Energetic and economic analysis of a stand alone photovoltaic system with hydrogen storage

C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa*, V. Varano
Department of Civil, Energetic, Environmental and Material Engineering
Mediterranea University of Reggio Calabria, Italy

*e-mail: matilde.pietrafesa@unirc.it

ABSTRACT

The study describes a stand-alone photovoltaic system in which the storage is realized using electrolytic hydrogen, converted into electricity in fuel cells. The aim of the research is the optimization of the sizing of the system elements chain (photovoltaic generator, electrolyzer, tank, fuel cell) with respect to the electric load to fulfil.

A positive annual balance between hydrogen production and consumption must be guaranteed; furthermore, energy production surplus that cannot be stored or converted into hydrogen due to batteries or tanks capacity limits must be avoided.

The energetic analysis and that of hydrogen production and consumption have been carried out on an hourly basis using the HOMER software.

The study shows that, being the load active in the evening and the system disconnected from the grid, excess energy cannot be exploited unless large tanks are used, if high gas pressures are to be avoided. Consequently, the system use in public areas or residential buildings, where visual impact generated by tanks is hardly acceptable and safety rules do not allow high gas pressures, is advisable only in grid-connected configurations. Such problems are by far reduced when a marked self consumption is present.

KEYWORDS

Renewable energy sources (RES), photovoltaic (PV), energy storage, electrolysis, hydrogen, fuel cell

1 INTRODUCTION

The new sustainable, distributed energy paradigm that should be established in the next future is mainly based on micro-generation from renewable energy sources [1], smart grids, electric mobility, energy storage and hydrogen.

Very large is the number of researches concerning the use of RES: [2] investigated whether it is possible to cost-effectively employ 100% RES to produce electricity to meet cities' loads or partial loads; [3] presents a snapshot of diverse energy topics from bioenergy and biogas, storage, district heating and carbon emissions within the framework of sustainable development, [4] contains a conceptual framework and a mathematical model is introduced to simulate the time evolution of the energy balance of energy conversion technologies in order to choose the best option; [5] reports a statistical methodology with a hierarchical cluster analysis of regional typologies according to energy consumption and deployment, and develops administrative tools to draw decisions in planning energy policy in Greece; in [6] the technological change towards cleaner energy technologies developed in Denmark is described, together with the difficulties and challenges arisen; in [7] two different shading effects on energy production of a PV generator, originated by tilted strings and projected by an adjacent tower building, have been analysed, in [8] it is discussed how to overcome some institutional barriers met when radical technological changes, such as the replacement of fossil fuel with renewable energy, are to be implemented.

Electricity production from *RES*, although characterized by a variable and unpredictable over time availability, as discussed in [9], can efficiently satisfy loads using the support of energy storage systems. Different techniques are today used to store both electric and thermal energy, making use of mechanical, electric, chemical, thermal and biological systems, the most widespread and versatile of which are presently batteries. [10] presents an analysis of financial mechanisms in support to new pumped hydropower storage projects in Croatia; [11] evaluates a thermal energy storage system, using different *Phase Change Materials*, to recover for other applications waste thermal energy released in industrial processes; [12] examines the impacts of compressed air energy storage in a pool based wholesale electricity market, [13] develops a simulation model for the optimization of an autonomous RES system for combined heat and power generation, where thermal and electrical loads are met utilizing photovoltaic-thermal panels (PVT), wind turbines, thermal and electrical storage and electric heater; in [14] a multi-objective optimization of batteries and hydrogen storage technologies for remote PV systems is presented, minimizing the total levelized cost while fulfilling consumer satisfaction; in [15] an energetic, economic and environmental analysis of two configurations of a self-sufficient system for energy production from RES and hydrogen storage is presented.

Nevertheless, one of the most environmentally sustainable methods to accumulate renewable energy is its use as a primary source for the production of electrolyte hydrogen in periods and places of excess production and the subsequent use of the gas in fuel cells for electricity generation in periods or places with demand peaks or supply shortages.

The fundamental aspects of electrolytic hydrogen and its use as energy carrier are discussed in [16]; in [17] a system aimed at hydrogen production through electrolysis from renewable source (PV, wind generators), its storage and reconversion in fuel cells is presented; in [18] the *Hydrogen Research Institute* presents a stand-alone renewable energy system based on energy storage in the form of hydrogen, where the oxygen produced by the electrolyzer during hydrogen production is also stored at high pressure to be re-utilized, after a purification and drying process, as oxidant in fuel cells in place of compressed air, increasing system performance significantly; in [19] different connections series-parallel are adopted on two main types of electrolysers, *tank cells* and *filterpress* ones.

Electrolysis of water from RES is, among processes used for hydrogen production, the only one that guarantees zero emissions into the atmosphere, being its only byproducts water and heat, thus avoiding emissions of greenhouse gases such as carbon dioxide.

Comparative studies among hydrogen production methods are reported in [20], overview of 14 hydrogen production methods and discussion of technical and economic aspects; in [21] the processes of hydrogen and electricity production, conversion and storage are compared in terms of energy and economic expenditure for each stage; in [22] solar hydrogen production methods and their current status are assessed, together with preliminary energy and exergy efficiency analyses for a photovoltaic-hydrogen/fuel cell hybrid energy system in Turkey; [23] describes the advances in hydrogen production; [24] presents, with a cradle to grave approach, a critical analysis of all the major pathways to produce and utilize hydrogen as an energy carrier to generate heat or electricity, showing that still no available pathway, irrespective of whether it uses fossil fuels, nuclear fuels, or renewable technology as the primary energy source, is as efficient as using the electric power or heat directly from any of these sources; [25] reports the main characteristics of existing processes and technological routes for hydrogen production in many countries, as well as the prominent research on its technology and processes and the trends of its economy; [26] gives an overview of the state-of-the-art on hydrogen production technologies using renewable and sustainable energy resources; [27] is a review that analyzes the industrial and emerging hydrogen production technologies; in [28] a novel CPC reactor designed for solar photocatalytic hydrogen production is evaluated.

Hydrogen can be produced either in large plants located in areas where energy from *RES* is abundant and exploitable with greater convenience, and then transported to the final use point, or through small generation units that, exploiting local renewable energy potential, produce it as close as possible to the final use point. It can exploit different domestic renewable and low-carbon resources and address multiple applications across stationary, transportation and portable power sectors. Energy is thus provided at all scales, ranging from micro-power sources for small consumer devices to multi-MW power plants.

Examples of the versatility of hydrogen plants are reported in the following articles. In [29] a new methodology is proposed to identify the optimal configuration and operation of a RES-based hydrogen supply system, integrating multiple resources for electricity generation (wind turbine, photovoltaic panels and dish-stirling power systems) and various hydrogen production technologies (water splitting using alkaline electrolyzer and biomass gasifier) in order to minimize the total annual cost; [30] presents the energetic, economic and environmental sustainability of a self-sufficient photovoltaic system for energy production in buildings, using hydrogen storage and fuel cells; [31] compares two different models of a stand-alone energy system based on renewable sources (solar irradiance and micro-hydro power) integrated with a system for hydrogen production (electrolyzer, compressed gas storage and proton exchange membrane fuel cell); [32] demonstrates the technical and economic feasibility of the on-site electricity and hydrogen production (stand-alone renewable energy system with photovoltaic arrays) connected to a microgrid, with a small battery acting as a short-term energy storage, compared to the commercial electricity from the grid and diesel gensets; in [33] an autonomous photovoltaic-based system is modelled for residential applications, integrated to an electrolyser-hydrogen storage-fuel cell subsystem to fully fulfill a varying load profile throughout the year; a stationary application is given in [34], where a system aimed at hydrogen production through electrolysis from RES (both PV and wind generators), its storage and reconversion in fuel cells is presented.

Due to its environmental sustainability and energetic performances, the scientific interest for hydrogen use as energy vector is today becoming widespread and the transition from fossil fuel to hydrogen use is more and more discussed. In [35] the global energy transition from fossil fuel to hydrogen utilization is described, together with the environmental benefits of hydrogen combustion; [36] reports a history of hydrogen economy; [37] discusses the environmental dangers of dependence on fossil fuels, presenting the history of hydrogen energy and current research toward a hydrogen-based economy, discussing the social, political, and economic difficulties in replacing current energy systems with an entirely new one; moreover it demonstrates that the environmental and health benefits would far outweigh the costs; [38] aims to provide a comprehensive coverage of the most relevant aspects related to the wider use of hydrogen in the energy system; in [39] recent developments in the production applications and storage of hydrogen, together with its environmental impacts as energy carrier are emphasized; in [40] the exigency to have an optimal transition rate to renewable energy systems with hydrogen as an energy carrier is described, to be determined through very complex models and constant monitoring and adjustment of parameters; [41] demonstrated how the benefits and sustainability of hydrogen systems can be observed using thermodynamics, life cycle assessment and exergy methods; the importance of hydrogen systems in mitigating environmental impacts, including climate change, is highlighted throughout.

Several aspects connected to hydrogen introduction into the market, such as performance, transmission and distribution, infrastructures, environment, cost, market and social indicators are in depth analysed in the literature. [42] gives an overview of the potential on multi-criteria assessment of hydrogen systems: selecting the criteria referring to performance, environment, market and social indicators, the assessment procedure and its comparison with new and renewable energy systems are presented; in [43] hydrogen performance, cost assessment and environmental impact, including the stages of storage, transmission and distribution of three different delivery pathways (by pressurized tanks, as cryogenic liquid and through gas pipelines) are undertaken comparatively; [44] proposes a sustainable hydrogen infrastructure that supports the transition towards a low-carbon transport system in the United Kingdom, the future demand of which is forecasted using a logistic diffusion model, which reaches 50% of the market share by 2070; the optimisation model combines the infrastructure elements in order to minimise its present value using a discounted cash-flow analysis; as concerns use for mobility, [45] reviews the feasibility and impacts of all stages from production to final use of hydrogen as a resource for mobility purposes, approaching technological, economic and environmental issues.

Within the frame of increasing interest toward hydrogen technology, in the present study the energetic behavior of a stand-alone PV system, aimed at satisfying the lighting needs of a parking area of the *Mediterranea* University of Reggio Calabria (Italy) has been simulated with a hourly step. Energy storage is achieved through production of electrolytic hydrogen, converted into electricity in fuel cells.

Aim of the study is the optimization of the sizing of the system elements chain (photovoltaic generator, electrolyzer, tank, fuel cell) with respect to the electric load to fulfil.

A positive annual balance between hydrogen production and consumption must be guaranteed, furthermore, both photovoltaic generator and tank have to be adequately sized not to have large PV production surplus that cannot be converted into hydrogen due to tanks or batteries capacity limits: being the system disconnected from the grid, not used surplus energy is present so that large tanks are required to avoid deep gas compression.

Being the system configuration a stand alone one, this phase must receive particular attention. In this aim the analysis explored if it is advisable using the system only for storage purposes (in absence of daily consumption and presence of large excess energy), in a public area where visual impact generated by large tanks is hardly acceptable and safety rules do not allow high gas pressures. Such problems are in fact by far reduced when a marked self consumption from PV for load satisfaction is present.

2 STRUCTURE OF THE STAND ALONE PHOTOVOLTAIC SYSTEM

A scheme of the examined plant and its components are respectively reported in Figures 1 and 2.

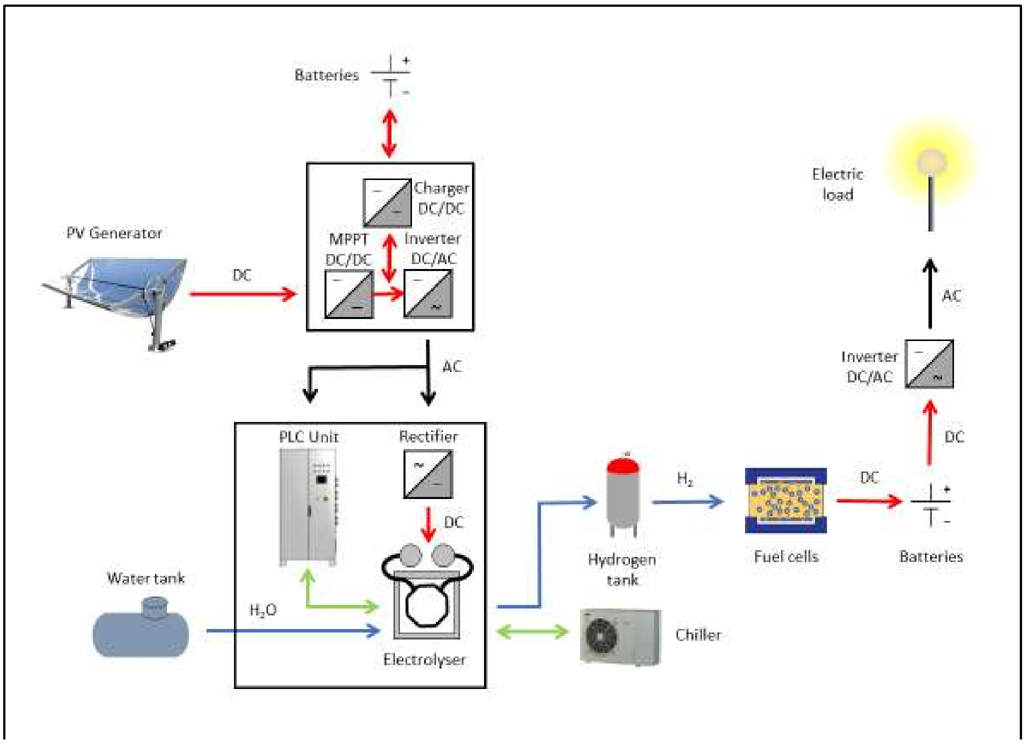


Figure 1 - Scheme of the stand alone photovoltaic plant with hydrogen storage

Figure 2 – Components of the system (electrolyser, inverter and batteries for PV production, chiller, controller, tank, fuel cells, inverter and batteries for fuel cell production)

The system consists of an electric power generation system endowed with photovoltaic panels, an inverter equipped with a battery pack, an electrolyzer for hydrogen production, a tank for its storage, a fuel cell for its conversion and production of electricity, stored in a second battery pack coupled to a second inverter to feed the load.

Its operation is as follows. The power produced by PV generator passes through an inverter for conversion into AC, necessary inlet to the electrolyser auxiliaries. It is then absorbed by the electrolyser to produce hydrogen; DC required by electrolysis is obtained inside the electrolyzer itself. A fuel cell converts the stored hydrogen into electrical energy, sending it to a second battery pack, after which a second inverter supplies energy needed to meet the load in absence of solar radiation.

2.1 Photovoltaic system

Photovoltaic concentration panels have been used, the technical characteristics of which are shown in Table 1, mounted on a biaxial solar tracker; the generator total power provided by the simulation is 9.7 kW_p.

Table 1 - Characteristics of PV panels

Concentration panels		Bi-axial solar tracker	
Type of cells	Triple-junction	Power	100 W
Optic concentrator	Fresnel lens	Zenith rotation angle	5°- 90°
Maximum power	≈ 200 Wp	Azimuth rotation angle	300°
Efficiency (η)	31,8%		
NOCT	50°C		
Temperature coefficient (β)	-0,34 %/°C		
Passive cooling through metal heatsink			

2.2 Inverter

Between the photovoltaic panels and the load, downstream of the DC panel, there is a single device that includes both a DC/DC converter, with charge regulator function for the first battery pack, Maximum Power Point Tracker (MPPT) and a three-phase DC/AC inverter, which makes alternating current available in the cabinet containing the electrolyser. DC required for its operation is supplied by a dedicated controlled rectifier.

The characteristics of the inverter are reported in Table 2.

In case of a prolonged absence of power demand by the load and of fully charged storage systems (both batteries and hydrogen tank), the inverter automatically interrupts photovoltaic generation.

Table 2. Characteristics of the inverter

Nominal power	10’000 VA
Efficiency	97.6%
DC input	720 VDC - 11 A
AC output	400 VAC - 50 Hz 15 A

2.3 Battery

Downstream the inverter a 240 V pack of 5 lithium batteries with 12 kWh total capacity is present to accumulate energy generated by PV generator. Each battery has a nominal voltage of 48 V and a nominal capacity of 50 Ah. They have reduced self discharge and maintain charge up to 6 months, with no memory effect.

2.4 Electrolyser

It is an electrochemical converter able to split the water molecule into its two components (hydrogen and oxygen), the main technical characteristics of which are reported in Table 3. Starting from demineralized water and photovoltaic energy, the electrolyser produces hydrogen during the day, which is compressed and stored in the tank and sent to the fuel cell at night.

The set (or stack) of the electrolysis cells, with a configuration of filter-press, is obtained by coupling in series a number of cells with a section assigned to obtain the desired productivity. Each cell has two electrode compartments (cathodic and anodic) in which respectively hydrogen and oxygen are generated, kept separate from the cell diaphragm, permeable to electrical charges. The produced hydrogen volume is twice that of oxygen.

Table 3. Main technical characteristics of the electrolyser

Stack capacity	2 Nm^3/h
Electric power	2 -10 kW
Operating pressure	20 bar
Operating temperature	80 °C
Amount of demineralized water	1.9 l/h
Fixed residue	max 2 mg/l
Purity of stored hydrogen	99,99 %
Conversion efficiency	60%

The reactions occurring at the electrodes are:

cathode $2H^+ + 2e^- \rightarrow H_2$
anode $2OH^- \rightarrow \frac{1}{2} O_2 + H_2O + 2e^-$

A flow of direct current crosses the cells in series, providing the energy needed to power the electrolysis process. An electrolytic solution ensures the electric transport in ionic form, in addition to the H+ and OH- ions. An alkaline electrolyte is used, a solution of 20-30% potassium hydroxide (KOH) in water, excellent electricity conductor with few stability and corrosion problems. In input to the electric cabinet, there is a 400 V three-phase AC current is divided among the various single-phase users of the system: lights, sockets, air conditioner, refrigerating chiller and auxiliaries such as fans, water pump, heater, valves. In the same cabinet an AC/DC power transformer-rectifier makes DC available for the electrolysis process.

Hydrogen is purified in a dedicated section by filters for KOH and oxygen removing and water absorption. At the end of the process hydrogen has a purity of 99.99%. The excess heat released during the process is removed by a water-cooling circuit.

2.5 Tank

Hydrogen is stored in a tank with a capacity of 0.7 m^3, protected from direct solar radiation and placed in a dry, cool and ventilated environment.

2.6 Fuel cell

It is an electrochemical device that transforms chemical energy into electrical energy in direct current, used to power an electrical load. A fuel (hydrogen) and an oxidant (oxygen or air) enter the cell, from which direct current, water and heat are obtained. Inside the cell there are two electrodes (anode and cathode), respectively lapped by the fuel and the oxidizer, separated by an electrolyte for the conduction of the ions produced by a reaction and consumed by the other, closing the electric circuit. The effluent is pure water, free of polluting substances.

When H_2 is introduced into the cell, the production of ions and electrons is activated in the contact zone between the anode and the electrolyte:

anode $$H_2 \rightarrow 2H^+ + 2e^-$$

Two flows originate, both ending at the cathode, the first linked to the electrons moving through the load connecting the electrodes (user), the second due to the movement of ions H^+ through the membrane.

The second part of the redox reaction takes place on the cathode: the electrons combine with the hydrogen cations and a certain amount of oxygen, generating water:

cathode $$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

The scheme of the process is reported in Figure 3.

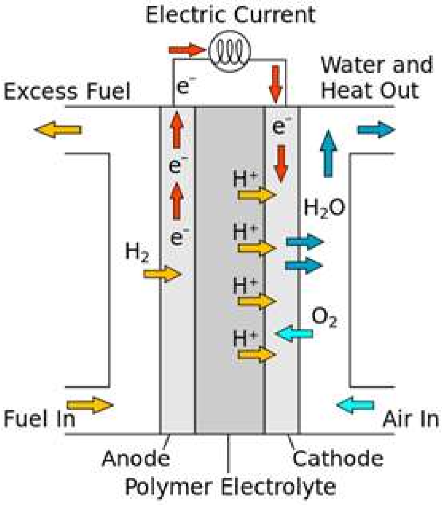


Figure 3. Scheme of a fuel cell

Compared to an accumulator, in which the electrodes are consumed during discharge and must be regenerated during recharging, the fuel cell produces energy as long as reagent is supplied to the electrodes, which are not consumed, but only constitute the support on which the chemical reactions occur.

To obtain the desired power and voltage, several cells are arranged in series, by means of bipolar plates, to form a stack; more assembled stacks get the required power generators.

The main technical characteristics of the used fuel cell (*Proton Exchange Membranes*, *PEM*s) are shown in Table 4; it delivers a power of 1’676, with a constant conversion efficiency $\varepsilon_{EL} = 0.4$. It is equipped with a controller, which manages the interface and the communication with the other units (batteries and inverter).

Table 4. Characteristics of the fuel cell.

Delivered power	1’676 W
Efficiency	40%
Maximum H_2 consumption	1.37 Nm^3/h

H_2 purity	99.95 %
H_2 pressure	0.43 bar

2.7 Battery

At the exit from the fuel cell there is a 48 V battery pack for energy accumulation, operating as a buffer to regulate the power supply: each battery has a nominal voltage of 12 V and a nominal capacity of 92 Ah.

2.8 Inverter (second pack)

An inverter with combined functions of DC/AC inverter and device for managing the battery charge status is used, the characteristics of which are reported in Table 5. It transforms the DC current output from the batteries, making it available to the AC load.

It is set with a minimum activation threshold for the voltage: for accumulator voltages above 48 V the system works in the direction:

batteries → inverter → utility

and the fuel cell is in stand-by mode, for lower voltages the fuel cell supplies current to the accumulator pack up:

fuel cell→ batteries

up to the shutdown procedure.

Table 5. Characteristics of the multifunction inverter

Nominal power	3000 VA
DC input	48 VDC 50 A
AC output	230 VAC 50 Hz 13 A
Max power of charge/discharge	900 W
Efficiency	98%

2.9 Control system

A control system, *Programmable Logic Controller* (PLC), monitors and controls all the process parameters in order to guarantee its correct execution, as well as to ensure the safety and efficiency of the system. If the value of one of the parameters is not respected, it emits alarms and stops the gas production; under certain conditions the gases produced are automatically removed by inert gas injection. The PLC also allows remote operation, except for turning the system on and off.

3 METHODOLOGY OF ANALYSIS OF THE SYSTEM FUNCTIONING

The energetic analysis of the system is aimed at determining the optimal configuration to fulfil the load, that, being in the evening, is not directly connected to the inverter downstream of PV generator, but is powered only by the fuel cell.

Fixed the input power of the electrolyser (Tab.3), the maximum power delivered by the fuel cell (Tab. 4) and the tank capacity, the power of PV generator and the number of tanks have been determined. The global efficiency ε of the process is:

$$\varepsilon = \varepsilon_{EL} \times \varepsilon_{FC} = 0.6 \times 0.4 = 0.24$$

A necessary condition for the system to function properly is to achieve a positive annual balance between hydrogen production and consumption: the storage must therefore have the capacity to meet periods of low production, such as winter. Furthermore, PV generator and tank must be adequately sized so as not to have large PV production surplus that cannot be converted into hydrogen due to tanks or batteries capacity limits. The energetic analysis and that of hydrogen production have been carried out on an hourly basis using *HOMER* simulation and optimization model (*Hybrid Optimization of Multiple Energy Resources*), a dynamic software developed by the USA *National Renewable Energy Laboratory* (*NREL*) for the evaluation of technologies and plants for thermal and electrical power generation.

3.1 Determination of the electrical load

The study started estimating with hourly step the electrical load (headlights lighting parking areas of the *Engineering Departments*) that could be supplied by the fuel cell. Taking into account power losses, the maximum power that the cell can deliver is 1’300 W. Attention has been focused on 52 lamps with 25 W power each, with a total annual consumption 5’694 kWh; their monthly consumption is shown in Figure 4.

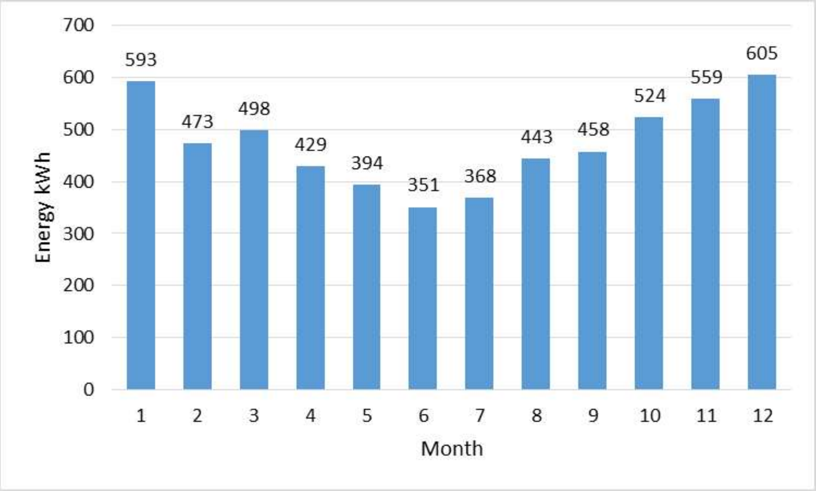


Figure 4 - Monthly load

3.2 Climatic data

Hourly air temperature values registered by a meteorological station installed next to the system were used; the station is flanked by a pyranometer that provided hourly values of the global solar radiation incident on horizontal surface. The reference period is the year 2017.

Figure 5 shows the monthly maximum and average solar radiation on the horizontal, while in Figure 6 the monthly average daily trends in the months with maximum and minimum irradiation, June and December, are shown.

Figure 5 – Monthly maximum and average values of daily solar radiation on the horizontal

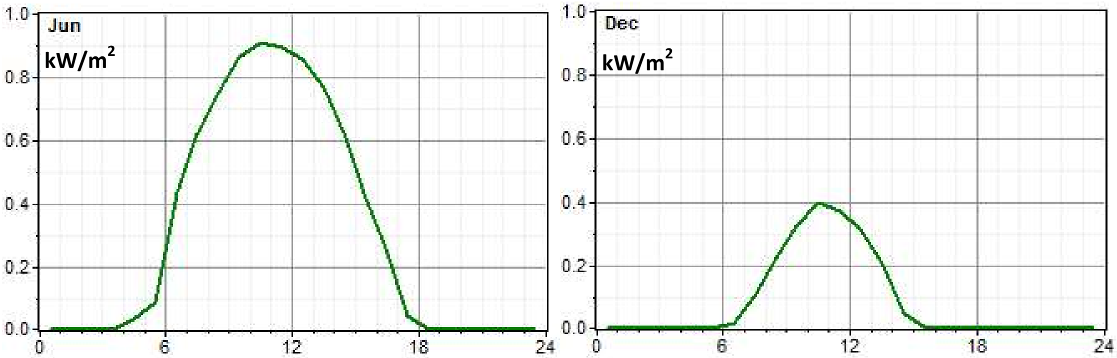


Figure 6 - Average hourly solar radiation in June and December 2017

3.3 Hydrogen production and consumption

With reference to the maximum energy hourly entering the electrolyser, E_{max} = 10 kWh, hydrogen production at the pressure *p = 1,01325 bar* and temperature *T = 0 °C* is:

$$\dot{V}_{H_2} = 2\,\frac{Nm^3}{h}; \qquad \dot{m}_{H_2}^{max} = \dot{V}_{H_2}^{max} \times \rho_{H_2} = 0.18\,\frac{kg}{h} \tag{1}$$

being its density $\rho_{H_2} = 0,0899\ kg/Nm^3$.

Stored volume A_{H_2} is given by:

$$A_{H_2}^{t+1} = A_{H_2}^{t} + V_{H_2}^{t} \tag{2}$$

wherein the volume $V_{H_2}^{t}$ is positive in the production phase and negative in the consumption one.

The tank capacity has been dimensioned in relation to the maximum accumulation during the year at the pressure of 250 bar, using the expression:

$$Vs = \frac{A_{max} \times \rho_{H_2} \times R \times T}{p \times PM_{H_2}} \tag{3}$$

where:

A_{max} hydrogen maximum yearly accumulation

ρ_{H_2} hydrogen density

R gas constant
T temperature
p pressure
PM_{H_2} hydrogen molecular weight

The gas compression absorbs about 2% of its energy content.
The volume consumed by the fuel cell is:

$$V_{H_2}^{t} = \frac{E_{FC}}{\varepsilon_{FC} \times pci_{H_2}} \tag{4}$$

where:
E_{FC} energy delivered by the fuel cell
ε_{FC} efficiency of the fuel cell
pci_{H_2} hydrogen calorific value ($3\frac{kWh}{Nm^3}$).

4 RESULTS AND DISCUSSION

Table 2 shows the production and consumption of both energy and hydrogen in the components, Figure 7 shows the monthly mean values of PV daily power and its monthly energy production, whereas Figure 8 depicts energy monthly produced by the fuel cell.

Table 2 – Energy and hydrogen production and consumption in the system components

Yearly electric energy (kWh)		Yearly hydrogen mass (kg/year)	
Photovoltaic energy production	21’046	Produced	351
Electrolyser input energy	18’437	Consumed	314
Fuel cell production	6’282	Stored	37
Load consumption	5’694		

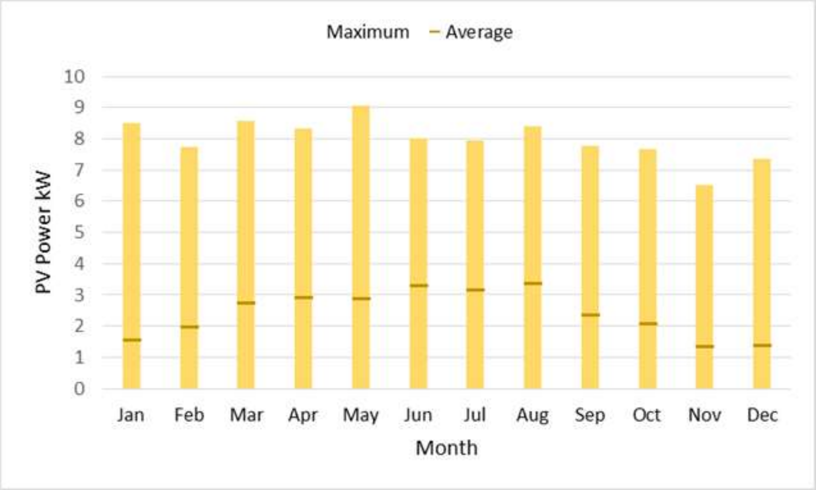


Figure 7 – Maximum and average PV daily power and energy production on a monthly base

During the year the electrolyzer produces 351 kg of hydrogen and the fuel cell consumes 314 kg, with a positive balance (37 kg).

The capacity of the tanks, sized in relation to the maximum value of the fixed annual storage (A_{max} = 100 kg), at the pressure of *250 bar,* resulted 4.54 m^3; adopting 0.75 m^3 tanks, **six** of them should be used. In Fig. 9 the monthly average hydrogen production is shown.

It can be seen that in August and September production is low compared to the potential PV production, contrary to what would be expected: this happens because the tank is saturated and the production stops; the annual excess of photovoltaic energy is 2’564 kWh (Fig. 10): it should be delivered to a daytime load in order to improve the economic convenience of the system.

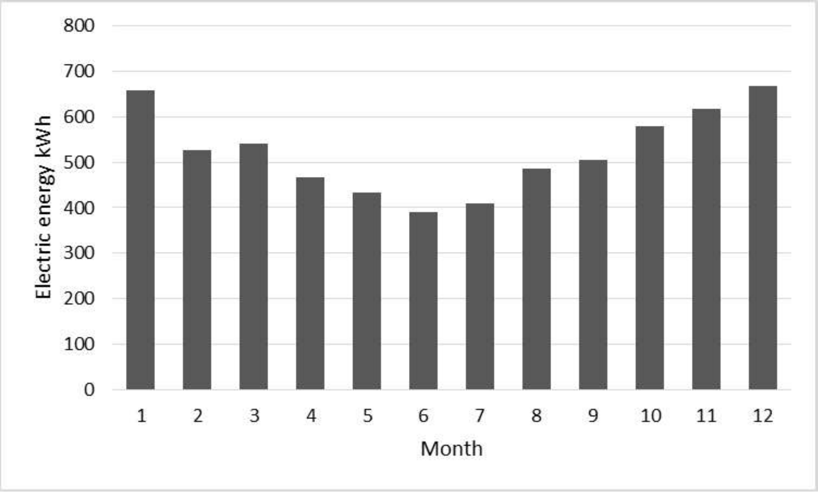


Figure 8 - Fuel cell energy production

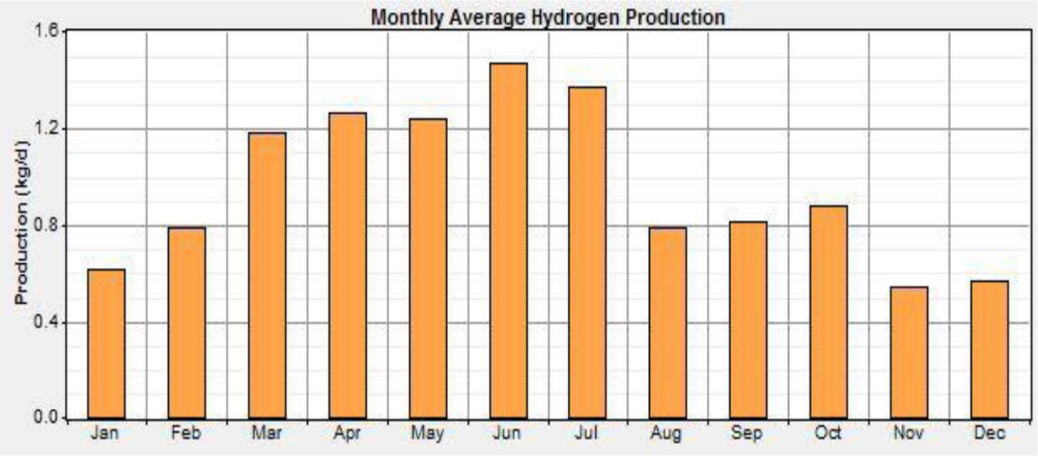


Figure 9 – Electrolyser hydrogen production

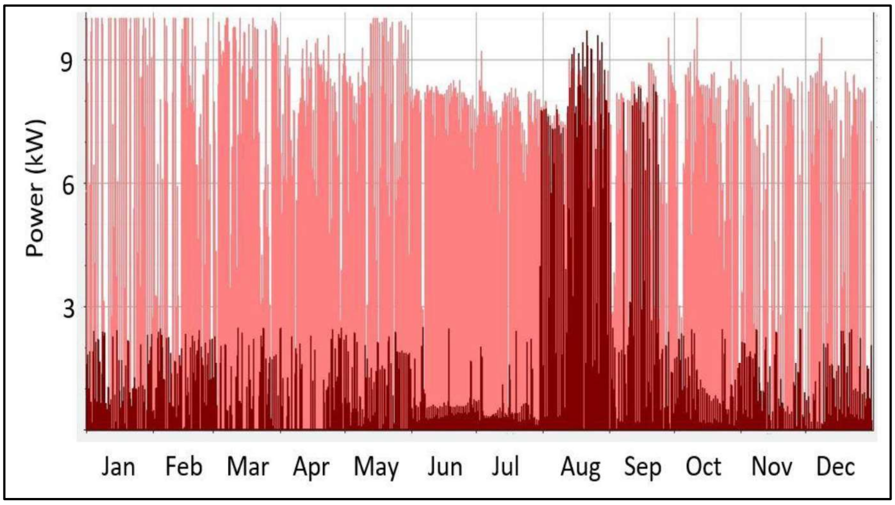


Figure 10 – Electrolyser input power (in pink) and power surplus (in red)

Figure 11 shows hydrogen mass daily accumulated in the tank: it tends to empty in winter as consumption exceeds production, vice versa in summer hydrogen accumulates being production higher than consumption; from August to October it cannot be stored due to the tanks capacity limits.

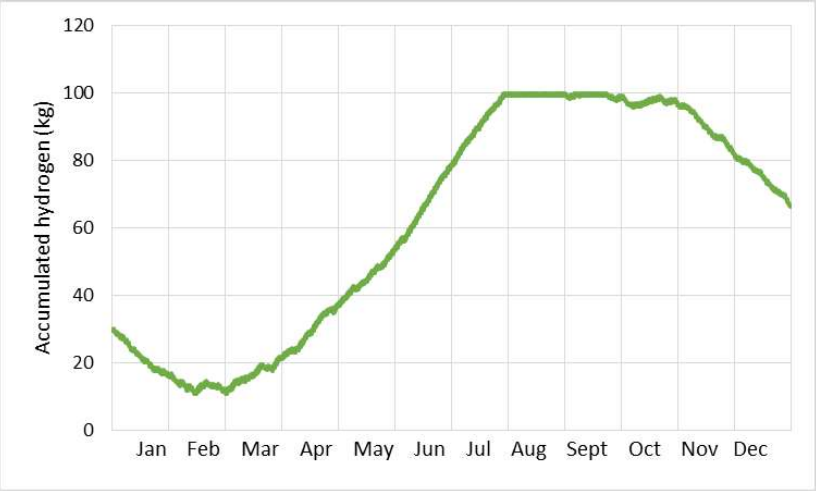


Figure 11 – Stored hydrogen mass

Figure 12 shows the hourly trends of average monthly daily powers in the representative months of August and December: produced by PV panels, absorbed by the electrolyzer, supplied by the fuel cell and consumed by load; it can be seen that in August the photovoltaic energy not used by the electrolyzer is very high. In relation to the fuel cell, the no-power trends in Figure 12 refer to daytime, in which it does not consume being lighting switched off. Figure 13 shows hydrogen level in the tanks in the same months.

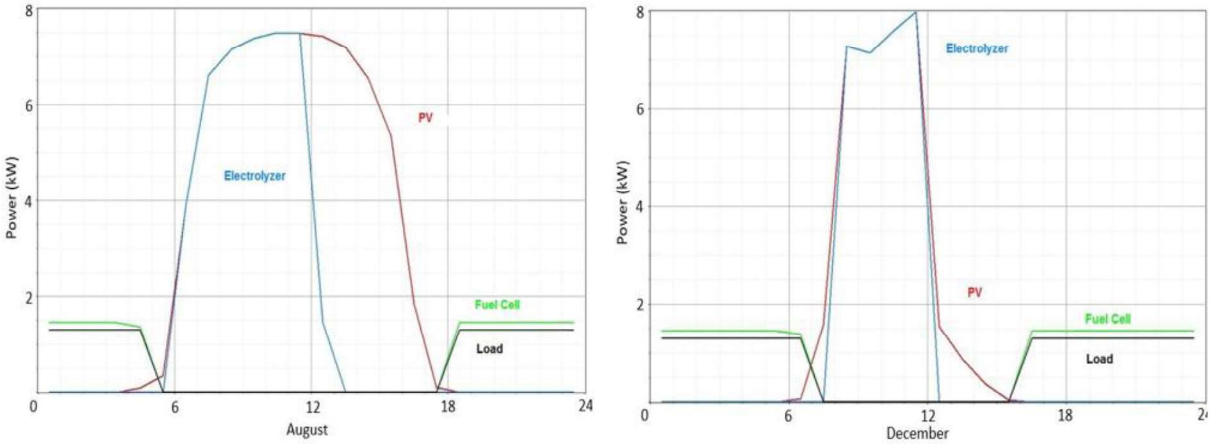


Figure 12 - Hourly power trend in the system components in August and December

If the use of six tanks is not possible for occupancy reasons, and a further gas compression is not advisable, being the plant area frequented by students, to reduce the non-used PV energy in summer months and hydrogen accumulation plateau from August to October in Figure 9, the only solution that can be adopted is to reduce the load and the generator power. Consequently, a second analysis was conducted, reducing the electrical load to 1’100 W (Figure 12), supplying six 150 W lamps and two 100 W LED projectors, and as a consequence the generator power to 7.35 kWp.

Figure 14 shows the monthly trend of the load, corresponding to an annual consumption of 4’818 kWh. In this case the maximum hydrogen accumulated mass was 80 kg. The results of the simulation are shown in Table 3. Figure 15 shows the monthly mean values of the daily power and the monthly energy production of the PV system, while Fig. 16 shows energy monthly produced by the fuel cell.

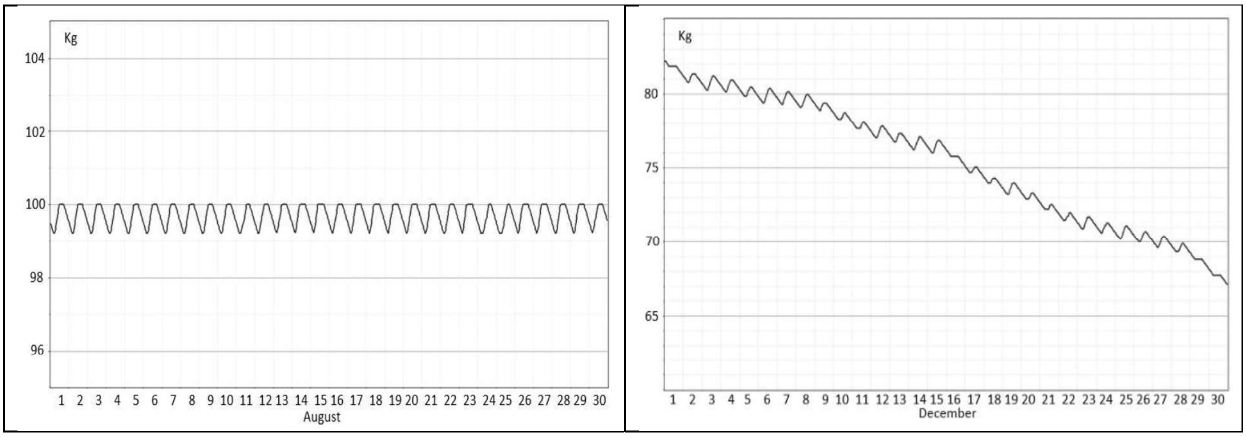


Figure 13 - Trend of hydrogen mass in the tank in August and December

Figure 14 - Monthly load

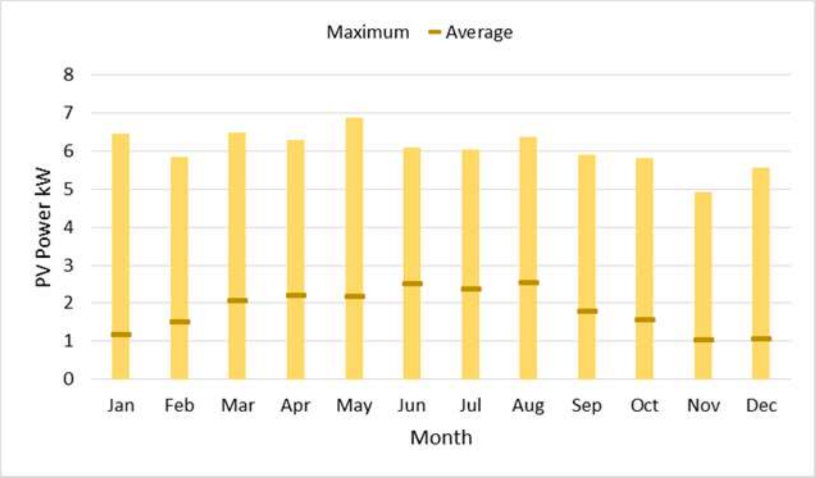
Table 3 – Production and consumption of energy and hydrogen of the system components

Yearly electric energy (kWh)		Yearly hydrogen mass (kg/year)	
Photovoltaic energy production	15’947	Produced	280
Electrolyser input energy	14’723	Consumed	266
Fuel cell production	5’319	Stored	14
Load consumption	4’818		

The capacity of the tanks, dimensioned in relation to the maximum storing fixed in the year, A_{max} = 80 kg, at *250 bar*, is 3.40 m^3: using 0.75 m^3 tanks it is necessary to foresee five of them.

The fuel cell yearly consumes 266 kg of hydrogen, whereas the electrolyzer produces 280 kg, with an average monthly trend shown in Figure 17; the difference between yearly production and consumption is lower (14 kg) than in the previous case.

In this case the photovoltaic energy non used by the electrolyzer is reduced to 1’190 kWh (Figure 18) and there is no hydrogen surplus in the warmer months (Figure 19).



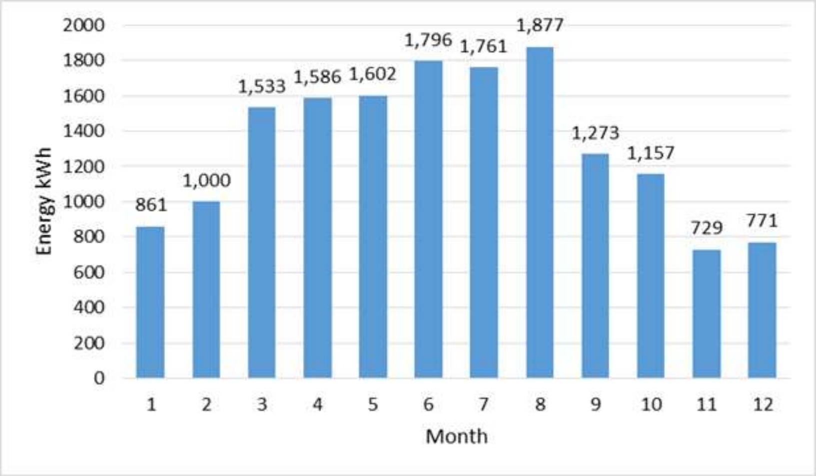


Figure 15 - Maximum and average PV daily power and energy production on a monthly base

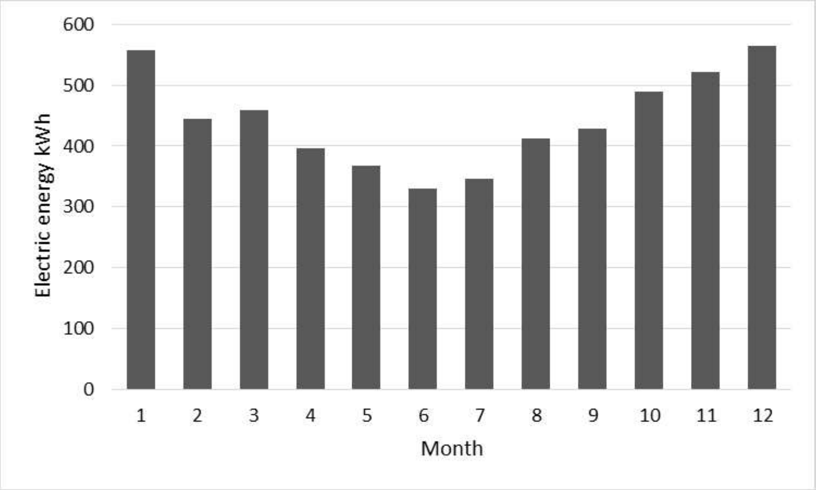


Figure 16 – Fuel cell monthly energy production

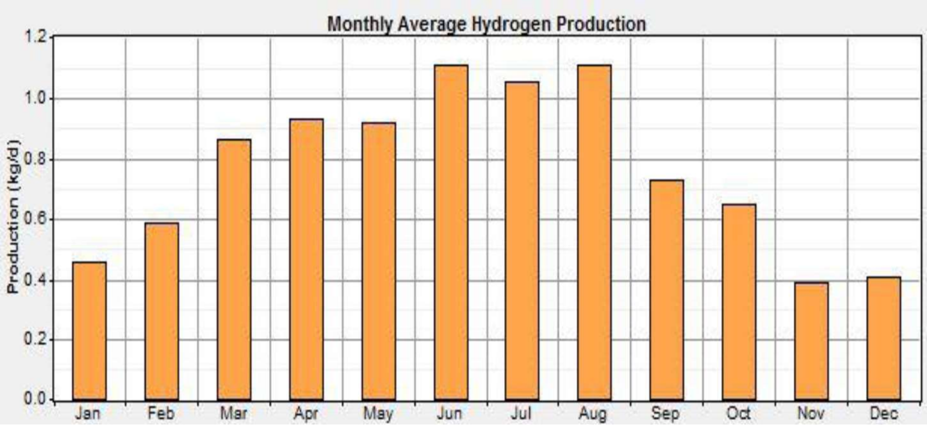


Figure 17 – Electrolyser hydrogen production

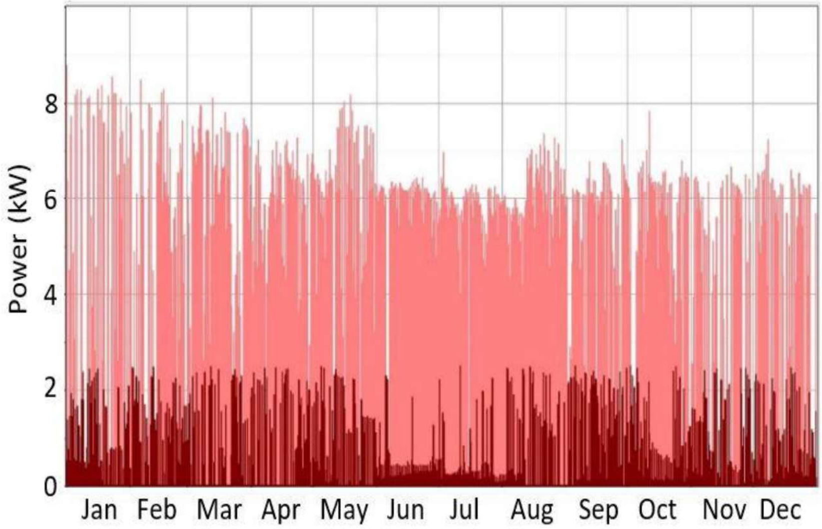


Figure 18 - Electrolyser input power (in pink) and power surplus

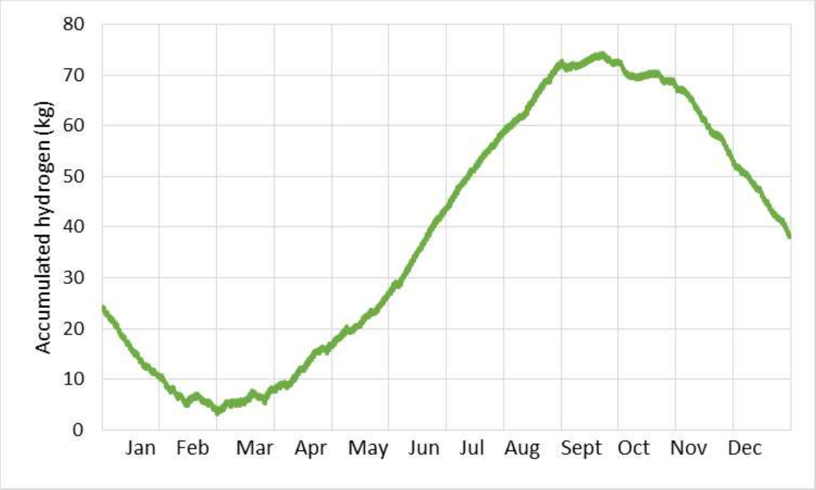


Figure 19 – Stored hydrogen mass

Figure 20 shows, with reference to the months of August and December, the hourly trends of the powers: produced by PV panels, absorbed by the electrolyzer, supplied by the fuel cell and absorbed by the load; compared to the previous case, it is evident the absence of the marked surplus of photovoltaic diurnal production. Figure 21 shows the hydrogen level in the tanks.

From the above it follows that, being the load active in the evening and the system disconnected from the grid, surplus energy is very abundant and can be exploited only using large tanks or adopting high gas pressures: if this is to be avoided, it follows that the only solution that can be adopted is the reduction of the generator peak power and of the load.

This means that, if daily consumption is limited and consequently abundant excess energy is produced, the use of the system in public areas or residential buildings (where visual impact generated by large tanks is hardly acceptable or safety rules do not allow high gas pressures) is advisable only in grid-connected configurations, or in stand alone one only for small sizes of the generator power.

On the contrary, for industrial purposes, where safety rules are less severe and visual impact is not a problem, the system potentiality can be usefully exploited. Such problems are by far reduced is a marked self consumption from PV is possible to satisfy the load.

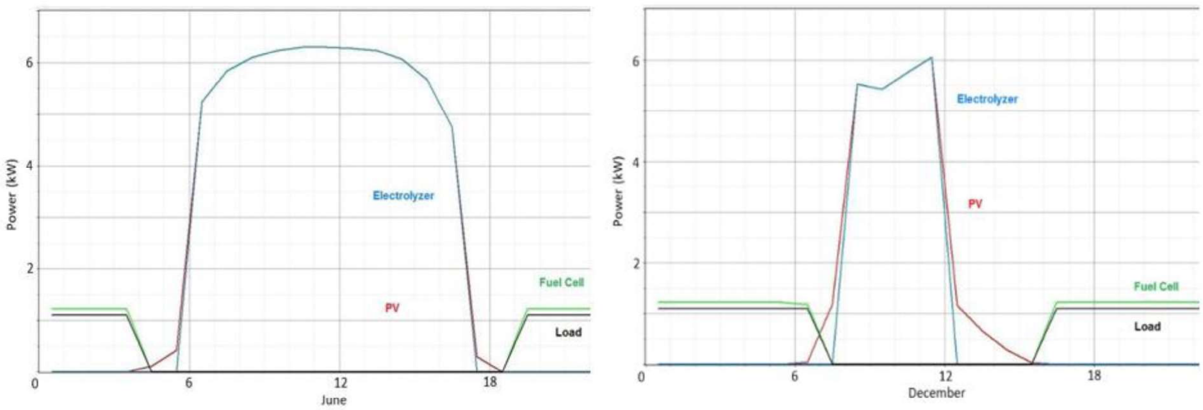


Figure 20 - Hourly power trend for the various components in August and December

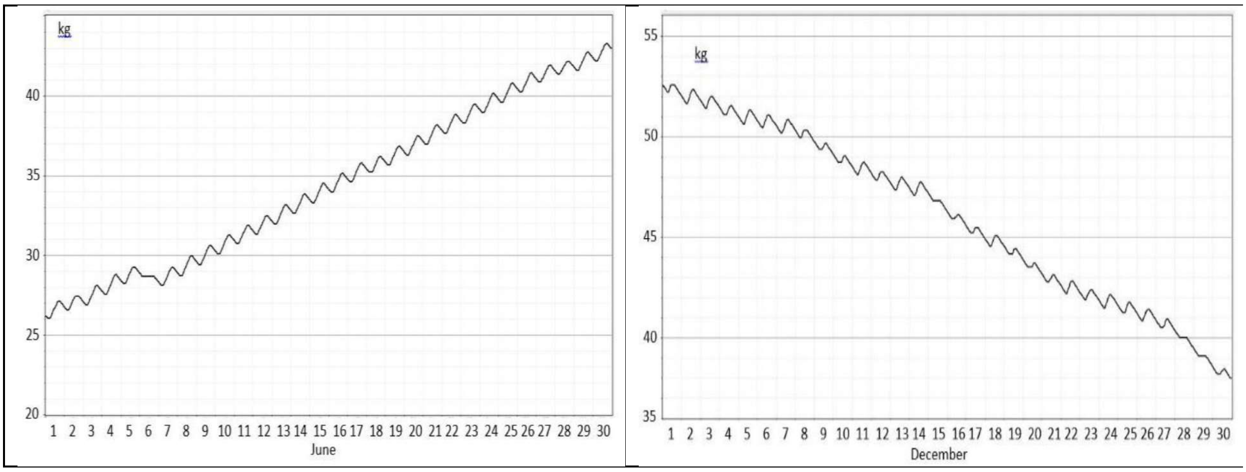


Figure 21 - Hydrogen mass in the tank in August and December

5 ECONOMIC CONSIDERATIONS

Two indicators were used to make economic evaluations on the system, *COE* (*cost of energy*) (€/kWh) and *NPC* (*net present cost*) (€).

$$COE = \frac{\sum_{j=1}^{n} \frac{I_j + C_j - c \cdot E_{thermal}}{(i+r)^j}}{\sum_{j=1}^{n} \frac{E_t}{(i+r)^j}}$$

where:

- j year
- n years of plant life
- I_j investment cost [€]
- C_j maintenance and components replacement cost [€/year]
- c cost of thermal energy [€/kWh]
- $E_{thermal}$ yearly produced thermal energy [kWh/year]
- E_j yearly produced electric energy [kWh/ year]
- r rate of return [%].

COE provides the kWh average cost, obtained by dividing the actualized cost of electricity production, less any benefits, for the total production of useful electricity.

With an initial investment of € 100’000 for the entire system, maintenance costs of € 200/year, life time 20 years and a rate of return of 1%, its value is 0.80/kWh: high figure compared to the all-inclusive cost of energy withdrawal from the national electric grid (€ 0.22/kWh). To get a *COE* close to this value, the system should cost € 28’000.

Economic convenience could increase using excess photovoltaic electricity and thermal energy produced by the electrolyzer, currently not used: in such case the annual cost of electricity production will be reduced by that required to meet the corresponding electrical and thermal loads.

NPC (€) represents the discounted value of the net costs related to the plant life (20 years):

$$NPC = \sum_{j=1}^{n} \frac{C_j - B_j}{(1+r)^j} + I_0$$

with:

- j year
- n years of plant life
- I_o investment cost [€]
- C_j maintenance and components replacement cost [€/year]
- B_j benefits [€/year]
- r rate of return [%].

Also *NPC* is strongly influenced by the high cost of the hydrogen storage system. With the present cost *NCP* is about € 105’000, higher than the investment cost; the referred cash flow is reported in Figure 22.

NPC referred to non-intervention condition is € 24’000, so that at the moment the economic advantage of the investment with respect to energy withdrawal from the grid could arise only from investment costs equal to about a quarter of its current one.

It should be anyway underlined that the analysed system is essentially a research one, aimed at exploring hydrogen potentialities and criticalities for storage purposes: consequently, it has not been designed in order to minimize its cost, but only to accessorize a photovoltaic stand alone system with the aim to study hydrogen energetic behavior as energy vector for accumulation. This has implied avoidance of day loads satisfaction, far more convenient from an economical point of view, and connection to the grid, that could have received energy surplus otherwise lost.

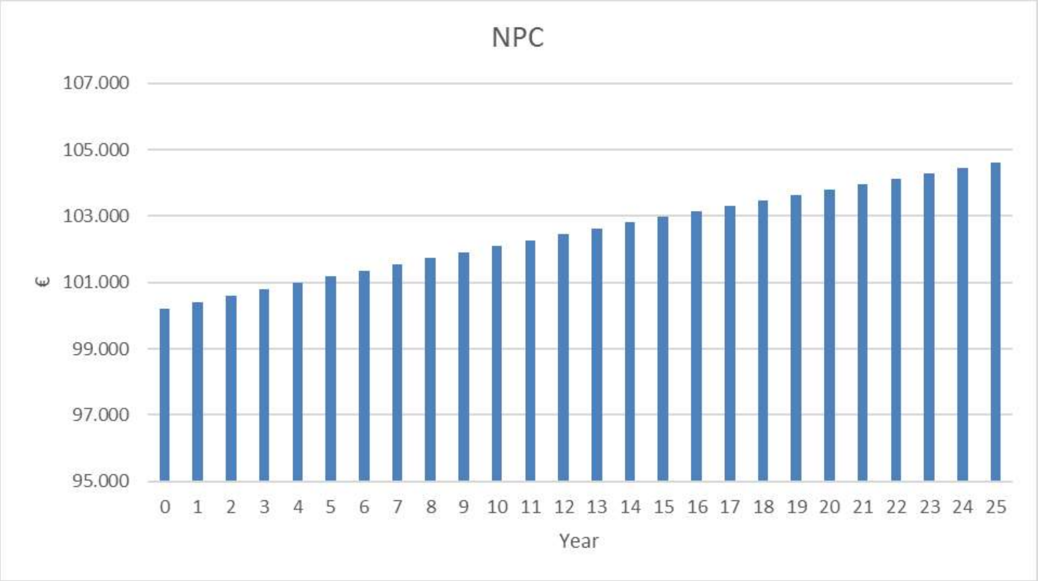


Figure 22 – Cash flow of the investment.

6 CONCLUSIONS

In a post-carbon economy, with a new energetic paradigm based on distributed and sustainable energy, hydrogen is considered by most the leading energy vector.

As an application of its technologies, the work presents the analysis of a stand alone PV system aimed at satisfying the lighting needs of a university car park, generating hydrogen by electrolysis of water, subsequently stored in tanks and converted into electricity in fuel cells.

The purpose of the study is to size and optimize the system production chain with reference to the input power to the electrolyzer, that is supplied by a concentration PV generator with a two-axis solar tracker, to the output power from the fuel cell and to the tank capacity.

The efficiency of the global process (hydrogen production, storage and conversion) is 24%.

A necessary condition for the system to function properly is to achieve a positive annual balance between hydrogen production and consumption; moreover, the storage must meet periods with low production such as winter. In addition, both photovoltaic generator and tank have to be adequately sized not to have large production surplus that cannot be converted into hydrogen due to tank or battery capacity limits.

Starting from air temperature and solar radiation values registered on site, the energetic analysis and that of hydrogen production have been carried out using the software *HOMER*, a simulation and optimization model for thermal and electrical power generation. The software was used to determine the hourly profiles of both photovoltaic energy and hydrogen production, as well as to assess hourly stored hydrogen and consumed in the fuel cell.

The analysis has showed that, being the load active in the evening and the system disconnected from the grid, excess energy can be exploited only using large tanks or adopting high gas pressures. Consequently, the use of the system in public areas or residential buildings, where visual impact generated by large tanks or safety rules do not allow high gas pressures, is advisable only in grid-connected configurations, or in stand alone ones only for small generator sizes. Such problems are by far reduced is a marked self consumption from PV is present.

From an economic point of view, the assessment of *COE* and *NPC* indicators has confirmed the current non-competitiveness of electrolytic hydrogen for energy storage, due to the still high investment cost of the system: in order to have acceptable pay back times, its cost should be reduced to about 1/4 of its current value. Also the cost of the energy unit stored in hydrogen is presently far greater than that produced by photovoltaic or wind systems or taken from the grid.

Consequently, in the aim to obtain the quick and effective penetration of hydrogen into the market, it is urgent to enact incentivizing policies, attributing to its technologies fares able to cover the additional costs of its production, storage and conversion.

ACKNOWLEDGMENT

This work was carried out within the research project n. 201594LT3F, “Research for SEAP: a platform for municipalities taking part in the Covenant of Mayors”, which is funded by the *PRIN* (*Programmi di Ricerca Scientifica di Rilevante Interesse Nazionale*) of the Italian Ministry of Education, University and Research.

NOMENCLATURE

p	pressure
T	temperature
E_{max}	maximum input energy to the electrolyzer
$V_{H_2}^t$	hourly produced hydrogen volume at atmospheric pressure
$\dot{m}_{H_2}$	hourly produced hydrogen mass
ρ_{H_2}	hydrogen density
t	time
E_{FC}	energy delivered by the fuel cell
ε_{FC}	fuel cell efficiency
pci_{H_2}	hydrogen calorific value
A_{H_2}	stored hydrogen volume
V_S	tank capacity
A_{max}	maximum yearly stored hydrogen volume
R	gas constant
PM_{H_2}	hydrogen molecular weight
η	efficiency
$NOCT$	nominal operating cell temperature
β	temperature coefficient
COE	cost of energy
NPC	net present cost
j	year
n	years of plant life
I_j	investment cost
C_j	maintenance and components replacement cost
c	cost of thermal energy
$E_{thermal}$	yearly produced thermal energy
E_j	yearly produced electric energy
I_0	investment cost
B_j	benefits
r	rate of return

REFERENCES

1. OJEU, On the promotion of the use of energy from renewable sources, *Official Journal of the European Union*, N. 140, pp. 63-73, 05 June 2009.

2. A. Foley, A.G. Olabi, Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change, *Renewable and Sustainable Energy Reviews*, Vol. 68, Part 2, pp. 1112-1114, 2017. DOI: 10.1016/j.rser.2016.12.065
3. A. Narayanan, K. Mets, M. Strobbe, C. Develder, Feasibility of 100% renewable energy-based electricity production for cities with storage and flexibility, *Renewable Energy*, Vo.134, pp. 698-709. DOI: 10.1016/j.renene.2018.11.049
4. C. Gonçalves da Silva, Renewable energies: choosing the best options. *Energy*, Vol. 35, Issue 8, pp. 3179-93, 2010. DOI: 10.1016/j.energy.2010.03.061
5. Kyriakopoulos, G. Arabatzis, P. Tsialis, K. Ioannou, Electricity consumption and RES plants in Greece: Typologies of regional units, *Renewable Energy*, Vol. 127, pp.134-144, 2018. DOI: 10.1016/j.renene.2018.04.062
6. F. Hvelplund, Renewable energy and the need for local energy markets. *Energy*, Vol. 31, Issue 13, pp. 2293-302, 2006. DOI: 10.1016/j.energy.2006.01.016
7. A. Malara, C. Marino, A. Nucara, M. Pietrafesa, F. Scopelliti, G. Streva, Energetic and economic analysis of shading effects on PV panels energy production, *International Journal of Heat and Technology,* Vol. 34, No. 3, pp. 465-472, 2016. DOI: 10.18280/ijht.340316
8. H. Lund, The implementation of renewable energy systems. Lessons learned from the Danish case. *Energy,* Vol. 35, Issue 10, pp. 4003-9, 2010. DOI: 10.1016/j.energy.2010.01.036
9. Vad Mathiesen, N. Duić, I. Stadler, G. Rizzo, Z. Guzović, The interaction between intermittent renewable energy and the electricity, heating and transport sectors, *Energy,* Vol. 48, pp. 406-414, 2012, Elsevier. DOI: 10.1016/j.energy.2012.10.001
10. G. Krajacic, D. Loncar, N. Duic, M. Zeljko, R.L. Arantegui, R. Loisel, I. Raguzin, Analysis of financial mechanisms in support to new pumped hydropower storage projects in Croatia, *Applied Energy*, Vol. 101, pp. 161-171, 2013. DOI: 10.1016/j.apenergy.2012.07.007
11. A.M. Lopez-Sabiron, P. Royo, V.J. Ferreira, A. Aranda-Uson, G. Ferreira, Carbon footprint of a thermal energy storage system using phase change materials for industrial energy recovery to reduce the fossil fuel consumption, *Applied Energy*, Vol. 135, pp. 616-624, 2014. DOI: 10.1016/j.apenergy.2014.08.038
12. A. Foley, D. Lobera, Impacts of compressed air energy storage plant on an electricity market with a large renewable energy portfolio, *Energy*, Vol. 57, pp. 85-94, 2013. DOI: 10.1016/j.energy.2013.04.031
13. A. Lorestani, M.M. Ardehali, Optimization of autonomous combined heat and power system including PVT, WT, storages, and electric heat utilizing novel evolutionary particle swarm optimization algorithm, *Renewable Energy*, Vol. 119, pp. 490-503, 2018. DOI: 10.1016/j.renene.2017.12.037
14. S. Avril, G. Arnaud, A. Florentin, M. Vinard, Multi-objective optimization of batteries and hydrogen storage technologies for remote photovoltaic systems. *Energy,* Vol.35, Issue 12, pp.5300-5308, 2010. DOI: 10.1016/j.energy.2010.07.033

    C. Marino, A. Nucara, M. Pietrafesa, A. Pudano, An energy self-sufficient public building using integrated renewable sources and hydrogen storage, *Energy*, Vol. 57, pp. 95-105, 2013, Elsevier Science. DOI: 10.1016/j.energy.2013.01.053
15. N.A. Kelly, Hydrogen production by water electrolysis, *Advances in Hydrogen production storage and distribution*, 159-185, 2014. DOI: 10.1533/9780857097736.2.159
16. C. Marino, A. Nucara, M. Pietrafesa, A. Tripodi, Hydrogen production from RES, storage and reconversion in fuel cells. *Proceedings of the 14th International Building Simulation Conference,* Hyderabad - India, December 7-9, 2015.
17. K. Agbossou, M.L. Kolhe, J. Hamelin, E. Bernier, T.K. Bose, Electrolytic hydrogen based renewable energy system with oxygen recovery and re-utilization, *Renewable Energy*, Vol. 29, Issue 8, pp. 1305-1318, 2004. DOI: 10.1016/j.renene.2003.12.006

18. A. Knut, Hydrogen production by electrolysis. In: Hydrogen power: theoretical and engineering solutions. *Proceedings of the HYPOTHESIS II Symposium,* Grimstad, Norway, August 18-22, 1997, London: Klewer Academic Publishers, Ed T.O. Saetre, 1998.
19. P. Nikolaidis, A. Poullikkas, A comparative overview of hydrogen production processes, *Renewable and sustainable energy reviews*, Vol. 67, pp. 597-611, 2017. DOI: 10.1016/j.rser.2016.09.044
20. O.V. Marchenko, S.V. Solomin, The future energy: Hydrogen versus electricity, *International Journal of Hydrogen Energy,* Vol. 40, Issue 10, pp. 3801-3805, 2015. DOI: 10.1016/j.ijhydene.2015.01.132
21. A.Yilanci, I. Dincer, H.K. Ozturk, A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications, Progress in Energy and Combustion Science, Vol. 35, Issue 3, pp. 231-244, 2008. DOI:10.1016/j.pecs.2008.07.004
22. N. Goel, D.J. Goswami, S.T. Mirabal, H.A. Ingley, Hydrogen Production, *Advances in Solar Energy: An Annual Review of Research and Development,* Vol. 15, pp. 411-16, 2003.
23. F. Kreith, R. West, Fallacies of a Hydrogen Economy: A Critical Analysis of Hydrogen Production and Utilization, *Journal of Energy Resources Technology,* Vol.126, pp. 249-257, 2004. DOI: 10.1115/1.1834851
24. T. Da Silva Veras, T.S. Mozer, D. Da Costa Rubim Messeder dos Santos, C. Aldarada da Silva, Hydrogen: Trends, production and characterization of the main process worldwide, *International Journal of Hydrogen Energy,* Vol. 42, Issue 4, Pages 2018-2033, 2017. DOI: 10.1016/j.ijhydene.2016.08.219
25. S.E. Hosseini, M.A. Wahid, Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development, *Renewable and sustainable energy reviews,* Vol. 57, pp. 850-866, 2016. DOI: 10.1016/j.rser.2015.12.112
26. R. Chaubey, S. Sahu, O.O. James, S. Maity, A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources, *Renewable and sustainable energy reviews,* Vol. 23, pp.443-462, 2013. DOI: 10.1016/j.rser.2013.02.019
27. F. Cao, Q. Wei, H. Liu, N. Lu, L. Zhao, L. Guo, Development of the direct solar photocatalytic water splitting system for hydrogen production in Northwest China: Design and evaluation of photoreactor, *Renewable Energy*, Vol. 121, pp. 153-163, 2018. DOI: 10.1016/j.renene.2018.01.016
28. W. Won, H. Kwon, J. Han, J. Kim, Design and operation of renewable energy sources based hydrogen supply system: Technology integration and optimization, *Renewable energy*, Vol. 103, pp. 226-238, 2017. DOI: 10.1016/j.renene.2016.11.038
29. C. Marino, A. Nucara, M. Pietrafesa, A. Pudano, M. Tripodi, Energetic, economic and environmental sustainability of integrated techniques for energy production in buildings using hydrogen as storage system. *Renewable Energy & Power Quality Journal,* Vol. 10, Issue 1, pp. 663-668, 2012. DOI: 10.24084/repqj10.663
30. M. Santarelli, S. Macagno, Hydrogen as an energy carrier in stand-alone applications based on PV and micro-hydro systems. *Energy*, Vol. 29, Issue 8, pp. 1159-82, 2004. DOI: 10.1016/j.energy.2004.02.023
31. J. Carroquino, V. Roda, R. Mustata, J. Yago, L. Valino, A. Lozano, F. Barreras, Combined production of electricity and hydrogen from solar energy and its use in the wine sector, *Renewable Energy*, Vol. 122, pp. 251-263, 2018. DOI: 10.1016/j.renene.2018.01.106
32. A. Arsalis, A. N. Alexandrou, G. E. Georghiou, Thermoeconomic modelling of a completely autonomous, zero-emission photovoltaic system with hydrogen storage for residential applications, *Renewable Energy,* Vol. 126, pp. 354-369, 2018. DOI: 10.1016/j.renene.2018.03.060

33.C. Marino, A. Nucara, M. Pietrafesa, Electrolytic hydrogen production from renewable source, storage and reconversion in fuel cells: the system of the Mediterranea University of Reggio Calabria, *Energy Procedia*, Vol. 78, pp. 818-823, 2015. Elsevier Science. DOI: 10.1016/j.egypro.2015.11.001

34. M. Momirlana, T.N. Veziroglu, The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet, *International Journal of Hydrogen Energy*, Vol. 30, Issue 7, pp.795-802, 2005. DOI: 10.1016/j.ijhydene.2004.10.011

35.J.O.M. Bockris, The hydrogen economy: Its history, *International Journal of Hydrogen Energy*,Vol. 38, Issue 6, pp. 2579-2588, 2013. DOI: 10.1016/j.ijhydene.2012.12.026

36. P. Hoffmann, Tomorrow's Energy: Hydrogen, Fuel Cells and the Prospects for a Cleaner Planet. Cambridge, Massachusetts: *The MIT Press*, 2001. DOI: 10.1017/S1466046602251261

37.M. Ball, M. Weeda, The hydrogen economy – Vision or reality?, *International Journal of Hydrogen Energy,* Vol. 40, Issue 25, pp. 7903-7919, 2015. DOI: 10.1016/j.ijhydene.2015.04.032

38. S. Sunita Sharmaa, G. Krishna, Hydrogen the future transportation fuel: From production to applications, *Renewable and sustainable energy reviews,* Vol. 43, pp. 1151-1158, 2015. DOI: 10.1016/j.rser.2014.11.093

39. F. Barbir, Transition to renewable energy systems with hydrogen as an energy carrier. *Energy* Vol. 34, Issue 3, pp. 308-12, 2009. DOI: 10.1016/j.energy.2008.07.007

40.I. Dincer, M.A. Rosen, Sustainability aspects of hydrogen and fuel cell systems, *Energy for sustainable development*, Vol.15, Issue 2, pp. 137-146, 2011. DOI: 10.1016/j.esd.2011.03.006

41. N.H. Afgan, M.G. Carvalho, Sustainability assessment of hydrogen energy systems, *International Journal of Hydrogen Energy,* Vol. 29, Issue 13, pp. 1327-1342, 2004. DOI: 10.1016/j.ijhydene.2004.01.005

42.M.E. Demir, I. Dincera, Cost assessment and evaluation of various hydrogen delivery scenarios, *International Journal of Hydrogen Energy,* Vol. 43, Issue 22, pp. 10420-10430, 2018. DOI: 10.1016/j.ijhydene.2017.08.002

43. M. Moreno-Benito, P. Agnolucci, L.G. Papageorgiou, Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development, *Computers and chemical engineering,* Vol.102, Pages 110-127, 2017. DOI: 0.1016/j.compchemeng.2016.08.005

T. Sinigaglia, F. Lewiski, M.E.S. Martins, J.C.M. Siluk, Production, storage, fuel stations of hydrogen and its utilization in automotive applications-a review, *International Journal of Hydrogen Energy*, Vol.42, Issue 39, Pages 24597-24611, 2017. DOI: 10.1016/j.ijhydene.2017.08.063