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Transportation Research Procedia 70 (2023) 20–27

Transportation Research Procedia

www.elsevier.com/locate/procedia

8th International Electric Vehicle Conference (EVC 2023)

Application of Solid Oxide Fuel Cells on Hybrid Electric Vehicles Operating in Fleet

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Abstract

Solid oxide fuel cells (SOFCs) are well suited to be used with different fuels, including methane and biomethane. Therefore, it may be useful to study their possible application on board hybrid electric vehicles and exploit the fuel cell system, which is characterized by high efficiency, and allow the use of biomethane as a renewable green energy source. Furthermore, there is not yet a consolidated hydrogen distribution network for automotive use, while biomethane would make it possible to take advantage of the existing distribution network and infrastructures of methane. SOFC technology is well suited to be used on vehicles operating in fleets, with a consistent and known mission through the working days, which helps to mitigate SOFCs known limitations such as slow transients and long ignition times. In this work, a model of a fuel cell hybrid vehicle equipped with a SOFC is presented and then used for the sizing of a door-to-door waste collection vehicle. After that, a case study has been carried out considering such a vehicle working on a real-world, door-to-door waste collection mission profile (maximum around 10h/days shift for 7days/week), showing the entire potential of this architecture in terms of environmental impact.

Keywords: mathematical modelling; alternative propulsion; solid oxide fuel cell; vehicle model; energy consumption

1. Introduction

Solid oxide fuel cells (SOFCs) are well suited to be used with different fuels (Lu et al., 2018), including methane and biomethane. For this reason, it may be useful to study a possible application of the latter on board hybrid electric vehicles.

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2352-1465
10.1016/j.trpro.2023.10.004

Hydrogen Fuel Cell technology is already adopted on board vehicles, while the application of SOFC systems to the automotive world is still being studied due to their limitations: slow transients and long ignition times. With SOFC technology it is possible to exploit the fuel cell system characterized by high efficiency (Krummrein et al., 2018) and allow the use of biomethane, a renewable green energy source, for which it would be possible to exploit the supply infrastructure already existing for methane, therefore solving the problem of creating a new hydrogen distribution network.

In the present work, a model of a fuel cell hybrid vehicle equipped with a SOFC has been realized, taking into account the state of the art of SOFC systems, their characteristics and criticalities. Furthermore, the SOFC model has been integrated into a model for the simulation of electric and hybrid vehicles longitudinal dynamics (Sandrini et al., 2022, 2021; Zecchi et al., 2022) (see also (Daniel Chindamo et al., 2014; D. Chindamo et al., 2014)). Considering the slow transient and the long ignition times, the SOFC system is not suitable as a primary energy source. The model in question therefore presents a SOFC system that acts as a generator. It is particularly suitable for vehicles operating in fleet, with a predefined, repeatable, and known mission. In particular, in order to scale the SOFC system and the battery pack correctly, a specific model was created for a door-to-door waste collection vehicle. Another important criticality of SOFCs is its fragility, it is therefore necessary to find, through future research, a solution to this problem before the actual implementation of a vehicle equipped with SOFC technology.

In the literature, several articles present SOFC systems for automotive use, but often no model for the vehicle layout is proposed, for example: (Lawlor et al., 2017) discusses about SOFC system as range extender; (Rafikiran et al., 2022) focuses mainly on a technique for controlling the SOFC system; (Udomsilp et al., 2020) is focused on the strategies for improving electrochemical performance of SOFCs; (Ma et al., 2018) considers SOFCs powered by a mixture of hydrogen, water, carbon monoxide and carbon dioxide gas (not methane or biomethane); (Kerviel et al., 2018) accurately describes proton exchange membrane fuel cell and SOFC system, but not the vehicle model adopted for the simulation. Instead, (Ma et al., 2021) proposes a hybrid SOFC/battery vehicle configuration, with SOFC system which can both charge the battery pack and propel the vehicle. Quite often however, the SOFC system is unable to meet the power demand in transients due to its peculiar behavior. Another problem described in (Ma et al., 2021) is also the slow start-up time of SOFCs. Finally, (Tanozzi et al., 2019) describes a SOFC range extender combined with gas turbines, mainly focusing on thermal aspects. This last work is therefore interesting for future developments of the work proposed in this paper.

Nomenclature

SOC	State of Charge
SOFC	Solid Oxide Fuel Cell
TEST	Target-speed EV Simulation Tool

2. Methodology

Considering SOFC features and limitations, the assumptions reported in Table 1 have been made for the implementation of the vehicle model: SOFC system always active, even when the vehicle is off duty, and acting therefore as a constant power generator to charge the battery pack. So, it is necessary to consider a vehicle that works in a fleet, with a predefined mission (in this work a door-to-door waste collection vehicle) and during the inactivity phases the vehicle must be connected to the electricity grid to send power to the grid itself after the battery pack has reached the desired SOC (State of Charge).

Table 1. SOFC system characteristics and limitation are listed on the left. Some references that can be found in the literature are also specified. The assumptions adopted in order to overcome each limitation are listed on the right; they are actually the peculiarities of the solution proposed in this paper.

SOFC characteristics and limitations	Hypotheses adopted for model construction
Different possible feeds (Lan and Strunz, 2017; Lu et al., 2018)	Use of SOFC powered by methane or biomethane
Slow transient (order of minutes)	SOFC as a range extender (generator)
Long start-up times (Chen et al., 2018; Ma et al., 2021) (order of hours)	SOFC always active
Fragility due to high operating temperatures (Ma et al., 2021) and different thermal expansion coefficients (Ehsani et al., 2018)	Need for accurate thermal management
Low vibration resistance	To be solved for the implementation of the system on the real-world vehicle

The vehicle used in the model is the rear-wheel-drive waste collection vehicle used for what is mentioned as low-performance validation of the TEST model in (Sandrini et al., 2021). The main data of the vehicle is reported in Table 1 of (Sandrini et al., 2021) (frontal area of 3 m^2, drag coefficient of 0.7, front and rear rolling radius of 0.35 m), while the traction motor torque characteristics are shown in Figure 5 of (Sandrini et al., 2021) (160 kW and 380 Nm nominal, 50 Nm of torque limit for regenerative braking). Unlike what is reported in (Sandrini et al., 2021), the vehicle in question is equipped with a SOFC system on board, a total transmission ratio equal to 6.22, a variable mass during the missions (vehicle empty weight is 1900 kg, driver mass is 80 kg, while the payload is the variable mass carried by the vehicle, see Fig. 1). The battery pack system is the object of sizing, considering an inverter efficiency of 0.88 in discharge and 0.8 in charge.

The model has been tested on 10 speed profiles, each one with its own mass variation profile as well, as described in Table 2 (see also Fig. 1). They relate to 10 different, real-world daily missions ranging from an urban city cycle to suburban to intracity. They have all been acquired through a MoTeC datalogger during daily operation, as performed by the vehicle every two weeks. The TEST model described in (Sandrini et al., 2022, 2021; Zecchi et al., 2022) was used for these simulations. It takes into account the power used by the vehicle auxiliaries as set for each simulation in the item “Total power of the auxiliaries [W]” in Table 2, which corresponds to the sum of the average power consumed by the electric and hydraulic auxiliaries, on each speed profile. For this study, the SOFC system is seen in the TEST model (Sandrini et al., 2021) as a sort of “black box”, where only the constant power supplied by the fuel cell and an efficiency relating to the DC/DC converter and equal to 90% are considered.

Table 2. Main information of the speed profiles of the waste collection vehicle mission.

Speed profile n°	Distance travelled [km]	Average speed [km/h]	Profile time [h:min:s]	Maximum speed [km/h]	Average electrical power [W]	Average hydraulic power [W]	Total power of the Auxiliaries [W]
1	34.707	8.8	3:56:31	86.4	540.9	215.6	756.5
2	39.361	8.3	4:42:59	55	442.6	174.6	617.2
3	43.570	9.0	4:51:34	62.5	671.6	73.3	744.9
4	13.780	13.6	10:07:08	108.7	531.2	131.5	662.7
5	81.789	16.1	5:04:55	105.5	561.5	241.0	802.5
6	50.003	9.0	5:32:58	75.1	566.9	247.2	814.1
7	72.137	12.4	5:47:39	83.3	597.3	202.6	799.9
8	60.671	14.7	4:07:42	85.7	540.9	303.6	844.5
9	89.048	16.1	5:31:43	106.6	498.7	267.7	766.4
10	85.977	19.5	4:24:27	92	457.6	255.3	712.9

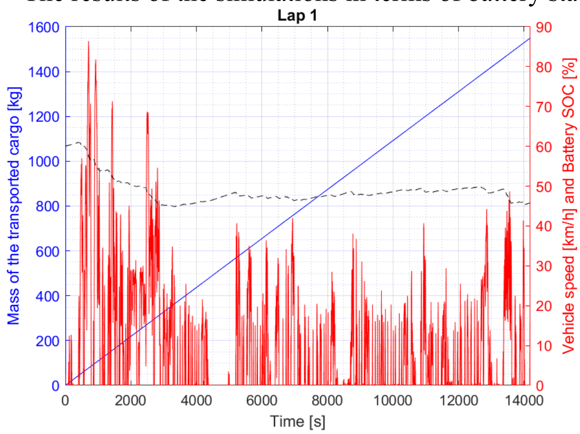
The system has been sized by minimizing the power output of the SOFC and the capacity of the battery pack on the basis of the longest mission profile (profile 4, about 10 hours), in such a way as to be able to carry out this profile without any stopping and to exploit as much SOC range as possible. A charging stop has been planned for the most energy demanding profile (profile 9) only.

3. Results and Discussion

After an iterative simulation process for the longest mission profile, a suitable compromise for both battery pack size and SOFC power rating has been achieved as: battery pack capacity equal to 30 Ah; and SOFC power rating equal to 3 kW. Using these values, a SOC field ranging from a maximum of 95.6% to a minimum of 20.6% is exploited for the longest profile, with an initial SOC equal to 90%.

This way the vehicle is also able to cover the most energy-demanding profile (profile 9) provided the vehicle stops for 90 minutes halfway through, with all auxiliaries off and the SOFC system running to recharge the battery pack. By doing so, profile 9 was divided into two parts: profile 9.a from the start to the charging stop, and profile 9.b from the end of the charging stop to the end of profile 9.

The results of the simulations in terms of battery state of charge (SOC) are presented in Fig. 1.



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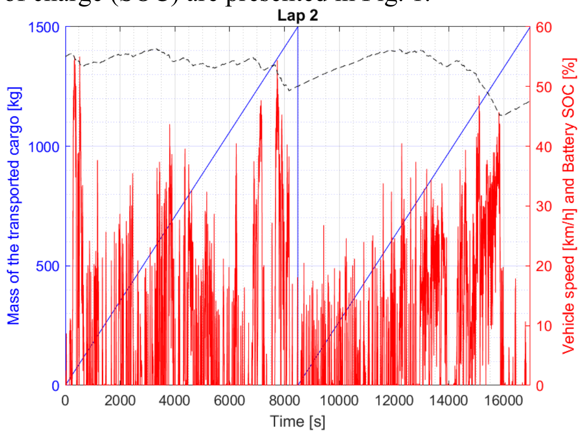

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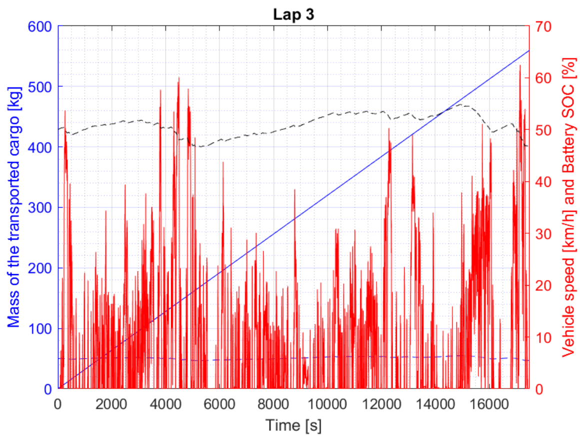

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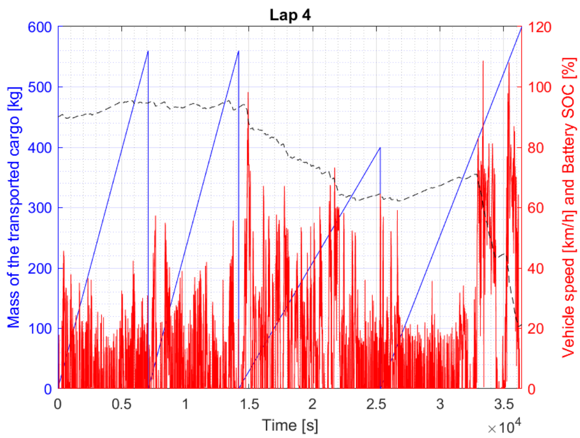

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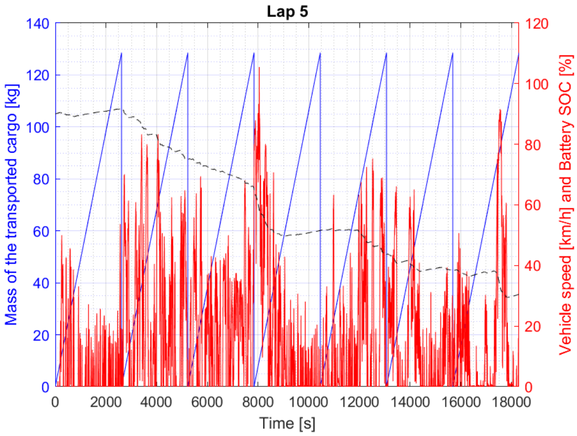
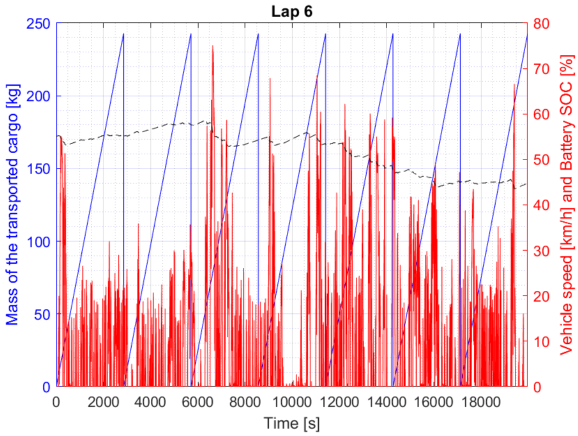
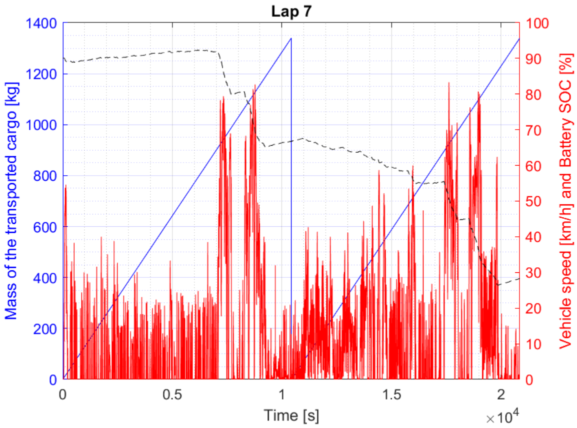
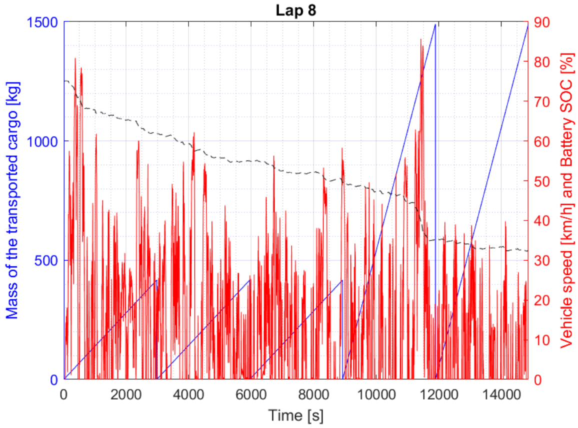
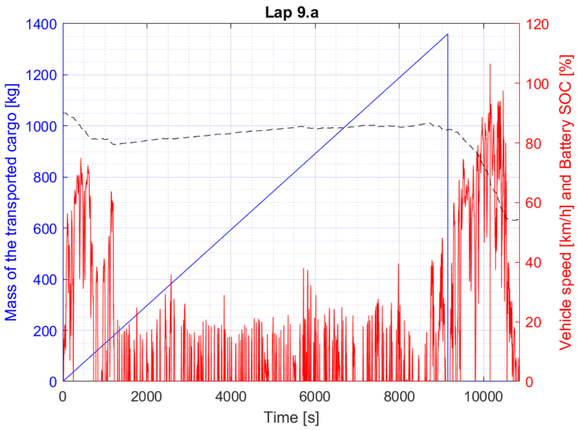
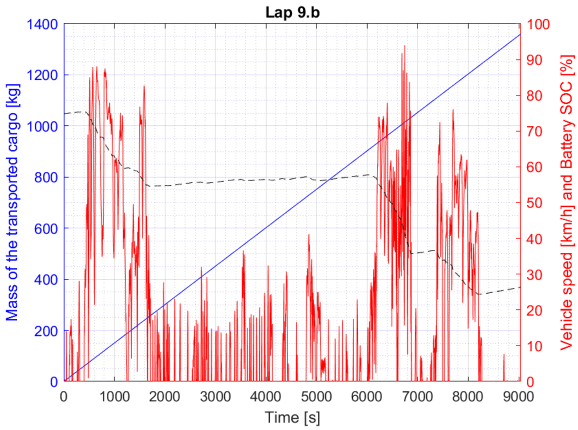

Lap 5
Mass of the transported cargo [kg]
Vehicle speed [km/h] and Battery SOC [%]
Time [s]
(e)

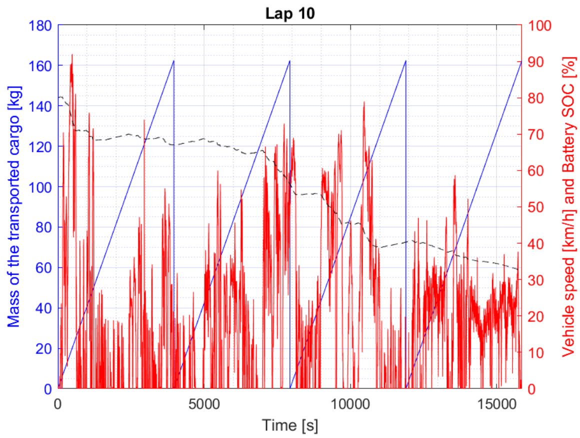

Lap 6
Mass of the transported cargo [kg]
Vehicle speed [km/h] and Battery SOC [%]
Time [s]
(f)


Lap 7
Mass of the transported cargo [kg]
Vehicle speed [km/h] and Battery SOC [%]
Time [s]
×10^4
(g)

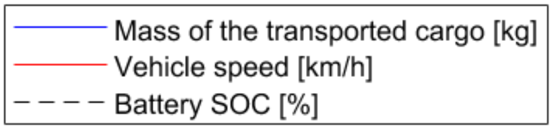

Lap 8
Mass of the transported cargo [kg]
Vehicle speed [km/h] and Battery SOC [%]
Time [s]
(h)


Lap 9.a
Mass of the transported cargo [kg]
Vehicle speed [km/h] and Battery SOC [%]
Time [s]
(i)


Lap 9.b
Mass of the transported cargo [kg]
Vehicle speed [km/h] and Battery SOC [%]
Time [s]
(j)



(k)



(l)

Fig. 1. Speed profiles of the mission, carried load (waste mass) and battery SOC: (a) profile 1; (b) profile 2; (c) profile 3; (d) profile 4; (e) profile 5; (f) profile 6; (g) profile 7; (h) profile 8; (i) profile 9.a; (j) profile 9.b; (k) profile 10; (l) legend for the interpretation of the graphs.

In Figure 1 it is possible to observe the 10 speed profiles obtained thanks to GPS acquisitions; the trend over time of the load transported by the vehicle, approximated taking into account the vehicle tares in the waste unloading phases; and, finally, the result in terms of SOC obtained by means of simulations with the TEST model.

Table 3 summarizes the main results obtained by means of the TEST model (Sandrini et al., 2021) simulations on the 10 speed profiles of the daily mission for the above-mentioned waste collection vehicle equipped with SOFC nominal power 3 kW and battery pack capacity 30 Ah. In particular, the recharge time presented in the last column of Table 3 corresponds to the time needed to recharge the battery pack from the final SOC of the considered profile back to the initial SOC of the profile itself, with the vehicle off duty (therefore with no consumption by the vehicle auxiliaries) and, as specified above, the SOFC system always on. However, in Table 3 there is an exception regarding the recharge time associated with both profiles number 9. The recharge time associated with profile 9.a corresponds to the recharge time of an hour and a half of the intermediate stop of profile 9, set up in order to be able to complete this profile while avoiding that the SOC drops too low i.e., below 20%. The recharge time associated with profile 9.b is instead the time required to recharge the battery pack from the final SOC of the profile 9.b back to the initial SOC of the profile 9.a. Furthermore, by adding all the recharge times shown in Table 3, it is possible to obtain the total recharge time of the mission, remembering that the latter is performed in two weeks, working 10 days every 2 weeks and each working day corresponds to the execution by a single vehicle of the fleet of each of the 10 speed profiles.

Considering the two weeks (336 hours) of the mission and the ten daily profiles, subtracting from 336 hours the time in which the SOFC system operates to provide energy for the mission, i.e., during the vehicle use phases (about 54 hours) and in the battery pack recharge time (about 29 hours), in the remaining time (about 253 hours), the SOFC system supplies power to the stationary electricity grid (758 kWh every two weeks).

Finally, considering a SOFC methane consumption equal to 0.23 $m^3\ h^{-1}\ kW^{-1}$ according to (Aguiar et al., 2007), the fuel consumption of the 3 kW SOFC system under examination is 0.69 $m^3\ h^{-1}$. Knowing all times of the missions (mission profile times, recharging times with the vehicle inactive and periods in which the SOFC system feeds current into the grid with the vehicle off), it is therefore possible to estimate the relative methane (or biomethane) consumption, as stated in Table 4.

Table 3. Main results of the simulations with the waste collection vehicle model equipped with SOFC for each of the 10 speed profiles. In particular, the item “SOC range [%]” refers to the portion of SOC used along the mission profile, it is therefore calculated as the difference between the maximum SOC and the minimum SOC reached during the profile under scrutiny.

Speed profile n°	Initial SOC [%]	Final SOC [%]	Maximum SOC [%]	Minimum SOC [%]	SOC range [%]	Profile Time [h:min:s]	Recharge time [h:min:s]
1	60 *	45.7	61.0	44.8	16.1	3:56:31	1:02:45
2	55 *	47.6	56.4	45.1	11.3	4:42:59	0:32:25
3	50 *	47.1	54.9	46.6	8.2	4:51:34	0:12:44
4	90 *	21.3	95.6	20.6	74.9	10:07:08	5:02:09
5	90 *	30.4	91.7	29.5	62.2	5:04:55	4:22:07
6	55 *	44.8	58.6	43.5	15.1	5:32:58	0:44:50
7	90 *	28.3	92.3	26.4	66.0	5:47:39	4:31:14
8	75 *	32.4	75.1	32.2	42.9	4:07:42	3:07:13
9.a	90 *	54.4	90.1	54.1	36.0	3:01:02	1:30:00 *
9.b	74.8	26.3	75.5	24.4	51.1	2:30:41	4:39:57
10	80 *	32.9	80.2	32.7	47.6	4:24:27	3:27:05

* Parameter defined after several iterations of the simulation.

Table 4. Methane (or biomethane) consumption, every two weeks, for each phase of the vehicle’s life. In particular, the traction phase includes both the phase in which the battery pack is recharged by the SOFC generator while driving the speed profiles, and the phase in which the vehicle is switched off and the SOFC system sends power to the battery pack and not to the electricity grid.

<table>
<tr><th>Total</th><th>Phase</th><th>Sub-phase</th></tr>
<tr><td rowspan="3">Every two weeks
$231.8\ m^3$</td><td rowspan="2">Traction, for recharging the battery pack
$57.5\ m^3$</td><td>During vehicle’s mission (vehicle on)
$37.3\ m^3$</td></tr>
<tr><td>During recharge phases (vehicle off)
$20.2\ m^3$</td></tr>
<tr><td>Vehicle off, for recharging the electricity grid
$174.3\ m^3$</td><td></td></tr>
</table>

From the results, presented in Table 4, it can be observed that the consumption of methane is not balanced as regards battery recharging and recharging of the electricity grid. The model could therefore have room for improvement, testing new compromises between battery pack capacity and SOFC system target power.

However, the feasibility, in terms of energy and power, of a vehicle operating in fleet equipped with a SOFC generator has been confirmed, therefore the same approach and methodology adopted for the model of this specific door-to-door waste collection vehicle can also be applied to the sizing and modelling of a generic hybrid SOFC/battery pack vehicle that operates in fleet or in any case with predefined, repeatable, and known mission profiles.

4. Conclusion

The aim of this study was to investigate the possibility to employ a fuel cell powered hybrid powertrain fueled by methane or biomethane. This has been done through a model-based design approach, using a consolidated vehicle modelling architecture/tool (Sandrini et al., 2022, 2021; Zecchi et al., 2022). The system identified features a SOFC as a generator, which is never turned off, and which supplies current to the electricity grid in the event that the vehicle is off duty, and the battery pack does not need recharging. The model was created and sized for a waste collection vehicle, with a number of predefined missions, which therefore lends itself to the application of the SOFC technology. Power delivered by the fuel cell and battery pack capacity have been optimized to values of 3 kW and 30 Ah respectively, adopting the appropriate arrangements in terms of charging stops. However, the capacity of the battery pack and the target power of the SOFC generator could be re-calibrated by considering additional aspects, for example to obtain a better ratio between biomethane consumption for traction and for recharging the electric grid. In addition, it is possible to optimize the system by using the power sent to the electricity grid to recharge other vehicles in the fleet. The work carried out is repeatable and can be the initial step for future works aimed at exploiting SOFC technology in the automotive sector, paying attention to the fact that it is necessary to solve the problem of fragility of solid oxide fuel cells before installing them on a vehicle.

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