigma R(v(t))$, then the equation of motion (1) can be written as:

$$T(v(t)) + \sum R(v(t)) = m \cdot \alpha \cdot \frac{dv}{dt} \tag{2}$$

where m is the gross mass of the vehicle, α is the inertial rotational mass coefficient, and v is the vehicle speed (α is coefficient taking into account the inertial effect of rotating parts within the vehicle).

Given the speed function $v(t)$, the traction thrust $T(v(t))$ is computed as:

$$T(v(t)) = m \cdot \alpha \cdot \frac{dv}{dt} - \sum R(v(t)) \tag{3}$$

The total resistance to the vehicle motion $\Sigma R(v(t))$ is given by:

$$\sum R(v(t)) = R_W(v(t)) \mp R_S + R_A(v(t)) \tag{4}$$

where R_W is the rolling resistance, R_S the slope resistance, and R_A the air resistance, as follows:

$$R_W(v(t)) = m \cdot (k_{r1} + k_{r1}\, v^2(t)) \tag{5}$$

$$R_S = m \cdot g \cdot sin(\beta) \tag{6}$$

$$R_A(v(t)) = k_a \cdot A_f \cdot v^2(t) \tag{7}$$

where g is the gravitational acceleration, β is the angle of the road slope, k_a is the aerodynamic coefficient, k_{r1} and k_{r2} are rolling resistance coefficients, and A_f is the front area of the vehicle. Those values have to be detailed for each the single vehicle and road pavement. Data used in this simulation are reported for the purpose of this paper in Table 1.

Table 1. Vehicle and power unit features.

Model Parameter	Symbol	Unit	Value
DC voltage bus	V	V	360
Steady EM power	kW	kW	210
Vehicle length	L	M	10.5
Vehicle mass	m	kg	11,150
Gross mass (88 passengers)	m_g	kg	17,790
Vehicle Frontal Area	A_f	m^2	
Aerodynamic coefficient	k_a	N s^2 m^{-4}	1.53
Rolling resistance coefficients	k_{r1}	m s^{-2}	0.15
	k_{r2}	m^{-1}	5×10^{-6}
Rotating parts inertial coeff.		None	1.05
Electrical drive efficiency	η_D	none	0.8
Transmission efficiency	η_t	none	0.93
FC stacks number	$FC_{\#}$	none	3
FC stacks power	P_{FC1}—P_{FC2}—P_{FC3}	kW	15—30—60
FESS modules number	$FESS_{\#}$	none	6
Single FESS module power	P_{FESS}	kW	180
Single FESS module energy	E_{FESS}	Wh	375
Single FESS module weight	W_{FESS}	Kg	58.5
Overall FESS bench energy	$E_{FESS\text{-}Tot}$	kWh	2.250

Considering regenerative electrical braking, the electrical traction power $P_u(t)$ is calculated as:

$$\begin{cases} P_u(t) = \frac{T(v(t))v(t)}{(\eta_t \eta_D)} & \text{if } T(v(t))v(t) > 0 \\ P_u(t) = T(v(t))v(t)\eta_t \eta_D & \text{if } T(v(t))v(t) < 0 \end{cases} \tag{8}$$

where η_t is the transmission efficiency and η_D is the efficiency of the electrical traction drive, i.e., the converter and the motor.

The model also applies limits on maximum applicable braking power, considering the repartition of weight on traction and rolling vehicle axes and the limits imposed to vehicle adherence. Moreover, energy is not recovered if the state of charge (SOC) of the energy storage is full. Full detail about the braking model is given in [36].

Regarding the FC, a proton exchange membrane (PEM) type was selected; it was considered a voltage generator modelled by means of its voltage–current static characteristic, disregarding its dynamic behavior and any time delay. Since the FC operates at constant power, a constant efficiency (η_c) is assumed in the model.

The FESS model was based on the stored kinetic energy:

$$E_K = \frac{1}{2} I \omega^2 \tag{9}$$

where I is the moment of inertia of the rotor and ω is the rotational speed. The amount of useful energy for a given rotational speed range can be calculated as:

$$E_{K,u} = \frac{1}{2} I (\omega_{\max}^2 - \omega_{\min}^2) \tag{10}$$

where $\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum values of the rotor angular speed, respectively.

4. Case Study Definition

A vehicle's fuel consumption and efficiency mainly depend on its powertrain configuration, but they are also affected by other parameters, such as passenger load, drive speed, number of stops, road grade, and traffic conditions. In order to evaluate the effects of these factors on fuel consumption, a real bus route was selected as a case study.

Input data defining the simulation (data about vehicle, drive cycle, and path topography) were experimentally acquired on an electric bus operating in real traffic conditions over a urban bus line in the city of L'Aquila in Italy (Line 2 of the city's transport network—a roundtrip tour of about 17 km length), shown in Figure 4. Table 1 illustrates the main data of the selected roundtrip cycle; the path is fully in an urban context, with a speed limit of 50 km/h.

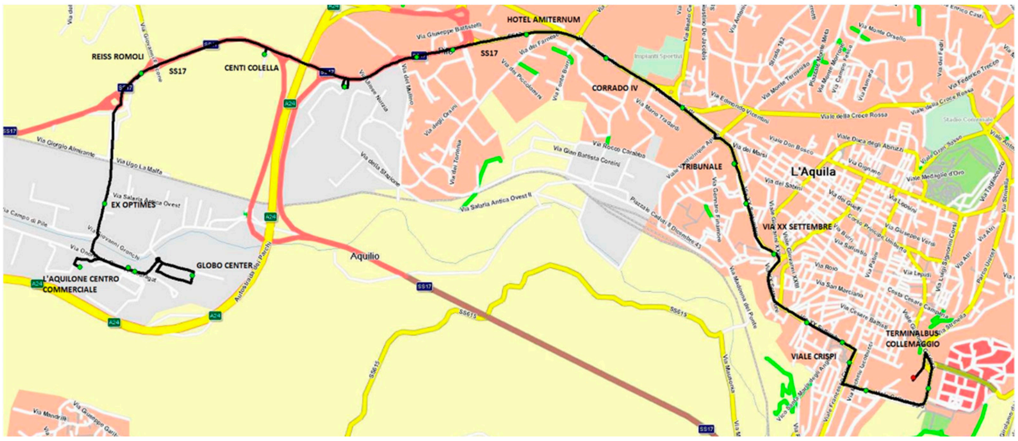

Figure 4. Line 2 of the L'Aquila transport network (black line). Source: Azienda Mobilita Aquilana (AMA) (L'Aquila public transport company).

A transit bus was simulated based on data gained on an instrumented BEV by IVECO (Model "UrbanWay Euro6") circulating in the city of L'Aquila. The bus has an 88-passenger carrying capacity at full load. Its main characteristics are listed in Table 2. The complete mathematical model of the vehicle was calibrated and validated through a detailed experimental activity [36,37].

Table 2. Round trip main data.

Parameter	Value
Total cycle length	17 km
Maximum grade	–4.2%–4.2%
Total cycle time	48 min
Average speed	20 km/h
Maximum speed	54 km/h

Figure 5 shows the vehicle cycle in terms of speed and grade vs. mission time. Data were obtained by both a GPS acquisition device installed on board and the processing of the main operating parameters measured by vehicle ECU (through vehicle CAN communication protocol).

Given that the speed profile and the path characteristics are imposed and all the quantities in the right side of Equation (3) are known, the traction thrust $T(v(t))$ and the power at vehicle wheels $T(v(t))v(t)$ (Figure 6) can be computed. Then the electrical traction power $P_u(t)$ is calculated by Equation (8), and the HPU can be sized.

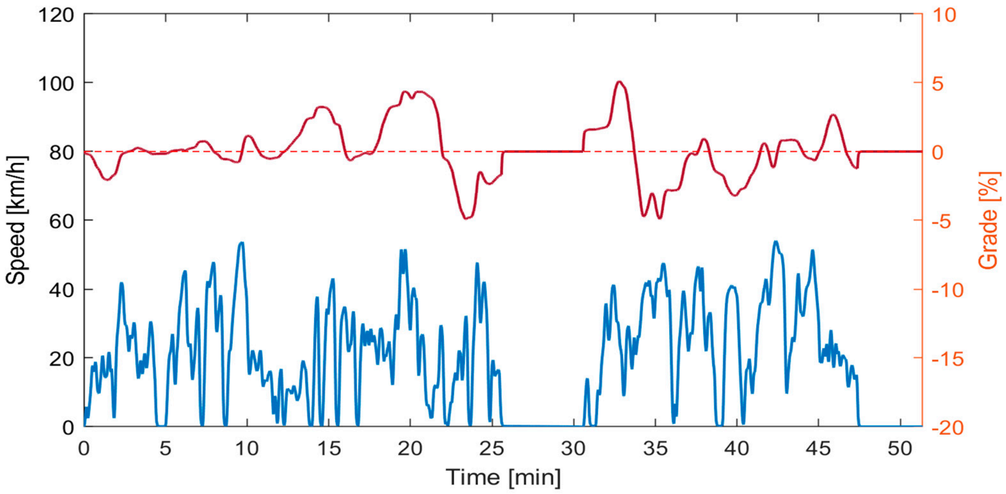

Figure 5. Speed and road grade profiles of vehicle mission.

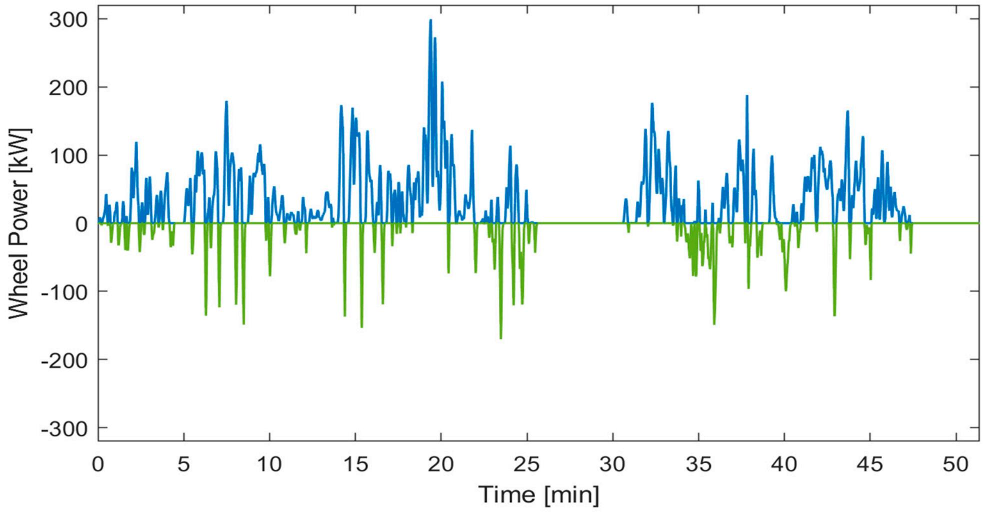

Figure 6. Power profile at vehicle wheels.

5. Simulation and Results

The system design in terms of power and energy was carried out by means of preliminary simulations of the model. The results shown in the following figures are relative to the optimized system design: an HPU with three FC stacks operating in on/off mode at their best efficiency point (around 80% of their nominal maximum power, at 11.5 kW, 23 kW, and 46 kW, respectively) was used.

FC cells technical data are based on the performances of a 30 kW cell by Arcotronics measured experimentally in a previous research activity by the authors. The sizes of the three stacks were chosen in a 1:2:4 ratio. The independent activation of the three stacks made it possible to obtain seven different output power levels (1/7–7/7 of max power output).

The simulation was performed by selecting FESS modules by GNK Hybrid Power [40], with a specific power of 3.15 kW/kg and a specific energy of 6.4 Wh/kg). Six of these modules proved to be enough for the fulfilment of the simulated mission. All the modules were grouped together and managed as a single bench.

The control strategy of the HPU was based on the knowledge of the FESS state of charge (SOC) as the controlled variable. In particular, as it is shown in Figure 7, seven SOC activation levels were defined to increase the FC power output (step 1/7 of the overall power) when crossed with negative slope (green dashed lines) and the other seven levels (blue dashed lines) were used to decrease the FC power if crossed with positive slope, on a "relays-based" approach, which can be realized for practical automotive applications.

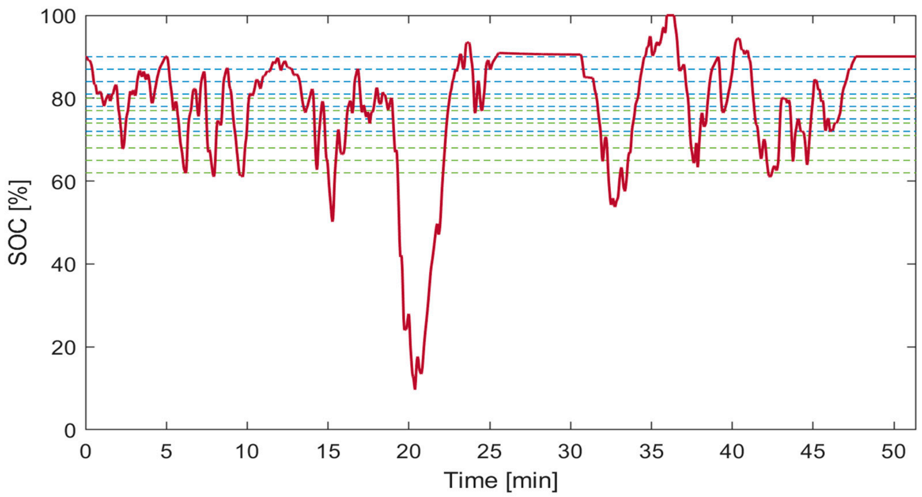

Figure 7. Flywheel energy storage system (FESS) bench state of charge.

The FESS SOC profile is also reported in Figure 8; it shows that the FESS is well dimensioned in terms of its storable energy amount, with its SOC oscillating between 50% and 90% most of the time. There is only a small critical time interval in which it gets as low as almost 10%, and the FESS saturates (100%) in a negligible time interval.

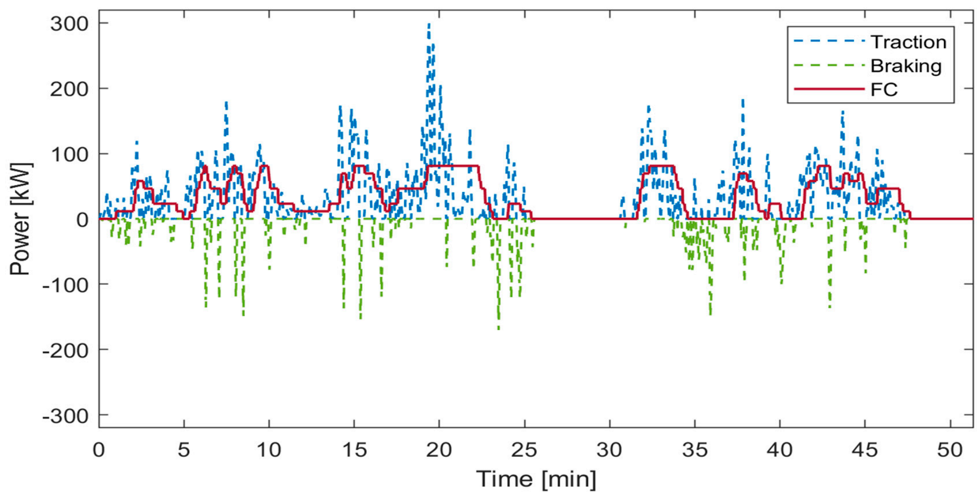

Figure 8. Electric power profiles: traction (blue), regenerative braking (green), and fuel cell (FC) (red).

Correspondingly, the FC and FESS power requirements were obtained and reported in Figures 8 and 9; of course, the FESS power was used to compute the FESS SOC oscillations (Figure 7).

The FC power output demand had to be produced through the independent activation of the three installed stacks, as above described. Figure 10 reports a graphical representation of the partitioning of the FC stack and of the independent activation of the three stacks.

Lastly, Figure 11 reports a Sankey-type diagram of the overall energy fluxes among the various components of the power unit. All data represented are the result of the complete dynamic simulation of the vehicle on the given mission; all vehicle variables were calculated vs. time with a time resolution of 0.1 s and then integrated vs. time to obtain overall energy fluxes between the components. The Sankey diagrams are automatically sketched by the SW tool.

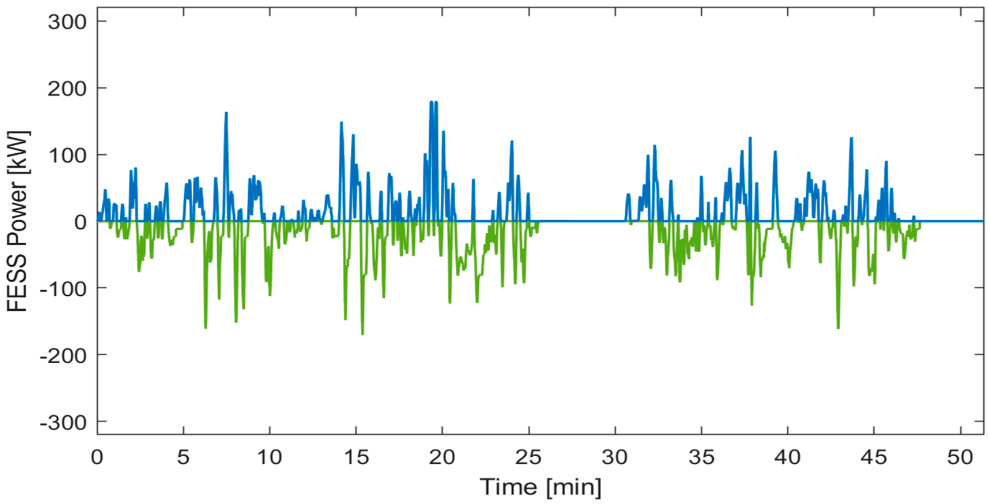

Figure 9. Power profile of the FESS bench.

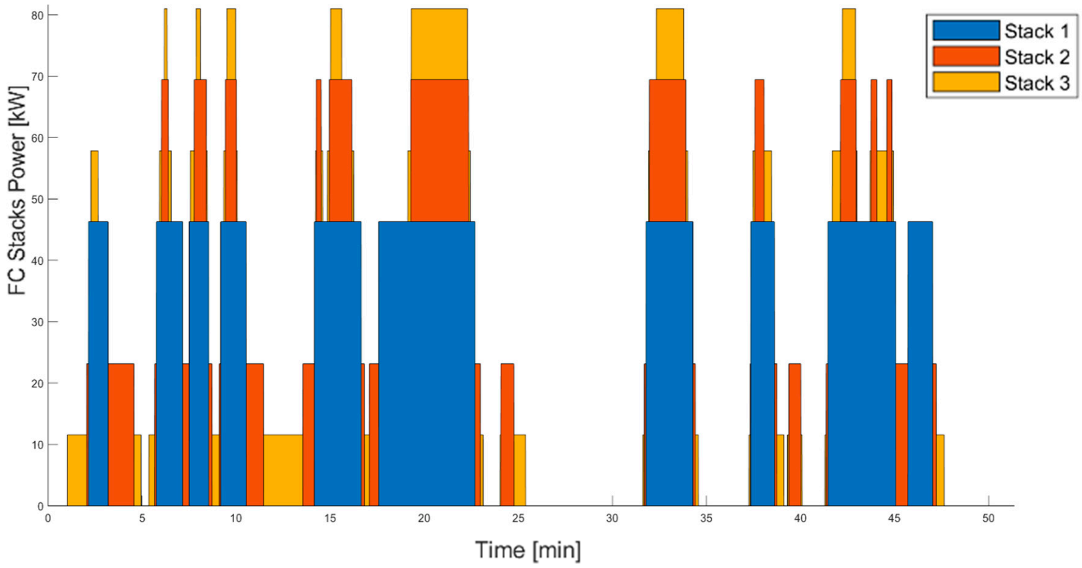

Figure 10. FC stacks partitioning and activation.

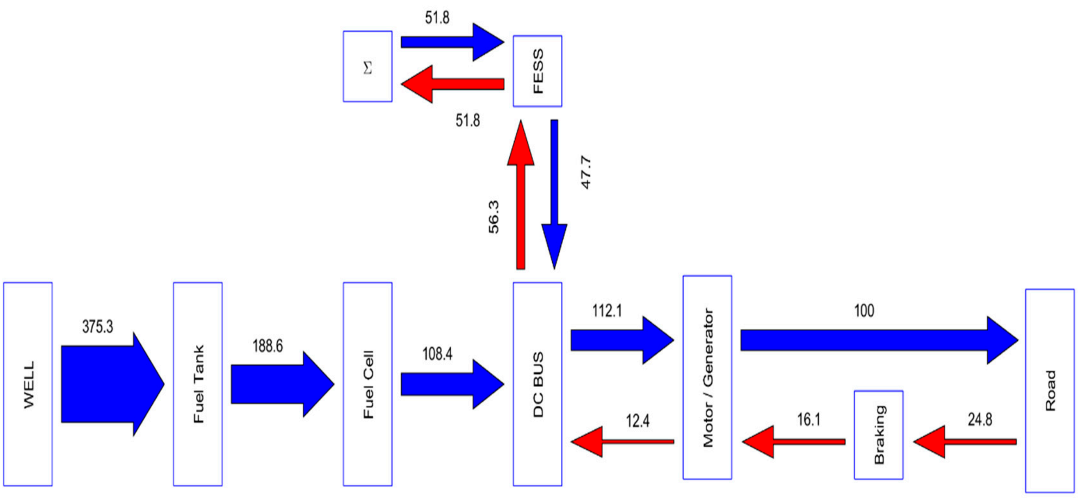

Figure 11. Vehicle energy balance (referred to 100 road energy output: 81.7 Wh/(km*ton)). Well-to-wheels (WTW) impact evaluated based on H_2 by CH4 production technologies, according to data from [41].

Energy requirements were calculated by the model up to the hydrogen fuel tank. Those were then extended on a well-to-wheels basis, making use of data of energy requirements in H_2 production by the JRC [42].

6. Benchmark Case: Single Fuel cell Stack

The previous results were compared with those obtained, considering a PU consisting of a single FC operating in on/off mode.

A similar procedure was adopted to design the hybrid system in terms of power and energy. The optimized system design led to the definition of an FC rated power of 54 kW (2/3 of the overall FC rated power of the previously proposed HPU) and an FESS bench composed of 12 FESS modules by GKN. Increased storable energy (up to 4.5 kWh, i.e., twice the previously required value) is needed to cover the higher differences between instantaneous FC power output and road power requirements. Obviously, the on/off switch of the FC is now based on a single hysteresis band.

The results corresponding to those reported in the above figures are shown in Figure 12, Figure 13, and Figure 14 for this benchmark vehicle, and the comparison in terms of the FC energy required for the round trip can be deduced from Figure 15. Despite the different configurations of the two hybrid systems, the overall fuel consumptions are very close to each other, since in both cases the FCs always work at the maximum efficiency value, and the amount of electricity required is almost the same. It means that the two systems are functionally equivalent, and other parameters and economic and environmental considerations (e.g., regarding Pt fuel cell contents) should be taken into account to make a rational and proper choice. Optimal choice is the object of following evaluation by the authors.

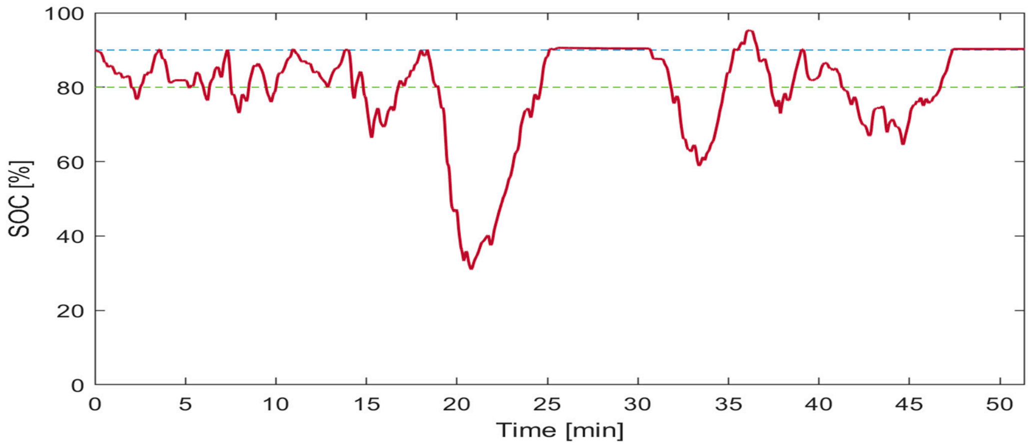

Figure 12. FESS bench state of charge.

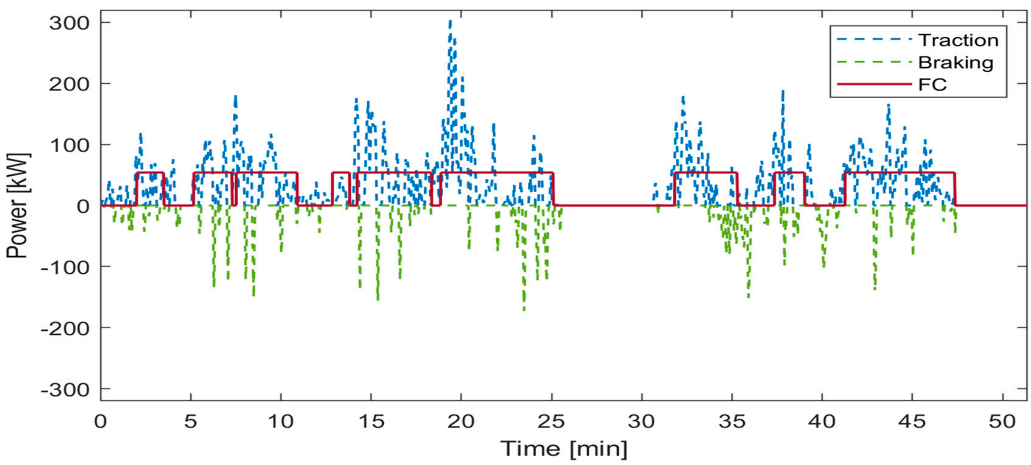

Figure 13. Electric power profiles: traction (blue), regenerative braking (green), and FC (red).

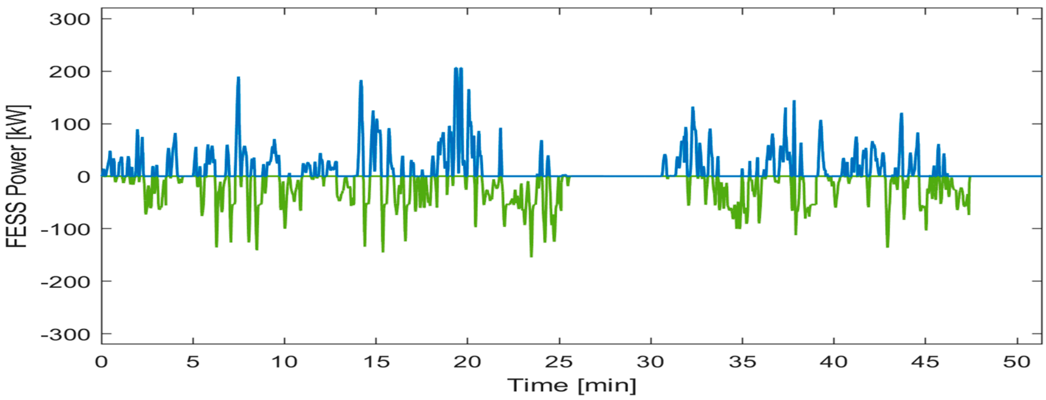

Figure 14. Power profile of the FESS bench.

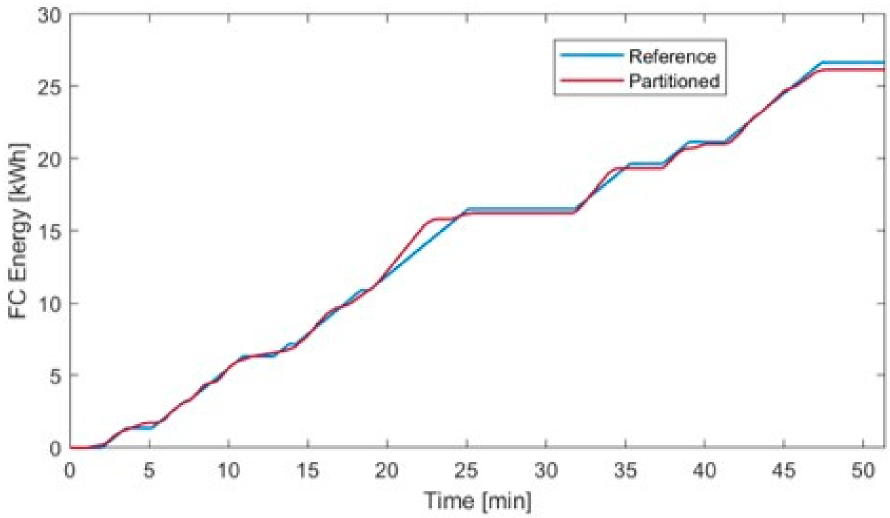

Figure 15. FC output energy: Comparison between FC partitioned in three stacks, and benchmark single stack case.

7. Conclusions

The authors propose the design of a novel hydrogen-fueled hybrid power unit for zero-emission city transit bus applications; the powertrain consists of an electric drive fed by a hybrid power unit composed of a functional coupling of a high specific power flywheel energy storage system (FESS) and a high specific energy hydrogen fuel cell (FC).

The FC power unit is partitioned into a number of stacks: each of these is on/off operated around its best-efficiency operating point; power transients are mainly covered by the FESS bench. The control strategy of the power unit, based on the state of charge of the FESS, may activate the three stacks independently, resulting in seven different available power levels for the FC power unit, all obtainable with its maximum efficiency performances.

The performances of the proposed vehicle on a reference mission were simulated through a modular and parametric approach; each part of the model was separately calibrated and validated by experimental data from literature.

The simulation results highlight that the proposed hybrid power unit and control strategy make it possible to obtain an overall power output for the FC stacks which better follows road power demands (if compared to more traditional FC power units), maintaining the overall system energy efficiency with a 50% overall increment of installed FC power output (increasing from 54 kW to 81 kW), and a corresponding 50% decrement of installed FESS storable energy (decreasing from 4.5 kWh to 2.25 kWh). The objective of maintaining the cell as far as possible while steadily operating is achieved by the three separate FC partitions, while the need for electric storage is halved. The overall fuel consumptions of the two hybrid systems are very close to each other, since in both cases the FCs always work at the maximum efficiency value. Choice between the two solutions depends on a number of possible considerations, including vehicle flexibility and adaptability to other paths (having a higher installed FC power) and also cost constraints, considering unitary cost of the FC installed power (€/kW) and the unitary cost of the FESS installed energy (€/kWh), and environmental constraints (viability of Pt for the FC stacks).

Our research limited its attention to vehicles operating on predetermined paths and on some experimentally-measured vehicle missions. Next steps in research will focus also on the effects of traffic conditions on power transients and overall energy requirements. Research under development will try to overcome these constraints through a predictive approach.

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