Technical feasibility study of a renewable fuel cell/electrolyzer poly-generative system

Giuseppe De Lorenzo*, *Orlando* Corigliano, *Francesco* Piraino, *Matteo* Genovese and *Petronilla* Fragiacomo

Department of Mechanical, Energy and Management Engineering, University of Calabria, 87036 Arcavacata di Rende (CS), Italy

Abstract.
Recently the European Commission presented the REPowerEU plan to rapidly reduce dependence on fossil fuels, accelerate the green transition and tackle the climate crisis through greater and better use of renewable energy sources. In Europe from 2035 with the "Fit for 55" climate package, pure electric or hybrid fuel cell electric vehicles will replace new pure or hybrid ICE vehicles fed by gasoline or diesel to reduce pollution and the generation of climate-altering gas emissions. Based on this context, in this article a poly-generative energy system for the hydrogen, electric and thermal powers production is defined to satisfy the needs of pure electric or hybrid fuel cell electric mobility and/or the electric/thermal loads of a residential building located in Rende (Italy) on two typical winter and summer days. It consists mainly of an SOFC system fed by biogas or bio-methane in cogenerative arrangement, a photovoltaic system and a PEM electrolyzer. Technical feasibility study results of the system show that for the mixed fleet of 30 vehicles the output electrical and thermal powers and hydrogen production are respectively 60 kW, 19 kW, 3.1 kg (biogas) and 60 kW, 33 kW, 3.1 kg (bio-methane). Furthermore, the system covers totally the electric load in summer day and at 80% (biogas) or totally (bio-methane) the thermal load for hot water production in summer and winter days.

1 Introduction

Problems related to climate change and air pollution are pushing the entire scientific community to start a massive energy transition, so enabling the shift from a fossil fuel-based economy to a new paradigm [1, 2].

The transport sector plays a fundamental role in a sustainable and efficient development model, because a third of energy consumption and about a quarter of greenhouse gas emissions are attributable to it in Europe [3].

By 2035, Europe will ban new gasoline or diesel vehicles under the "Fit for 55" climate package [4]. This will drive the adoption of electric or hybrid fuel cell vehicles to curb pollution and climate-altering gas emissions.

The scientific community recognizes hydrogen as a key element in the new energy paradigm. Serving as an energy carrier, hydrogen can be stored and used as needed, facilitating the generation of clean emissions. The objectives of reducing polluting gases in the atmosphere can push the expansion of a hydrogen economy, especially in connection with the use of renewables [5].

* Corresponding author: address: Via P. Bucci,87036 Arcavacata di Rende (CS), Italy, Phone: +39 0984 494942, e-mail: giuseppe.delorenzo@unical.it

The European Commission presented the REPowerEU plan [6] to rapidly reduce dependence on Russian fossil fuels, accelerate the green transition and tackle the climate crisis through greater and better use of renewable energy sources and biofuels.

Meanwhile, the production of renewable energy has grown exponentially recently, moving of 110 GW (2011) to 280 GW (2020) [7]. For this purpose, renewable energy can be stored as green hydrogen for the refueling of the hybrid electric fuel cells vehicles [8, 9].

The solid oxide fuel cells systems can be fed by different biofuels, such as syngas [10, 11] or dry biogas [12] or a steam/biogas mixture [13] or bio-methane [14]. They exhibit high efficiency in generating both electric and thermal energy.

Green hydrogen is inextricably linked to electrolyzers, and to fuel cells, which are the quintessential devices for converting it into highly efficient electric energy for green mobility. Among the various water electrolysis technologies, alkaline (A) and proton exchange membrane (PEM) technologies have reached a fair stage of maturity and commercial penetration [15].

Hence, the challenge is to turn to highly efficient poly-generative systems connected to renewable sources and biofuels to support green mobility and stationary loads.

In literature there are not many articles on fuel cell based poly-generative systems with hydrogen production [16-19], and most consider systems for stationary application while not supporting the new green mobility.

In this article, a fuel cell based poly-generative energy system fed by dry biogas or bio-methane is defined for the hydrogen, electric and thermal powers production. It is designed to satisfy the needs of pure electric or hybrid fuel cell electric mobility and/or the electric and thermal loads of a residential building located in Rende (Italy), considering the typical winter and summer days.

A preliminary technical feasibility study of the system is carried out to evaluate its electric/ thermal powers and efficiencies and hydrogen production for a defined fleet of pure electric and hybrid Fuel Cell (FC) electric vehicles, supposed at the service of the building inhabitants. Moreover, the coverage percentages of the building's electrical and thermal loads guaranteed by the system are evaluated in the two typical days.

2 Background

This section highlights the starting state of the user for building a strategy and paving the way to the development of an efficient energy system.

The electric needs are associated to the electric devices as light plants, home appliances, any electric heating driven, etc., while the thermal requirements are due to heating and domestic hot water. For this case study, the choice is turned to a residential building with an ample flat space used as garden and parking. Electric energy and heat consumption are calculated having as basis residential loads related to southern Italy [20, 21]. The consumptions are evaluated per surface occupied, according to the extreme cases of the year: in the mid-winter day and in the summer one.

The electrical and thermal specific consumptions for hot water production and for heating $P_{el,sp}$, $P_{th,sp,hwp}$ and $P_{th,sp,heating}$ are shown in table 2.

Figure 1 illustrates the residential building taken as reference with the indications of the main geometric dimensions and of the cardinal points. It is located in the urban area of Rende, Cosenza, Italy (39°20′ N 16°11′ E). It has 5 floor and 3 different apartment net useful surfaces (100, 150 and 200 m^2).The surfaces suitable to host PV panels are the roof surfaces (1, 2, 3, 4 and 5) and the space used as parking.

The PV module, chosen for this application, is a commercial product [22], with a surface encumbrance of 1.134 m x 1.722 m. Other useful information retrieved from the data sheet

are the electric efficiency of 20.44 %, the nominal condition, in terms of voltage and electric current, of respectively 42.3 V and 9.69 A, thus offering a nominal power of 410 W.

The photovoltaic panels on the building overlap the roof surfaces, thus meaning that tilt angle and orientation are bound by the same roof self. On the other hand, for the parking, inclination and orientation can be chosen freely. The tilt angle of PV panels on the roof is 7°, while for parking a value equal to the latitude is chosen as appropriate. As for the orientation, the PV component installed on surface 1 faces the south, components 2 and 4 face the west side, components 3 and 5 face the east side. For the parking surface, all the PV panels face the south side.

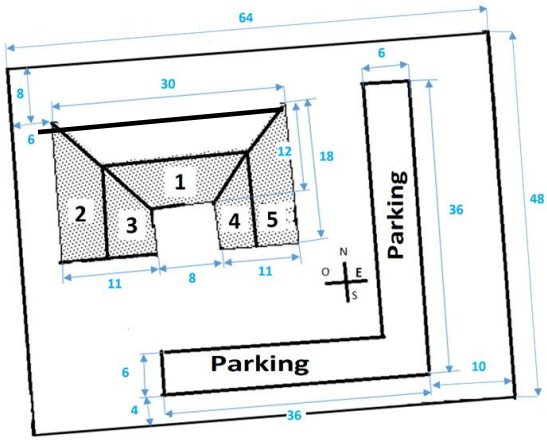

Fig. 1. Suitable parts of the roof and parking to host the PV panels

Every family consisting of an average of 4 people has 2 vehicles according to [23]. The fleet of vehicles is composed of 3 different types of vehicles (A: Fiat 500E; B: Tesla model Y long range; C: Toyota Mirai MY23 Pure), whose technical data are reported in [24-26]. The types A and B vehicles are pure electric for small and medium distances, while vehicle C is FC hybrid electric vehicle for long distance. The number and the average daily distances traveled for the vehicles A, B and C are reported in table 1.

Table 1. Number and average distances of the vehicles

Type of vehicle	Number of vehicles	Distance [km]
A	15	41 [27]
B	14	272
C	1	394

3 Methods

This section focuses on energy analysis of end-users and computational tools, which are used to carried out the energy analysis of the poly-generative system.

For the entire building, the time trends of the electric load and of the thermal loads for heating and hot water production, $L_{el,build}(t)$, $L_{th,hw,build}(t)$ and $L_{th,heat,build}(t)$ are calculated through equations (1):

$$\begin{aligned} L_{el,build}(t) &= (1 + f_{aux}) \cdot L_{el,spec}(t) \cdot \left(A_{ap1} + A_{ap2} + A_{ap2}\right) \cdot n_{floor} \\ L_{th,hw,build}(t) &= L_{th,hw,spec}(t) \cdot \left(A_{ap1} + A_{ap2} + A_{ap2}\right) \cdot n_{floor} \\ L_{th,heat,build}(t) &= L_{th,heat,spec}(t) \cdot \left(A_{ap1} + A_{ap2} + A_{ap2}\right) \cdot n_{floor} \end{aligned} \quad (1)$$

In equations (1) A_{ap1}, A_{ap2}, A_{ap3} are the useful surfaces of the apartments; n_{floor} is the floor number and f_{aux} is the increase in electric power consumed for common services, the lighting of the stairs and garages equal to 0.10.

The electrical and thermal loads for hot water production and for heating, P_{el}, $P_{th,hwp}$ and $P_{th,heating}$ of the residential building are calculate through equations (1) and are presented in table 2.

Table 2. Electrical and thermal specific consumptions and loads of the residential building

	Summer				Winter					
Hour h	$P_{el,sp}$ W m^{-2}	$P_{th,sp,hwp}$ W m^{-2}	P_{el} kW	$P_{th,hwp}$ kW	$P_{el,sp}$ W m^{-2}	$P_{th,sp,hwp}$ W m^{-2}	$P_{th,sp,heating}$ W m^{-2}	P_{el} kW	$P_{th,heating}$ kW	$P_{th,hwp}$ kW
1	3.125	0	7.734	0	2.625	0	5.875	6.497	13.219	0
2	2.625	0	6.497	0	2.125	0	5.875	5.259	13.219	0
3	2.5	0	6.188	0	2	0	5.875	4.950	13.219	0
4	2.375	0	5.878	0	2	0	5.875	4.950	13.219	0
5	2.4375	0	6.033	0	2.275	0	5.875	5.631	13.219	0
6	2.775	0	6.868	0	3.5	0	5.875	8.663	13.219	0
7	3.25	4.375	8.044	9.844	4.5	4.375	17.5	11.138	39.375	9.844
8	3.375	8.5	8.353	19.125	4.1875	8.5	36.875	10.364	82.969	19.125
9	3.375	21.25	8.353	47.813	4	21.25	38.75	9.900	87.188	47.813
10	3.375	8.5	8.353	19.125	3.75	8.5	37.5	9.281	84.375	19.125
11	3.625	2.25	8.972	5.063	3.8125	2.25	35	9.436	78.750	5.063
12	3.9375	2.25	9.745	5.063	4.2875	2.25	30	10.612	67.500	5.063
13	4.125	2.25	10.209	5.063	4.625	2.25	32.5	11.447	73.125	5.063
14	4.25	2.25	10.519	5.063	4.75	2.25	31.25	11.756	70.313	5.063
15	4	0	9.900	0	4.65	0	28.75	11.509	64.688	0
16	3.9375	0	9.745	0	4.8125	0	30	11.911	67.500	0
17	3.9375	2.25	9.745	5.063	5.5	2.25	30.625	13.613	68.906	5.063
18	4.5	2.25	11.138	5.063	6.5	2.25	31.875	16.088	71.719	5.063
19	5.375	4.5	13.303	10.125	7.5	4.5	33.125	18.563	74.531	10.125
20	5.875	17.5	14.541	39.375	7.625	17.5	43.75	18.872	98.438	39.375
21	6.0625	17.5	15.005	39.375	7.1875	17.5	42.125	17.789	94.781	39.375
22	5.375	4.5	13.303	10.125	5.6875	4.5	25.625	14.077	57.656	10.125
23	4.375	2.25	10.828	5.063	4.375	2.25	11.75	10.828	26.438	5.063
24	3.625	0	8.972	0	3.4375	0	5.875	8.508	13.219	0

Based on the number, the technical specifications [24-25] and the distances traveled of the pure electric vehicles (types A and B vehicles), 8 charging points are estimated for the vehicles electric recharging at an electric power of 7.5 kW. The 15 type A electric vehicles will be recharged at the first charging point, while the other 14 type B electric vehicles will be recharged at the other 7 charging points. The time required for recharging of all the pure electric vehicles is evaluated to be about 11 hours in a maximum recharge time window of 12 hours ranging from 8 pm to 8 am.

For the electric charging of all pure electric vehicles, a total electric power of 60 kW is required for the entire charging time. The electric power for the electric charging of all vehicles has to be supplied by the solid oxide fuel cell system fed by biogas or bio-methane.

Based on the technical specifications [26] and the distance traveled, the type C vehicle requires a daily hydrogen mass of about 3.11 kg.

The sizing of the PV system passes through the choice of the photovoltaic module, appropriately evaluating its technical specifications. From the acquisition of the energy characteristics and the dimensions of the module, knowing the installation surface, the maximum number of panels allowed is calculated, therefore the size of the system.

The next step concerns the photovoltaic power actually yielded. This parameter depends on the solar radiation captured in the place of installation by the single PV components. Hence, the determination procedure of the profiles of electrical power produced by the entire PV system in the two typical summer and winter days is reported.

For the calculation of the solar radiation, the known model for the radiation incident on the oriented plane is used, following the instructions reported in the regulation UNI 10349. The model is summarized in equation (2):

$$H_\psi = (H_b \cdot R_b) + (H_d \cdot R_d) + \rho \cdot H \cdot \frac{1-\cos(\psi)}{2} \tag{2}$$

In equation (2), H_ψ, H, H_b and H_d are respectively the global radiation on the inclined plane, the global radiation, the direct radiation and the diffused radiation in the horizontal plane; ψ is the inclination angle of the surface; R_b is the ratio between the direct radiation incident on the surface and that incident on the horizontal plane; R_d is the ratio between the diffused radiation incident on the surface and that incident on the horizontal plane; ρ is the value of the albedo.

The selection of the electrolysis technology was directed towards Proton Exchange Membrane (PEM) electrolysis.

A calculation tool based on the dynamic simulation model of a PEM electrolyzer system was ad hoc set up in Simulink® environment in [28].

The comparison between the PEM electrolytic stack static experimental data found in literature [29] and the static polarization and electric power curves produced by the simulation model showed a good agreement between the simulation model results and the experimental data.

The calculation tool is used to outline the trend of the hydrogen production efficiency for the PEM electrolyzer system as the stack operating current varies and to identify its optimal operating field.

The hydrogen production efficiency of the PEM electrolyzer system, $\eta_{H_2\,prod}$, is calculated through equation (3):

$$\eta_{H_2\,p} = \frac{\dot{m}_{H_2,p} \cdot HHV}{P_{el,in,sys}} \tag{3}$$

In equation (3), $\dot{m}_{H_2,p}$ and HHV are the hydrogen mass flow and high heating value and $P_{el,in,sys}$ is the electric power absorbed by the system.

The Solid Oxide Fuel Cell (SOFC) system is dedicated to the production of the electric energy needed to the types A and B electric vehicles in both winter and summer.

Two different types of Solid Oxide Fuel Cell (SOFC) systems are considered: the first one is not conventional system, because it is directly fed by dry and purified (without sulphur compound) biogas and the second one is commercial system and it is fed by bio-methane, which is produced from the purified biogas through a CO_2 separation process, and water.

The electrical and thermal efficiencies of the SOFC systems (SS) are defined in equations (4):

$$\eta_{el,SS} = \frac{P_{el,net,SS}}{G_{bio} \cdot LHV_{bio}}$$
$$\eta_{th,SS} = \frac{P_{th,net,SS}}{G_{bio} \cdot LHV_{bio}} \tag{4}$$

where: $P_{el,net,SS}$ and $P_{th,net,SS}$ are the net electrical and thermal powers produced by the systems, while G_{bio} and LHV_{bio} are the mass flow and the low heating value of the feeding biogas or bio-methane.

The first SOFC system was described and studied from an energy viewpoint in [12].

It is composed of innovative SOFCs, which can operate at intermediate temperature (800°C) and in which at the anodes the direct dry methane electrochemical oxidations are realized, reducing the risk of carbon deposition [12]. The innovative SOFCs are experimentally tested in [12].

For a high quality biogas ($\%_{v,CH4}$=60% and $\%_{v,CO2}$=40%) feeding, it achieves the maximum electrical efficiency of about 0.42 and a thermal efficiency of 0.13.

The second SOFC system fed by bio-methane is obtained by appropriately scaling the product Bluegen BG-15, which is manufactured and marketed by Solydera s.p.a. The technical specification of the product are available in [14] and it achieves the maximum electrical efficiency of about 0.57 and a thermal efficiency of 0.31.

For the SOFC systems, the electrical and thermal efficiencies are considered to vary slightly with increasing size, as the SOFC stack technology is modular.

4 Results

In this paragraph, the main results on the different units of the poly-generative system (PV system, Hydrogen production system and Solid oxide fuel cell systems fed by biogas or bio-methane) and on the entire poly-generative system are presented.

4.1 *PV system*

Table 3 reports the dimensioning, indicating per zone of installation the various notable parameters. It contains the number of panels suitable to be applied on the surface, organization of PV rows, PV gross and active surfaces, orientation and tilt angle. For example, zone 1 is suitable to host 20 PV panels, organized by 3 rows with respectively 9, 7 and 4 panels. The PV gross surface is 39.05 m^2, while the active one is 35.38 m^2. As can be observed, the parking space offers the highest PV surface with its 117 panels. Totally, the PV system observes a DC electric power installed of 74.21 kW.

The above-mentioned procedure is applied to the winter day (16 December) and summer day (16 June) to calculate the captured solar power and the DC electric power delivered by the PV system, which are shown in Figure 2.

Table 3. PV system dimensioning

PV panel efficiency[%]							20.44
PV panel nominal power [W]							410
Single PV panel (1134 mm x 1722 mm) size [m^2]							1.953
Zone	**PV panels**	**Rows**	**Numbers per row**	**PV gross surface [m^2]**	**PV active surface [m^2]**	**Orientation**	**Tilt angle [°]**
1	20	3	(9/7/4)	39.05	35.38	SOUTH	7
2	14	2	(8/6)	27.34	24.77	WEST	7
3	8	2	(5/3)	15.62	14.15	EAST	7
4	8	2	(5/3)	15.62	14.15	WEST	7
5	14	2	(8/6)	27.34	24.77	EAST	7
Parking	117	2	(2/26); (5/13)	228.47	206.98	SOUTH	Latitude
Total	181			343.45	320.2		

In December the PV system starts to produce from 8 am to 8 pm, while in June form 6 am to 7 pm. In December the maximum DC electric power delivered is about 37 kW, while

in June is about 63 kW. Totally, the PV system delivers the DC electric energies of 214 kWh in the winter day and 489 kWh in the summer day.

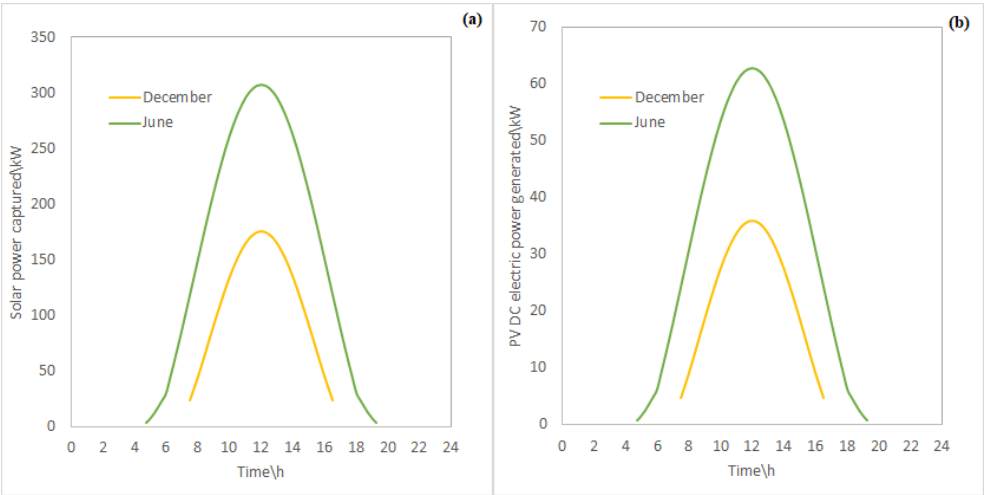

Fig. 2. Captured solar power (a) and DC electric power delivered by the PV system

4.2 *Hydrogen production system*

The hydrogen production system is composed of a Proton Exchange Membrane (PEM) electrolyzer, which generates hydrogen at low pressure (up to 15 bar) from distilled water using the electric energy produced by PV system and of a compression section, which generates hydrogen at high pressure (up to 750 bar) to refuel the fuel cell hybrid electric vehicle.

The PEM electrolyzer system reaches a good H_2 production efficiency, referred to hydrogen HHV, of about 0.65 at a maximum hydrogen flow percentage of about 60%.

The production efficiency of the PEM electrolytic stack varies little with increasing size, as the PEM electrolyte stack technology is modular.

The net H_2 production efficiency of the PEM electrolyzer system increases slightly little as its size increases as its auxiliary devices become more efficient as the size increases.

Therefore, the H_2 net production efficiency of the small size PEM electrolyzer system is conservative when it is referred to large size PEM electrolyzer systems and it is used in this study to calculate the specific energy consumption of a large size PEM electrolyzer system.

The hydrogen necessary to the type C vehicle is produced by PEM electrolyzer system absorbing a constant electric power of about 23 kW for 9 hours and then it is compressed up to 750 bar absorbing an additional energy of 14.6 kWh in both winter day and summer day.

The energy necessary to hydrogen production and compression is produced totally by PV system in both winter day and summer day.

A battery pack is dimensioned ad hoc for the PV system to make the electrolyser operate at its good efficiency both in winter and in summer day and to track and totally cover the electrical load of the building in summer day.

4.3 *Solid oxide fuel cell systems fed by biogas or bio-methane*

The SOFC systems produce the electric power necessary to recharge the types A and B electric vehicles in both the winter and summer day. It operates continuously 24 hours a day at a nominal electric power of about 27 kW. Another battery pack is dimensioned ad hoc for the SOFC system to make it operate continuously at its good efficiency and to totally cover the electrical load of the pure electric vehicles fleet both in winter and in summer day.

The net SOFC systems output thermal energies, which consider the heat exchange between hot exhaust gases from the systems and the cold fluid (typically water for sanitary purposes or for heating), are used to cover the building thermal loads for the hot water production and for heating in both the winter and summer day.

4.4 *Poly-generative system*

The poly-generative system uses renewable energy sources (sun and biofuels: biogas or bio-methane) to produce the electric energy for charging the types A and B electric vehicles and to generate the compressed hydrogen to refuel the type C vehicle in both the winter and summer day. In this way, the new fleet of green vehicles does not affect the national electric grid.

Figure 3 shows the main energy sections, the related energy inputs/outputs and the efficiencies in the two different scenarios considered. Table 4 shows the performance parameters.

The electric energy produced by PV system covers totally the electric energy consumption for hydrogen production and compression in both the winter and summer day.

Table 5 shows the coverage percentages of the electric and thermal energies produced by the poly-generative system on the building electric and thermal loads in both the winter and summer day.

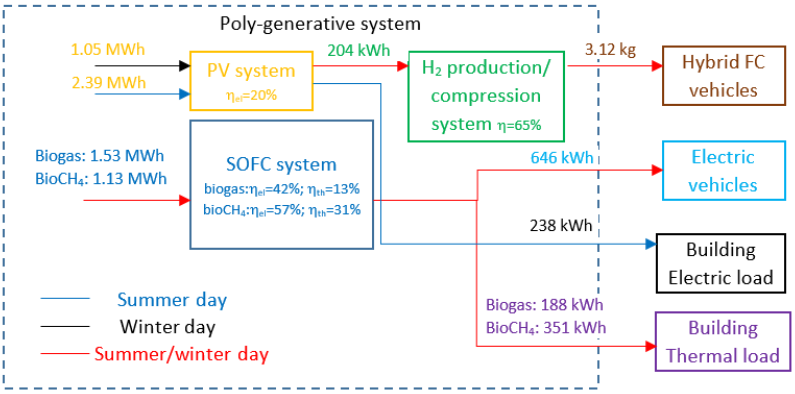

Fig. 3. Energy inputs/outputs and efficiencies of the poly-generative system main components

Table 4. Performance parameters and biofuels consumptions of the poly-generative system

	Unit	Dry biogas feeding	Bio-CH_4 feeding
η_{el}	-	0.42	0.57
η_{th}	-	0.13	0.31
$m_{biofuel}$	kg	313	82
m_{H2}	kg	3.12	3.12

The chain poly-generative system-pure electric vehicles exhibits global efficiencies of about 43% (biogas feeding) and of about 51% (bio-methane feeding). These performance levels surpass those of the Internal Combustion Engine (ICE) based vehicles fed by high quality biogas (28.45% [30]) and bio-methane (39% [31]).

The poly-generative system enables the long-term storage of renewable energy in the form of hydrogen, which can fuel the long-range hybrid fuel cell vehicles.

Moreover, conventional ICEs do not recover thermal energy and release it as waste. In contrast, the poly-generative system efficiently recovers and utilizes the produced thermal energy for hot water generation and heating purposes. Additionally, electric and hybrid fuel

cell vehicles will be able to recover the mechanical energy during the deceleration phases through the regenerative breaking.

Table 5. Coverage percentages of the electric and thermal energies produced by the poly-generative system on the building electric and thermal loads

Building loads	**Coverage percentages\%**
Electric load in summer day	over 100%
Thermal load for hot water production in both the winter and summer day	81% (biogas feeding) 100% (bio-methane feeding)
Thermal load for heating in winter day	9.4 % (only bio-methane feeding)

5 Conclusions

This article reported on the technical feasibility study of the renewable fuel cell/electrolyzer poly-generative system fed by renewable energy sources (sun and biofuels: biogas or bio-methane), which supported the green electric (types A and B vehicles) and hybrid fuel cell (type C vehicle) mobility for a building located in the urban area of Rende, Cosenza, Italy. It produced the electric energy for charging of the types A and B electric vehicles and the compressed hydrogen for refueling the type C vehicle in both the winter and summer day.

The electric and thermal efficiencies of the system fed by dry biogas or bio-methane were respectively 0.42 and 0.13 (biogas feeding) or 0.57 and 0.31 (bio-methane feeding).

The total daily masses of biogas or bio-methane consumed and of compressed hydrogen produced were respectively about 313 kg, about 82 kg and about 3.12 kg in both the winter and summer day.

The electric energy of the PV system with a nominal DC electric power of 74.21 kW covered totally the electric energy consumption for hydrogen production and compression in both the winter and summer day. In the summer day, the surplus of electric energy of the PV system covered totally the building electric load.

The output thermal energy of the system fed by dry biogas or bio-methane covered totally (bio-methane feeding) and partially at about 81% (dry biogas feeding) the building thermal load for hot water production in both the winter and summer day and partially at about 9.4% (bio-methane feeding) the building thermal load for heating in the winter day.

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