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Hydrogen station evolution towards a poly-generation energy system

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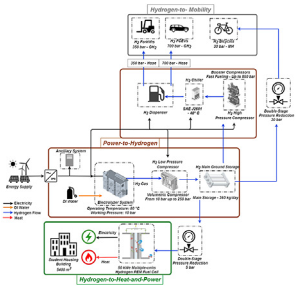
HIGHLIGHTS

- Presentation of a new concept of Multi-modular Hydrogen Energy Station.
- Hydrogen Mobility based on FCEVs, forklifts, and hydrogen bicycles.
- Fuel Cell-based cogeneration system for heat and power generation.
- 360 kg of daily hydrogen for 41 vehicles, 43 bicycles, and 28 fuel cell forklifts.
- LCOH of 10.39 €/kg and ROI of 14.43% for the hydrogen facility.

GRAPHICAL ABSTRACT



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ABSTRACT

The present paper analyzes an innovative energy system based on a hydrogen station, as the core of a smart energy production center, where the produced hydrogen is then used in different hydrogen technologies adopted and installed nearby the station. A case study analysis has been proposed and then investigated, with a station capacity of up to 360 kg of hydrogen daily generated, located close to a University Campus. A hydrogen mobility network has been included, composed of a fuel cell hydrogen fleet of 41 vehicles, 43 bicycles, and 28 fuel cell forklifts. The innovative proposed energy system needs to meet also a power and heat demand for a student housing 5400 m^2 building of the University Campus. The performance of the system is presented and investigated, including technical and economic analyses, proposing a hydrogen refueling station as an innovative alternative fuel infrastructure, called Multi-modular Hydrogen Energy Station, marking its great potential in future energy scenarios.

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Introduction

Hydrogen technologies have been identified as the most suitable solutions for the decarbonization of several energy sectors [1,2], including stationary generation, grid-stabilization, energy storage, and automotive applications [3,4]. Under the support of private councils and government actions, the hydrogen economy is steadily taking place, above all concerning the mobility sector [5]. As a matter of fact, Fuel Cell Electric Vehicles (FCEVs) are showing greater efficiency than conventional vehicles [6,7], and higher mileage and faster refueling than the total electric vehicles (EVs) [8]. Several automakers, such as Toyota, Hyundai, and Honda, have commercially deployed their hydrogen FCEVs, and they are on the road already in Europe [9,10], Japan [11], and California [12,13]. Despite that, several barriers are slowing down these technologies spreading out [14]. Among all, the high investment costs of the hydrogen refueling infrastructures and the low hydrogen demand at end-user levels cause financial uncertainty, affecting the business development [15,16]. The chicken-and-egg problem is still present, and more hydrogen stations need to be installed, both with private efforts and government supports [17].

Actions are needed to strengthen the hydrogen station business case [18]. To address these needs and gaps, the scientific community is diligently focusing on potential systems integrations to foster and accelerate the energy transition towards a hydrogen economy [19], or investigating innovative hydrogen production processes [20,21] and enhancement of available technologies [22,23].

Renewable energies coupling with hydrogen production can enhance the matching between energy production [24] and user demand [25,26], decreasing the levelized cost of hydrogen and thus increasing the revenues [27]. The new concept of green and low-carbon hydrogen can open new paths and strategies for the energy sector decarbonization [28].

Ramadan [29] proposed a new label for sustainable energy systems, called “Green to Green (G2G)”, mainly based on hydrogen production and storage processes and their integration with renewable energies. Hydrogen is indeed one of the best available options, if coupled with green sources and uses, to decarbonize the overall chain of energy systems [30]. In this train of thought, several authors investigated the performance of hydrogen-based energy systems.

Nguyen et al. [31] have performed a techno-economic feasibility study of a hydrogen production system, focusing on large-scale facilities. Their study showed how low levelized costs of hydrogen, comparable to steam-reforming production, can be achieved from green energy sources if the demand increases and the facilities boost their size. Schnuelle et al. [32] investigated the coupling between photovoltaic systems and Proton Exchange Membrane (PEM) and Alkaline electrolyzers, providing dynamic modeling of the individual systems and of their integration. The authors proposed and analyzed several energy Key Performance Indicators (KPIs), used also for economic analysis, showing attractive financial results, such as a competitive net production cost of hydrogen of 4.33 €/kg. Significant results have been obtained also by Temiz and Dincer [33], who analyzed the energy and economic performance of the integration of a thermochemical hydrogen production process, powered by a concentrated solar system, and integrated with geothermal power plants and thermal energy storage systems. The analyses showed a cost of hydrogen of 2.84 $/kg. Chrysochoidis-Antsos et al. [34] analyzed the potential integration between wind farms and existing hydrogen refueling stations, in the Netherlands, highlighting that almost 5% of the existing stations can be locally integrated with the installation of wind turbines, to produce green hydrogen. Dagdougui et al. [35] performed an optimization analysis for a network of green hydrogen refueling infrastructures, investigating the energy flows concerning the production and the demand nodes. The authors have then marked how the analyzed system found its optimal configuration with an additional hydrogen industrial market.

Nistor et al. [36] proposed a comprehensive modeling tool to analyze a hydrogen fuelling station from a technical and economic point of view. The model has been applied to a case study in the UK, called Island Hydrogen, revealing hydrogen as a cost alternative to petrol. Nicita et al. [37] proposed a comprehensive technical and economic tool, to investigate the performance of a solar-hydrogen production facility, and its business case, analyzing several potential sources of revenues: hydrogen as medical/technical gas and oxygen selling. The analysis has shown how a small size green hydrogen production system can be profitable if multiple sources of revenues are possible. Cavana and Leone [38] evaluated the potentialities of a market interconnection between Europe and North Africa to build a more resilient and reliable hydrogen supply chain. More in detail, the authors analyzed different hydrogen blending scenarios in the natural gas grid, to size hydrogen production facilities operating via water electrolysis systems, by minimizing the compression levels in hydrogen storage.

The critical operation of hydrogen fueling stations in the first years of hydrogen economy development and maturity in California has been analyzed by Samuelsen et al. [39]. The authors provided and shared interesting data on refueling profiles during different days, evaluating how the different refueling profiles have an important impact on the station design and on the cost of hydrogen to the driver.

Different reliability challenges are indeed important, including the performance of hydrogen compressors and hydrogen pre-cooling units. Some examples of recent research trends dealing with component investigations are: Ligen et al. [40], who investigated the performance of hydrogen booster compressors, Gkanas et al. [41], who proposed a new station design with dual-stage metal hydride hydrogen compressors, and Chen et al. [42], who analyzed the performance of novel cooling systems, based on vortex tubes.

Among the different hydrogen-based applications, power-to-gas-related technologies could also generate new sources of revenues [43], creating a bridge between the natural gas grid and the electricity distribution grid [44,45]. Nastasi et al. [46] have highlighted how “interconnection between electricity, heat and transport sector” is needed, and their work has investigated the great potentiality of Power-to-Hydrogen enabling further business case for power-to-heat (P2H), analyzing several urban energy scenarios. Potentially, the produced hydrogen can be blended with Natural Gas (NG), being used in conventional technologies but operating with lower emissions [47]. This

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option could be a key enabler for those applications where a new installation could be hampered by the need to preserve the heritage, such as in Historical Centres and Museums [48]. It is indeed noticeable how Power-to-Gas applications (P2G) within hydrogen technologies could guarantee flexibility, partial energy independence, avoiding the issues related to energy price fluctuations and shifts as well CO_2 emission reductions, above all for distributed energy systems, such as energy hub, industrial areas and smart-grid [49]. Robinius et al. [50] investigated the possibility to access a new potential market for Power-to-Gas by installing electrolyzers in substitutions of energy network expansions by means of cables, guaranteeing the same voltage level. As a result of their analysis, the authors marked how the electrolyzer full load operation and other customers for hydrogen selling can meet and justify the higher electrolyzer investment cost. Another potential hydrogen end-user is within stationary electricity production and cogeneration (CHP) applications [51]. Calise et al. [52] have analyzed a green energy production facility and a fuel cell-based power generation system, to meet electrical and thermal demand. A sensitive analysis has been carried out, highlighting how a fuel cell nominal power of 100 kW resulted to be the optimal size to balance cost and revenues. Özgür and Yakaryılmaz [53] proposed a comprehensive review on Proton Exchange Membrane (PEM) based CHP systems, including an exergy and energy analysis identifying the most important operating parameters. Boait and Greenough [54] investigated the role of PEM CHP systems in the UK, comparing them with other technologies, such as engine-based CHP applications. Results have marked the great potential of such systems in terms of heat generated and electricity produced. A more innovative and disruptive concept for multiple-energy generation systems is the so-called “Power-to-H3”, recently introduced by van der Roest et al. [55]. Multi-generation systems based on hydrogen technologies are indeed considered as smart and innovative energy systems, which can potentially power the society of the future, from a sustainable production [56] to a smart final utilization [57].

Urban mobility and car-sharing programs can also increase station capacity usage [58]. Existing hydrogen stations can deliver hydrogen for urban or private fleets [59], as well as for light-duty applications in urban environments, such as bicycles [60], or within large warehouses, with material handling vehicles [61]. The current technologies are still responsible for high pollution and emissions, above all in crowded and touristic places [62,63], and hydrogen technologies could represent a faster way to decarbonize road transport [64]. This new approach of analyzing Mobility and Energy systems as two inter-connected hubs is rapidly gaining credits [65], above all within the innovative concept of Smart Energy City [66]. Considering the emergent trend of the Smart City [67], where transportation is gaining more and more the connotation of service, a digital communication between hydrogen production and hydrogen load could be a dynamic enabler to address the common static asset of the hydrogen infrastructure. Dispenza et al. [68] proposed an in-depth analysis of the first Italian hydrogen refueling station for hydrogen buses, seen within a Smart City concept to fuel a hybrid electric fuel cell minibus, an electric minivan, and two fuel cell electric bicycles. Apostolou et al. [69] investigated the integration of small light-duty mobility hydrogen-based, such as hydrogen bicycles, and their refueling process and integration with a hydrogen station, with a PEM on-site production unit. Caponi et al. [70] investigated the performance of a hydrogen fueling station serving heavy-duty mobility, filling heavy-duty buses. The authors provided a 0D model to assess the thermodynamic performance of hydrogen refueling processes, validated with experimental data, by meeting the requirements of SAE protocols [71,72]. Other authors investigated the refueling process performance, such as Chaet et al. [73], proposed innovative and novel hydrogen fueling protocol standard, to achieve a better flexibility and a more versatile application, and Liu et al. [74] who analyzed fast-refueling process for on-board storage.

Apostolu [75] presented a comprehensive investigation on hydrogen-based mobility via fuel-cell electric bicycle under low-pressure hydrogen storage. The author proposed a methodology to analyze during the experiments the energy performance of the bicycle in different routes, by analyzing also the results of different questionnaires provided to the bicycle users. Finally, an economic investigation was performed, assessing the refueling cost per km of such technologies.

Carlos Fúnez Guerra et al. [76] analyzed a heavy-duty mobility scenario, based on hydrogen trains and hydrogen fueling stations, by considering on-site hydrogen production via water electrolysis. The authors carried out a comprehensive techno-economical investigation, and the analyses showed an interesting market potential in terms of net present value, return of the investment, and internal rate of return, as well as with important carbon dioxide savings and marked energy performance.

As a new emergent trend, Vehicle-to-Grid options offer a new concept of intelligent and energy-active mobility. Cao and Alanne [77] proposed an innovative integration between zero-emission buildings with FCEVs, under different energy market scenarios. Their investigated system was also equipped with an electrolyzer, to produce hydrogen for the vehicle/building needs. Kovač et al. [78] investigated the effect of thermal insulation for on-site hydrogen production and refueling station, for an existing facility in Croatia, finding interesting results: 10 °C of temperature increase could shorten the life of electrical-related parts by about 50%, and identifying as optimal working temperature 25 °C in summer operation and 16 °C in winter operation.

Among the several research deliverables the scientific literature offers, different aspects relating to hydrogen infrastructures, both for facilities for production and storage, as well as for dispensing, have previously been analyzed, but there is still a lack of an overall investigation that could lead to an important uncertainty and to under-estimate the real energy demand, as well as affecting the technical-economic investigations for a comprehensive and potential business case.

In this train of thought, to address this research gap and to give a contribution to the scientific community, this paper proposes an innovative energy system based on a hydrogen station, as the core of a smart energy production center. In fact, in view of a future expansion of hydrogen technologies, refueling stations will be used more and more in a Smart Energy Grid, where various forms of energy are stored as hydrogen gas. The proposed research is focused on further developments and integration of hydrogen refueling stations within a more comprehensive energy system. In particular, on

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the potential and the performance of a hydrogen refueling station in a process of energy integration with different hydrogen end-user applications. The investigations will then focus on hydrogen mobility and fuel cell-based poly-generation systems. These technologies are indeed thought to be distributed in the areas adjacent to the refueling station, ad-hoc designed for these applications, to increase the capacity factor of the infrastructure itself, allowing the integration of the investigated technologies with the hydrogen refueling station, towards an innovative and more comprehensive concept of “Multi-modular Hydrogen Energy Station”, where the facility is conceptualized to provide hydrogen for multiple applications rather than just light-duty vehicles, transferring the results to several potential hydrogen end-user levels. In fact, the hydrogen station energy flows and business case are strictly dependent on the utilization factor of the station, i.e. on how many vehicles the station can refuel daily. This utilization factor, rather than being conditioned by the nominal capacity to refuel a certain daily quantity of vehicles, and therefore to have an upper maximum limit, is conditioned by the scarce presence of hydrogen vehicles in circulation. It seems realistic to think that, in view of a future expansion of the national park of hydrogen-electric vehicles, in the years to come, the refueling stations will be used more and more, to move towards the “Hydrogen Economy”, that is a hydrogen-based economy, which envisages a type of economic system where various forms of energy are stored in the form of hydrogen for its applications in several energy sectors.

This newly proposed concept considers a hydrogen station as a multi-service facility, by integrating several applications, such as Hydrogen-to-Power-and-Heat, Hydrogen-to-High-Pressure-End-Users (Mobility and Storage), and Hydrogen-to-Low-Pressure End Users (Mobility and Cogeneration). As a novelty, this paper aims to advance the current state of the art in this direction by performing a mathematical model and tool that focuses on the several components in hydrogen infrastructure, contributing to the understanding and exploiting this disruptive technology for the production and storage of clean energy. Numerical models are then ad-hoc developed to simulate the novel concept of hydrogen station as a multi-service hydrogen infrastructure with an on-site production unit via water electrolysis, storing and dispensing hydrogen at different pressure levels. Therefore, as a novelty, this paper presents numerical modeling of hydrogen stations as part of multi-service infrastructure with on-site electrolytic production with storage and dispensing at multiple pressures.

In this paper, a future scenario has been indeed investigated for a hydrogen refueling station, by means of a mathematical model ad hoc built-in Matlab/Simulink environment. A greater number of vehicles and hydrogen transport systems with fuel cell powertrain, supported by the installation of additional hydrogen technologies located in the areas adjacent to the station for the production of electric/thermal energy, will allow greater use of the station itself.

A main station is considered as the scenario for a case-study analysis, with a station capacity of up to 360 kg of hydrogen daily generated, located close to a University Campus, namely the University of Calabria, in Southern Italy (IT). Fuel cell electric vehicles and a light-duty vehicle fleet, such as forklifts and bikes, will be considered as part of the hydrogen load, within the Campus mobility. A combined heat and power system, based on fuel cell technology, will be adopted to satisfy the electric/thermal partial needs of the Campus.

The performance of the system is presented and investigated, including technical and economic analysis, to show the potentialities of the integration of a hydrogen refueling station and mobility into a more comprehensive energy system.

Numerical modeling description

Hydrogen station – power-to-hydrogen

A hydrogen station is usually composed of a production and storage area, and a dispensing zone, as shown in Fig. 1.

An Alkaline electrolyzer has been considered for hydrogen production. The authors have already developed, implemented, and validated a zero-dimensional electrolysis model following a multi-physics and dynamic approach. The model has been already widely compared with the existing polarization curve and company datasheet [79]. Then the system operation has been deeply investigated and seven energy parameters have been validated with experimental data. The model is scalable and it has already been compared with different sizes of existing electrolyzers, showing a good match with real data [80].

For a summary reason, only main equations and main model operation traits will be reported.

The system energy balance is ruled by Equation (1), where the main energy-consuming components are the Alkaline electrolyzer, with the stack energy consumption $E_{j,\ el}$, and its related auxiliary equipment, $E_{j,aux}$, the storage compressor, $E_{\ j,comp}$, and, when needed, the booster units, $E_{\ j,booster}$, and the hydrogen chiller, $E_{\ j,cool}$. The overall energy demand is met by powering the hydrogen station with energy coming from the national grid, $E_{j,supplied}$.

$$E_{j,\ el} + E_{j,aux} + E_{\ j,comp} + E_{\ j,booster} + E_{\ j,cool} = E_{j,supplied} \tag{1}$$

Considering a daily operation, the energy consumption can be calculated and integrated from the system power, reported in Equation (2), for a daily operation (86,400 s).

$$\mathrm{E_i} = \frac{\int_0^{86400} \mathrm{W_i}\,dt}{3.6}\,[kWh\,/\,day] \tag{2}$$

Hydrogen production and the electrolyzer power depend on the operational current (I), influenced by Faraday's efficiency, $\eta_{F,el}$, as reported in Equation (3), where N_c is the number of series-connected cells, and on the electrolyzer cell voltage, U_c, including also the over-voltages, calculated via a semi-empirical correlation. A high-efficiency operation has been analyzed and found when the stack operates with a current between 100 A and 135 A, thus the current setpoint and number of cells are chosen within the high-performance range [79]. Faraday Efficiency has been modeled with interpolation as a function of stack current I, retrieved from experimental data.

$$\mathrm{W}_{j,\ el} = \mathrm{N_c} \cdot I \cdot U_c = \left(\dot{m}_{H2,el} \cdot \frac{z \cdot F}{\eta_{F,el} \cdot \mathrm{MW}} \right) \cdot U_c \tag{3}$$

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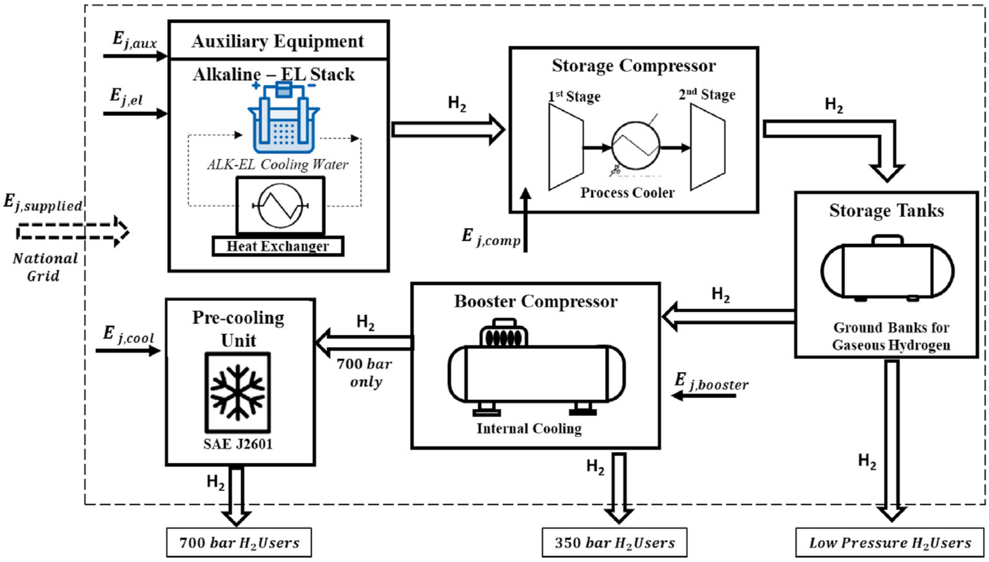

Fig. 1 – Hydrogen station scheme.

Since the electrolyzer voltage and over-voltages are affected by the operating temperature, a thermal energy balance has to be solved for the electrolyzer system, as shown in Equation (4). The chemical reaction releases heat, $\dot{Q}_{gen}$, which has to be disposed of to assure a uniform temperature operation. Thus part of the heat transfer is transferred to the external environment via convective and conductive phenomena, $\dot{Q}_{loss.el}$, while the cooling system takes care of the remaining part, $\dot{Q}_{cool,el}$.

$$\dot{Q}_{gen,el} - \dot{Q}_{loss.el} - \dot{Q}_{cool,el} - C_t \frac{dT_{el}}{dt} = 0 \tag{4}$$

The energy consumption of the ancillary system, $W_{j,aux}$ (cooling fan, security instrument, etc.), needs to be calculated to calculate the overall system power, and it is obtained by means of a fitting curve from stack power experimental data and system power [79].

A hydrogen station layout normally includes the presence of the first stage of compression, storage, the second stage of compression, cooling systems, and dispenser [81]. The proposed station layout includes a first step of compression up to 200 bar, in order to guarantee a storage level for the hydrogen bicycles and hydrogen fuel cells. The authors have already presented and deeply discussed a mathematical model concerning the whole subsystem of a storage compressor, including its energy performance and required cooling balance of the plant [80,82]. For summary reasons, it will not be presented again, but it has been used to investigate the performance of the considered system.

Since Fuel Cell Electric Vehicles (FCEVs) require 700 bar dispensing processes, and forklifts require 350 bar compressed hydrogen, a compression block has to be considered in the station layout, integrated also with a hydrogen pre-cooling unit to perform a fast and safe 700 bar fuelling process [83]. For the purposes of this paper, the high-pressure compression (up to 700 bar) and the dispensing process are considered to operate and require a specific energy consumption of 2.25 kWh/kg [84]. The pre-cooling unit is considered to add an energy rate of 1.40 kWh/kg [85].

Based on a previous authors' investigation [86], a hydrogen loss percentage of 2% has been included, to simulate a real hydrogen station operation, by taking into account dispenser rebooting and buffer tank de-fueling, losses during a refueling process, hydrogen purification, and purge procedure during the electrolyzer operation.

Simulating a dynamic operation of the hydrogen infrastructure, the model takes into account the station energy consumption and the overall system efficiency since they are the main parameters that can affect the advanced hydrogen mobility system.

Hydrogen-to-power-and-heat

As already discussed above, the innovative proposed energy system needs to meet also a power and heat demand for the Campus. Data on heating and electricity of a student housing building have been retrieved from Asmar and Tilton's analysis on Arizona State University's innovative student housing buildings [87]. The building considered in the present paper is characterized by occupancy sensors and shaded windows, “including dormitories as well as laundry rooms, study areas, kitchens, a dining hall, etc”. The energy intensity results have been re-scaled to a 5400 m^2 building case study and reported in Fig. 2. The maximum electric power has been considered to be 60 kW_e, and the heat demand requires hot water at 65 °C. An hour distribution has been included, separated in “Peak” and “Off-Peak” hours, in accordance with the Italian bi-hours tariffs, shown in Fig. 3, with a load distribution of 35% within the peak hours, and the remaining demand within the off-peak hours.

The cogeneration unit is a 5-multiple hydrogen PEM fuel cells, whose single unit performance is listed in Table 1. Efficiencies have been extrapolated from the current performance of high-temperature PEM fuel cell systems, reported by Hydrogen Europe [88].

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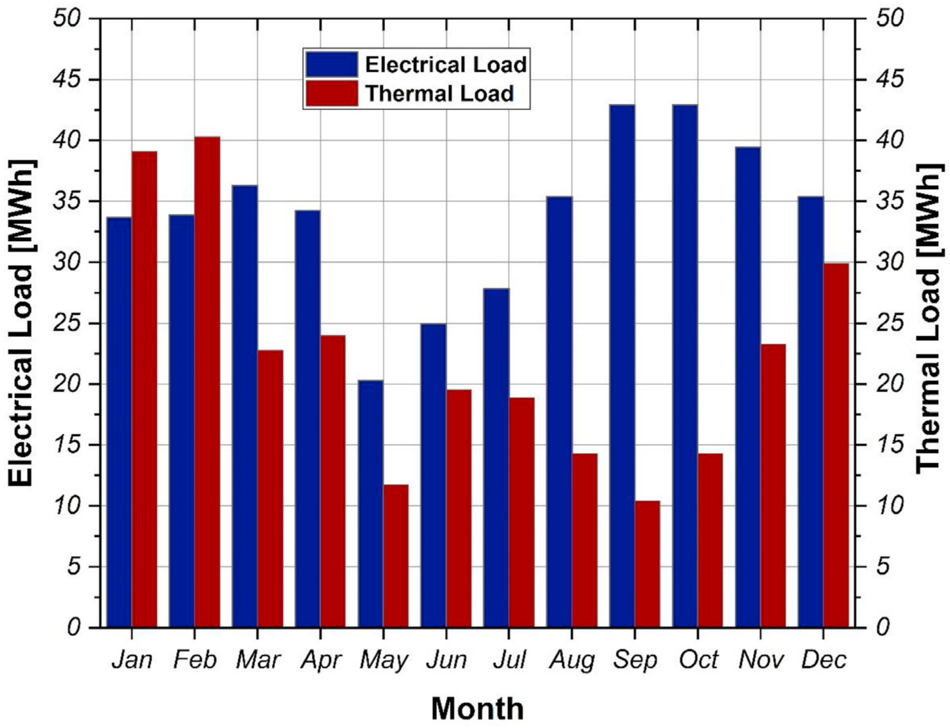

Fig. 2 – Monthly energy demand for student housing.

The plant scheme is shown in Fig. 4. The fuel cell system operates with the supplied hydrogen and external air, producing electricity and heat. The electrical output of the fuel cell stack is in direct current, and a power converter is needed to power the electrical loads with alternate current and voltage. The produced heat is recovered thanks to an external heat exchanger, by generating hot water at 65 °C.

The PEM fuel cell system (FC) is considered to operate at nominal power, as shown in Equation (5). The annual energy is indeed calculated through Equation (6), and it is composed of two main rates: the electrical energy supplied to the utilities, E_{CHP}, required by the load, and the energy rate in surplus, E_{sold}, which is sold to the national electric grid.

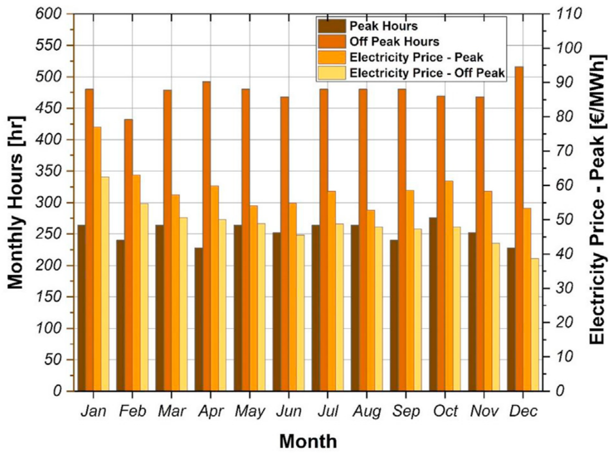

Fig. 3 – Load hourly distribution and national electricity price, according to the Italian tariffs.

Table 1 – PEM fuel cell performance.

Parameter	Value
Net Electric Power [kW_e]	10
Electric Efficiency [%]	45
Total Efficiency [%]	92
Hydrogen LHV [kWh/kg]	33.33

$$W_{FC} = W_{FC,nom} \quad (5)$$

$$E_{FC} = \frac{\int_0^{86400} W_{FC} dt}{3.6} = E_{CHP} + E_{sold} \quad (6)$$

The amount of hydrogen required by the system is as a function of the operating power, W_{FC}, and the hydrogen lower heating value, LHV. The hydrogen flow rate is calculated as shown in Equation (7), including the energy rates belonging to the fuel cell electrochemistry, $\eta_{e,FC}$, to the losses on the power converter, $\eta_{DC/AC}$, and to the parasitic currents, via the adoption of the Faraday efficiency, $\eta_{F,FC}$.

$$\dot{m}_{H2,FC} = \frac{W_{FC}}{\eta_{e,FC} \cdot \eta_{DC/AC} \cdot \eta_{F,FC} \cdot LHV} \quad (7)$$

The heat generated by the fuel cell system is transferred to the hot water through a heat exchanger. The losses generated within the heat recovery unit are included in the calculation by considering the heat exchange efficiency. Other losses, included in the calculation of the heat generated by the fuel cell cogeneration unit shown in Equation (8), account for the

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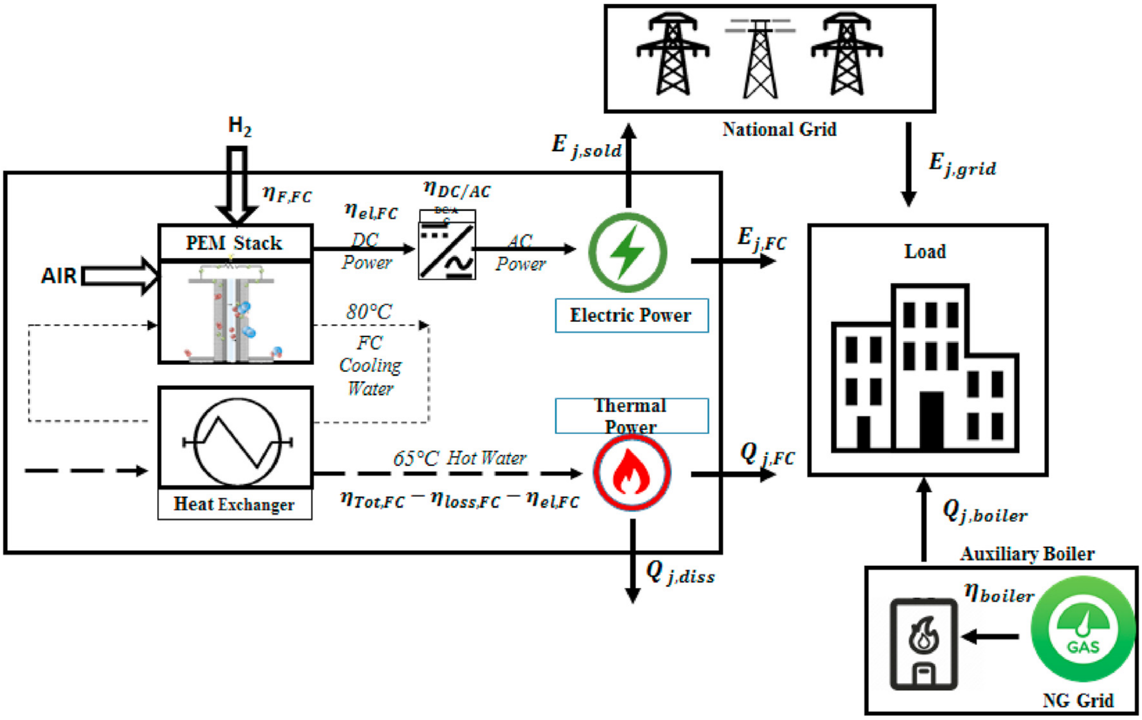

Fig. 4 – PEM fuel cell cogeneration plant scheme.

thermal dispersion on the fuel cell casing and on the fuel cell stack electrochemistry.

The overall amount of thermal energy produced during the year is then calculated through Equation (9). Once generated, the thermal energy is directly supplied to the load, or dissipated when not needed.

$$\dot{Q}_{FC} = \eta_{HE} \cdot \dot{m}_{H2,FC} \cdot LHV \cdot [\eta_{Tot,FC} - \eta_{loss,FC} - \eta_{el,FC}] \tag{8}$$

$$Q_{FC} = \frac{\int_0^{86400} \dot{Q}_{FC}\, dt}{3.6} = Q_{CHP} + Q_{diss} \tag{9}$$

The criteria of energy shares between the grid, the load, and the CHP unit are established by solving the two hourly energy balance equations, Equation (10) and Equation (11), for the electrical area and the thermal area. The electrical energy balance involves the FC CHP system, $E_{j,\,FC}$, the energy overproduced and sold to the national grid, $E_{j,sold}$, the energy required by the electrical load, $E_{j,L}$, and the energy supplied by the national grid, $E_{j,grid}$. The thermal balance includes the thermal energy produced by the cogeneration unit, $Q_{j,\,FC}$, the thermal load, $Q_{j,L}$, the energy supplied by the auxiliary boiler, $Q_{j,boiler}$, when needed, and the thermal energy dissipated if the CHP unit is overproducing, $Q_{j,diss}$.

$$E_{j,\,FC} - E_{j,L} - E_{j,sold} + E_{j,grid} = 0 \tag{10}$$

$$Q_{j,\,FC} - Q_{j,L} - Q_{j,diss} + Q_{j,boiler} = 0 \tag{11}$$

Hydrogen-to-mobility

A hydrogen mobility network has been proposed and then investigated in the Campus closer areas. Particularly, a fuel cell hydrogen fleet of 41 vehicles is included in the analysis, as the main core of the mobility. For students and campus facilities, 43 bicycles have been considered, while for the campus warehouses and laboratories, 28 fuel cell forklifts work as material handling machines. Fuel Cell Electric Vehicles (FCEVs) require 700 bar dispensing processes, forklifts require 350 bar compressed hydrogen (CGH_2), while hydrogen bicycles require 30 bar for the metal hydride storage (MH). Table 2 reports the hydrogen vehicles' main features, with the hydrogen fuel economy and the amount of stored hydrogen for each vehicle typology.

Hydrogen bicycles are refueled by employing a double-stage pressure reduction, directly drawing hydrogen from the main storage tanks. The valve behavior can be thermodynamically modeled via an isenthalpic process, as shown in Equation (12), by considering the change in pressure and the negative Joule-Thompson coefficient, ensuring that overheating phenomena and temperature increase over 80 °C do not occur. Hydrogen real gas equation has been adopted and reported in Equation (13), retrieved from NIST Database on gas thermodynamics [94]. The same process is considered to be used to supply hydrogen to the CHP FC system.

Table 2 – PEM fuel cell vehicles.

Parameter	Fuel Cell Car [89,90]	Fuel Cell Forklift [91,92]	Hydrogen Bicycles [93]
Hydrogen Demand Percentage [%]	80	19.50	0.5
Storage [–]	CGH_2	CGH_2	MH
Store Hydrogen [kg]	5	1.8	0.03
Fuel Economy	100 km/kg	1.8 shift/full tank	1.35 km/g

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$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_h \text{ when } h_{in}(T_{in},\ p_{in}) = h_{out}(T_{out},\ p_{out}) \tag{12}$$

$$\rho_{H_2} = \frac{p_{H_2}}{R_g T_{H_2}\left(1+\ \alpha \frac{p_{H_2}}{T_{H_2}}\right)} \tag{13}$$

Hydrogen-based forklifts require hydrogen at 350 bar, and a further stage of compression is needed. The compressor model has been already presented and discussed in the "Hydrogen Station – Power-to-Hydrogen" Section. Higher pressure is needed when an FCEV has to be fueled, up to 700 bar, and the hydrogen flow must be cooled down to −40 °C in a pre-cooling unit (Hydrogen Chiller).

Economic analysis

To analyze the proposed layout from an economic perspective, the investigation has been divided into two steps: determination of the hydrogen price (through the Levelized Cost of Hydrogen Method, LCOH), and study of economic key indicators (Net Present Value - NPV, Return on Investment – ROI, and Pay-back Period - PBP).

To calculate the PBP, Equation (14) has been applied, identifying the year when the cumulated yearly cash flows of the business case, YCF_k, defined as revenues minus costs, with a general inflation rate g, considered 3%, equals the initial investments, I_o.

$$\sum_{k=1}^{n} \frac{YCF_k \cdot (1+g)^k}{(1+i)^k} = I_o \tag{14}$$

The return-on-investment (ROI) is calculated via Equation (15), assessing the potential benefits of the business case study compared to the overall initial investment. A_k represents the depreciation of the year k, and it corresponds to the sum of the depreciation of the r components of the energy system, calculated as a yearly fixed rate and included each year for the lifespan n_i of the corresponding component, i, as shown in Equation (16).

$$ROI = \frac{\left[\frac{1}{n} \cdot \sum_{k=1}^{n} (YCF_k - A_k)\right]}{I_o} \tag{15}$$

$$A_k = \sum_{i}^{r} \frac{C_{capex,k}}{n_i} \tag{16}$$

The LCOH method [95] has been applied considering the station investment costs and operation and maintenance rates, divided by the hydrogen annual production, as shown in Equation (17). The investment costs need to be annualized by means of the discount rate, i, considered with a value of 7% for the purposes of this analysis, for the whole system lifespan, set to 20 years.

$$LCOH = \frac{C_{capex} \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} + C_{opex}}{m_{H_2}} \tag{17}$$

The operating and maintenance costs, besides the component maintenance services, include also the annual electricity cost, c_e, and the natural gas supply cost, c_{NG} according to the Italian tariffs and fees [96], as well as the annual water cost, $c_{w,el}$, retrieved from an Italian Water Management Company, for industrial purposes [97].

Table 3 shows the capital expenditures (CAPEX) and the operational expenditures (OPEX) for each system component.

For the PEM Cogeneration plant, economic data from State of the Art Mid-Size commercial units have been taken into account and listed in Table 4. A Capex of 425 k€ has been considered as capital cost, with a 10-years lifetime, 97% of plant reliability, and 75€/MWh for the operation costs.

The costs are then defined as in Equation (18), taking into account the electricity bought from the national grid, the cost of the natural gas supply to operate the auxiliary boiler, the cost of the water required by the electrolysis process, the cost of hydrogen (produced by the station and then supplied to the FC), the capital expenditures and the operational expenditures of the systems, and the replacement costs.

$$C_k = c_e \cdot E_{grid,k} + c_{NG} \cdot \frac{Q_{boiler,k}}{\eta_{boiler} \cdot \rho_{NG} \cdot LHV_{NG}} + c_{w,el} \cdot \frac{\dot{m}_{w,el,k}}{\rho_w} + c_{H_2} \cdot m_{H_2FC,k} + \sum_{i}^{r} (C_{capex,k} + C_{opex,k}) + \sum_{i}^{d} C_{rep,k} \tag{18}$$

The revenues related to the investigated business case are proportional to the electricity sold to the national grid, E_{sold}, the hydrogen dispensed to the mobility network, $m_{H_2,disp,k}$ and to the cogeneration system, $m_{H_2,\ FC,k}$, as shown in Equation (19). Among the other revenues, particular focus has to be paid to the avoided costs, AC_k, described in Equation (20) and Equation (21). The main rates of the avoided costs are the savings related to the energy produced by the CHP unit, and the avoided natural gas costs, thanks to the thermal energy supplied by the PEM cogeneration system. Under specific circumstances, two more benefits can be included: tax reduction and the acquisition of Energy Efficiency Credits. These conditions are defined by specific values of two parameters: the primary-energy-saving index (PES) and the global efficiency, η_g.

$$R_k = p_e \cdot E_{sold} + p_{H_2,disp} \cdot m_{H_2,disp,k} + p_{H_2,FC,k} \cdot m_{H_2,\ FC,k} + AC_k \tag{19}$$

$$if\ PES < 0 \cdot \eta_g < 0.75\ AC = c_e \cdot E_{CHP} + (c_{NG} - tax) \cdot \frac{Q_{CHP}}{\eta_{boiler} \cdot \rho_{NG} \cdot LHV_{NG}} \tag{20}$$

$$if\ PES > 0 \cdot \eta_g > 0.75\ AC = c_e \cdot E_{CHP} + (c_{NG} + tax) \cdot \frac{Q_{boiler}}{\eta_{boiler} \cdot \rho_{NG} \cdot LHV_{NG}} + 0.086 \cdot c_{EEC} \cdot K \cdot \left(\frac{Q_{CHP}}{\eta_{ref,th}} + \frac{E_{CHP}}{\eta_{ref,e}} - F_{CHP}\right) \tag{21}$$

The primary energy-saving index (PES) accounts for potential benefits and the accreditation for a cogeneration power plant operating with high energy efficiency (CAR) [105]. It is defined as in Equation (22), and the operation of the CHP unit is defined as "high efficient" if the resulting PES value is at least 10% or, in the case of micro-cogeneration units, if it assumes any positive value [106]. The regulation is ruled by the Italian by the Directive 2004/8/CE. Another important

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Table 3 – Hydrogen station – equipment and costs.

Equipment and Cost Action	Capital Expenditures CAPEX [k€]	Operational Expenditures - OPEX [%]	Lifetime [yr]
Alkaline Electrolyser [98]	$1.2 \cdot W_{el}$	4	20
Water Purification System	$1.2/m^3/day$	1	20
Storage Compressor [99]	$40.035 \cdot W_c^{0.6038}$	2	15
Main Storage Tanks [100]	$0.34306 \cdot exp^{(0.02005 \cdot p)}$	8	30
Hydrogen Boosters [100,101]	$51.901 \cdot TP^{0.65}$	2	10
Hydrogen Pre-cooling Unit [89,102]	143.475/kg H_2/min	2	15
Dispensing Unit [103]	91.810/unit	1.1	10
CE (European Certification Mark)	10	–	–
Civil Works	80	–	–
Permits	14	–	–

Table 4 – PEM cogeneration unit cost [104].

Parameter	Cost
CAPEX [k€/kW$_e$]	8.5
OPEX [€/MWh$_e$]	76
Lifetime [yr]	20
Availability [%]	97
Stack Durability [kh]	50
Permits [% of CAPEX]	14

parameter for CAR accreditation is the global efficiency, calculated with Equation (23), and it represents the overall efficiency of the cogeneration units. When its calculation assumes values over 75%, together with a positive PES value, the CHP operation can benefit from taxation reduction on the natural gas supply and the acquisition of Energy Efficiency Credits (EECs) [107], which are a tradable commodity, and then revenue for the power plant owner [108].

$$PES = \left(1 - \frac{1}{\frac{Q_{CHP}}{\eta_{conv,th} \cdot F_{CHP}} + \frac{E_{CHP}}{\eta_{conv,e} \cdot F_{CHP}}}\right) \tag{22}$$

$$\eta_g = \frac{Q_{CHP} + E_{FC}}{\dot{m}_{H2,FC} \cdot LHV} \tag{23}$$

Case study description

As mentioned above, the analyzed system is composed of a hydrogen station, as the core of a smart energy production center, where the produced hydrogen is then used in different hydrogen technologies adopted and installed nearby the station. The model can be divided into three main areas: hydrogen station system (power-to-hydrogen), hydrogen-to-power-and-heat applications, and hydrogen-to-mobility system. Fig. 5 describes the layout of the system and the main parameters of the operation.

The hydrogen production facility includes the hydrogen generation unit and the needed components to efficiently produce and store 360 kg of daily hydrogen since the present size is considered to be critical as a “main-hydrogen-station”, installed in strategic areas for sustaining a cluster organization [109,110]. The electrolyzer operates at 80 °C, and it will produce hydrogen at 10 bar. A volumetric compressor will increase the pressure up to 250 bar. The produced hydrogen will be further used for a hydrogen-based cogeneration system and multiple hydrogen mobility scenarios. For the purpose of this paper, the two areas are considered to be independent, since the station has to offer a multi-service operation for applications that require different pressure levels and system layout. For an instance, Fuel Cell Electric Vehicles require 700 bar dispensing processes, forklifts require 350 bar compressed hydrogen, while hydrogen bikes required 30 bar for metal hydride storage. Hydrogen bicycles will be fueled by means of a double-stage pressure reducer. As already discussed above, the innovative proposed energy system needs to meet also a power and heat demand for a student housing building on the Campus. A double-stage pressure reducer is derived from the main storage tanks to fulfill this purpose. When higher pressure is required, for forklifts and fuel cell electric vehicles (FCEVs), the station has to operate with higher pressure, involving hydrogen compressors and a pre-cooling unit, in accordance with Protocol SAE J2601 [111] for a safe and fast refueling process. The dispenser is equipped with a double-side hose, for a 350 fuelling process, and for a 700 bar process.

Discussion of the results

The mathematical model developed and implemented in Matlab/Simulink allowed the energy simulation of the hydrogen facility, in order to investigate the system performance. The main operating parameters of each component are presented in Table 5. The Alkaline electrolyzer resulted to have a specific power consumption of 62 kWh$_e$/kg, with an efficiency of 54%, and 19.5 kWh$_e$/kg of needed cooling energy.

The electrolyzer size, a key factor for the equipment capital expenditure, resulted to be 845 kW$_e$, requiring 0.47 Nm^3/h of water (24.5% more than the ideal condition) per kg of the produced hydrogen. The storage compressor has to process a mass flow rate of 15 kg/h, requiring 184 kWh$_e$ of cooling energy for its daily operation and achieving a peak electric power of 38 kW$_e$. The system storage capacity accounts for 360 kg per day, by considering 6 tanks, each with a volume of 2.3 m^3. All the high-pressure components (boosters, chiller, and dispensing units) have been sized to guarantee a full tank for FCEV (5 kg) in 5 min [111].

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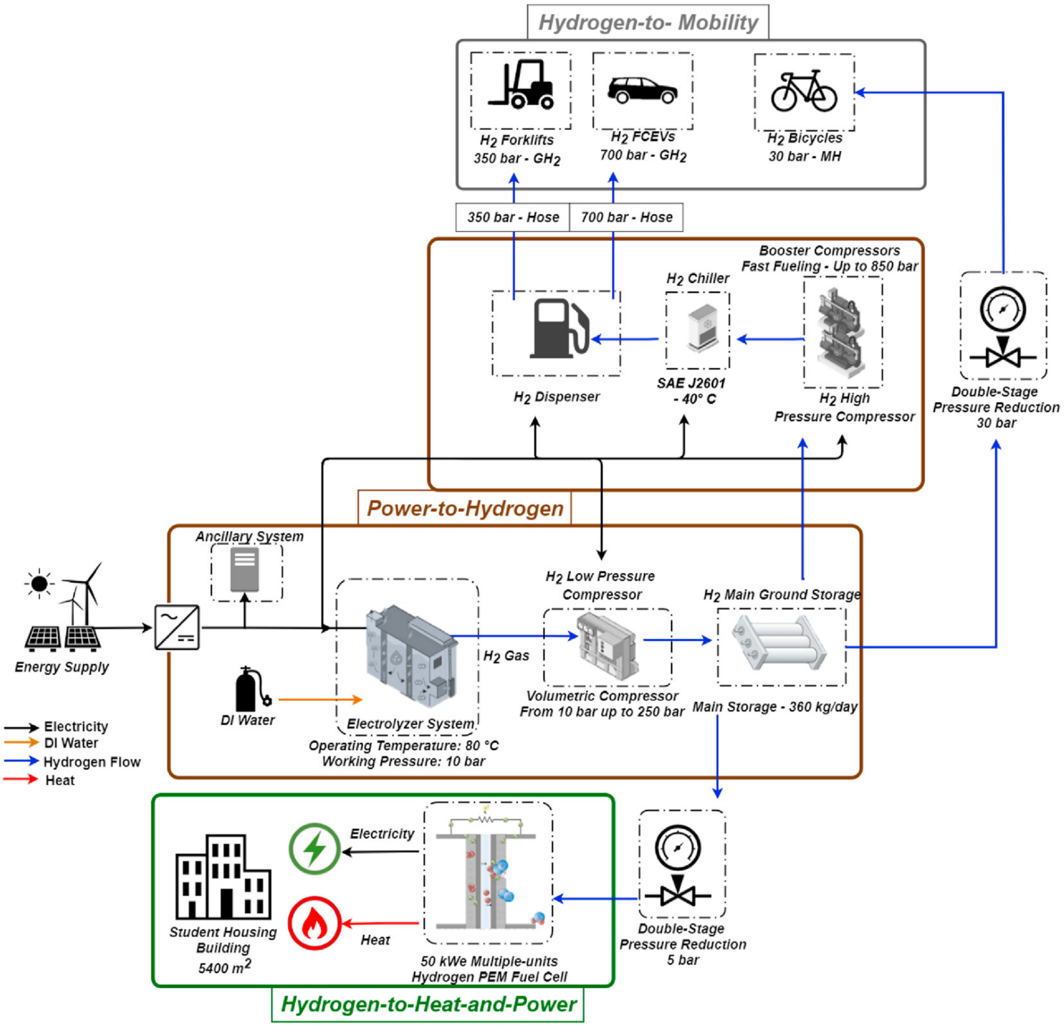

Fig. 5 – Hydrogen station layout for a poly-generation system.

Table 5 – Hydrogen station Specs.

Component	Parameter	Value	Unit of Measure
Electrolyser	Nominal Temperature	80	°C
	Operating Pressure	10	bar
	Max Power	845	kW_e
	Energy Consumption	62	kWh_e/kg
	Water Consumption	0.47	Nm^3/h
	Daily Capacity	360	kg/day
Storage Compressor	Flow Rate	15	kg/hr
	Cooling Needed	184	kWh_t
	Max Power	38	kW_e
Pressure Tanks	Volume	6 × 2.3	m^3
	Nominal Pressure	200	bar
Booster Compressor	Max Flow Rate	1	kg/min
	Energy Consumption	2.25	kWh_e
Pre-cooling Unit	Flow Rate	1	kg/min
	Energy Consumption	1.4	kWh_e
Double-hose Dispenser	Max Flow Rate	1	kg/min
	Delivery Pressure	350–700	bar

The hydrogen demand, shown in Fig. 6, is almost constant through the year, per each month, assuming a value of around 11 tons of hydrogen. The highest amount of hydrogen required by the end-users belongs to the hydrogen fleet of fuel cell electric vehicles, with a percentage of almost 60%. The second highest load is required by the cogeneration power plant, with an average hydrogen request of 24%, followed by the hydrogen forklifts, 14%, and by the hydrogen bicycles, which corresponds to the small quantities on the top portion of each bar in Fig. 6.

To satisfy the hydrogen load, the hydrogen station resulted to require a monthly energy demand ranging from 650 to 675 MWh_e, except for February, which has a lower energy demand, of about 610 MWh_e, as presented in Fig. 6. The electricity is thought to be supplied by the national energy grid. The main energy share corresponds to the production and storage process, which includes the alkaline electrolyzer operation, its balance of plant, and the storage compressor. Their consumption resulted to be around 97% of the overall station consumption. The dispensing process, both for 350 bar and 700 bar fills shares 2.5–3% of the energy request, while the

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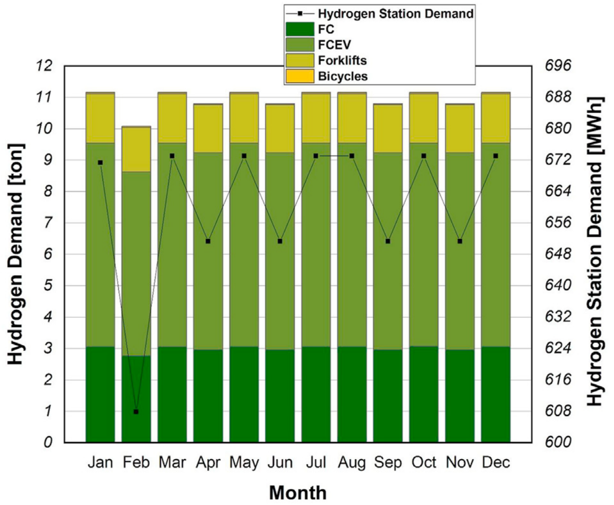

Fig. 6 – Hydrogen Station Load and Energy Consumption during the year.

pre-cooling, required only for the 700 bar refueling process, accounts for the remaining part.

The cogeneration power plant, working at fixed power 50 kW_e, meets, for most of the months, the electric load request, as shown in Fig. 7a for the Off-Peak operation, and Fig. 7b for the Peak operation. During the year, the PEM FC-based cogeneration unit produces 152 MWh_e within the peak hours and 286 MWh_e off-peak. No grid integration is indeed needed during the months of March, May, June, July, and August, as well as for the month of January. Part of electricity is sold to the national grid during these months, in a small portion (a minimum value of 0.15 MWh_e in February, and a maximum value of 17 MWh_e in May). Grid integration is needed for the off-peak hours in February (0.42 MWh_e), and for the peak hours of April (0.58 MWh_e) and December (0.98 MWh_e). September, October and November require a grid integration for the load energy request both for the peak (respectively 3, 1.2 and 1.2 MWh_e) and off-peak operation (3.9, 4.45, 2.2 MWh_e).

Fig. 8 presents the results of investigations on the thermal balance between the CHP unit and the student housing. The FC produces almost a monthly uniform thermal energy of 38 MWh_t. The thermal load is totally satisfied from March to December when the PEM FC system overproduced thermal energy, which partially has to be dissipated. The coldest months, January and February, required an integration from the auxiliary boiler, with a minimum value of 0.25 MWh_t in January, and a maximum value of 5.2 MWh_t in February.

The system sizing and the energy investigation produced the needed results for carrying out the economic analysis, where operating parameters, component sizes, and energy, water, and natural gas expenditures are needed. As described above, the financial investigation has been divided into two steps: determination of the hydrogen price, and study of economic key indicators. The Levelised Cost analysis showed an LCOH of 10.39 € per kg of hydrogen produced. Based on the current hydrogen prices comparison [112], a value of 15€/kg of hydrogen has been considered, allowing a certain margin of profit. Fig. 9 shows the results of the financial analysis, both for the hydrogen station and for the PEM cogeneration plant.

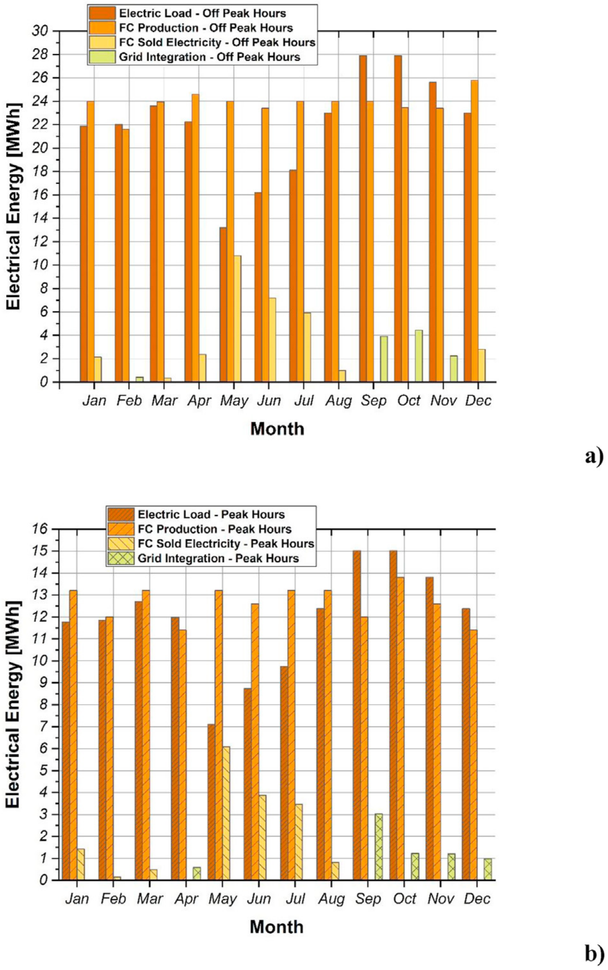

Fig. 7 – Electrical Energy Distribution during the year for the Off-Peak Hours (a) and for the Peak Hours (b).

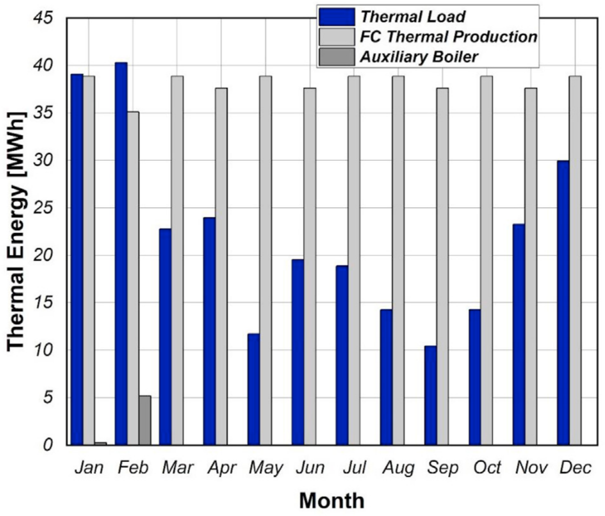

Fig. 8 – Thermal energy requested by the load, produced by the FC system, and integrated by the auxiliary boiler.

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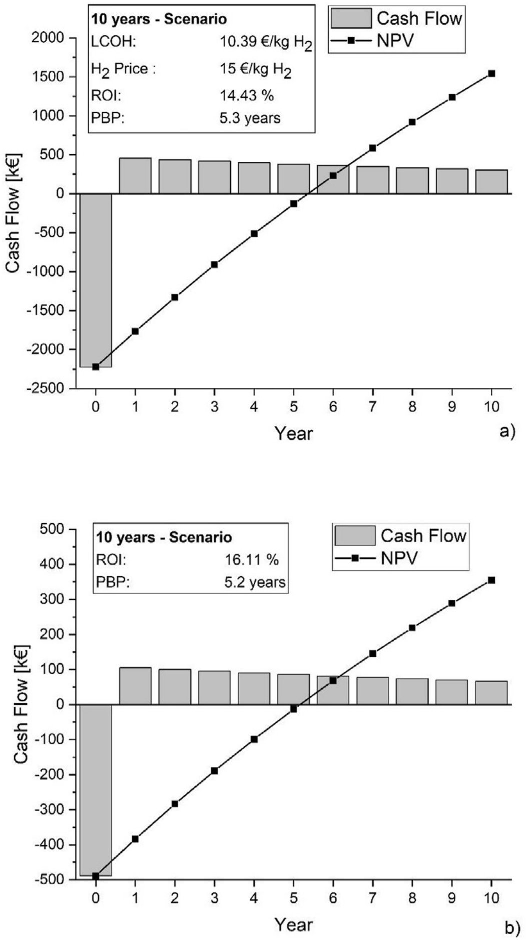

Fig. 9 – Financial forecasting for the hydrogen facility (a) and hydrogen PEM cogeneration plant (b).

The hydrogen station has been considered operating with an availability of 98%. The revenues (almost 100 k€ per year) come from the hydrogen sold for the mobility network in the Campus closer areas. Particularly, the fuel cell hydrogen fleet of 41 vehicles accounts for 80% of the revenues coming from the mobility network, followed by the 28 fuel cell forklifts (19.5%) and the 43 hydrogen bicycles (0.5%). Considering a 10-years scenario, the facility needed an initial investment of 2220 k€, resulting in a 14.43% ROI and a pay-back period of 5.3 years, with an overall NPV of 1540 k€ in 10 years.

The PEM Cogeneration plant worked at full power, with an availability of 97%. The needed investment cost for the unit resulted to be 488 k€. The hydrogen needed to run the system has been considered to directly come from the one produced by the station itself, with no-charge, since its cost is already included in the hydrogen facility analysis. The PEM unit has produced 438 MWh_e and 458 MWh_t per year, requiring on average 98 kg of daily hydrogen. Excess of the produced electricity and electricity/natural gas costs in absence of cogeneration has been considered as the facility's revenues. In the absence of cogeneration, electricity and gas needed to operate the boiler must be purchased from external entities. The cost items related to the connection to the network are neglected, as well as those related to the purchase of the boiler and the construction of the heat distribution network since the building has been considered to already exist and therefore not in the planning stage. The energy calculation has been performed on an annual basis therefore the data relating to the individual months have been analyzed in order to obtain the amount of the expenditure for the 365 days. Considering a 10-years scenario, the cogeneration facility needed an overall initial investment of almost 500 k€, resulting in a 16.11% ROI and a pay-back period of 5.2 years, with an overall NPV of € 355 k€ in 10 years.

The financial forecasts have highlighted how a greater number of vehicles and hydrogen transport systems, supported by the production of electric/thermal energy, could really allow greater use of the station itself, improving the business case itself.

Conclusion

The present paper analyzed an innovative energy system based on a hydrogen station, as the core of a smart energy production center, where the produced hydrogen is then used in different hydrogen technologies adopted and installed nearby the station. A hydrogen mobility network has been investigated in the Campus closer areas. Particularly, a fuel cell hydrogen fleet of 41 vehicles is included in the analysis, as the main core of the mobility, 43 bicycles and 28 fuel cell forklifts working as material-handling machines. The innovative proposed energy system needs to meet also a power and heat demand for a student housing 5400 m^2 building of the University Campus. The chosen cogeneration unit is a hydrogen 50 kW_e PEM.

The Levelised Cost analysis showed an LCOH of 10.39 € per kg of hydrogen produced for the hydrogen production facility, with an overall NPV of more than 1500 k€ in 10 years, a 14.43% of ROI, and 5.3 years of PBP. For the cogeneration plant, the PEM unit has produced 438 MWh_e and 458 MWh_t, requiring on average 98 kg of daily hydrogen. Its related business case analysis has shown a 16.11% of ROI and a pay-back period of 5.2 years, with an overall NPV of 355 k€ in 10 years.

The investigated performance of the system, including the technical and economic analysis, has shown the potentialities of the integration of a hydrogen refueling station and mobility into a more comprehensive energy system.

It can be concluded how hydrogen refueling stations, and hydrogen technologies for mobility, power-to-heat, and for the combined generation of electricity and heat, have been extensively investigated, through numerical models and analyses of technical/economic scenarios. These technologies were then integrated with the hydrogen refueling stations and analyzed through the simulation of various case studies. Hydrogen proved to be an efficient and powerful energy carrier.

Considering the positive results, the proposed concept of "hydrogen station evolution towards a poly-generation system" can be considered as a key step to support the energy transition and the horizontal penetration on several energy sectors. This new definition of hydrogen station enables a new role for this innovative energy system: the infrastructure can finally operate as a multi-service facility, fully exploiting hydrogen as an energy carrier in all its definition and potential applications, dispensing the on-site produced green hydrogen to serve the local and the national economy.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

A_k	Annual Depreciation [€]
AC	Avoided Cost [€]
C	Cost [€]
C_{capex}	Capital Expenditure Cost [€]
C_{opex}	Operational Expenditure Cost [€]
C_{rep}	Replacement Cost [€]
C_t	Total thermal capacity of the electrolyzer[kJ /K]
c_{EEC}	Cost for the Acquisition of Energy Efficiency Credits, 250 [€/credit]
c_e	Grid Electricity Cost [€/kWh]
c_{H_2}	Hydrogen Cost [€/kg]
c_{NG}	Natural Gas Cost [€/Nm^3]
$c_{w,el}$	Annual water cost [€/m^3]
d	Number of components requiring replacement [–]
E	Energy [kWh]
F	Faraday constant, 96485000 [Coulomb/kmol]
F_{CHP}	Energy Content of the fuel supplied to the cogeneration system [kWh]
g	General inflation rate [–]
h	Specific enthalpy [kJ/kg]
I	Direct Current [A]
I_o	Initial Investment required to run the business case [€]
i	Discount rate [–]
K	Harmonization coefficient, 1.4 [-]
k	Generic Year [–]
LHV	Hydrogen Lower Heating Value, 33.33 [kWh/kg]
LHV_{NG}	Natural Gas Lower Heating Value, 31.66 [MJ/Nm3]
m	Mass [kg]
$m_{H_2,disp}$	Dispensed Hydrogen Mass [kg]
$m_{H_2,\ FC}$	Hydrogen Mass necessary to run the fuel cell system [kg]
$\dot{m}$	Mass Flow Rate [kg/s]
$\dot{m}_{w,el,k}$	Water Mass Flow Rate required by the electrolyser [kg/s]
n	Lifespan [yr]
MW	Molecular Weight [kg/kmol]
N_c	Number of cells [–]
PES	Primary Energy Saving [–]
p	Pressure [MPa]
p_e	Electricity Price when sold to the national grid [€/kWh]
$p_{H_2,disp}$	Hydrogen Price when dispensed to the mobility system [€/kg]
$p_{H_2,FC}$	Hydrogen Price when supplied to the fuel cell system [€/kg]
Q_{boiler}	Thermal Energy supplied to the load by the auxiliary boiler [kWh]
Q_{CHP}	Thermal Energy supplied to the load by the cogeneration system [kWh]
Q_{diss}	Thermal Energy in excess and dissipated [kWh]
Q_{FC}	Thermal Energy produced by the fuel cell cogeneration system [kWh]
$\dot{Q}_{FC}$	Thermal Power produced by the fuel cell cogeneration system [W]
$\dot{Q}_{cool}$	Heat transfer rate required to cool down the electrolyzer system [W]
$\dot{Q}_{FC}$	Thermal Power produced by the fuel cell cogeneration system [W]
$\dot{Q}_{gen}$	Heat transfer rate generated by the electrolyzer chemical reaction [W]
$\dot{Q}_{loss}$	Heat transfer rate of the electrolyzer caused by external temperature [W]
R	Revenue [€]
R_g	Hydrogen gas constant, 4124.3 [J/kg K]
r	Number of equipment components of the investigated system [–]
T	Temperature [K]
TP	Compressor Maximum Throughput [kg/h]
tax	Tax rate associated to Natural Gas Purchase [€/Nm^3]
U_c	Electrolyser Cell Voltage [V]
W	Power [W]
YCF_k	Cash Flow per year [€]
z	Number of free electrons [–]

Greek

α	Hydrogen Real Gas Equation Coefficient, 1.9155e-6 [K/Pa]
ρ_{H_2}	Hydrogen Density [kg/m^3]
ρ_{NG}	Natural Gas Density [kg/Nm^3]
ρ_w	Water Density [kg/m^3]
η_{boiler}	Auxiliary Boiler Efficiency, 0.87 [-]
$\eta_{DC/AC}$	Power Converter Efficiency, 0.9 [-]
$\eta_{e,FC}$	Fuel Cell System Electrical Efficiency [–]
$\eta_{F,el}$	Electrolyser Faraday Efficiency [–]
$\eta_{F,FC}$	Fuel Cell Faraday Efficiency, 0.9 [-]
η_g	Cogeneration System Global Efficiency [–]
η_{HE}	Heat Recovery System Efficiency, 0.85 [-]
$\eta_{loss,FC}$	Fuel Cell Heat Loss on the External Case, 0.01 [-]
$\eta_{conv,e}$	Conventional Electrical Efficiency in No-CHP scenario, 0.467 [-]
$\eta_{conv,th}$	Conventional Thermal Efficiency in No-CHP scenario, 0.8 [-]
$\eta_{ref,e}$	Reference Electrical Efficiency for the Italian Scenario, 0.409 [-]
$\eta_{ref,th}$	Reference Thermal Efficiency for the Italian Scenario, 0.9 [-]
$\eta_{Tot,FC}$	Fuel Cell System Total Efficiency [–]
μ_{JT}	Joule-Thomson Coefficient [K/Pa]

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Subscript

aux	Parameter related to the electrolyzer ancillary system
boost	Parameter related to the booster compressor system
CHP	Parameter related to the cogeneration system
cool	Parameter related to the cooling system
comp	Parameter related to the storage compressor system
disp	Parameter related to the dispensing system
el	Parameter related to the electrolyzer
FC	Parameter related to the fuel cell system
grid	Parameter related to energy supplied by the national grid to the load
H_2	Parameter related to hydrogen
i	Parameter related to the generic parameter i
in	Parameter related to the inlet section
j	Parameter related to the generic hour j
k	Parameter related to the generic year k
L	Parameter related to the load
nom	Parameter related to nominal values
out	Parameter related to the outlet section
sold	Parameter related to energy sold to the national grid
stack	Parameter related to the cell stack
supplied	Parameter related to the energy supplied to the hydrogen station
system	Parameter related to the cell system

Abbreviation

CAPEX	Capital Expenditures
CGH_2	Compressed hydrogen
CHP	Cogeneration of Heat and Power
EEC	Energy Efficiency Credits
FCEV	Fuel Cell Electric Vehicle
LCOH	Levelised Cost of Hydrogen
MH	Metal hydride storage
NPV	Net Present Value
OPEX	Operational Expenditures
PEM	Polymer Electrolyte Membrane
PES	Primary Energy Saving
ROI	Return on Investment

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