Technical analysis of a renewable woody biomass generator/electrolyzer poly-generative system

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Abstract.
In the REPowerEU plan, the European Commission has envisaged a rapid reduction in dependence on fossil fuels, an acceleration of the green transition and has shown its willingness to tackle the climate crisis by resorting to greater and better use of renewable energy sources. Furthermore, from 2035 the "Fit for 55" climate package aims to reduce emissions of pollutants and climate-altering gas emissions and to encourage the diffusion of new pure electric or fuel cell hybrid electric vehicles. In this context, this article deals with a poly-generative energy system for the production of H_2, electric and thermal powers. It is able to satisfy the new vehicles needs and/or the electric/thermal loads of a rural building located in Rende (Italy, Lat. 39.3°N) on two typical winter and summer days. The poly-generative system is mainly composed of an energy system fed by woody biomass in a cogenerative arrangement, a photovoltaic system and a PEM electrolyzer. Technical analysis of the system shows that for the mixed fleet of 30 vehicles the output electrical and thermal powers and hydrogen production are respectively of about 50 kW, 97 kW and 9.23 kg. Furthermore, the system covers totally the electric load on summer days and the thermal load for hot water production in the summer and winter days.

1 Introduction

In Europe from 2035 with the "Fit for 55" climate package [1], new pure or hybrid internal combustion engine vehicles fed by gasoline or diesel will no longer be sold and they will be progressively replaced by pure electric or hybrid fuel cell electric vehicles to reduce pollution and the generation of climate-altering gas emissions.

This new green mobility requires an increase in the electric power produced and the new generation of hydrogen.

The European Commission presented the REPowerEU plan [2] 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. In this framework, poly-generation and multi-source systems [3, 4] represent valuable technical solutions. In order to improve the renewable share, an important component is represented by photovoltaic systems, which are now a well-consolidated technology able to produce an important amount of renewable energy [5, 6].

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The energy produced from renewable sources can be stored in the form of green hydrogen, which can refuel hybrid electric fuel cell vehicles [7, 8].

Green hydrogen can be produced through electrolyzers, using electric energy from renewable sources. The alkaline (A) or proton exchange membrane (PEM) electrolyzers are the most common and commercial electrolyzers [9].

Furthermore, Combined Heat and Power (CHP) systems represent an effective alternative to traditional energy systems based on standard separate electric and thermal energy generation. In this framework, the Internal Combustion Engines (ICE) are considered a well-known, reliable, and flexible technology [10]. In fact, they can be also fed by biofuels, such as syngas [11] produced by the gasification of woody biomass.

The integration of an ICE based CHP system fed by syngas with PEM electrolyzer supplied by electric energy produced from Renewable Energy Sources (RES) generates an ICE based poly-generative energy system.

An investigation of the recent literature revealed that there are not many articles on poly-generative systems with hydrogen production [12-15] and most articles consider the system used for stationary application and not to support the new green mobility, which is the focus of this work.

In this article, an ICE based poly-generative energy system fed by syngas, produced by the gasification of woody biomass, for hydrogen, electric and thermal powers production is defined. It is designed to satisfy the needs of pure electric or hybrid fuel cell electric mobility and the electric/thermal loads of a countryside building located in Rende (Italy, Lat. 39.3°N) on two typical winter and summer days. Moreover, the ICE is capable of operating under partial load conditions to increase the flexibility of the overall system.

A preliminary technical analysis of the system is carried out to evaluate its electric/thermal powers/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, in the two typical days the coverage percentages of the building's electrical and thermal loads guaranteed by the system are evaluated.

2 Countryside building and vehicle fleet

In this section, the thermal and electric power time trends are defined according to the user and the volumes, which are considered supplied by the poly-generative system. The electric needs are associated with the electric devices such as light plants, home appliances, any electric heating driven systems, etc., while the thermal requirements are due to heating and domestic hot water. For the specific case study, the choice is turned to a countryside building with an ample flat open space used to host the photovoltaic (PV) system.

The electric and thermal consumptions calculated on average for a sample of consumers located in southern Italy [16, 17] are taken as reference and 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, as was done in [18].

Based on this, the electrical and thermal loads of the 5-floor countryside building with 3 different apartment net useful surfaces (100, 150 and 200 m^2) located in Rende (Italy) are presented in [18].

The countryside building is the same as the one analyzed in [18] and the entire building the time trends of the electric and thermal loads for heating and hot water production, $L_{el,build}(t)$, $L_{th,hw,build}(t)$, $L_{th,heat,build}(t)$, are the same as those shown in [18]. Also in this article an increase in electric power consumed for common services, the lighting of the stairs and garages, a fraction f_{aux} of 0.10 is considered.

Every family consisting of an average of 4 people has 2 vehicles based on what is reported in [19]. The fleet of vehicles is composed of 3 different types of cars (A: Fiat 500E; B: Tesla model Y long range; C: Toyota Mirai MY23 Pure), whose technical data are reported in [20-22]. The types A and B vehicles are pure electric for small and medium distances, while vehicle C is FC hybrid electric vehicle for long distances. The number and the average daily distances traveled for the vehicles A, B and C are reported in table 1.

For the distance traveled by vehicle A, a 10% increase over what was reported in [23] was considered to take into account the travel to the city center.

Table 1. Type, number and average distances of the vehicles

Type of vehicle	Vehicles number	Distance [km]	Number and power of the electric charging points	Number and electric power of the hydrogen production points
A	15	45.1	1 at 7.5 kW	-
B	12	299	6 at 7.5 kW	-
C	3	389	-	1 at 71 kW

Based on the vehicles number, the technical specifications [20-22] and the distances traveled of the pure electric vehicles, 7 charging points are estimated for the vehicle's 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 12 type B electric vehicles will be recharged at the other 6 charging points. The time required for recharging all vehicles is evaluated to be about 11.8 hours in a maximum recharge time window of 12 hours ranging from 8 pm to 8 am.

For the electric charging of all vehicles, a total electric power of 52.5 kW is required for the entire charging time. The electric power for the electric charging of all vehicles is supplied by the ICE system fed by syngas, which is produced through the gasification of woody biomass.

3 Photovoltaic system

In this paragraph, the sizing of the photovoltaic (PV) system is carried out, passing 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, and therefore the size of the system.

A countryside building is considered. It is located in the countryside area of Rende, Cosenza, Italy (39°20′ N 16°11′ E) and it has an open rectangular area 25 m long and 40 m wide, which is suitable to host PV panels, which face the south side.

The PV panel, chosen for this application, is a commercial product [24], with a surface encumbrance of 1.038 m x 1.755 m. In the nominal condition other useful information retrieved from the datasheet are the electric efficiency of 20.9 %, the voltage and electric current, of respectively 34.51 V and 11.01 A, offering an electric power of about 380 W.

Table 2 show the sizing and the main parameters. It contains the number of panels, which are suitable to be applied on the surface, the organization of PV rows, PV gross surfaces, orientation and tilt angle. The PV system is composed of 552 panels.

The next step concerns the photovoltaic power actually yielded. This parameter depends on the solar radiation captured in the place of installation by the PV panels.

Hence, the determination procedure of the profiles of electrical power produced by the entire PV system in the typical summer and winter days is reported.

The PV module is simulated in TRNSYS 18 environment. Climatic data have been acquired in a weather station located at the University of Calabria and have been provided as input to an external data reader. TRNSYS employs components that simulate different solar systems. They are called "Types", and each one implements the specific model of the considered component. Then Types are connected to each other in a way that the output of one represents the input for another one. More in particular, solar radiation on the horizontal plane was decomposed in direct and diffuse components thanks to Type 16a. This component interpolates radiation data, calculates several quantities related to the position of the sun, and estimates insolation on a number of surfaces of either fixed or variable orientation. The PV module is simulated with Type 103b and is operated in maximum power conditions. This component is appropriate for modeling the electrical performance of mono and polycrystaline photovoltaic panels and makes the PV panel to operate at its maximum power point. According to the manufacturer data-sheet, the temperature coefficient of Isc was set to 0.004596 A/K and the temperature coefficient of Voc was set to -0.11 V/K. The type is able to provide directly the array power at maximum power point. Simulations are carried out with a 15 minutes time step.

Therefore, the procedure is applied to a winter day (16 December) and a summer day (16 June). Such days are selected in order to consider representative summer and winter conditions, especially in terms of available solar radiation. Hence, the DC electric power delivered by the PV system is calculated and it is shown in figure 1.

Table 2. PV plant dimensioning

PV panel efficiency[%]						20.9
PV panel nominal power [W]						380
Single PV panel (1038 mm x 1755 mm) size [m^2]						1.822
Zone	**PV panels**	**Rows**	**Numbers per row**	**PV gross surface [m^2]**	**Orientation**	**Tilt angle [°]**
Photovoltaic field	552	23	24	1005.6	SOUTH	Latitude
Total	552			1005.6		

In December, the PV plant starts to produce electric power from 6:30 am to 3 pm, while in June from 4:15 am to 6 pm. In December the maximum DC electric power delivered is about 130 kW, while in June is about 150 kW. Totally, the PV plant delivers the DC electric energy of 605 kWh on the winter day and the DC electric energy of 1019 kWh on the summer day.

4 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 the PV plant and a compression section, which generates hydrogen at high pressure (up to 750 bar) to refuel the fuel cell hybrid electric vehicle.

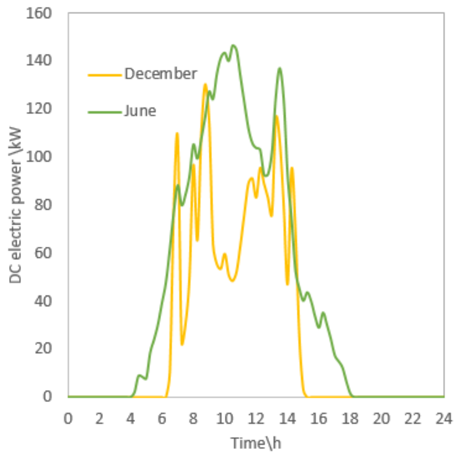


Fig. 1. DC electric power delivered by the PV system

A calculation tool based on the dynamic simulation model of a PEM electrolyzer system was ad hoc set up in Simulink® environment in [25] and further described in [18].

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

Based on the technical specifications [20-22] and the distance traveled, type C vehicles require a daily hydrogen mass of about 9.23 kg. The hydrogen necessary for the type C vehicle is produced by PEM electrolyzer system absorbing a constant electric power of about 71 kW for 8.5 hours. Then it is compressed up to 750 bar absorbing an additional energy of about 43.2 kWh in both the winter and summer day. The energy necessary to hydrogen production and compression is produced totally by PV system in both the winter and summer day.

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

5 ICE based co-generator fed by syngas from woody biomass

Since a total electric power of 52.5 kW is required for the electric charging of all vehicles, an Internal Combustion Engine (ICE) fed by syngas derived from woody biomass gasification is selected to produce an electric power of 50 kW. The national electric grid supplies the remaining electric power of 2.5 kW. The heat recovery process involves extracting useful heat from the lubricant oil and exhaust gas to generate hot water or provide heating. The engine achieves an electrical efficiency of approximately 0.33 and a thermal efficiency of 0.64 [26]. It consistently supplies a steady electric power for 11.8 hours per day. This power unit efficiently meets the energy demands of types A and B electric vehicles during both winter and summer.

The engine is capable of operating at a partial load, down to 50% of its capacity, which is typical for ICEs. This ensures that the performance remains close to its nominal specifications. The assessment of performance degradation was derived from a study conducted on a similar-sized internal combustion engine fuelled by syngas [26]. Specifically, figure 2 shows as at 50% of the load, the electrical efficiency decreases to approximately 28%, which is still a significant value for efficient system operation. Conversely, there is a corresponding increase in thermal efficiency, reaching approximately 70% when considering the same load reduction.

6 Discussion of the results on Poly-generative system

The poly-generative system uses renewable energy sources (sun and biofuel: syngas) to produce the electric energy for charging the types A and B electric vehicles and the compressed hydrogen for refueling the type C vehicle on both the winter and the summer day.

Figure 3 shows the time trends of the electric and thermal powers and the hydrogen mass, which are produced by the poly-generative system in a day.

The percentage electric and thermal efficiencies of the ICE based system fed by syngas are 33% and 64%.

The national electric grid supplies only a small integration of electric power (2.5 kW). In this way, the new fleet of green vehicles is almost completely powered by the poly-generative system.

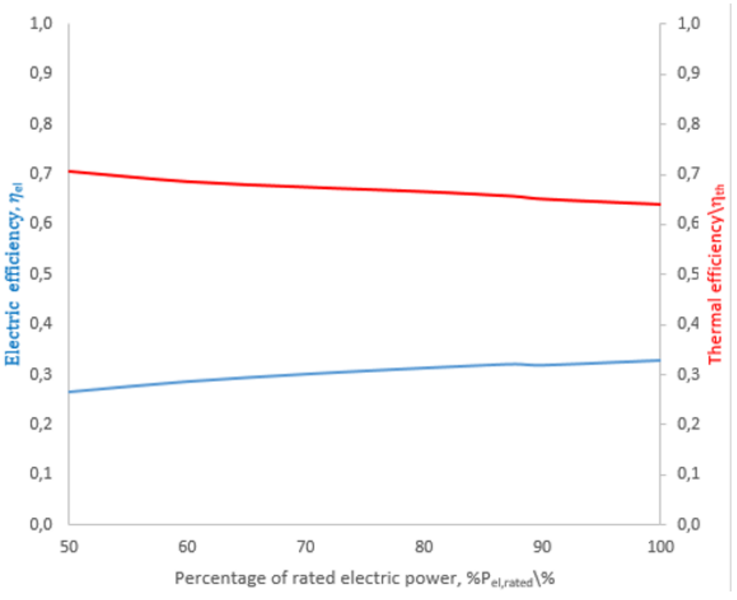


Fig. 2. Thermal and electric efficiencies of the internal combustion engine as a function of the percentage of rated electric power

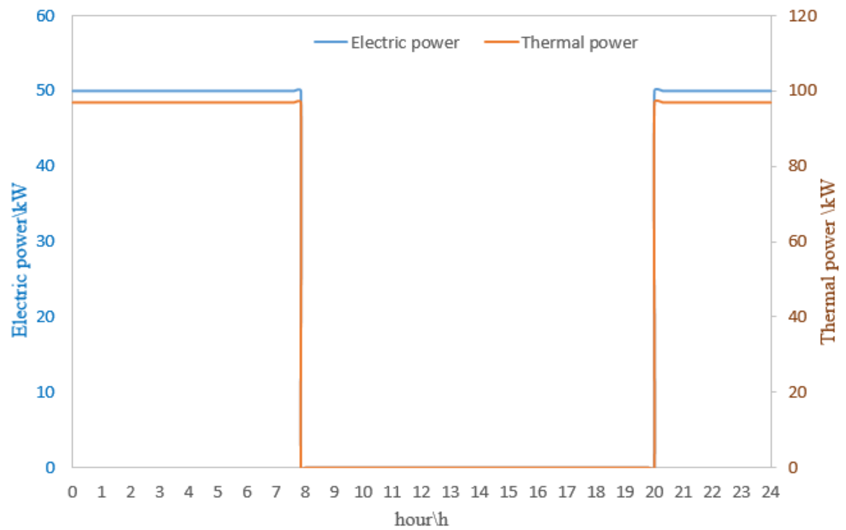
The total daily mass of woody biomass consumed is respectively about 12 kg on both the winter and the summer day, while the output daily mass of compressed hydrogen is about 9.23 kg.

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

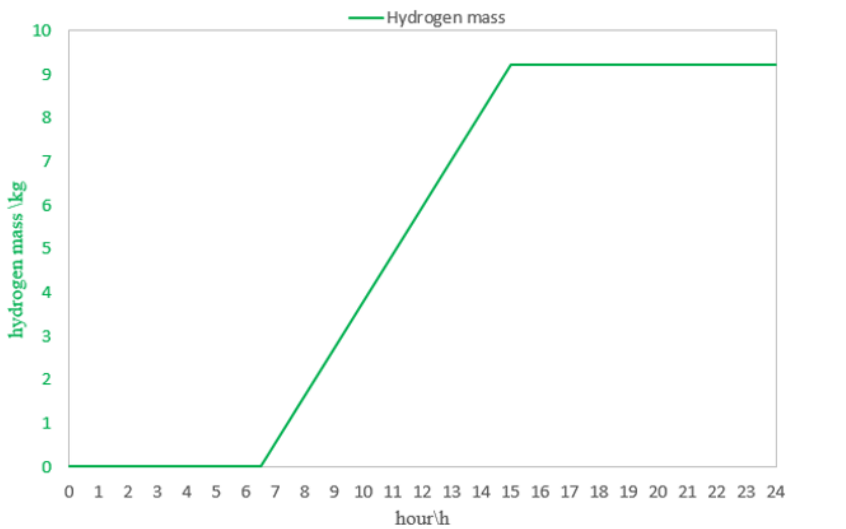
In summer day, the surplus of electric energy produced by the PV plant is stored in a properly dimensioned battery pack and it can cover totally the building's electric load on the same day.

The output thermal energy of the system can cover totally the building thermal load for hot domestic water production on both the winter and the summer day.

Moreover, the output thermal energy of the system can cover partially at about 71.3% the building's thermal load for heating on the winter day.



(a)



(b)

Fig. 3. Time trends of the electric and thermal powers (a) and of the hydrogen mass (b), which are produced by the poly-generative system in a day

7 Conclusions

This article reports on a technical feasibility study of a renewable ICE/electrolyzer poly-generative system. In literature, most papers focus on poly-generative systems for stationary application, not supporting the new green mobility. Therefore, a design procedure was developed, starting from the choice of the countryside building to be served, passing through the PV plant dimensioning in order to account for the primary electric power, assessing successively the electrolyzer system.

The design of the PV system was constrained to the surface suitable to host the PV system.

The types (A and B: short- and medium-range pure electric vehicles; C: long-range hybrid fuel cells electric vehicle), fleet size and distances were defined for the building users.

The poly-generative system, which is fed by renewable energy sources (sun and biofuel: syngas produced through the woody biomass gasification) can operate under partial load conditions and produces electric energy for charging types A and B electric vehicles and compressed hydrogen for refueling the type C vehicle on both the winter and the summer day. It requires a small electric power integration (2.5 kW) from the national electric grid.

The percentage electric and thermal efficiencies of the system fed by syngas were respectively 33% and 64%.

The total daily mass of woody biomass consumed was about 12 kg in both the winter and summer day, while the output daily mass of compressed hydrogen was about 9.23 kg.

The electric energy of the PV plant covered totally the electric energy consumption for hydrogen production and compression.

On the summer day, the surplus of electric energy from the PV plant covered totally the building’s electric loads.

The output thermal energy of the system covered totally the building thermal load for hot domestic water production on both the winter and the summer day and partially at about 71.3% of the building thermal load for heating in the winter day.

The poly-generative system allowed using a biofuels such as the syngas derived from woody biomass gasification to produce contemporary electric energy for short-middle range pure electric vehicles and thermal energy and accumulating the solar energy, which cannot be used in the short term, to produce hydrogen for long-range hybrid fuel cell vehicles.

The thermal energies produced by the ICE fed by syngas is recovered for hot water production and for the heating in the countryside building. Furthermore, the electric and hybrid fuel cell vehicles will be able to recover the mechanical energy during the deceleration phases (regenerative breaking).

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