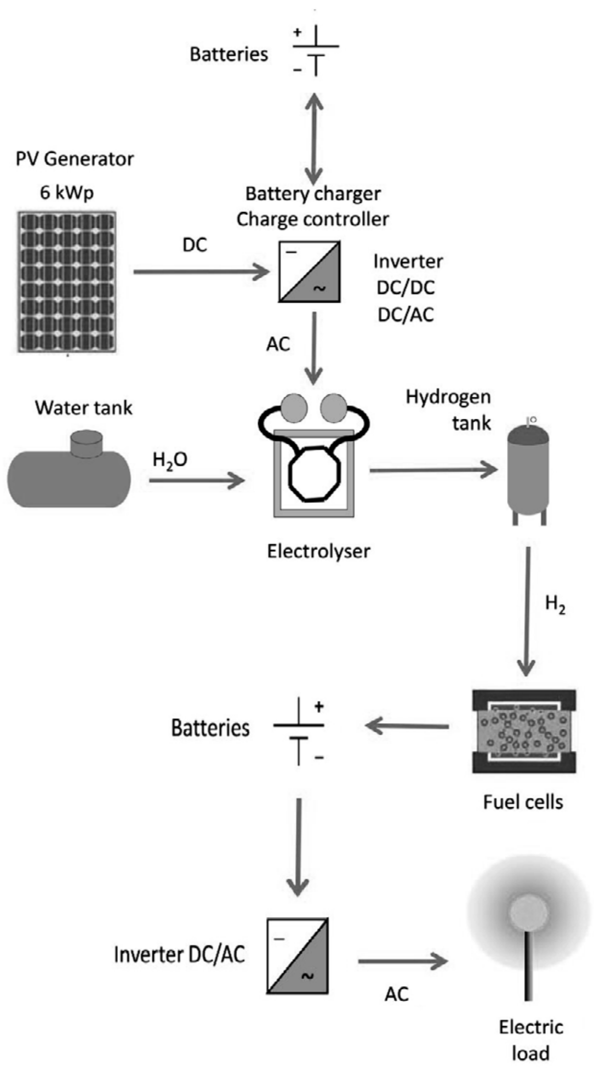
LA MEDITERRANEA VERSO IL 2030
Studi e ricerche sul patrimonio storico e sui paesaggi antropici, tra conservazione e rigenerazione

a cura di Marina Mistretta, Bruno Mussari, Adolfo Santini



Un caso studio di impianto per la riqualificazione sostenibile degli edifici basato sullo stoccaggio e sulla riconversione dell'idrogeno prodotto usando l'energia solare

Rosario Carbone, Concettina Marino, Antonino Nucara, Maria Francesca Panzera, Matilde Pietrafesa
rosario.carbone@unirc.it, concettina.marino@unirc.it, antonino.nucara@unirc.it, francesca.panzera@unirc.it, matilde.pietrafesa@unirc.it

Nell'odierno processo di decarbonizzazione e transizione verso un'economia verde basata sulla produzione di energia distribuita e sostenibile, l'idrogeno è considerato il vettore energetico più promettente, grazie alle sue molteplici proprietà: è pulito, versatile e ha un'alta efficienza di combustione. In particolare, l'energia rinnovabile potrebbe essere utilizzata come fonte primaria per la produzione di idrogeno vicino al punto di utilizzo finale, sfruttando appieno il potenziale energetico locale. Tuttavia, l'attuale costo della sua tecnologia richiede ancora ulteriori ricerche e sviluppi, necessari per ottenere la sua rapida ed efficace penetrazione nel mercato. Inoltre, al momento le infrastrutture di stoccaggio e distribuzione dell'idrogeno, fondamentali per renderlo utilizzabile e competitive, sono ancora lacunose.
In questo scenario, il lavoro analizza un sistema fotovoltaico (PV), dotato di sottosistemi di stoccaggio e riconversione dell'idrogeno. L'impianto tecnologico è pensato per essere facilmente integrato negli edifici per una loro riqualificazione sostenibile; in questa fase, il caso di studio testato era finalizzato alla alimentazione di una parte delle utenze elettriche dell'Università Mediterranea di Reggio Calabria.
In breve, a partire dalla generazione fotovoltaica di elettricità, l'idrogeno viene ottenuto attraverso la produzione elettrolitica, immagazzinato e poi riconvertito in elettricità utilizzando le celle a combustibile. Lo studio è chiaramente in linea con i principali Obiettivi dell'Agenda 2030 per uno sviluppo sostenibile.

THE MEDITERRANEA TOWARDS 2030
STUDIES AND RESEARCH ON HISTORICAL HERITAGE AND ANTHROPIC LANDSCAPES, CONSERVATION AND REGENERATION
www.archistor.unirc.it
ArcHistoR EXTRA 6 (2019)
ISSN 2384-8898
Supplemento di ArcHistoR 12/2019
ISBN 978-88-85479-08-1
DOI: 10.14633/AHR184
OPEN ACCESS

A Case-Study Plant for a Sustainable Redevelopment of Buildings Based on Storage and Reconversion of Hydrogen Generated by Using Solar Energy

Rosario Carbone, Concettina Marino, Antonino Nucara, Maria Francesca Panzera, Matilde Pietrafesa

A new sustainable energy paradigm should be established in the next future to fully realize the decarbonization process. It should be based on *RES* distributed micro-generation[1], smart grids[2], electric mobility[3], storage and hydrogen.

Buildings and their construction sectors, in particular, are globally responsible of 36% of global final energy consumption, corresponding to nearly 40% of CO_2 emissions[4]. This can be easily linked to the population growth and to the changes in the society, making people work more and spend more time indoors[5]. In this frame, redevelopment of buildings by introducing technological plants based on *RES* distributed micro-generation could be very effective.

RES electricity production, characterized by variable and unpredictable over time availability, can efficiently satisfy loads coupled with storage systems. They are based on different techniques[6]:

1. Hvelplund 2006; Official Journal of the European Union (OJEU) 2009; Gonçalves da Silva 2010; Lund 2010; Malara *et alii* 2016; Foley, Olabi 2017; Kyriakopoulos *et alii* 2018; Narayanan *et alii* in press.

2. Gelazaskas, Gamage 2014; Siano 2014.

3. Briggs *et alii* 2016; Gattuso *et alii* 2016; Sinigaglia *et alii* 2017.

4. International Energy Agency (IEA) 2019.

5. Cao *et alii* 2016.

6. Krajacic *et alii* 2012; Foley, Lobera 2013; Lopez-Sabiron *et alii* 2014.

mechanical, electric, chemical, thermal and biological, although the most widespread and versatile systems are at the moment batteries[7].

One of the most environmentally sustainable methods to accumulate renewable energy is its use as a primary source for electrolytic hydrogen production[8], subsequently reconverted in electricity in fuel cells[9]; production can take place both in large plants or in small generation units close to the final use point (buildings)[10]. Hydrogen production and reconversion process is the only generating no carbon dioxide emissions, being its only byproducts water and heat[11].

Due to its environmental sustainability and energetic performances (it is clean, versatile and has a high combustion efficiency), interest for hydrogen use as energy carrier is today increasing[12]. It can address multiple power sectors and applications across stationary[13], transportation[14] and portable; it can provide energy at all scales, ranging from micro-power sources for small devices to multi-MW power plants[15].

In the paper a low-power (6 kWp) PV system providing electrical energy for the lighting of a University parking is presented, together with its energetic behavior. The storage of the generated electrical energy is basically achieved through production and accumulation of electrolytic hydrogen, reconverted into electricity, when needed, by using fuel cells.

7. Carbone 2015.

8. Knut 1998; Agbossou *et alii* 2004.

9. Hoffmann 2001; Kelly 2014; Marino *et alii* 2015.

10. Santarelli, Macagno 2004; Avril *et alii* 2010; Dincer, Rosen 2011; Marino *et alii* 2012; Chaubey *et alii* 2013; Marino *et alii* 2013; Marino *et alii* 2015; Won *et alii* 2017.

11. Goel *et alii* 2003; Kreith, West 2004; Hosseini, Wahid 2016; Da Silva Veras *et alii* 2017; Carroquino *et alii* 2018; Lorestani, Ardehali 2018.

12. Afgan, Carvalho 2004; Momirlana, Veziroglu 2005; Barbir 2009; Bockris 2013; Marchenko, Solomin 2015; Ball, Weeda 2015; Nikolaidis, Poullikkas 2017; Cao *et alii* 2018.

13. Moreno-Benito *et alii* 2017.

14. Demir 2018.

15. Yilanci *et alii* 2008; Sunita Sharma, Krishna 2015; Arsalis *et alii* 2018.

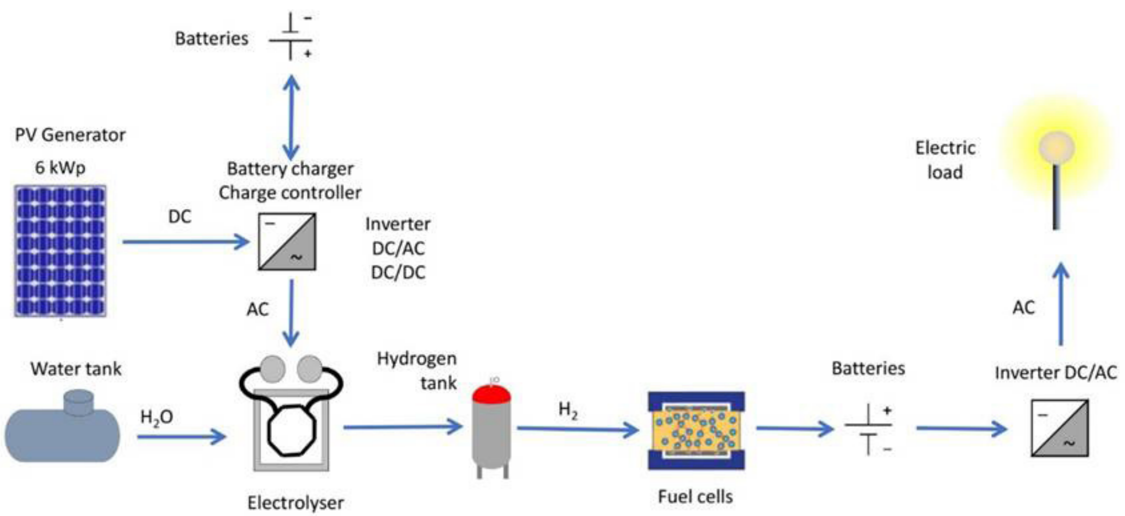


Figure 1. Scheme of the PV plant with hydrogen generation, storage and reconversion (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

Structure of the Technological Plant

The case-study plant (fig. 1) essentially consists of: a RES section, based on PV panels and an hybrid inverter equipped with a first-level battery pack, a hydrogen production section, containing an electrolyzer, a water tank and a tank for the gas storage, a power section, based on a fuel cell, coupled to a second-level battery pack and an inverter specifically devoted to the feeding of the load, and a control section, with a Programmable Logic Controller (PLC) for monitoring process execution.

The system operation is as follows: during the day, the electrical power produced by PV panels is converted into alternating current by the three-phase inverter for supplying the electrolyzer generating hydrogen. The surplus PV power is managed by the same hybrid inverter for charging the first-level battery. A fuel cell converts hydrogen into electrical energy when it is needed, sending it to a second-level battery pack, after which a second inverter supplies the AC load, also in absence of solar radiation.

Maximum power	360 W_p
Efficiency (η)	22,1%
Temperature coefficient (β)	-0.29%/°C
NOCT	41,5°C

Left, table 1. Characteristics of PV panels; bottom, table 2. Characteristics of the hybrid inverter.

Nominal power	6000 VA	Max power of charge/discharge	6000 W
DCinput	720 VDC 11 A	Efficiency	97.6%
ACoutput	400 VAC 50 Hz9 A		

PV Generator

The 6kWp PV generator consists of monocrystalline silicon panels, the technical characteristics of which are shown in Table 1. It is formed by 2 strings connected in parallel, each consisting of 9 panels in series, with 15° lying, S-SE (160°N) facing.

Three-Phase Hybrid Inverter

Between the PV panels and the load there is a single device that includes a DC/DC converter (with charge regulator function for the first-level battery pack), double Maximum Power Point Tracker (MPPT) and a three-phase DC/AC inverter. DC required for electrolyzer operation is supplied by a dedicated controlled rectifier. The characteristics of the inverter are reported in Table 2; it supplies with priority the electrolyzer and subsequently other loads.

First-Level Battery Pack

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.

Stack capacity	2 Nm^3/h
Amount of demineralized water	1.9 l/h
Electric power	2 -10 kW
Conversion efficiency	60%
Operating pressure	20 bar
Operating temperature	80 °C
Purity of stored hydrogen	99,99 %
Supplying Voltage	400 VAC, 50 Hz

Table 3. Technical characteristics of the electrolyzer.

Demineralizer

The electrolyzer needs demineralized water with the characteristics shown in Table 3; it is contained in a water tank for its reintegration.

Electrolyzer

Starting from demineralized water and PV energy, the electrolyzer produces hydrogen which is compressed and stored in the tank before being sent to the fuel cell. Its main characteristics are reported in Table 3.

Separation Tanks

Hydrogen and oxygen generated in the cell come out in a two-phase composition (liquid and gas) mixed with KOH particles, and enter into separation tanks where the gaseous phases separate from the liquid ones, which deposit on the bottom of the tank and return into the electrolyzer. Potassium hydroxide is entirely reused, while water must be reintegrated.

Gas Purifier

Before being released the two gases are purified by filters. Hydrogen is purified in a dedicated section by filters for KOH and oxygen removing and water absorption.

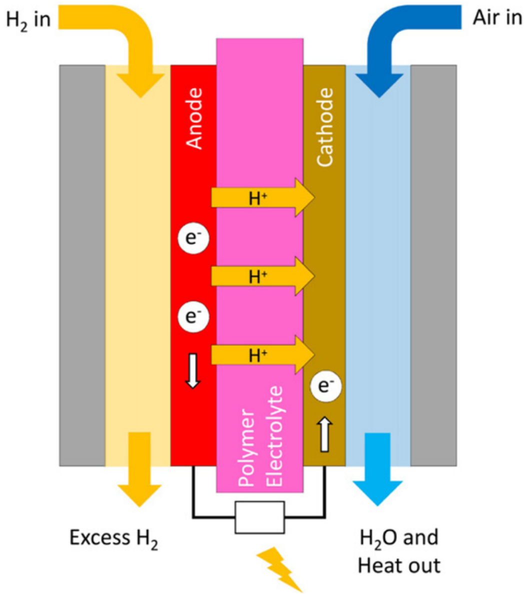


Figure 2. Scheme of a Fuel cell (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

Water Refrigerating Chiller

The excess heat released during the process is removed by a water-cooling circuit which exchanges heat with the electrolyte that is recirculated. Its cooling power is 7.5 kW.

Storing Tank

Hydrogen is stored in a tank with a capacity of 0.7 m3 at a maximum pressure of 30 bar, protected from direct solar radiation and placed in a dry, cool and ventilated environment.

Fuel Cell

Fuel cell transforms chemical energy into electrical energy in direct current. A fuel (typically hydrogen) and an oxidant (oxygen or air) enter the cell, from which direct current, water and heat

Delivered power	1'676 W	Storing temperature	-30 - 40 °C
Output voltage	47 ÷ 57 Vdc	Environment temperature	- 45 - 70 °C
Maximum H_2 consumption	1.37 Nm^3/h	Cabinet temperature	0 - 60 °C
Efficiency	40%	H_2pressure	0.43 bar
Input current for auxiliaries	220/50 VAC/Hz	H_2 purity	99.95 %

Table 4. Characteristics of the fuel cell.

Nominal power	3000 VA	Max power of charge/discharge	900 W
DC input	48 VDC 50 A	Efficiency	98%
ACoutput	230 VAC 50 Hz13 A		

Table 5. Characteristics of the fuel cell inverter.

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.

A scheme of the process is reported in Figure 2.

The most suitable cells for our case are the Proton Exchange Membranes (PEMs) which main characteristics are shown in Table 4.

Second-Level Battery Pack

At the exit from the fuel cell there is a 48 V battery pack for energy accumulation: each battery has a nominal voltage of 12 V and a nominal capacity of 92 Ah.

Fuel Cell Inverter

The fuel cell inverter is used both for supplying the AC load and for regulating charge of the second-level battery; its characteristics are reported in Table 5.

Control System

A Programmable Logic Controller (PLC) monitors and controls all process parameters in order to guarantee its correct execution, as well as to ensure the safety of the system. In case of failures, it emits alarms and stops the gas production.

Starting Operation

In order to work in safety conditions and prevent explosions, the plant is inertized both at its turning on and off through nitrogen injection, at a pressure of 7-25 bar; this operation eliminates oxygen in the starting phase and hydrogen in the stopping one, depressurizing the system.

Analysis of the System Functioning

The energetic analyses were conducted starting from the values of the maximum power delivered by the fuel cell and the input power to the electrolyzer, for determining the optimal system configuration to fulfil the load.

A necessary condition for the system to function properly is to achieve a positive annual balance between hydrogen production and consumption: the storage system must therefore have the capacity to meet periods of low production, such as winter. Furthermore, the PV generator and the tank must be adequately sized so as not to have PV production surplus that cannot be converted into hydrogen due to tank capacity limits (0.75 m^3) or stored in the batteries.

The global efficiency of the process is:

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

where:

ε_{EL} electrolyzer efficiency

ε_{FC} fuel cell efficiency.

The energetic analysis and that of hydrogen production have been carried out on an hourly basis using the HOMER simulation and optimization model (Hybrid Optimization of Multiple Energy Resources), a dynamic software developed by the National Renewable Energy Laboratory (NREL), USA, for the evaluation of technologies and plant types with thermal and electrical generation.

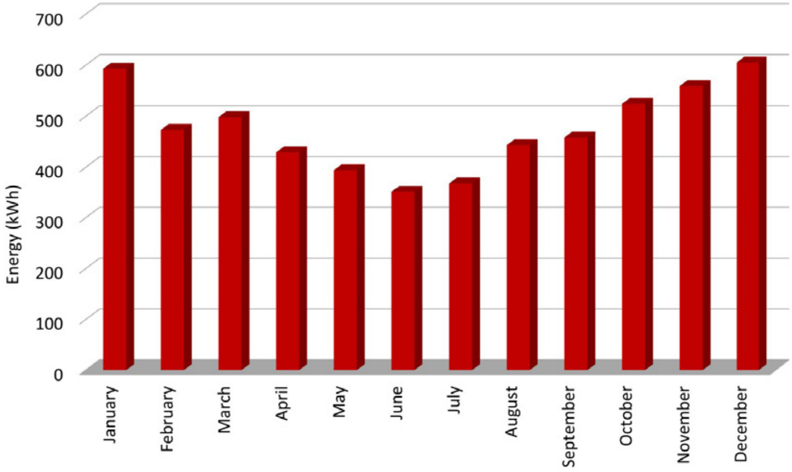


Figure 3. Monthly trend in load electricty consumption (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

Electrical Load

First step was the assessment of the hourly electrical load of headlights for the lighting of the parking areas of Engineering Departments. Operating in the evening, the load is powered only by the fuel cell.

Considering the maximum power deliverable by the fuel cell (1’676 W) and taking into account power losses, the maximum load that can be supplied by the cell is 1’300 W. Attention has been focused on 52 lamps of 25 W each, for a total power of 1’300 W and an annual consumption of 5’694 kWh. The monthly consumption trend is shown in Figure 3.

Climatic Data

Hourly values of the global solar radiation incident on a horizontal surface, registered by a pyranometer installed next to the system, were used. Hourly air temperature data have been registered by a flanked meteorological station. The analyzed reference period is the year 2017.

Figure 4 shows the monthly maximum and average values of solar radiation on the horizontal in the year, while in Figure 5 the monthly average daily trends in the months of maximum and minimum irradiation (June and December 2017) are shown.

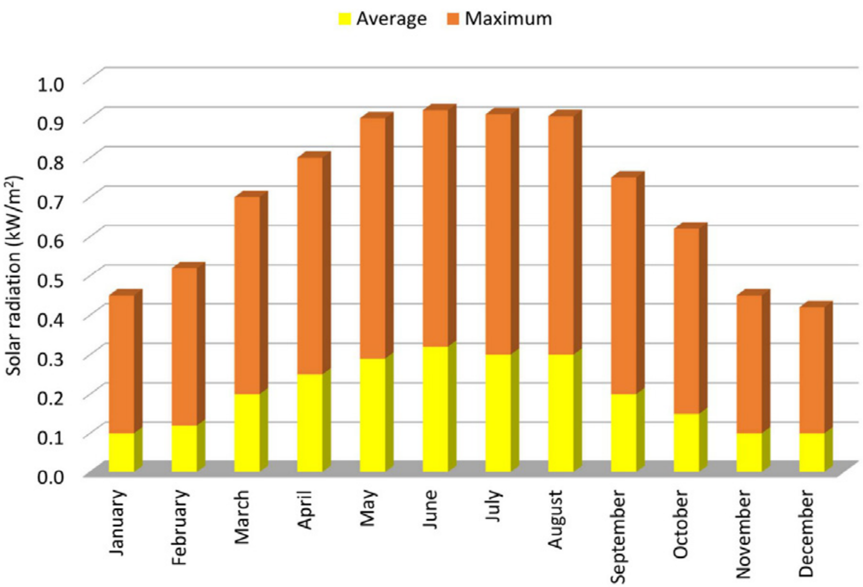


Figure 4. Monthly maximum and average values of daily solar radiation on the horizontal (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

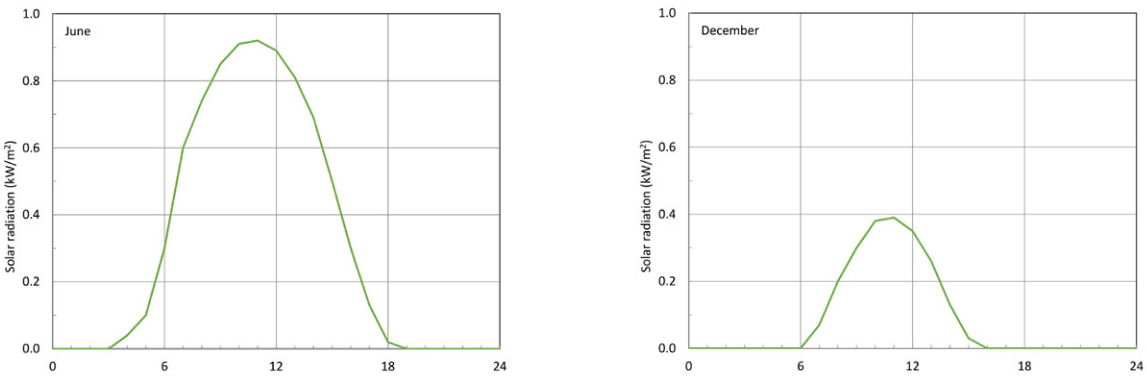


Figure 5. Average hourly solar radiation profile in June and December 2017 (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

PV System

Figures 6 and 7 respectively show the monthly mean values of the daily power and the monthly energy production of the plant. The yearly energy production is 10.244 kWh: it is partly sent to the electrolyzer and partly stored in batteries.

Hydrogen Production and Efficiency

Hourly hydrogen production, at pressure p = 1,01325 bar and temperature T = 0 °C, with reference to the maximum hourly energy entering the electrolyzer ($Emax$= 10 kWh) is:

$$V_{H_2}^{max} = 2\ Nm^3$$

$$m_{H_2}^{max} = V_{H_2}^{max} \times \rho_{H_2}$$

where ρ_{H_2} is hydrogen density ; $(0,0899 \frac{kg}{Nm^3})$; it follows:

$$m_{H_2}^{max} = 2\ Nm^3 \times 0,0899\ kg/Nm^3 = 0.18\ kg.$$

Electrolyzer efficiency is given by:

$$\varepsilon_{EL} = \frac{pci_{H2}}{electrolyserconsumption}$$

where ρci_{H_2} is hydrogen lower calorific value $(3 \frac{kWh}{Nm^3})$ whereas electrolyzer consumption is $\frac{kWh}{Nm^3}$.

Consequently:

$$\varepsilon_{EL} = \frac{3\frac{kWh}{Nm^3}}{5\frac{kWh}{Nm^3}} = 0.6$$

During the year the electrolyzer produces about 341 kg of hydrogen.

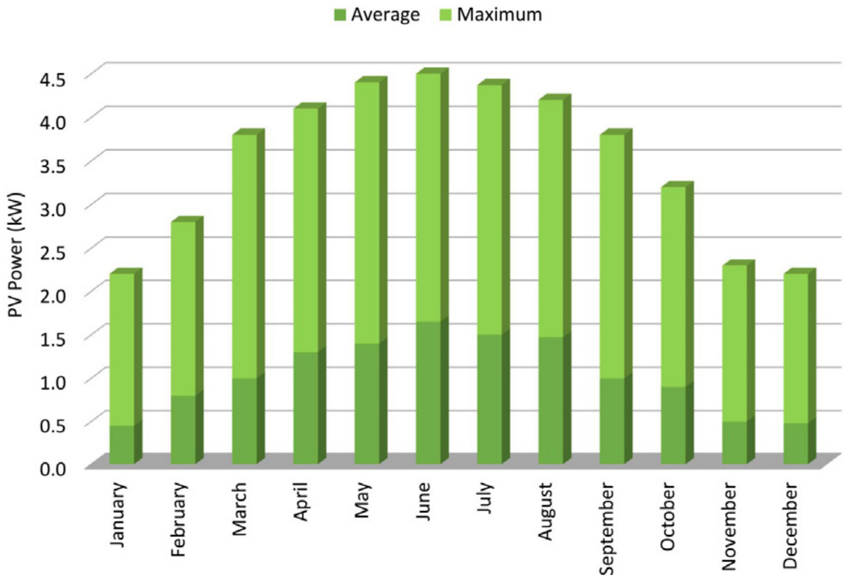


Figure 6. Maximum and average daily power production on a monthly base (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

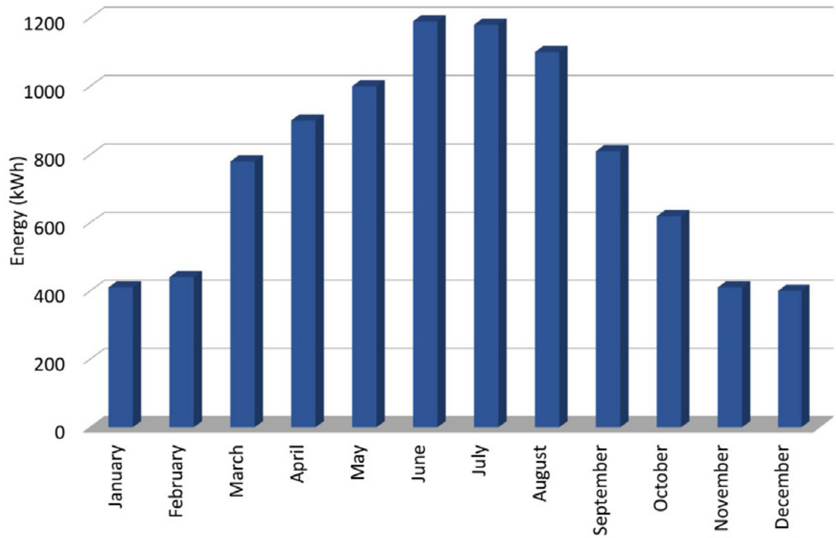


Figure 7. Energy production of the plant on a monthly base (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

Stored Hydrogen and Tank Capacity

Stored hydrogen volume A_{H_2} is given by:

$$A_{H_2}^{t+1} = A_{H_2}^{t} + V_{H_2}^{t}$$

wherein the volume $V_{H_2}^{t}$ is positive in the production phase and negative in the consumption one. The capacity of the tank is dimensioned in relation to the maximum storage during the year Amax:

$$V_s = \frac{A_{max} \times \rho_{H_2} \times R \times T}{p \times PM_{H_2}}$$

where:
A_{max} is hydrogen maximum storage during the year
ρ_{H_2} is hydrogen density
R is gas constant
T is the temperature
p is hydrogen maximum pressure in the tank
PM_{H_2} is hydrogen molecular weight

Being the maximum annual storage A_{max} = 30 kg, the capacity of the tank, at maximum pressure 250 bar (compression absorbs about 2% of the gas energy content) is 1.02 m^3; for a tank volume 0.75 m^3 it is necessary to use 2 tanks.

Hydrogen Consumption and Fuel Cell Production

Hydrogen volume consumed by the fuel cell is given by:

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

where:

E_{FC} energy delivered by the fuel cell

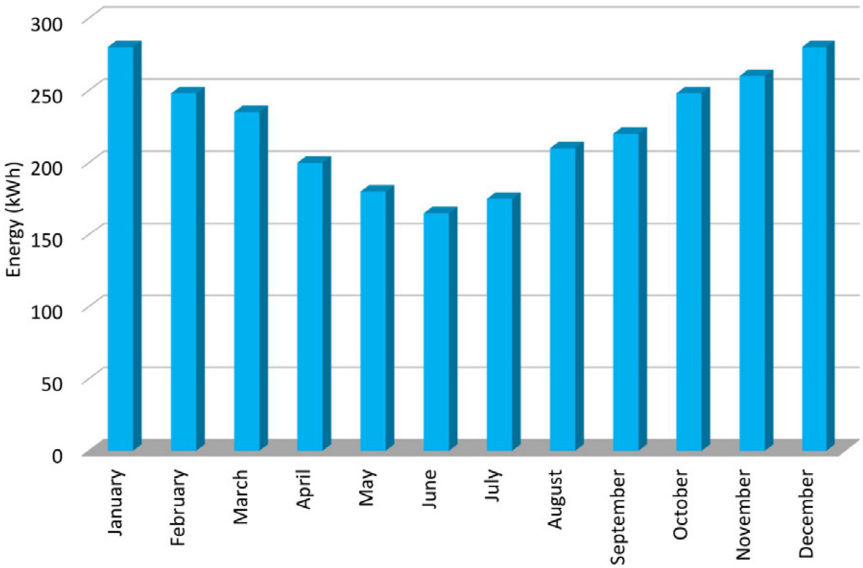


Figure 8. Fuel cell energy production (the figure was produced on its own by the Authors expressly for the submitted work R. Carbone, C. Marino, A. Nucara, M.F. Panzera, M. Pietrafesa).

ε_{FC} efficiency of the fuel cell
PCI_{H_2} hydrogen calorific value $(3\ kWh/Nm^3)$.

During the year the fuel cell consumes 119 kg of hydrogen whereas the electrolyzer produces 125 kg: consequently the difference between annual production and consumption is 6 kg. The energy monthly produced is shown in Figure 8.

Summary Results

Table 6 shows the values of production and consumption of both energy and hydrogen in the various components.

Yearly electric energy (kWh)		Yearly hydrogen mass (kg/year)	
PV energy production	10.244	Produced	125
Electrolyzer input energy	5.388	Consumed	119
Fuel cell production	2.445	Stored	6
Load consumption	4.964		

Table 6. Production and consumption of energy and hydrogen in the various components.

Economic Considerations

With an initial investment of € 100'000 for the entire system, the energy production cost is 0.80 €/kWh: high figure compared to the value of 0.22 €/kWh of energy withdrawal from the national electric grid; in order to become competitive the system should cost about ¼ of present value.

Economic convenience increases using PV production redundancies; also thermal energy produced by some components of the system (electrolyzer and fuel cell), currently not used, could be exploited. In this case, the annual cost of electricity production will be reduced by that required to meet the electrical and thermal loads.

Conclusions

An application of hydrogen technologies for the sustainable redevelopment of buildings has been presented and discussed. The paper analyses a photovoltaic (PV) system, equipped with hydrogen production, storage and reconversion subsystems; the sizing procedure of its components chain has been evidenced with detail.

The main critical aspects of electrolytic hydrogen production and reconversion in fuel cells consist in the low global efficiency of the process (24 %) and in the big hydrogen volumes necessary to satisfy the demand. Moreover, the cost of the energy unit stored in hydrogen presently is greater than the unitary one produced by PV or wind systems or taken from the grid.

Consequently, although mature, from an economic point of view, hydrogen technology currently is non-competitive and in order to have acceptable pay back times the system investment cost should be reduced to about 1/4 of the current value or incentivizing policies should be introduced for attributing to hydrogen production fares able to cover major costs of its technology.

Hoping also for a rapid evolution of its transport and storage techniques, hydrogen technologies might be widely adopted in public buildings for respecting UE standards concerning the nZEBs.

Bibliography

Afgan, Carvalho 2004 - N.H. Afgan, M.G. Carvalho, *Sustainability assessment of hydrogen energy systems*, in «International Journal of Hydrogen Energy», 2004, 29, Issue 13, pp. 1327-1342, https://doi.org/10.1016/j.ijhydene.2004.01.005 (accessed 15 March 2019).

Agbossou *et alii* 2004 - K. Agbossou *et alii*, *Electrolytic hydrogen based renewable energy system with oxygen recovery and re-utilization*, in «Renewable Energy», 2004, 29, Issue 8, pp. 1305-1318, https://doi.org/10.1016/j.renene.2003.12.006 (accessed 25 October 2019).

Arsalis, Alexandrou, Georghiou 2018 - A. Arsalis, A.N. Alexandrou, G.E. Georghiou, *Thermoeconomic modelling of a completely autonomous, zero-emission photovoltaic system with hydrogen storage for residential applications*, in «Renewable Energy», 2018, 126, pp. 354-369, https://doi.org/10.1016/j.renene.2018.03.060 (accessed 7 April 2019).

Avril *et alii* 2010 - S. Avril *et alii*, *Multi-objective optimization of batteries and hydrogen storage technologies for remote photovoltaic systems*, in «Energy», 2010, 35, Issue 12, pp. 5300-5308, https://doi.org/10.1016/j.energy.2010.07.033 (accessed 9 October 2019).

Ball, Weeda 2015 - M. Ball, M. Weeda, *The hydrogen economy. Vision or reality?*, in «International Journal of Hydrogen Energy», 2015, 40, Issue 25, pp. 7903-7919, https://doi.org/10.1016/j.ijhydene.2015.04.032 (accessed 18 March 2019).

Barbir 2009 - F. Barbir, *Transition to renewable energy systems with hydrogen as an energy carrier*, in «Energy» 2009, 34, pp. 308-312, https://doi.org/10.1016/j.energy.2008.07.007 (accessed 18 March 2019).

Bockris 2013 - J.O.M. Bockris, *The hydrogen economy: Its history*, in «International Journal of Hydrogen Energy», 2013, 38, pp. 2579-2588, https://doi.org/10.1016/j.ijhydene.2012.12.026 (accessed 18 March 2019).

Briggs et *alii* 2016 - I. Briggs *et alii, Sustainable non-automotive vehicles: The simulation challenges*, in «Renewable and Sustainable Energy Reviews», 2016, 68, Part 2, pp. 840-851, https://doi.org/10.1016/j.rser.2016.02.018 (accessed 13 March 2019).

Cao, Dai, Liu 2016 - X. Cao, X. Dai, J. Liu, *Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade*, in «Energy and Buildings», 2016, 128, pp. 198-213, https://doi.org/10.1016/j.enbuild.2016.06.089 (accessed 21 April 2019).

Cao et *alii* 2018 - F. Cao *et alii*, *Development of the direct solar photocatalytic water splitting system for hydrogen production in Northwest China: Design and evaluation of photoreactor*, in «Renewable Energy», 2018, 121, pp. 153-163, https://doi.org/10.1016/j.renene.2018.01.016 (accessed 7 April 2019).

Carbone 2015 - R. Carbone, *PV Plants with Distributed MPPT founded on Batterie*s, in «Solar Energy», 2015, 122, pp. 910-923.

Carroquino *et alii* 2018 - J. Carroquino *et alii*, *Combined production of electricity and hydrogen from solar energy and its use in the wine sector*, in «Renewable Energy», 2018, 122, pp. 251-263, https://doi.org/ 10.1016/j.renene.2018.01.106 (accessed 15 March 2019).

Chaubey *et alii* 2013 - R. Chaubey *et alii*, *A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources*, in «Renewable and sustainable energy reviews», 2013, 23, pp. 443-462, https://doi.org/10.1016/j.rser.2013.02.019 (accessed 12 September 2019).

Da Silva Veras *et alii* 2017 - T. Da Silva Veras *et alii*, *Hydrogen: Trends, production and characterization of the main process worldwide*, in «International Journal of Hydrogen Energy», 2017, 42, pp. 2018-2033, https://doi.org/10.1016/j.ijhydene.2016.08.219 (accessed 21 February 2019).

Demir, Dincera 2018 - M.E. Demir, I. Dincera, *Cost assessment and evaluation of various hydrogen delivery scenarios*, in «International Journal of Hydrogen Energy», 2018, 43, pp. 10420-10430, https://doi.org/10.1016/j.ijhydene.2017.08.002 (accessed 7 April 2019).

Dincer, Rosen 2011 - I. Dincer, M.A. Rosen, *Sustainability aspects of hydrogen and fuel cell systems*, in «Energy for sustainable development», 2011, 15, pp. 137-146, https://doi.org/10.1016/j.esd.2011.03.006 (accessed 9 September 2019).

Foley, Lobera 2013 - A. Foley, D. Lobera, *Impacts of compressed air energy storage plant on an electricity market with a large renewable energy portfolio*, in «Energy», 2013, 57, pp. 85-94, https://doi.org/10.1016/j.energy.2013.04.031 (accessed 25 May 2019).

Foley, Olabi 2017 - A. Foley, A.G. Olabi, *Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change*, in «Renewable and Sustainable Energy Reviews», 2017, 68, Part 2, pp. 1112-1114, https://doi.org/10.1016/j.rser.2016.12.065 (accessed 13 March 2019).

Gattuso *et alii* 2016 - D. Gattuso *et alii*, *Sustainable Mobility: Environmental and Economic Analysis of a Cable Railway, Powered by Photovoltaic System*, in «International Journal of Heat and Technology», 2016, 34/1, pp. 7-14, https://doi.org/10.18280/ijht.340102 (accessed 1 May 2019).

Gelazaskas, Gamage 2014 - L. Gelazaskas, K.A.A. Gamage, *Demand side management in smart grid: a review and proposal for future direction*, in «Sustainable Cities and Societies», 2014, 11, pp. 22-30.

Goel *et alii* 2003 - N. Goel, D.J. Goswami, S.T. Mirabal, H.A. Ingley, *Hydrogen Production*, in «Advances in Solar Energy: An Annual Review of Research and Development», 2003, 15, pp. 411-416.

Gonçalves da Silva 2010 - C. Gonçalves da Silva, *Renewable energies: choosing the best options*, in «Energy», 2010, 35, pp. 3179-3193, https://doi.org/10.1016/j.energy.2010.03.061 (accessed 13 March 2019).

Hoffmann 2001 - P. Hoffmann, *Tomorrow's Energy: Hydrogen, Fuel Cells and the Prospects for a Cleaner Planet*, The MIT Press, Cambridge, Massachusetts 2001, https://doi.org/10.1017/S1466046602251261 (accessed 13 October 2019).

Hosseini, Wahid 2016 - S.E. Hosseini, M.A. Wahid, *Hydrogen production from renewable and sustainable energy resources: Promising green energy carrier for clean development*, in «Renewable and sustainable energy reviews», 2016, 57, pp. 850-866, https://doi.org/10.1016/j.rser.2015.12.112 (accessed 21 February 2019).

Hvelplund 2006 - F. Hvelplund, *Renewable energy and the need for local energy markets*, in «Energy», 2006, 31, pp. 2293-2302, https://doi.org/10.1016/j.energy.2006.01.016 (accessed 13 March 2019).

Kelly 2014 - N.A. Kelly, *Hydrogen production by water electrolysis*, in A. Basile, A. Iulianelli (eds.), *Advances in Hydrogen production storage and distribution*, Woodhead Publishing, Cambridge 2014, pp. 159-185, https://doi.org/10.1533/9780857097736.2.159 (accessed 25 October 2019).

Knut 1998 - A. Knut, *Hydrogen production by electrolysis*, in T.O. Saetre (eds.), *Hydrogen Power: Theoretical and Engineering Solutions*, Proceedings of the HYPOTHESIS II Symposium, (Grimstad, Norway, August 18-22, 1997), Klewer Academic Publishers, London 1998, pp. 91-102.

KRAJACIC *ET ALII* 2012 - G. KRAJACIC *ET ALII*, *Analysis of financial mechanisms in support to new pumped hydropower storage projects in Croatia*, in «Applied Energy», 2012, 101, pp. 161-171, https://doi.org/10.1016/j.apenergy.2012.07.007 (accessed 21 April 2019).

KREITH, WEST 2004 - F. KREITH, R. WEST, *Fallacies of a Hydrogen Economy: A Critical Analysis of Hydrogen Production and Utilization*, in «Journal of Energy Resources Technology», 2004, 126, pp. 249-257, https://doi.org/10.1115/1.1834851 (accessed 21 February 2019).

KYRIAKOPOULOS *ET ALII* 2018 - G. KYRIAKOPOULOS *ET ALII*, *Electricity consumption and RES plants in Greece: Typologies of regional units,* in «Renewable Energy», 2018, 127, pp. 134-144, https://doi.org/10.1016/j.renene.2018.04.062 (accessed 13 March 2019).

LOPEZ-SABIRON *ET ALII* 2014 - A.M. LOPEZ-SABIRON *ET ALII*, *Carbon footprint of a thermal energy storage system using phase change materials for industrial energy recovery to reduce the fossil fuel consumption*, in «Applied Energy», 2014, 135, pp. 616-624, https://doi.org/10.1016/j.apenergy.2014.08.038 (accessed 25 May 2019).

LORESTANI, ARDEHALI 2018 - 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*, in «Renewable Energy», 2018, 119, pp. 490-503, https://doi.org/10.1016/j.renene.2017.12.037 (accessed 15 March 2019).

LUND 2010 - H. LUND, *The implementation of renewable energy systems. Lessons learned from the Danish case*, in «Energy», 2010, 35, pp. 4003-4009, https://doi.org/10.1016/j.energy.2010.01.036 (accessed 13 March 2019).

MALARA *ET ALII* 2016 - A. MALARA *ET ALII, Energetic and economic analysis of shading effects on PV panels energy production*, in «International Journal of Heat and Technology», 2016, 34/3, pp. 465-472, https://doi.org/10.18280/ijht.340316 (accessed 13 March 2019).

MARCHENKO, SOLOMIN 2015 - O.V. MARCHENKO, S.V. SOLOMIN, *The future energy: Hydrogen versus electricity*, in «International Journal of Hydrogen Energy», 2015, 40, pp. 3801-3805, https://doi.org/10.1016/j.ijhydene.2015.01.132 (accessed 18 March 2019).

MARINO *ET ALII* 2012 - C. MARINO *ET ALII*, *Energetic, economic and environmental sustainability of integrated techniques for energy production in buildings using hydrogen as storage system*, in «Renewable Energy & Power Quality Journal», 2012, 10, pp. 663-668, https://doi.org/10.24084/repqj10.663 (accessed 9 October 2019).

MARINO *ET ALII* 2013 - C. MARINO *ET ALII*, *An energy self-sufficient public building using integrated renewable sources and hydrogen storage*, in «Energy», 2013, 57, pp. 95-105, https://doi.org/10.1016/j.energy.2013.01.053 (accessed 12 September 2019).

MARINO *ET ALII* 2015a - C. MARINO *ET ALII*, *Hydrogen production from RES, storage and reconversion in fuel cells*, in V. GARG, J. MATHUR (eds.), Proceedings of the 14th International Building Simulation Conference, (Hyderabad, India, December 7-9, 2015), BS publications, Hyderabad 2015, pp. 1149-1156.

MARINO, NUCARA, PIETRAFESA 2015b - 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*, in «Energy Procedia», 2015, 78, pp. 818-823, https://doi.org/10.1016/j.egypro.2015.11.001 (accessed 1 October 2019).

Momirlana, Veziroglu 2005 - M. Momirlana, T.N. Veziroglu, *The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet*, in «International Journal of Hydrogen Energy», 2005, 30, pp. 795-802, https://doi.org/10.1016/j.ijhydene.2004.10.011 (accessed 15 March 2019).

Moreno-Benito, Agnolucci, Papageorgiou 2017 - M. Moreno-Benito, P. Agnolucci, L.G. Papageorgiou, *Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development*, in «Computers and chemical engineering», 2017, 102, pp 110-127, https://doi.org/0.1016/j.compchemeng.2016.08.005 (accessed 7 April 2019).

Narayanan *et alii* in press - A. Narayanan *et alii*, *Feasibility of 100% renewable energy-based electricity production for cities with storage and flexibility*, in «Renewable Energy», in press.

Nikolaidis, Poullikkas 2017 - P. Nikolaidis, A. Poullikkas, *A comparative overview of hydrogen production processes*, in «Renewable and sustainable energy reviews», 2017, 67, pp. 597-611, https://doi.org/10.1016/j.rser.2016.09.044 (accessed 18 March 2019).

Official Journal of the European Union (OJEU) 2009 - Official Journal of the European Union (OJEU), *On the promotion of the use of energy from renewable sources*, 5 June 2009, 140, pp. 63-73, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF

Santarelli, Macagno 2004 - M. Santarelli, S. Macagno, *Hydrogen as an energy carrier in stand-alone applications based on PV and micro-hydro systems*, in «Energy», 2004, 29, pp. 1159-1182, https://doi.org/10.1016/j.energy.2004.02.023 (accessed 15 October 2019).

Siano 2014 - P. Siano, *Demand responde and smart grids. A survey, in «*Renewable and sustainable energy reviews», 2014, 30, pp. 461-478.

Sinigaglia *et alii* 2017 - T. Sinigaglia *et alii*, *Production, storage, fuel stations of hydrogen and its utilization in automotive applications-a review*, in «International Journal of Hydrogen Energy», 2017, 42, pp. 24597-24611, https://doi.org/10.1016/j.ijhydene.2017.08.063 (accessed 13 March 2019).

Sunita Sharma, Krishna 2015 - S. Sunita Sharma, G. Krishna, *Hydrogen the future transportation fuel: From production to applications*, in «Renewable and sustainable energy reviews», 2015, 43, pp. 1151-1158, https://doi.org/10.1016/j.rser.2014.11.093 (accessed 7 April 2019).

Won *et alii* 2017 - W. Won *et alii*, *Design and operation of renewable energy sources based hydrogen supply system: Technology integration and optimization*, in «Renewable energy», 2017, 103, pp. 226-238, https://doi.org/10.1016/j.renene.2016.11.038 (accessed 21 September 2019).

Yilanci, Dincer, Ozturk 2008 - A. Yilanci, I. Dincer, H.K. Ozturk, *A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications*, in «Progress in Energy and Combustion Science», 2008, 35, pp. 231-244, https://doi.org/10.1016/j.pecs.2008.07.004 (accessed 7 April 2019).