HYDROGEN PRODUCTION FROM RES, STORAGE AND RECONVERSION IN FUEL CELLS

Concettina Marino[1], Antonino Nucara[1], Matilde Pietrafesa[1], Andrea Tripodi[1]
[1]DIIES – Dipartimento di Ingegneria di Ingegneria dell'Informazione, delle Infrastrutture e dell'Energia Sostenibile, University "Mediterranea" of Reggio Calabria, Reggio Calabria, Italy

ABSTRACT

In the paper a system aimed at hydrogen production through electrolysis from renewable source (PV, wind generators), its storage and reconversion in fuel cells is presented. It is a prototype which is being implemented at the "*Mediterranea*" University of Reggio Calabria (Italy) in order to investigate the improvement potentiality of the whole process in relation to both weather and load conditions. The analysis here presented is aimed at a preliminary simulation of the system with a view to assessing the global amount of hydrogen that can be produced during a year using the renewable sources, that are being installed at the site, as power input. The result has to be considered as a first stage to outline the load which can be supplied also considering the dimension of the hydrogen tank.

INTRODUCTION

Increasingly, among scientists, economists and politicians, widespread concerns regard the new energetic paradigms that are urgently required in order to prevent dangerous climatic changes and obtain efficient emission reduction. To pursuit this aim, in the next future, global agreements might be established among the world's governments, in order to prevent dramatic temperature increases and guarantee ecosystems safety.

This implies that new strategies should be designed in order to drive a quick transition towards carbon free energy models suitable for replacing the present, obsolete, centralized management model, under the aegis of a sustainable wide resource autonomy. The new distributed energy regime should be based on a set of innovative processes involving: renewable energy production, microgeneration, smart grids, electric mobility, energy storage and Hydrogen (Alajlan, 1999; Allegrezza et al., 2012; Beaudin et al., 2010; Cotana et al., 2011; Divya and Ostergaard, 2009; El-Shatter et al., 2006; Graham and Holland, 1990; Ibrahim et al., 2008; Nelson et al., 2006; Parida et al., 2011; Razykov et al., 2011).

In order to carry out such a deep transformation, a redesign of the city energy infrastructure must be realized effectively, implementing the *smart city* model, a urban model merging in a single infrastructure ICT, energy management and transportation systems.

In the new urban model, based on a distributed energy regime, larger diffusion will be given to RES, such as PV systems, and to different forms of energy storage and energy carriers.

In this context, increasingly, hydrogen seems suited to performing as either energy carrier or storage (Marino et al., 2013, 2012). It is not pollutant (water is the only product of its combustion in pure Oxygen and no greenhouse gases, particularly CO_2, are produced), versatile, shows a very high combustion efficiency and does not require time consuming recharging, like electric batteries usually do.

Nevertheless, its low volumetric energy content, requiring high pressures for its storage, still represents its main drawback, together with the lack of exploitable infrastructures.

Moreover its cleanest production method, electrolysis, totally free from environmental impacts, still requires large electricity amounts, that make it convenient only in case of low energy cost that, in turn, implies energy surplus exploitation or RES production.

Consequently, at the moment, its technology still requires relevant funds and a quick, effective penetration into the market, extending its present industrial applications to widespread uses as a fuel, would necessarily require economic breakthroughs.

To reach this aim a technological improvement, involving systems and designing procedure, is also required. System components, as a matter of fact, should be efficiently and appropriately dimensioned, taking into account the load and its time variability.

Within this frame, in the paper, a system aimed at Hydrogen production through electrolysis from renewable source (PV and wind generators), storage and reconversion in fuel cells is presented.

It is being installed at the *Mediterranea* University of Reggio Calabria (Italy) and will be used as a prototype to investigate about the potentiality of the whole process in relation to both weather conditions and load structure.

The research is meant to address the storage issue and its link to load configuration, trying to analyze the potentiality of the system in supplying a specific energy end-use.

The final goal would be the design of a configuration that can be used as a contributing factor in meeting building energy demand. As a matter of fact, such an innovative storage system could have a pivotal application in the context of the Nearly-Zero Energy Building patterns (OJEU, 2010).

In this paper the components of the system, its dimensioning and the whole energy conversion process are described.

Moreover, the analysis here presented is aimed at a preliminary simulation of the system with a view to assessing the global amount of hydrogen that can be produced during a year using the renewable sources, that are being installed at the site, as power input. The result has to be considered as a first stage to outline the load which can be suitably supplied, also considering the capacity of the hydrogen tank.

DESCRIPTION OF THE SYSTEM

The system consists of *a Process unit*, governing electrolysis, hydrogen storage and reconversion in electric energy in fuel cells, and a *Power supply unit*, supervising, together with the *Programmable Logic Controller*, the control of all the system parameters, in order to guarantee the correct process functioning (Marino et al., 2015).

Its main components are the following (Figure 1):

1. renewable energy power generators;
2. inverter;
3. deionized water tank;
4. electrolyzer;
5. hydrogen analyzer and purifier;
6. storage tank;
7. fuel cell;
8. control system.

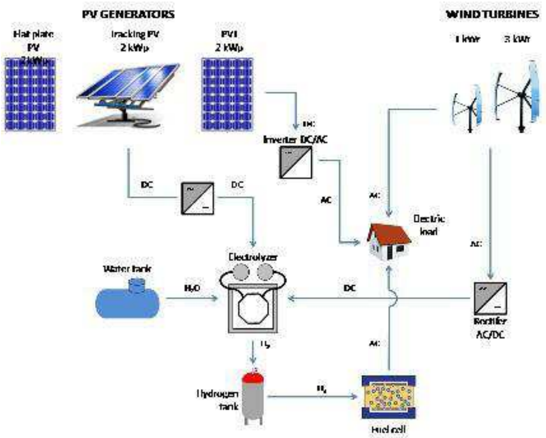

Figure 1 Sketch of the whole system

Renewable energy power generators

They consist of:

a) a photovoltaic plant, with a peak power of 2 kW_p;
b) a photovoltaic plant equipped with solar tracker, with a peak power of 2 kW_p;
c) a hybrid photovoltaic-thermal plant, with an electric peak power of 2 kW_p;
d) two vertical axis wind turbines, with rated power of 1 kW and 2 kW.

Inverter

The electrolyzer requires DC power supply, therefore an electronic converter AC/DC connects the wind plant to the system, whereas, a DC/DC converter realizes the connection to the PV source in order to optimize the energy flow, adapting it to the voltage level of the system.

Deionized water tank

Electrolysis requires deionized water, that is stored in a tank.

Electrolyzer

It consists of bipolar electrolytic cells and produces Hydrogen and Oxygen under pressure (the latter liberated into the atmosphere), without using compressors (Figure 2). In order to increase its efficiency, water is made highly conductive by adding Potassium hydroxide (KOH) (Figure 3).

Figure 2 Stack and separator tanks.

The system efficiency is 0.75.

Hydrogen output purity is 99.8%, while its pressure is 20 bar.

The electrolyser, when supplied with the maximum input power (10 kW), has a maximum hourly Hydrogen production $\dot{V}_{H_2}$ = 2 Nm^3/h.

Consequently, the maximum hourly flow rate, $\dot{m}_{H_2}$, is:

$$\dot{m}_{H_2} = \dot{V}_{H_2} \times \rho_{H_2} \times \tau = 0.18 \text{ kg/h} \quad (1)$$

being Hydrogen density, ρ_{H_2}, equal to 0.0899 kg/Nm^3

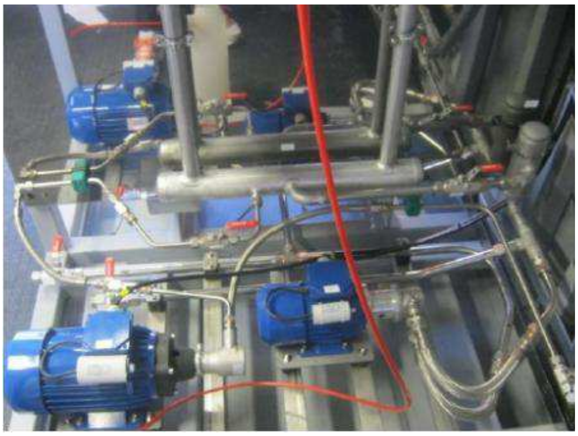

Figure 3 Water pump and electrolyte recirculation.

Hydrogen analyzer and purifier

The purification process evolves through various filters, having the task of deoxidizing hydrogen, recovering the residual KOH and absorbing the residual water. At the end of the process Hydrogen purity reaches 99.99% (Figure 4).

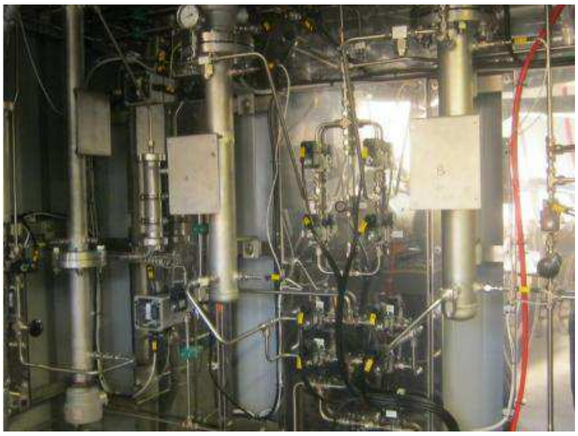

Figure 4 Hydrogen purifier.

Storage tank

The gas is stored under pressure in a tank with capacity of 75 l. The maximum allowed pressure is 30 bar, but, operatively, 20 bar are maintained. This condition allows about 15 Nm^3 of Hydrogen to be stored.

Fuel cell

A fuel cell with a rated power of 1.7 kW realizes the electric power conversion, by means of a pair of RedOx reactions. Particular attention must be paid to the separation membrane that requires a high purity level in Hydrogen input (99.99%).

The output current is DC and requires an inverter depending on the load features. There are also auxiliary systems: a controller, which manages the interface and communication between the cell and other units; accumulators, operating as buffers to regulate the output power and as backup unit when electrical current is temporary absent; an inverter, which, in addition to performing DC/AC transformation, is also used to manage the charge state of accumulators.

Fuel cell

A fuel cell with a rated power of 1.7 kW realizes the electric power conversion, by means of a pair of RedOx reactions. Particular attention must be paid to the separation membrane that requires a high purity level in Hydrogen input (99.99%).

The output current is DC and requires an inverter depending on the load features. There are also auxiliary systems: a controller, which manages the interface and communication between the cell and other units; accumulators, operating as buffers to regulate the output power and as backup unit when electrical current is temporary absent; an inverter, which, in addition to performing DC/AC transformation, is also used to manage the charge state of accumulators.

Control system (PLC)

A control system, remotely controllable, regulates and monitors all the process parameters and ensures the system safety, efficiency and correct functioning; manual operation is required only for both starting and shutdown phase. In case of deviation from standard values it immediately stops gas production.

The purity of hydrogen and oxygen is monitored by gas analyzers. In addition, the electrolyzer is provided with an analyzer of O2 in H2. Alarms are activated if such percentage is close to the maximum limit, in order to avoid the explosion of the mixture. In particular, three security control systems are present:

- pressure transducers, constantly controlling pressure values;
- mechanical safety valves, automatically depressurizing the system when 30 bar pressure is reached;
- Hydrogen leak detectors, switching off the system if gas percentage exceeds a preset threshold.

Phases of the process

The process evolves through different phases.

Before being switched on and after being switched off the system is made inert by inflating Nitrogen at low pressure, in order to allow air, Oxygen and Hydrogen to be eliminated.

Subsequently, a solution of demineralized water and electrolyte KOH flows through the electrolyzer, in order to increase the process efficiency and prevent detonations, as the Oxygen and the Hydrogen separating tanks communicate through a U-pipe. Pressurization starts automatically and electrolysis takes place. The produced Hydrogen and Oxygen are directed to the separating tanks where the pressure rises. For stoichiometric reasons, Hydrogen production is higher than the Oxygen one and a pressure unbalance would arise and must be prevented.

Both gases produced are biphasic (liquid and gaseous) and carry KOH particles into the separating tanks where gaseous phase separates from the liquid one. This last settles on the bottom of the tank and goes back to the electrolyzer carrying KOH which, unlike water which must be restored, is retrieved. From the tanks the two gasses separately flow through purifying filters to get rid of residual water; hence oxygen is discharged into the atmosphere, while Hydrogen flows through a back pressure controller, directed to a tank, where it is purified from the residual KOH electrolyte, which is retrieved and directed to the stack. The same purification regards Oxygen before its discharging.

The following process aims at the elimination of the residual Oxygen from Hydrogen: in order to prevent the formation of explosive mixtures, O2 concentration must be lower than 1.6% (law limit). Hydrogen reaches a purity of 99.9% and is stored in a tank, located in a dry and cool environment, ventilated and shaded from direct solar radiation.

Finally, when the tank pressure exceeds 5 bar, the fuel cell is activated. The energy generated charges the buffer batteries up to a voltage of 55 V and goes in standby. When the voltage lowers below 49 V, the cell automatically starts energy production to charge again the battery. The control system handles the Hydrogen flow in order to meet the load power demand. The process continues until the plant is switched off .

ANALYSIS OF THE GLOBAL PROCESS

At the current state, the RES plants are being installed at the site.

The analysis here presented consists in a simulation of the whole system in order to assess the energy production from RES and the correspondent yearly hydrogen production.

The result is going to be used to outline the load which can be suitably supplied, also considering the capacity of the hydrogen tank.

The simulation has been carried out by means of a software suitable for systems optimization purpose: Homer (HOMER, 2015).

In the following paragraphs the procedures used to characterize both solar and wind source and to assess the energy production are described. Specifically, wind data were measured directly on site, while the solar radiation data reported in Huld et al. (2012) were used.

Energy production from renewable sources

Wind generators

The anemological characterization of the site was carried out by means of a measurement campaign, lasted a whole year and currently in progress. In particular, mean values of wind speed have been obtained with hourly time steps, at a height of 10 m above the ground.

The instrument used for the measurements is the *Vaisala Weather Transmitter WXT520*, that uses ultrasounds to determine horizontal wind speed and direction.

The WXT520 has been also utilized for the measurements of air temperature, relative humidity and barometric pressure at the site. Subsequently, the frequency distribution of the wind velocities has been determined and monthly average values have been calculated (Figure 5).

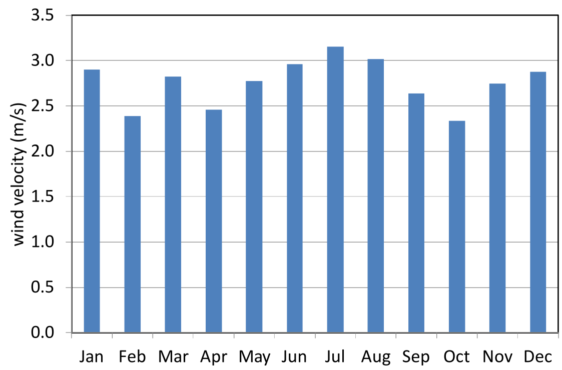

Figure 5 Monthly average of wind velocity.

Due to the short measurement period, covering only one year, the wind speed data currently available may not be sufficient to properly characterize the wind energy potential. For this reason, wind speed data were treated using statistical functions. Particularly, the Weibull density function has been used, which is:

$$f(v) = \left(\frac{k}{C}\right)\left(\frac{v}{C}\right)^{k-1} \exp\left[-\left(\frac{v}{C}\right)^{k}\right] \qquad (2)$$

where v is the wind speed, k the shape parameter and C the scale parameter. The results of the anemological measurement campaign, in terms of observed value and values calculated by mean of eq. (1), are reported in Figure 6.

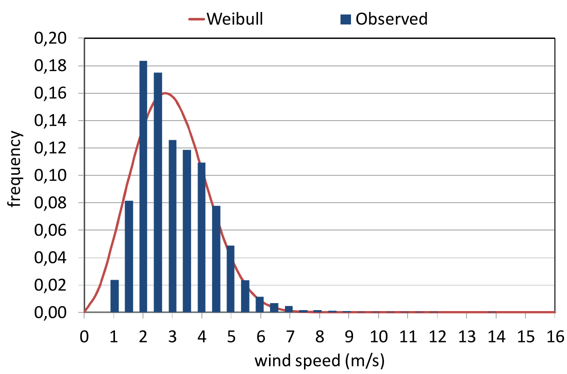

Figure 6 Frequency and probability density function of the wind velocity.

The energy generation systems consist of two vertical-axis wind turbines, with rated power respectively equal to 1 kW and 3 kW.

On the basis of the wind characteristics and of the power curves of the two wind generators, reported in Figure 7, the overall energy production has been evaluated by means of Homer model. In Figure 8 it is reported on a monthly time scale.

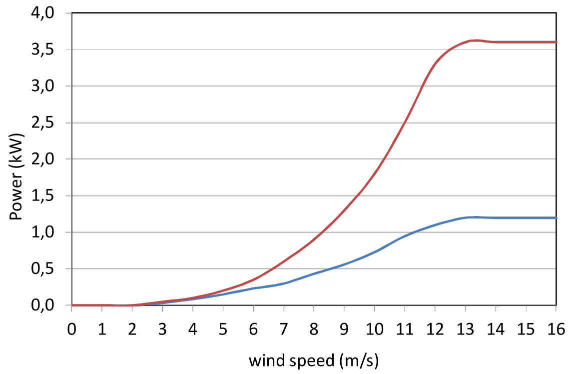

Figure 7 Wind turbine power curves.

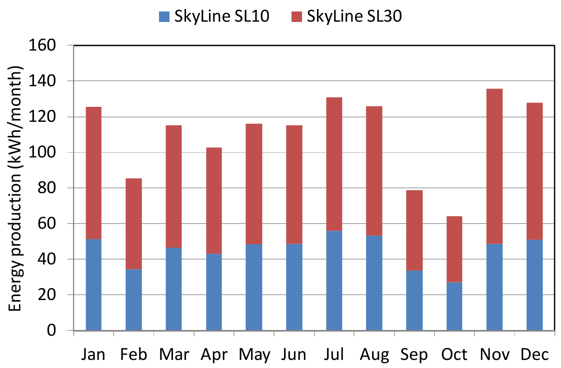

Figure 8 Monthly energy production of the wind generators

PV generators

The characterization of the solar resource at the site has been carried out exploiting the solar radiation data reported in Huld et al. (2012). Specifically, the global solar radiation on the horizontal plane (H_h) was used.

These data have been statistically elaborated by means of a stochastic procedure (Graham and Holland, 1990) with a view to obtaining hourly solar radiation data for a whole year. The results of this calculation are reported in Figure 9, where the frequency distribution of the hourly solar radiation data during the annual daylight time is depicted.

With regard to air temperature, which affects the solar system efficiency and is needed in order to assess the energy production, an experimental campaign was carried out, measuring the parameter during a whole year.

The Vaisala Weather Transmitter WXT520, in the configuration described in the previous paragraph, was used with this aim.

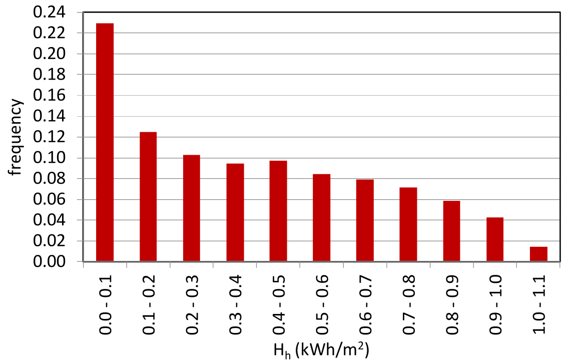

Figure 9 Frequency distribution of hourly solar radiation data during the daylight time for a whole year.

In Figure 10 the annual frequency distribution of the air temperature is depicted.

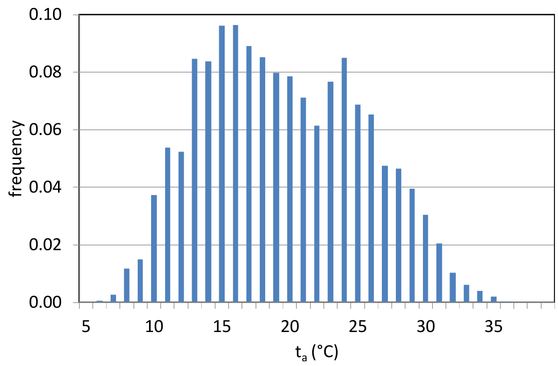

Figure 10 Frequency distribution of air temperature data during a whole year.

The designed solar generation system consists of :

- flat plate PV modules made of polycrystalline silicon cells (peak power $P_p = 2$ kW$_p$; slope 38°);
- biaxial solar tracking PV modules of monocrystalline silicon cells ($P_p = 2$ kWp);
- hybrid PVT modules of monocrystalline silicon cells (peak power $P_p = 2$ kW$_p$; slope 38°).

The feature of the modules (reference efficiency η_r, Nominal Cell Temperature *NOCT*, temperature coefficient β) are reported Table 1.

Table 1
Solar generation system features.

TYPOLOGY	η_r	***NOCT* (°C)**	**β (%/°C⁻¹)**
Flat plate PV	0.11	45	0.4
Tracking PV	0.13	45	0.4
PVT	0.15	46	0.4

In order to assess the energy production, Homer software was used (HOMER, 2015). It simulates the PV plant taking into account the variability of its efficiency with the climatic conditions of the site according to the equation:

$$\eta = \eta_r\left[1-\beta\left(t_a - t_r\right) - \beta\frac{\left(NOCT-20\right)}{800}H\right] \qquad (3)$$

where t_r is the reference temperature and H the solar radiation on the PV plane.

The results of the simulations in terms of energy production are reported in Figure 11.

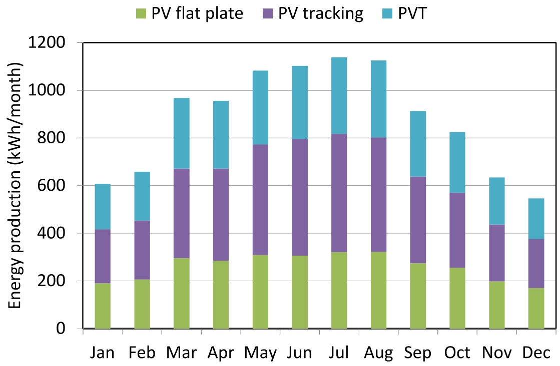

Figure 11 PV system energy production.

Hydrogen production, storage and reconversion

Yearly Hydrogen production

The Hydrogen production from both solar and wind source can be assessed once the global energy production, reported in Figure 12, is known.
In Figures 13 and 14 the monthly production from electrolyser and the yearly storable hydrogen amount are respectively reported.

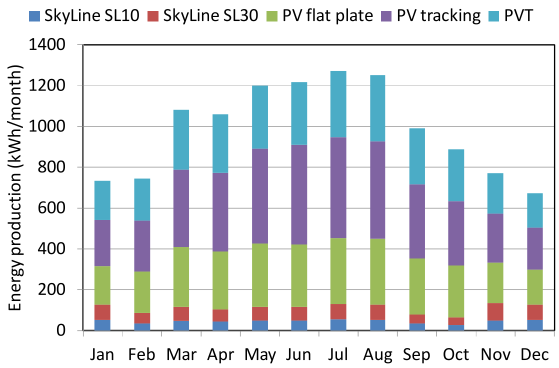

Figure 12 Total energy production from RES

In the studied configuration the whole energy production from RES has been sent to the electrolyser in order to assess the hydrogen flow rate which might be potentially obtained every month.
The next step of the research will be designed to address the effect of the load. Therefore, the further planned analysis will be carried out in transient regime and will be aimed at the assessment of the optimum configuration of the system, which is the configuration where the energy fluxes are controlled in order to maximize the satisfied fraction of the energy demand.

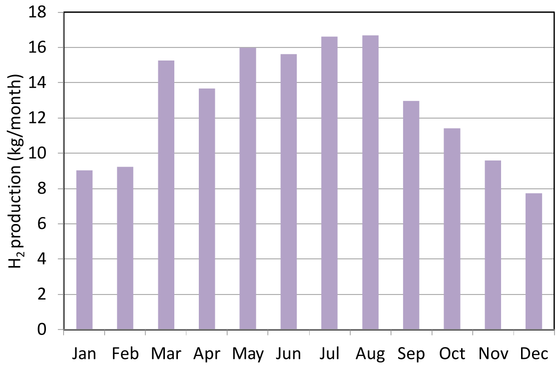

Figure 13 Electrolyser Hydrogen production.

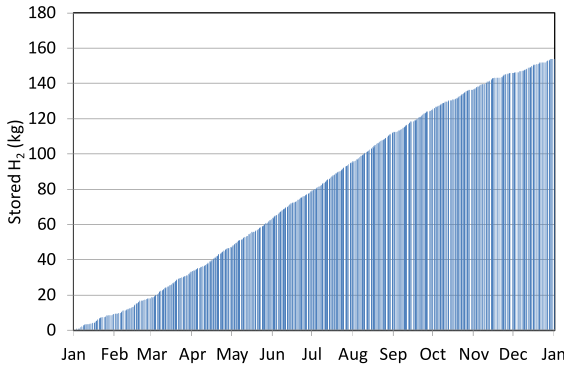

Figure 14 Yearly stored Hydrogen.

As a matter of fact, when the load is taken into account, the renewable source production is either totally or partially used to meet the energy demand, while only possible surplus is sent to the electrolyser whose production is stored to be, in turn, reconverted when RESs are not sufficient (e.g. during the evening hours). The transient regime analysis, hence, will allow all the energy quantities to be assessed, so that the tank capacity will be verified. Moreover several load configurations will be modelled in order to single out the structure that, considering also the climatic conditions at the site, is satisfied by the system to the best.

CONCLUSIONS

Effective policies aimed at emission reduction urgently require new energetic paradigms, in order to prevent dramatic temperature increases and dangerous climatic changes, guaranteeing ecosystems safety. This means giving up the present, obsolete, centralized management model and driving a quick transition towards carbon free ones, enforcing a wide, sustainable resource autonomy.

Such a deep transformation passes through a redesign of the present city energy infrastructures, implementing the *smart city* model, a urban model based on renewable energy, microgeneration, smart grids and energy storage.

In this context, Hydrogen has increasingly shown to be particularly suitable as an energy carrier, being not pollutant, versatile, with a high combustion efficiency and, compared to electric battery, not requiring time consuming recharging.

However, a set of problems prevent its exploitation on a large scale: relevant cost and absence of suitable infrastructures.

To solve these problems a technological improvement, involving systems and designing procedure, is required.

Within this frame, the research here presented is aimed at the analysis of the potentiality of hydrogen when used for energy storage.

To pursuit this aim an apposite system, producing hydrogen from RES through electrolysis and storing it for successive reconversion in a fuel cell, has been designed and here presented. The system is being installed at the *Mediterranea* University of Reggio Calabria and will be operating in the next few months.

Indeed, in the paper, the system is described and a preliminary simulation of the process is presented. The result, consisting in the hydrogen flow rate obtainable for the climate conditions of the site, is a crucial, albeit preliminary, information with a view to singling out the correct operative condition of the system (e.g. load and its variability with time).

The final goal of the whole research would be the design of a configuration that can be used as a contributing factor in meeting building energy demand. As a matter of fact, such an innovative storage system could have a pivotal application in the context of the Nearly-Zero Energy Building patterns (OJEU, 2010).

In this direction future stages of the research are being planned.

NOMENCLATURE

A	fuel cell autonomy
β	temperature coefficient
C	scale parameter
$\dot{C}$	input flow of the fuel cell
ε	efficiency
k	shape parameter
η_r	reference efficiency
H	solar radiation on the PV plane
H_h	solar radiation on horizontal plane
$NOCT$	Nominal Cell Temperature
M	mass
p	pressure
pci	lower calorific value
PM	molecular weight
R	universal gas costant
ρ	density
t_r	reference temperature
t_a	air temperature
v	wind speed
V	volume

Pedix

FC	fuel cell
H_2	hydrogen

REFERENCES

Alajlan, S.A., 1999. Photovoltaic grid-connection system as load-shaving tool in Riyadh, Saudi Arabia. Appl. Energy 63, 91–99.

Allegrezza, M., Giuliani, G., Mileto, G., Pietrafesa, M., Summonte, C., 2012. Impact of increased efficiency on cost of WP. 27th EU PVSEC Eur. Photovolt. Sol. Energy Conf.

Beaudin, M., Zareipour, H., Schellenberglabe, A., Rosehart, W., 2010. Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy Sustain. Dev. 14, 302–314.

Cotana, F., Rossi, F., Nicolini, A., 2011. Evaluation and Optimization of an Innovative Low-Cost Photovoltaic Solar Concentrator. Int. J. Photoenergy 2011.

Divya, K.C., Ostergaard, J., 2009. Battery energy storage technology for power systems - An overview. Electr. Power Syst. Res. 79, 511–520.

El-Shatter, T.F., Eskander, M.N., El-Hagry, M.T., 2006. Energy flow and management of a hybrid wind/PV/fuel cell generation system. Energy Convers. Manag. 47, 1264–1280.

Graham, V.A., Holland, K.G.T., 1990. A method to generate synthetic hourly solar radiation globally. Sol. Energy 44, 333–341.

HOMER, 2015. The Hybrid Optimization Model for Electric Renewables.

Ibrahim, H., Ilinca, A., Perron, J., 2008. Energy storage systems: Characteristics and comparisons. Renew. Sustain. Energy Rev. 12, 1221–1250.

Marino, C., Nucara, A., Pietrafesa, M., 2015. Electrolytic hydrogen production from renewable source, storage and reconversion in fuel cells: the system of the "Mediterranea" University of Reggio Calabria. Energy Procedia.

Marino, C., Nucara, A., Pietrafesa, M., Pudano, A., 2013. An energy self-sufficient public building using integrated renewable sources and hydrogen storage. Energy 57, 95–105. doi:10.1016/j.energy.2013.01.053

Marino, C., Nucara, A., Pietrafesa, M., Pudano, A., Tripodi, M., 2012. Energetic, economic and environmental sustainability of integrated techniques for energy production in buildings using hydrogen as storage system. Renew. Energies Power Qual. J. 10.

Nelson, D.B., Nehrir, M.H., Wang, C., 2006. Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems. Renew. Energy 31, 1641–1656.

OJEU, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), Official Journal of the European Union, L153 vol. 53,18th June 2010.

Parida, B., Iniyan, S., Goic, R., 2011. A review of solar photovoltaic technologies. Renew. Sustain. Energy Rev. 15, 1625–1636.

Razykov, T.M., Ferekides, C.S., Morel, D., Stefanakos, E., Ullal, H.S., Upadhyaya, H.M., 2011. Solar photovoltaic electricity: Current status and future prospects. Sol. Energy 85, 1580–1608. doi:10.1016/j.solener.2010.12.002