

Article

Optimized Design of a H₂-Powered Moped for Urban Mobility

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Abstract: Micro-mobility plays an increasingly important role in the current energy transition thanks to its low energy consumption and reduced contribution to urban congestion. In this scenario, fuel cell hybrid electric vehicles have several advantages over state-of-the-art battery electric vehicles, such as increased driving ranges and reduced recharge times. In this paper, we study the conversion of a commercial electric moped (Askoll eS₃[®]) into a fuel cell hybrid electric vehicle by finding the optimal design of the components through an optimization methodology based on backward dynamic programming. This optimal design and operation strategy can also be implemented with a rules-based approach. The results show that a system composed of a 1 kW proton exchange membrane fuel cell, a 2000 Sl metal hydride hydrogen tank, and a 240 Wh buffer battery can cover the same driving range as the batteries in an electric moped (119 km). Such a hybrid system occupies considerably less volume (almost 40 L) and has a negligibly higher mass. The free volume can be used to extend the driving range up to almost three times the nominal value. Moreover, by using a high-pressure composite tank, it is possible to increase the mass energy density of the onboard energy storage (although compression can require up to 10% of the hydrogen's chemical energy). The fuel cell hybrid electric vehicle can be recharged with green hydrogen that is locally produced. In detail, we analyze a residential scenario and a shared mobility scenario in the small Italian city of Viterbo.

Keywords: sustainable mobility; micro mobility; fuel cell hybrid electric vehicle; Worldwide Harmonised Light Vehicles Test Procedure; proton exchange membrane fuel cell; metal hydrides



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1. Introduction

The European Commission, with the goal of environmental protection, presented a detailed plan to reduce greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels [1]. Such a result will be the first step in a balanced pathway to achieving climate neutrality by 2050 [2]. In 2016, the European Union (EU) published the European Strategy for low-emission mobility [3], for which the relevant elements are: (i) increasing the efficiency of transportation systems, (ii) speeding up the deployment of low-emission alternative energy for transport [4], and (iii) moving towards zero-emissions vehicles (ZEVs). Despite ZEVs being pivotal to the effective realization of a decarbonized mobility system, more than 80% of cars sold are still based on traditional diesel or petrol internal combustion engines (ICEs). The ZEV market is dominated by battery electric vehicles (BEVs), which accounted for about 8% of the total car market in 2020 [5,6]. However, fuel cell electric vehicles (FCEVs) [7,8] offer several opportunities over BEVs, such as higher volume energy density of the storage system, longer driving range, shorter refueling times, and better drivability because their performance does not depend on the state-of-charge (SOC). Moreover, FCEVs can ease the integration of renewable energy sources (RESs) thanks to their flexibility in terms of fuel production, storage, and delivery. In this regard, the deployment of FCEVs based on blue and green H₂ must be addressed by considering

the whole chain from H₂ production, its long-term storage and distribution, on-board storage, and, finally, to the road. Fuel cell hybrid electric vehicles (FCHEVs) result from the combination of a fuel cell and battery as energy sources [9]. Such a combination enables keeping all of an FCEV's advantages while enabling optimization of the overall design [9,10]. Several challenges still hinder the success of FCEVs and FCHEVs over conventional vehicles for consumers. Such challenges include: higher initial cost, higher replacement cost, possible increases in weight, and uncertainty regarding long-term reliability.

Micro-mobility is an exponentially growing new trend [11], especially in urban environments [12]. In particular, battery light electric vehicles (B-LEVs) such as e-bikes, e-scooters, and e-mopeds [13] offer different advantages over traditional ICE-based four- and two-wheeled vehicles [14]. For example, B-LEVs require less energy for production and operation [15], positively affect urban congestion by using less driving space and parking, and generate significantly less harmful emissions and noise [16]. Thus, new ownership models, such as sharing services, applied to micro-mobility are gaining momentum in cities worldwide [17,18]. According to European Union guidelines, e-mopeds are two-wheeled motor vehicles with up to 4 kW electric motors [19]. The e-moped sharing market has been constantly growing from the very beginning. For example, the number of shared e-mopeds in circulation worldwide increased by 164% from 2018 to 2019 [20] and again by 58% in the following year [21]. The diffusion of electric micro-mobility can be further boosted by developing and implementing fuel cell hybrid light electric vehicles (FCH-LEVs), which include the aforementioned technical advantages.

Powertrain design and sizing is key for maximum vehicle efficiency and durability [22–24], especially for hybrid systems [25,26]. Application of optimal management of the powertrain to its design reduces both power demand and energy consumption, fostering the downsizing of components [27,28]. In fact, the operating efficiency largely depends on the control strategy [29,30], as demonstrated in several studies [31–34]. An optimal management design was proposed in [35] for a fleet of ZEVs. The potential of this design and appropriate control methods applied to the powertrains of e-moped FCH-LEVs has not been fully unveiled yet. In fact, only a few papers have studied the optimized design of FCHEVs in bikes [36,37], cars [38,39], and yard trucks [40]. Only a few prototypical examples of motorbikes [41] and e-moped FCHEVs exist [42].

The purpose of the manuscript is to assess the techno-economic feasibility of the conversion of a battery electric moped into a fuel cell (FC) electric moped. We develop an optimized sizing methodology for this conversion, which involves replacement of the Li-ion battery with an FC, one or more metal hydride (MH) tanks, and a Li-ion buffer battery (BB). We seek the optimal control and design strategy for the moped through a methodology based on backward dynamic programming: introduced in [29] and further developed in [30,43–45]. We also demonstrate that the methodology can be implemented through a rules-based approach. Finally, we evaluate the impact of the proposed fuel cell electric moped in a residential scenario and a shared mobility scenario in the small Italian city of Viterbo. Such an impact evaluation can be considered representative of many Mediterranean cities (1990 degrees Celsius during the day and a population between 50,000 and 100,000 individuals). For example in Italy and France, respectively, 44 and 42 cities have a population higher than 100,000, while, respectively, 92 and 82 cities have a population between 50,000 and 100,000.

2. System Description

Figure 1a represents the main elements of the two vehicle configurations we analyzed. In a battery electric moped, the electric energy is withdrawn from the Li-ion battery and then used by the electric motor for the drive motor. In the FC electric moped, the hydrogen is withdrawn from the MH tank and is oxidized to produce the energy utilized by the electric motor for the traction motor (see Figure 1b). For this application, we consider proton exchange membrane fuel cells (PEMFCs), which are the standard for mobility applications given their high power density, fast dynamics resulting from their low operating

temperature (60–80 °C), and their high durability [46,47]. We select metal hydrides to store hydrogen because this technology has a higher volumetric energy density at relatively low pressure (i.e., ≤ 15 bar) when compared to pressurized tank hydrogen storage. In both configurations, the motor works as an electric generator during deceleration to supply energy to the batteries.

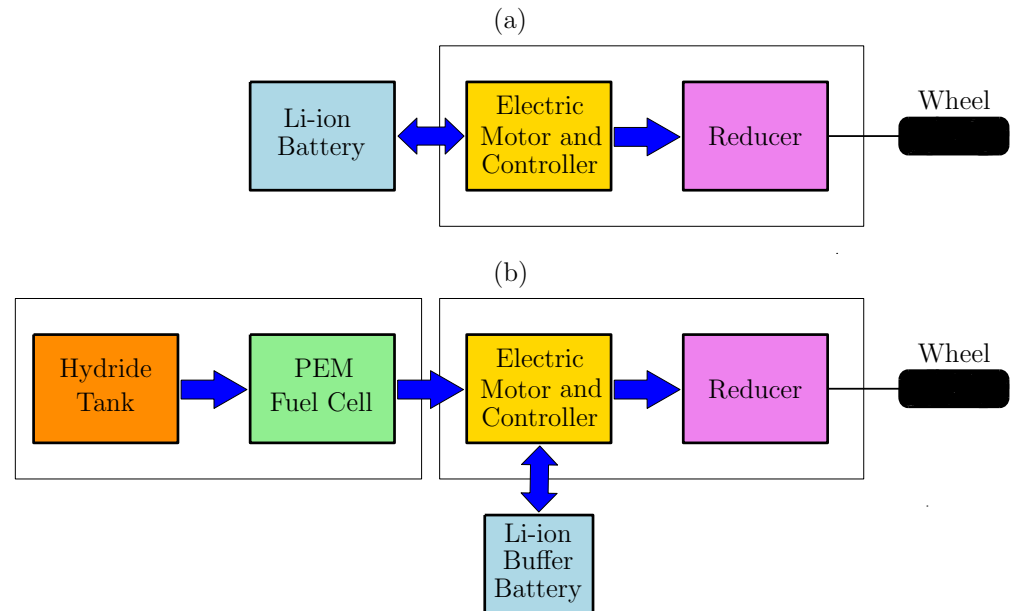


Figure 1. Schematic representation of the moped configurations: (a) main elements of the e-moped and (b) main elements of the FCH-LEV.

Vehicle Selection and Description

We select the Askoll eS₃[®] [48] as the reference e-moped for our case study because it was the most-sold e-moped in Italy over the period of January–November 2019 [49]. Moreover, in terms of cost, power, and battery capacity, it constitutes a representative solution of the best-selling electric mopeds in Europe [50]. The main characteristics of the Askoll eS₃[®] are shown in Tables 1 and 2.

Table 1. Relevant properties of the Askoll eS₃[®] [51].

Power of electric motor	2700	W
Maximum speed	66	km/h
Maximum torque (to the wheel)	130	Nm
Range	96	km
Width	1830	mm
Seat height	760	mm
Maximum height	1036	mm
Weight (without battery)	70	kg
Permissible maximum weight	245	kg
Cost	3790	EUR

Table 2. Relevant properties of the Askoll eS₃[®] batteries [52].

Battery	Li-ion	
Number of batteries	2	
Battery capacity (per battery)	1410	Wh
Battery Weight (per battery)	8.1	kg
Cost	900	EUR

3. Methods

3.1. Driving Cycle

We use the Worldwide Harmonised Light Vehicles Test Procedure (WLTP) to analyze the consumption and the performance of the moped. Such a procedure defines different driving cycles [53] according to the weight–power ratio (PMR), which is defined as:

$$PMR = \frac{P_{M,max}}{m_{tot}}, \quad (1)$$

in which $P_{M,max}$ is the nominal motor power, and m_{tot} is the total mass. For the Askoll eS3[®], $P_{M,max} = 2700$ W, and:

$$m_{tot} = m_e + m_b + m_p = 157 \text{ kg}, \quad (2)$$

where $m_e = 70$ kg is the empty mass of the e-moped (Table 1), $m_b = 16.2$ kg is the mass of the batteries (Table 2), and $m_p = 70.8$ kg is the mass that we assume for an average European passenger [54]. $PMR = 17.2$ W/kg < 22 W/kg; therefore, the Askoll eS3[®] belongs to the class 1 Worldwide Harmonised Light Vehicles Test Cycle (WLTC) (Figure 2). This cycle is 11.4 km long ($d_{WLTC,1} = 11.4$ km) and has a maximum speed of 64.4 km/h. It consists of three subcycles: the first one at low speed, the second one at medium speed, and the third at low speed, for a total duration of 1613 s.

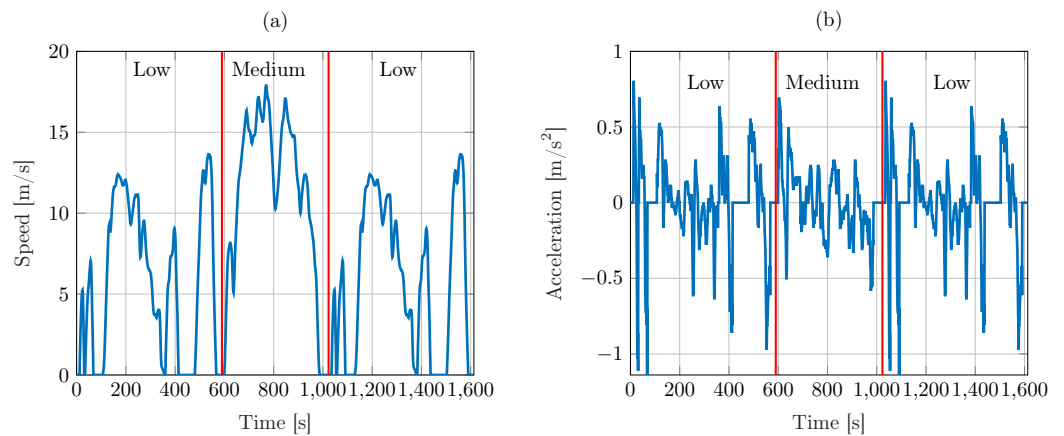


Figure 2. (a) Class 1 WLTC speed profile; (b) Class 1 WLTC acceleration profile.

3.2. Vehicle Modeling

The motor force F_W compensates for the aerodynamic drag and the inertia:

$$F_W(t) = \frac{1}{2} A_{CS} C_D \rho v(t)^2 + m_{tot} a(t), \quad (3)$$

where $v(t)$ and $a(t)$ are, respectively, the instantaneous speed and acceleration retrieved from the class 1 WLTC speed and acceleration profiles (Figure 2), A_{CS} is the cross section surface area, C_D is the drag coefficient, $\rho = 1.225$ kg/m³ is the air density at 15 °C and the atmospheric pressure, and m_{tot} is the total mass of the moped and the passenger: see Equation (2). In this equation, we discard the equivalent mass increase due to the angular moments of the rotating components of the moped and the gravitational resistance over slopes. The cross section surface area $A_{CS} = 0.52$ m² is the sum of the front area of the moped, the torso and neck of the passenger assuming average anthropometric values [55], and the helmet [56]. The instantaneous power to the wheel P_W is:

$$P_W(t) = F_W(t) v(t). \quad (4)$$

The power to the motor P_M considers the power loss due to the transmission:

$$\begin{cases} P_M(t) = P_W(t)/\eta_T & \text{if } P_W(t) > 0 \\ P_M(t) = P_W(t)\eta_T & \text{if } P_W(t) \leq 0 \end{cases}, \quad (5)$$

where $\eta_T = 0.912$ is the transmission efficiency [57]. We calculate the drag coefficient as $C_D = \frac{2P_{M,\max}}{A_{CS}\rho v_{\max}^3} = 1.26$ (with $v_{\max} = 18.3$ m/s and $P_{M,\max} = 2.7$ kW), having assumed that at maximum speed, the maximum motor power compensates for the aerodynamic drag. With this approach, we also embed the effect of the rolling resistance in C_D .

Electric and FC mopeds can perform regenerative braking. Therefore, the motor also works as a generator when $P_M(t) < 0$ in addition to producing power when $P_M(t) > 0$. The primary power P_P for the input and the output to/from the generator/motor has to consider the conversion efficiency:

$$\begin{cases} P_P(t) = P_M(t)/\eta_M & \text{if } P_M(t) > 0 \\ P_P(t) = P_M(t)\eta_G & \text{if } P_M(t) \leq 0 \end{cases}, \quad (6)$$

where $\eta_M = 0.8$ [58] is the motor efficiency, and $\eta_G = 0.4$ is the generator efficiency [57].

3.3. Optimized Control and Design

As demonstrated in several studies [31–34,59], the operating efficiency of any energy system, including powertrains, is largely determined by its control strategy [29,30]. Therefore, we optimally design the FCH-LEV components by leveraging an optimization methodology based on backward dynamic programming. This methodology was introduced in [29] and further developed in [30,43–45]. It determines the set-points of the active components of the energy system by minimizing a prescribed objective function over a determined time span. In general, it can account for: (i) thermal, cooling, and electrical loads; (ii) constraints related to the energy flows and to the dynamic behavior of the plant subsystems; (iii) power and efficiency derating with environmental conditions; (iv) fuel, maintenance, and cold start costs; and (v) the connection to a distribution/immission grid.

In this study, we select the operating cost (i.e., fuel consumption) as the objective function and the BB and FC as active components of the powertrain (see Figure 1). The input variables for optimization are the design performance of the active components, the variation of such performance at part load, and the required primary power demand P_P : see Equation (6). We realistically assume that the buffer battery charge and discharge efficiencies do not vary as a function of the set-point. The fuel cell is modeled with a black-box approach through its efficiency curves as functions of the set-point in order to obtain the part load performance: see Section 3.5. Specifically, the electric power output of the FC at time t is calculated as:

$$P_{FC}(t) = \Phi_{FC}(t)P_{FC,nom}, \quad (7)$$

where $\Phi_{FC}(t)$ is the set-point, and $P_{FC,nom}$ is the FC nominal power. The corresponding required input power is:

$$U_{FC}(t) = \frac{P_{FC}(t)}{\eta_{FC}(\Phi_{FC}(t))}, \quad (8)$$

where $\eta_{FC}(\Phi_{FC}(t))$ is the electrical efficiency. The problem is non-linear, as the efficiency is a function of $\Phi_{FC}(t)$. The economic objective function reads:

$$G_{Cost} = \sum_{t=0}^D C_F(t, s(t)), \quad (9)$$

where t is the time interval, $D = 1613$ s is the total duration of the class 1 WLTC, and C_F is the fuel cost. The cost is a function of the time interval and the plant state $s(t)$ (i.e., the

cluster of set-points of the active components). Equation (9) is subject to constraints related to the energy flows. The moped can be considered an isolated electrical energy system; therefore, the power balance for each time interval reads:

$$P_P(t) - P_{FC}(t) + P_{BB}(t) = 0 \quad \forall t, \quad (10)$$

where $P_{BB}(t)$ is the electrical power of the buffer battery. Note that $P_{FC}(t)$ is positive, $P_P(t)$ can be positive or negative (regenerative braking), while $P_{BB}(t)$ is positive when the battery stores energy and negative when it releases energy.

Equation (9) is discretized with respect to the time and to the plant state in order to represent the problem as an oriented and weighted graph. The optimal control strategy can be found by individuating the shortest path across the graph. The reader can consult [29,30,43,44] for more details on the optimization methodology.

3.4. Rules-Based Control and Design

Here, we present an alternative and easy to implement rules-based approach for control and design that is compared to the optimized methodology. Starting from the current tentative FC power P_{FC}^* , we are able to calculate the requested primary power P_{PB} and the produced primary power P_{FCB} : see Equations (11) and (12) below for the definitions. The power profiles are integrated in order to evaluate the energy equilibrium: if the produced energy is lower/greater than the requested energy, the current tentative FC power is increased/decreased by 0.1 W. Such a procedure is repeated until energy equilibrium is reached, given that we do not consider in this work the possibility of using the system as a plug-in FCH-LEV. We initialize the first tentative $P_{FC}^* = 580$ W as the integral average primary power demand $\bar{P}_P$.

Starting from the primary power P_P in Equation (6), we introduce P_{PB} , which is the required primary power while also considering the charge and discharge efficiency of the BB:

$$\begin{cases} P_{PB}(t) = P_P(t)\eta_{BC} & \text{if } P_P(t) \leq 0 \\ P_{PB}(t) = P_P(t) & \text{if } 0 < P_P(t) < P_{FC}^* \\ P_{PB}(t) = P_{FC}^* + \frac{P_P(t) - P_{FC}^*}{\eta_{BD}} & \text{if } P_P(t) \geq P_{FC}^* \end{cases}, \quad (11)$$

where $\eta_{BC} = 0.96$ is the BB charge efficiency [57], and $\eta_{BD} = 0.96$ is the BB discharge efficiency [57]. We note that P_{FC}^* is the FC power, which does not vary with time, following the results of the optimized methodology. When $P_P(t) \leq 0$, the generator produces power that is stored in the BB to be used later and therefore has to be reduced according to the battery charge efficiency. Conversely, when $P_P(t) > 0$, we observe two different cases. If $P_P(t) \leq P_{FC}^*$, the FC produces power that is directly used in the motor. Vice versa, if $P_P(t) > P_{FC}^*$, the excess over the FC power is provided from the BB, taking into consideration the discharge efficiency.

The primary power produced by the fuel cell P_{FCB} is also based on the charge and discharge efficiency of the buffer battery:

$$\begin{cases} P_{FCB}(t) = P_{FC}^*\eta_{BC} & \text{if } P_P(t) \leq 0 \\ P_{FCB}(t) = P_P(t) + (P_{FC}^* - P_P(t))\eta_{BC} & \text{if } 0 < P_P(t) < P_{FC}^* \\ P_{FCB}(t) = P_{FC}^* & \text{if } P_P(t) \geq P_{FC}^* \end{cases}. \quad (12)$$

Specifically, when $P_P(t) \leq 0$, the power produced from the FC goes entirely into the BB (with the associated charge efficiency). Conversely, when $0 < P_P(t) < P_{FC}^*$, the fuel cell satisfies $P_P(t)$ directly, and it sends only $P_{FC}^* - P_P(t)$ to the buffer battery (with the

associated charge efficiency). Finally, when $P_P(t) \geq P_{FC}^*$, all of the FC power is directly used by the motor.

3.5. Powertrain Component Modeling and Design

3.5.1. Fuel Cell

The integral average primary power demand is $\bar{P}_P = 580$ W, and this value is compared with the nominal power of commercially available air-cooled PEMFC stacks. In particular, we consider stacks with $P_{FC,nom}$ equal to 1 kW and 2 kW [60,61] to those with $P_{FC,nom} \geq \bar{P}_P$. We underline that having available power higher than the average required power increases the degrees of freedom for finding the optimized operation strategy and covers the energy losses due to buffer battery inefficiencies. Figure 3 represents the hydrogen consumption and the efficiencies of the systems as a function of the produced power and of the set-point Φ_{FC} . Other characteristics of the stacks are reported in Table 3.

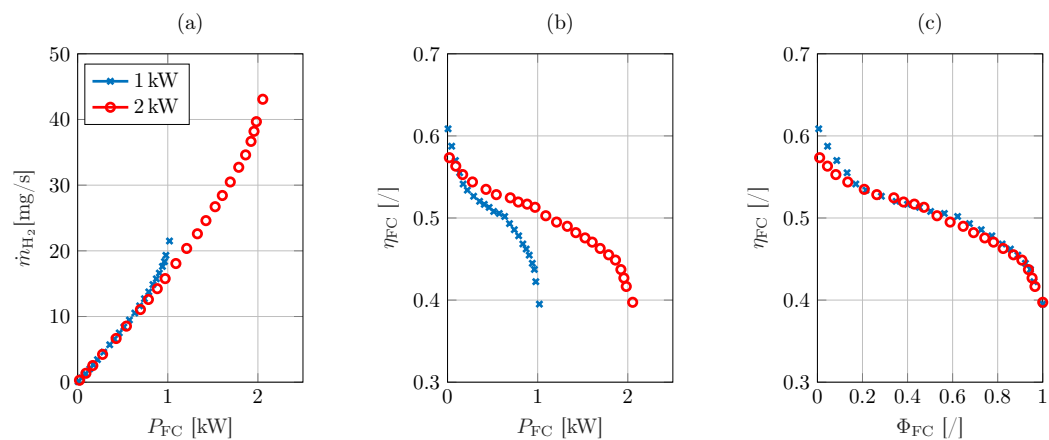


Figure 3. Experimental data of commercially available 1 kW and 2 kW air-cooled PEMFC stacks [60,61]: (a) consumed hydrogen mass flow rate ($\dot{m}_{H_2}$) versus electrical power (P_{FC}), (b) efficiency (η_{FC}) versus electrical power (P_{FC}), and (c) efficiency (η_{FC}) versus set-point (Φ_{FC}).

Table 3. Characteristics of commercially available 1 kW and 2 kW air-cooled PEMFC stacks [60,61].

	1 kW	2 kW
Utilization factor	0.83	0.8
Number of cells	48	48
Weight with auxiliaries [kg]	4.4	12.5
Length [m]	0.219	0.303
Width [m]	0.268	0.350
Height [m]	0.123	0.183
Estimated cost [62,63] [EUR]	5200	9500

3.5.2. Metal Hydrides

We determine the hydrogen consumption of the system by leveraging the required input power U_{FC} as determined through the optimization methodology: see Section 3.3. Specifically, the hydrogen mass required over all of the driving cycle reads:

$$m_{H_2} = \int_{t=0}^D \dot{m}_{H_2}(t) dt, \quad (13)$$

where $\dot{m}_{H_2}$ is the hydrogen flow rate required from the FC:

$$\dot{m}_{H_2}(t) = \frac{U_{FC}(t)}{LHV_{H_2}}. \quad (14)$$

$LHV_{H_2} = 120$ MJ/kg is the hydrogen lower heating value.

To store the required hydrogen mass, we consider commercially available MH tanks [64], the characteristics of which are reported in Table 4. We note that a detailed design of the system should also consider the thermal management of the MH [65]. In this preliminary work, we assume that the MH is always capable of supplying the required hydrogen flow rate, and we only consider the space required for the thermal management system without undertaking an in-depth design.

Table 4. Characteristics of commercially available metal hydride tanks [64] filled with AB₂ alloy.

Nominal capacity	2000	Sl
Weight	14	kg
Height	0.56	m
Diameter	0.11	m
Charge pressure	5–12	bar
Stored H ₂ mass	164	g
Estimated cost	4000	EUR

3.5.3. Buffer Battery

To determine the capacity of the buffer battery, we iteratively evaluate through the optimization methodology (see Section 3.3) to calculate the quantity of stored energy as a function of time:

$$c_{BB}(t) = e_{FC}(t) - e_{PB}(t) = \int_{t=0}^t P_{FC}(t)dt - \int_{t=0}^t P_{PB}(t)dt, \quad (15)$$

where $P_{PB}(t)$ is the primary power, which also takes into consideration the round-trip efficiency of the buffer battery, assuming, respectively, charge and discharge efficiencies equal to $\eta_{BC} = 0.96$ and $\eta_{BD} = 0.96$ [57]. Then, the capacity of the battery is the difference between the maximum and the minimum amounts of stored energy:

$$C_{BB} = \max(c_{BB}(t)) - \min(c_{BB}(t)). \quad (16)$$

Through the optimization methodology, we also evaluate the state-of-charge as a function of time:

$$SOC(t) = SOC(t-1) + \frac{P_{FC}(t) - P_{PB}(t)}{C_{BB}}. \quad (17)$$

Finally, we note that small commercial Li-ion batteries for light mobility applications have a specific cost of 1.5 EUR/Wh [66].

4. Results and Discussion

Figure 4 shows P_W , P_M , and P_P as a function of time for the class 1 WLTC. The figure shows the direct correlation between vehicle power and the driving cycle. We note that the power recovered during deceleration is limited due to low generator efficiency $\eta_G = 0.4$.

The batteries of the e-moped have a mass $m_b = 16.2$ kg and occupy the entire compartment under the saddle of the Askoll eS₃[®] [51]. From the technical sheet, such a space is estimated to be $V_b = 5.4 \times 10^{-2} \text{ m}^3 = 54 \text{ l}$. Considering the requested power profile P_P in Figure 4 and the charge and discharge efficiencies of the Li-ion batteries (both assumed to be 0.96 [57]), the nominal capacity of the e-moped $C_{EV} = 2820 \text{ Wh}$ allows for a nominal range $R_{EV} = 119 \text{ km}$, which corresponds to $n_{EV} = 10.4$ driving cycles.

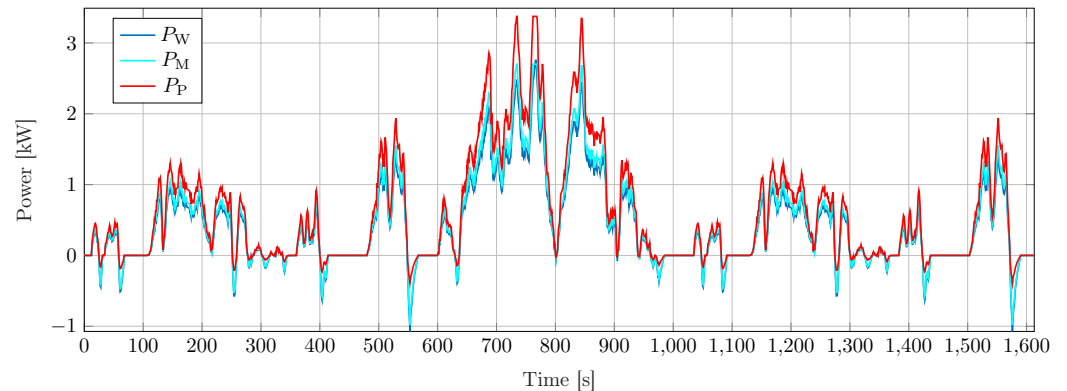


Figure 4. Power to the wheel P_W (blue curve), power to the motor P_M (cyan curve), and primary power P_P (red curve) as a function of time for the class 1 WLTC in Figure 2.

Through the optimization methodology from Section 3.3, we obtain for the FCH-LEV the power time series for the fuel cell and the buffer battery as reported in Figure 5, considering $P_{FC,nom}$ for both 1 kW and 2 kW. We note that the optimal operating strategy is to have a constant set-point for the FC and a load-following approach for the battery. Specifically, the battery operates at variable load because we realistically assume that the charge and discharge efficiencies do not vary as a function of the set-point. Vice versa, the FC constantly produces the 605 W necessary to guarantee energy equilibrium over the driving cycles. This power value is a function of the road load and is independent of the size of the FC. Due to the battery efficiencies, $P_{FC} > P_P$. We note that the results of the optimization procedure can also be justified by looking at the symmetrical efficiency curve around 605 W for both the 1 kW and 2 kW FCs: see Figure 3. The overall efficiency would be reduced by operating the FC at a variable set-point. In fact, if the FC were to be used in a load-following mode, producing for several time-steps power lower than 605 W (hence, with higher efficiency), in the following time-steps, it should produce power higher than 605 W (hence, with lower efficiency) to guarantee energy equilibrium. As a consequence, more energy would be produced at lower efficiency (higher set-point), decreasing the overall performance. Moreover, in the optimization process, we do not consider maintenance costs or degradation due to variable-set-point operation, hence further validating our results [67,68]. The operating difference between the 1 kW and 2 kW FCs relies on hydrogen consumption to produce the required 605 W. In fact, the stacks consume, respectively, $m_{H_2}(1 \text{ kW}) = 164 \text{ g}$ and $m_{H_2}(2 \text{ kW}) = 157 \text{ g}$ to cover the nominal range $R_{EV} = 119 \text{ km}$. The 2 kW stack consumes 7 g less hydrogen, because for the same power output, it works at a lower set-point and, hence, with higher efficiency (Figure 3). However, the 2 kW stack costs about twice as much as the 1 kW stack and has a mass about three times higher. Therefore, the marginal hydrogen savings do not justify the increase in cost and mass, and we select the 1 kW stack for the FCH-LEV.

Through the optimization methodology of Section 3.3, we also verify that the required BB capacity is $C_{BB} = 93 \text{ Wh}$ (see Figure 6). We note that by using the minimum required buffer battery capacity, there is only one value for the initial and final SOC that guarantees that over the entire driving cycle, $0 \leq SOC \leq 1$, and hence, the system is not flexible in operation. In addition, in the design methodology, we do not consider that the PEMFC stacks have a start-up time of 30 s, during which the BB has to provide all the required power. Therefore, we decide to oversize the battery capacity. Incidentally, the smallest commercial Li-ion batteries for mobility applications have a capacity of 240 Wh, which is more than two times $C_{BB} = 93 \text{ Wh}$ [66]. Therefore, we select the 240 Wh buffer battery [69], which has dimensions of $0.145 \text{ m} \times 0.308 \text{ m} \times 0.042 \text{ m}$ and a mass of 3.3 kg.

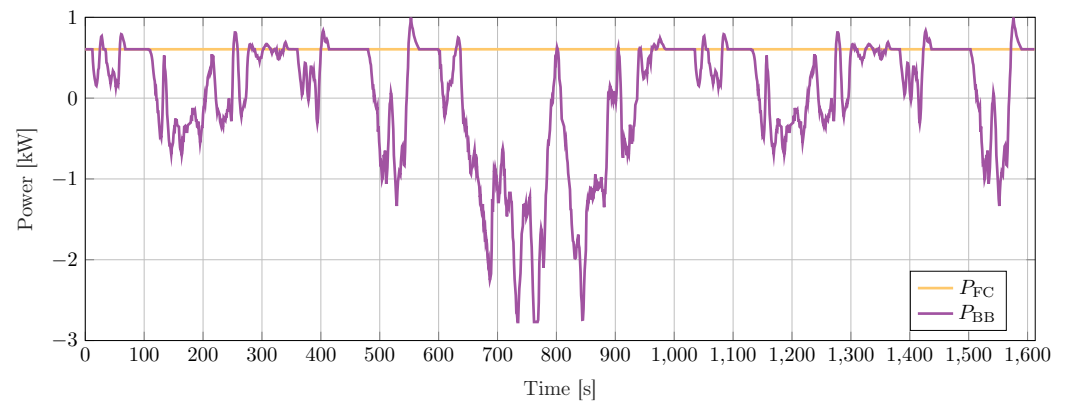


Figure 5. Optimized fuel cell power P_{FC} (orange curve) and buffer battery power P_{BB} (purple curve) as a function of time for the class 1 WLTC in Figure 2.

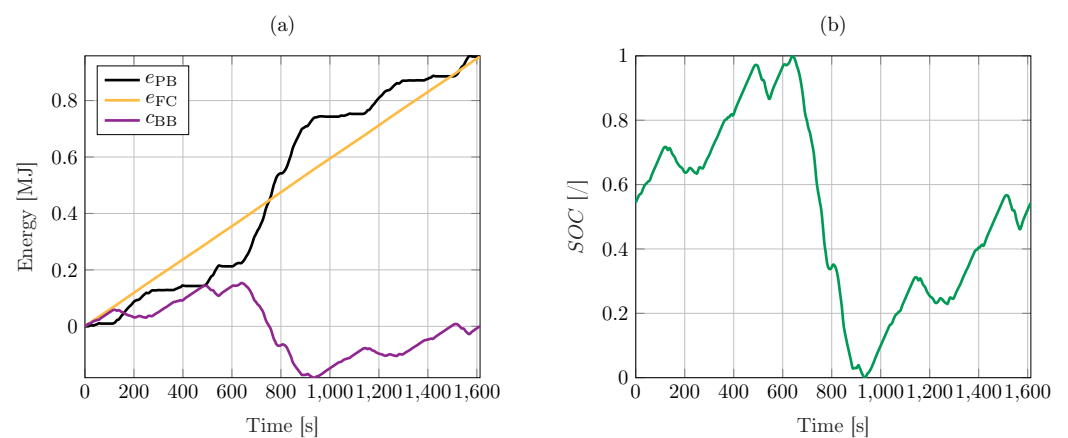


Figure 6. Characterization of the buffer battery: (a) energy produced by the fuel cell e_{FC} (orange curve), energy consumed by the moped e_{PB} (black curve), and quantity of stored energy c_{BB} (purple curve) as a function of time; (b) state-of-charge as a function of time.

The hydrogen mass consumed from the 1 kW FC for $n_{EV} = 10.4$ driving cycles, which composes the nominal range, is 164 g; matching the capacity of the 2000 SI MH tank characterized in Table 4. Therefore, an FCH-LEV composed of a 1 kW FC stack, a 240 Wh BB, and a 2000 SI MH tank can cover the same range as an equivalent e-moped (Case A in Table 5). The volume of this hybrid system is $V_h = V_{FC} + V_{BB} + V_{MH} = 7.2 \times 10^{-3} \text{ m}^3 + 1.9 \times 10^{-3} \text{ m}^3 + 5.3 \times 10^{-3} \text{ m}^3 = 1.44 \times 10^{-2} \text{ m}^3 = 14.4 \text{ l}$, and all of the elements of the FCH-LEV can be easily arranged to fit the volume under the saddle. In fact, the FC stack and the buffer battery are parallelepipeds [60,61,69], while the hydride tanks are commercially available as round or rectangular cylinders [64,70]. Moreover, a volume of $V_f = 39.6 \text{ L}$ (that is part of the volume occupied by the batteries of the e-moped $V_b = 5.4 \times 10^{-2} \text{ m}^3 = 54 \text{ l}$) is left free in the FCH-LEV. This space is 2.75 times higher than $V_h = 14.4 \text{ l}$. Therefore, we are confident that there is enough volume to host the thermal management system and eventually additional MH tanks. The mass of the hybrid system is $m_h = m_{FC} + m_{BB} + m_{MH} = 4.4 \text{ kg} + 3.3 \text{ kg} + 14 \text{ kg} = 21.7 \text{ kg}$, which is 5.5 kg higher than the mass of the batteries of the e-moped $m_b = 16.2 \text{ kg}$. In fact, the FCH-LEV has a higher volume energy density but a lower mass energy density. However, the 5.5 kg mass increase is almost negligible, as it is only 3.5% of the total mass $m_{tot} = 157 \text{ kg}$. In fact, repeating the design with $m_{tot}^c = 162.5 \text{ kg}$, the hydrogen consumption is $m_{H_2}^c(1 \text{ kW}) = 165 \text{ g}$ instead of $m_{H_2}(1 \text{ kW}) = 164 \text{ g}$. The e-moped has a cost of EUR 3790, EUR 1800 of which is attributable to the batteries (Tables 1 and 2). The system composed of the 1 kW FC stack, the 240 Wh BB, and the 2000 SI MH tank costs EUR 9560 (Tables 3 and 4). Such a price is more than five times the cost of the batteries in the e-moped and makes the FCH-LEV

not competitive economically. Moreover, a capillary hydrogen recharging infrastructure is still absent. However, in the near future, such limitations could be overcome thanks to hydrogen diffusion.

Table 5 reports the results of alternative configurations: Case eS₃ refers to the stock electric moped; Case A is the reference case for the conversion that includes one MH tank; Cases B and C have, respectively, two and three MH tanks; Case D has compressed storage at the pressure necessary to cover the nominal range using all of the available volume; Case E has 300 bar storage in the same maximum volume; Case F has compressed storage at 300 bar using the volume necessary to cover the nominal range.

Table 5. Characteristics of the different analyzed configurations for the moped conversion.

Case	Storage Volume [m ³]	Storage Mass [kg]	Range [km]	Storage Pressure [bar]
eS ₃	54	16.2	96	/
A	14.4	21.7	96	5–12
B	19.7	35.7	119	5–12
C	25	49.7	348	5–12
D	54	30.2	96	46
E	54	30.2	632	300
F	6.8	11.2	96	300

If two MH tanks are installed in the moped, the hybrid system has a mass of $m_h = m_{FC} + m_{BB} + 2m_{MH} = 35.7$ kg and occupies a volume of $V_h = V_{FC} + V_{BB} + 2V_{MH} = 1.97 \times 10^{-2} \text{ m}^3 = 19.71$ (case B in Table 5). Considering the increased mass, the nominal range is 234 km, which is only slightly lower than double the nominal range of the e-moped $R_{EV} = 119$ km. Similarly, with three MH tanks $m_h = 49.7$ kg, $V_h = 25$ l, and the nominal range is 348 km (Case C in Table 5). We highlight that the FCH-LEV is superior to the Li-ion e-moped in terms of attainable range. Therefore, a system composed of an FC and an MH tank can be considered a range extender for the base electric vehicle. In fact, the FCH-LEV can almost triple the nominal range with a negligible mass increase and with lower overall dimensions than the Li-ion batteries. Increasing the range is not physically possible with Li-ion batteries, as they occupy all the available volume. We also note that the free volume under the saddle when using three tanks is still $V_f = 29$ L, and it can be used for the thermal management system.

Finally, it is also possible to store the hydrogen on board with a high-pressure composite tank. In this case, the available volume is $V_b - V_{FC} - V_{BB} = 5.4 \times 10^{-2} \text{ m}^3 - 7.2 \times 10^{-3} \text{ m}^3 - 1.9 \times 10^{-3} \text{ m}^3 = 4.49 \times 10^{-2} \text{ m}^3 = 44.9$ l. A composite tank with such a volume stores $m_{H_2} = 164$ g at a pressure of 46 bar (Case D in Table 5). However, the typical operating pressure of composite tanks is 300 bar [71,72]. At this pressure, it is possible to store 1080 g of hydrogen, which is enough to cover more than six times the nominal range of the e-moped (Case E in Table 5). Composite tanks have an average specific weight of 500 kg/m³ [71,72]. Therefore, a 44.9 L composite tank has an estimated mass of 22.5 kg. Such a value makes the mass of the hybrid system $m_h = 30.2$ kg, which is 14 kg higher than the mass of the batteries of the e-moped. Alternatively, it is possible to store 164 g of hydrogen (which is enough to cover the nominal range) in a 6.8 l composite tank at 300 bar [73] (Case F in Table 5). Such a tank has a mass of 3.5 kg, resulting in $m_h = 11.2$ kg, which is lower than the mass of the batteries of the e-moped. The mass decrease also results in a reduction in the hydrogen consumption per cycle. Despite the possible advantages of high-pressure storage, we note that compression to 300 bar can require up to 10% of the hydrogen's lower heating value, thus increasing the H₂ recharge cost. Regarding the recharge time, a proper thermal management system can be developed for the metal hydrides in order to obtain results comparable to those of pressurized hydrogen storage.

We note that the optimized control strategy, consisting of a constant set-point for the FC and a load-following approach for the BB, can be straightforwardly implemented in an onboard control unit.

Applying the rules-based design procedure described in Section 3.4, we find that after 249 iterative integrations of Equations (11) and (12), $P_{FC}^{RB} = 605 \text{ W} = P_{FC}$ is the final iteration value of P_{FC}^* that guarantees energy equilibrium over the driving cycle (i.e., the state-of-charge of the BB at the beginning and at the end of the driving cycle is the same). This result is in accordance with the optimization methodology. Figure 7 represents the final iteration's instant values of P_{FCB} , which oscillate around P_{FC}^{RB} as a consequence of the variable quantity of power going into the buffer battery and the associated charge efficiency. In the same figure, we also represent the required primary power P_{PB} evaluated for the final iteration.

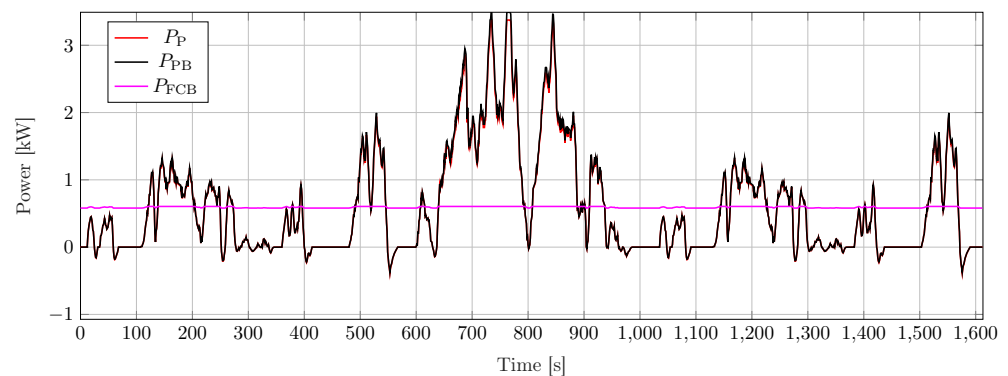


Figure 7. Required primary power P_P (red curve), required primary power with buffer battery P_{PB} (black curve), and primary power produced by the fuel cell P_{FCB} (magenta curve) as a function of time for the class 1 WLTC in Figure 2.

Impact on Mobility Systems

We evaluate the potential and the impact of a domestic total green energy system for recharging an FCH-LEV composed of a 1 kW FC stack, a 240 Wh BB, and a 2000 SI MH tank. We assume that a residential unit has a photovoltaic system installed that produces 3.3 kW_p. Using the PVGIS database [74] and considering the city of Viterbo, we obtain the typical hourly photovoltaic production for an entire year. Then, we use Energy Plus [75–77] to determine the hourly energy load reported in Figure 8, considering that Viterbo is classified as a heating-based climate according to the IEA [78]. For this analysis, we consider that the photovoltaic production in surplus of the residential load feeds a PEM electrolyser with an efficiency of 80% [79]. Such a system produces 68 kg of hydrogen per year. Considering that the FCH-LEV needs 164 g of hydrogen to cover the nominal range of $R_{EV} = 119 \text{ km}$, the residential total green recharge system can recharge the FCH-LEV 415 times per year (more than once per day), or equivalently, the FCH-LEV can cover more than 49,300 km per year with zero emissions.

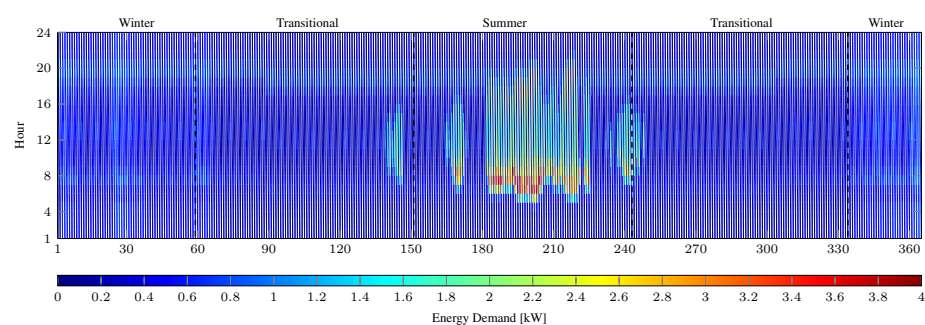


Figure 8. Hourly energy consumption of an apartment in the city of Viterbo (heating-based climate [78]).

According to a recent study [80], the students of the University of Tuscia, Viterbo, Italy, commute about 4 km per day, Monday to Friday. This is equivalent to 1040 km per year. Table 6 estimates the yearly emissions for this distance for the most common transportation systems [80–82]. We have assumed the emissions factors of a Euro 2 bus (the most used bus in Viterbo), a reference car (with a weighted average of all the emissions factors for the specific stock of cars on the roads of Viterbo), and a Euro 4 petrol moped. The ranges of the emissions for the bus and the car, respectively, consider variable occupancies of the vehicles of between 10 and 40 and between 1 and 4 passengers. Assuming that the FCH-LEV is fed with green hydrogen (zero total emissions), it is possible to avoid the release of these pollutants into the atmosphere. The yearly per capita equivalent CO₂ emissions in Italy for the transportation sector reached a value of 1680 kg in 2021 [83]. Therefore, by using an FCH-LEV instead of a petrol moped, the students could reduce their personal emissions for transportation by 6.7%. Moreover, given that the FCH-LEV consumes 164 g every 119 km, the yearly hydrogen consumption for every student would be 1433 g. By dedicating a photovoltaic system to hydrogen production in a total green shared recharge system, it is possible to obtain 35700 g/kW_p. Therefore, for each student, it would be necessary to install a 4×10^{-2} kW_p recharge system, or alternatively, every installed kW_p can satisfy the needs of 25 students. A recent survey of the buildings of the University of Tuscia revealed that in the scientific campus alone (which is made of modern buildings without architectural constraints) up to 450 kW_p of photovoltaic panels can be installed. Such a system could satisfy the mobility needs of 11,250 students, whereas the student population at the University of Tuscia in the academic year 2022/2023 consisted of about 7500 individuals [84].

Table 6. Emissions of conventional means of transportation for yearly average commute of a student in Viterbo [80–82].

	Bus	Car	Petrol Moped
PM2.5 [g]	4.4–17.7	36.4–145.6	/
PM10 [g]	5.5–21.8	13–52	/
NO _x [g]	221.3–885	124.8–499.2	93.6
COV [g]	12–47.8	39–156	176.8
CO [g]	46.8–187.2	358.8–1435.2	1185.6
CO ₂ [kg]	18.3–73.2	51.2–205	112.3

The results of this paper highlight the advantages of FCH-LEVs over traditional BEVs. In fact, when comparing zero-emissions vehicles, we have to focus on the overall value chain for mobility. A higher attainable driving range and lower expected recharge time increase the available operating time of the FCH-LEV over the e-moped. This aspect is particularly relevant considering that the development of electric mobility is deeply connected to a shared paradigm. In such a scenario, the same mobility demand can be accommodated for with fewer vehicles, leading to lower capital costs and emissions in production. Moreover, hydrogen has several intrinsic advantages. It can be produced from several RESs, such as biogas and wind or photovoltaic electric energy. Also, it can be stored even over seasonal time spans. Finally, natural gas distribution grids could be converted for hydrogen operation in the near future, decoupling the mobility energy demand from the electric distribution grid. This aspect is crucial when considering the increasing stress that intermittent RESs put on the grid.

5. Conclusions

Micro-mobility is increasingly popular due to several advantages, such as lower energy demand and less urban congestion, with respect to conventional internal-combustion-engine-based mobility. Nowadays, most micro-mobility vehicles are based on batteries. However, fuel cell light hybrid electric vehicles could be relevant to increase driving ranges and drivability and for reductions in recharge times. Therefore, we assess the techno–

economic feasibility of the conversion of a commercial battery electric moped (Askoll eS₃[®]) into a fuel cell hybrid electric moped. We leverage the class 1 Worldwide Harmonised Light Vehicles Test Procedure to characterize the energy consumption of the electric moped through a dynamic model that accounts for aerodynamic drag and inertia. In this process, we also consider the efficiency of the transmission, electric motor/generator, and buffer battery. Then, we find the optimal size of fuel cell, hydrogen storage, and buffer battery to replace the Li-ion batteries of the electric moped. For the conversion, we develop an optimized sizing methodology based on backward dynamic programming, and we also demonstrate that it can be implemented through a rules-based approach.

The results show that a 1 kW proton exchange membrane fuel cell, a 2000 Sl metal hydride hydrogen tank, and a 240 Wh buffer battery can cover the same range as the batteries in the electric moped (119 km). The hybrid system occupies 39.6 L less volume than the batteries but is 5.5 kg heavier. However, the mass increase is not relevant, being only 3.5% of the total mass. With current commercial quotations, the hybrid system costs EUR 9560, which is more than five times the cost of the batteries of the moped. However, we expect that the evolution of hydrogen-based technologies will lower the price. The empty volume resulting from the conversion can be used to install additional metal hydride tanks to increase the driving range with a negligible mass increase. In particular, with two tanks, it is possible to travel up to 234 km, while with three tanks, the driving range is 348 km. Moreover, using composite tanks, it is possible to cover the nominal range (119 km) with 6.8 L of hydrogen at 300 bar. Alternatively, by using all of the available volume under the saddle (44.9 L) for a composite tank, it is possible to cover the nominal range by storing hydrogen at 46 bar (with less energy required for compression). Such a configuration can also be used to store hydrogen at 300 bar, resulting in more than six times the nominal range.

A fuel cell hybrid electric vehicle can be recharged with green hydrogen, becoming completely emissions free. In particular, in a typical residential apartment with a 3.3 kW_p photovoltaic system, it is possible to produce on a yearly basis enough hydrogen to completely recharge the vehicle more than once per day. This estimation only considers surplus photovoltaic production with respect to the energy load of the apartment. Moreover, a fuel cell hybrid electric vehicle can also have relevant impact for shared mobility. For example, considering the university students in a small Italian city (Viterbo), it is possible to considerably reduce pollutants and greenhouse gas emissions (Table 6). Moreover, a dedicated photovoltaic system can produce the green hydrogen necessary for 25 students on a yearly basis for every 1 kW_p installed.

The results presented here can be further investigated by considering the design of a thermal management system: especially by focusing on the metal hydride tank and on the fuel cell stack. Finally, some advanced materials (e.g., metal hydride alloys) can be evaluated in order to improve the characteristics of the system, such as the energy storage density.

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