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Energetic, economic and environmental sustainability of integrated techniques for energy production in buildings using hydrogen as storage system

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Abstract

In present days increasing attention must be paid to the control of the use of fossil fuels, major cause of greenhouse gas emission and climate change; particularly, a significant portion of total energy is consumed in buildings and could be significantly reduced both increasing energy efficiency and using renewable sources.
At the moment, the intrinsic discontinuity of renewable energy limits its widespread use in buildings: anyway, integration of plants with energy storage systems could efficiently satisfy building energy demand. Within this frame, hydrogen has shown to be particularly fit in order to be used as an energetic carrier.
In this aim in the paper the energetic, economic and environmental sustainability of an auto-sufficient system for energy production in buildings, based on photovoltaic panels, hydrogen storage and fuel cells is presented.

Key words

Building sustainability, Building energy saving, Renewable energy, Fuel cells, Hydrogen

1. Introduction

Greenhouse gas emission reduction is one of the main challenges mankind has to face up in order to control dangerous climate changes. For this reason it represents the fundamental matter of international Agreements, such as the Kyoto Protocol, which ratify the actual commitment of participating Countries to reduce, gradually and effectively, their greenhouse gas emission rates by 2012.
In order to achieve the prefixed targets, particular attention must be paid to the control of excessive use of fossil fuels, major cause of greenhouse gas emission and climate change.

In this aim, the European Commission has recently fixed three main objectives to be achieved by 2020 [1]:

1) 20% reduction in primary energy consumption through increased energy efficiency;
2) 20% increase in the share of renewable energy sources;
3) 20% reduction in emissions of greenhouse gases with respect to the commitments of the Kyoto Protocol.

At the moment, in developed countries, a significant portion of the total primary energy is consumed in buildings and can be significantly reduced by adopting energy efficiency strategies and using renewable sources.
Consequently, further objective to be obtained by 2020, strongly recommended by the European Directives, is the obtainment of quasi-zero energy buildings, mainly consisting in passive buildings, essentially making use of natural energy sources [2].
Anyway, presently one of the greatest limitations in renewable energy widespread use lays in their intrinsic discontinuity; consequently, in order to efficiently satisfy building energy demand, an integration with energy storage systems is required if the use of traditional, fossil fuel plants is to be reduced.
In this frame, recently hydrogen has shown to be particularly fit in order to be used as an energetic carrier [3], [4].
It can be produced, stored and used in advanced systems associated with plants for energy production from renewable sources, allowing useful energy providing by means of its use in fuel cells.
Consequently, research for hydrogen sources useful for feeding hydrogen-air fuel cells represents at the moment

an important aspect of the hydrogen energy problems [5], [6].

In the paper, in order to contribute to characterize energy saving techniques, spreading the use of renewable sources in the building sector, an auto-sufficient system for energy production in buildings, also based on hydrogen storage is presented.

Aim of the system is both to make the building independent on the electric network and to overcome energy use dependence on discontinuity typical of solar energy.

Particularly, the study presents the simulation, on a monthly base, of the system energy behavior, allowing evaluation, from an energetic, economic and environmental point of view, of the sustainability of the selected self-sufficient plant typology, also on the basis of economic incentives provided by the Italian Government for energy production from renewable source.

2. Features of the proposed system

In order to overcome the intrinsic discontinuity of renewable sources, particularly the solar one, and to efficiently satisfy building energy demand, an integrated system for electric energy and hydrogen production, the gas storage and its use in fuel cells is proposed.

In particular, the system integrates a photovoltaic plant for the conversion of solar energy into electric energy, an electrolyser for hydrogen production, a pressure tank for the gas storage and fuel cells for electric energy production from hydrogen (Figure 1).

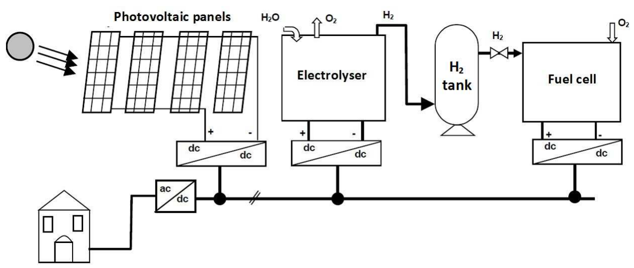

Fig. 1. Elements of the proposed system.

In the system, in order to reach energy independence from the national electric grid, the energy produced by the PV panels, when not directly used, is not sent to the grid, but is converted into hydrogen, in order to cover user's energetic demand in absence of suitable irradiation (i.e. during night or winter).

Therefore, for the system dimensioning, it is not sufficient to balance the panel energy production and the user's demand, as the former has to guarantee, in addition to the latter, also the energy amount necessary for hydrogen production. That is, panels must have a further production with respect to that directly used, able to satisfy, in the form of hydrogen, electricity demand in absence of production.

Consequently, the peak power of the PV field must be determined taking into account both contributions and not only energy used during irradiation periods.

In computing such exceeding production rate, particular attention must be paid, as the efficiency of the global system *electrolyser-fuel cell* is, at the moment, not very high, thus determining appreciably greater energy amounts.

Analysing the system functioning, it can be observed that, in every moment, when the power produced by the panels overcomes the energetic demand, the exceeding production is absorbed by the electrolyser, making up an energetic stock in the form of hydrogen, to be used when necessary in fuel cells.

Referring to hydrogen production and conversion, the most relevant aspects to be studied concern the definition of the electrolyser capacity, the choice of the storage system and of its pressure and the selection of the most performing fuel cell type and of its global power.

In general, the storage technical solutions presently have a fundamental role in the energetic and economic spread of hydrogen source, markedly affecting the distribution easiness of the carrier and its cost.

In particular, the value of the electrolyser capacity has been determined in the aim to absorb, and successively convert into hydrogen, the amount of energy corresponding to the difference between the peak of maximum production, occurring in the day with maximum irradiation, and the minimum daily consumption.

With regard to the storage system dimensioning, the period with exceeding production has been determined, that consists in the six months, from 1st April to 30th September, when hydrogen production exceed its consumption (summer period), whereas the remaining months of the year (winter period) consumption is prevailing.

Subsequently, the storage system has been designed taking into account the average daily difference occurring, in summer period, between hydrogen production and its use in lack of sufficient PV production.

In the system design, in order to obtain production levels suitable to the consumer's exigencies, guaranteeing, at the same time, acceptable occupations, the most appropriate storage pressure has been determined in order to reduce the gas occupation, very high at its production pressure.

Finally, it has been possible to evaluate the electrical power of the fuel cells from the knowledge of the alimentation supplied by the energy provider and the efficiency of the cell itself.

Considering the specific energy amount of the carrier, the hydrogen flow in input to the fuel cell, required in order to get the maximum instantaneous power has also been determined once known the average power to be provided.

The energetic autonomy of the system in days has at last been determined.

A further important evaluation to be considered has concerned the air flow necessary in the fuel cell in order to guarantee the correct oxigen flow. Considering the chemical reaction occurring at the cathode:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (1)$$

and the rate at which oxygen is present in atmospheric air, the necessary input air flow has been determined.

3. Case-study. Energetic, economical and environmental analysis of the proposed system

The case study used for the analysis consists of a public building, housing the *Regional Agency for Environmental Protection of Calabria* (*ARPACAL*), located in the Southern Italian town of Reggio Calabria (38.17°N, 15.67°E).
The building is endowed with a photovoltaic system consisting of 1200 modules of 185 W each, for a total peak power equal to 222 kWp. No shadowing elements are present in the area surrounding the panels.

A. Energetic analysis

The total yearly energy consumption of the building for the analysed year (2010) is equal to 140 MWh.
In order to obtain energetic evaluations, the photovoltaic plant has been simulated using PVSOL [7], a software that realizes a real time simulation.
The selected software well simulates systems with possible presence of shadowing and takes into account all the parasitic real phenomena. Moreover, it well simulates the local climate through a continually updated database of meteorological data, based on the last years ones, allowing a real time and transient state approach.
As it is known, two main elements characterize energy production:

1) the local weather data (temperature, wind speed, humidity) and their daily and yearly changes;
2) the technical characteristics of the plant (parasitic resistances, cable losses and plant architecture, use of subfields, use of one or more inverters).

Using the above cited software, the yearly produced and used energ rates have been determined (Table I). The corresponding monthly contributions are reported in Figure 2.
In Figure 3 an explicative sketch of the energy flows and the respective rates is reported, comparing the function of the *electrolyser-storage cylinder-fuel cell* system (dashed line), case b), with that of the electrical grid, case a).

Tab. I. Energy rates (AC current) for the analysed year

Yearly energy rates (MWh)				
Consumption	Produced PV energy	Directly used PV energy	Grid immission	Grid absorbtion
140.8	324.0	76.2	247.8	64.6

From Table 1 it results that about 248 MWh (grid immission), corresponding to about 259 MWh upstream of the inverters (the device efficiency is 95.5%) can be sent to the electrolyzer (it requires in input DC current): this means that a large energy amount must be stored in the form of hydrogen.
The next step has been the determination of the hourly electrolyser capacity, from the considerations reported in the previous paragraph, obtaining a value of 21 Nm^3/h.

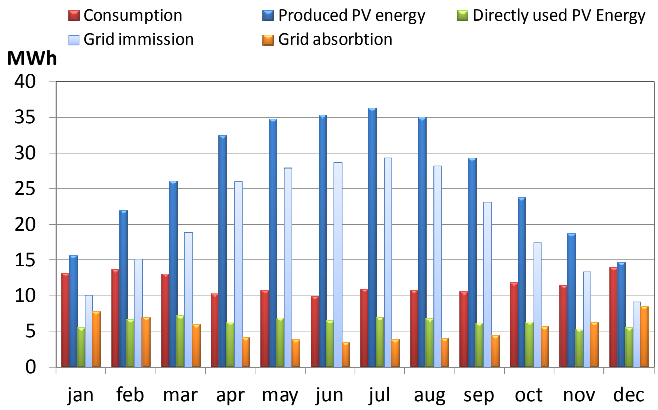

Fig. 2. Monthly energy rates for the analysed year.

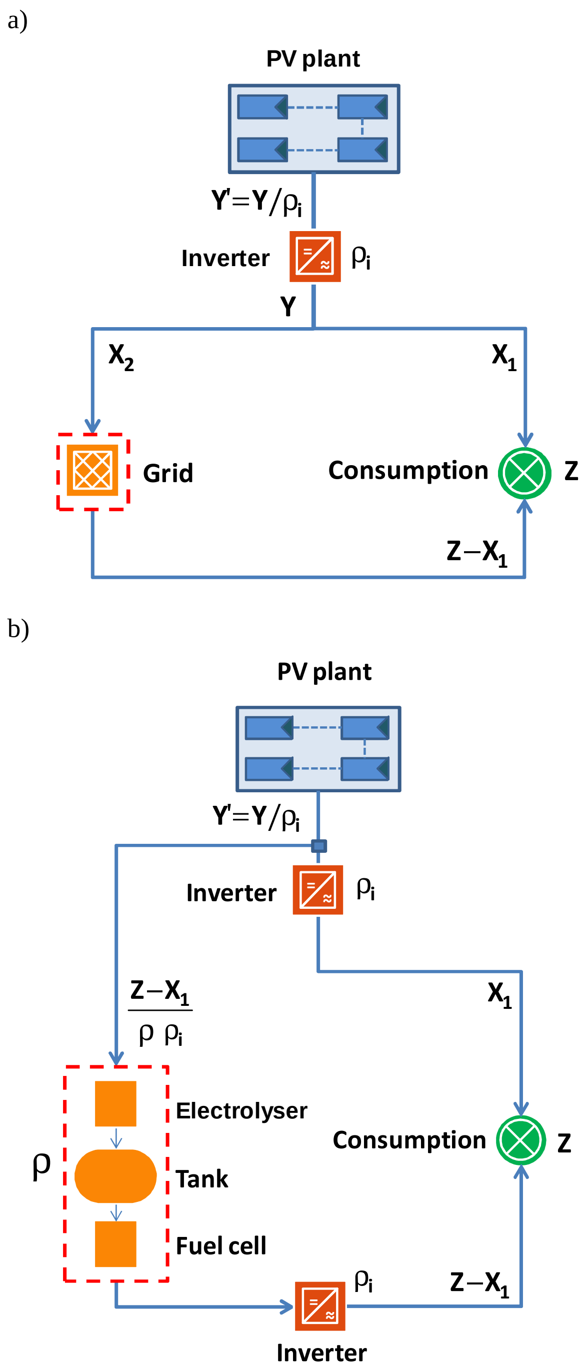

Fig. 3. Energy rates of the proposed integrated system.

Knowing the efficiency of the conversion process (electric energy - hydrogen - electric energy):

$$\rho_{tot} = \rho_{electrolyser} \times \rho_{fuel\ cell} = 0.625 \times 0.40 = 0.25 \quad (2)$$

on the basis of which an energy amount equal to four times the one necessary for a direct production must be provided by panels, the total energy production from hydrogen has resulted equal to 64.8 MWh.
This value is higher than the amount to withdraw from the network in absence of an hydrogen system (64.6 MWh, grid absorbtion, Table I), thus guaranteeing the self-sufficience of the whole system.
Figure 4 reports the daily average energy stored in form of hydrogen: it is evident that the global yearly gas production is greater than the corresponding consumption necessary to provide energy in lack of irradiation, thus guaranteeing the plant authonomy from the national electrical grid.
As far as the storage cylinder pressure is concerned, a value of 700 bars has been used: this value allows reduction of hydrogen volume at one tenth of its original value, occupied at the production pressure of 16 bar (about 1000 m^3).
In fact hydrogen density at the pressure of 700 bar (45 kg/m^3) allows a reduced volume of about 100 m^3, occupation compatible with that of a room.

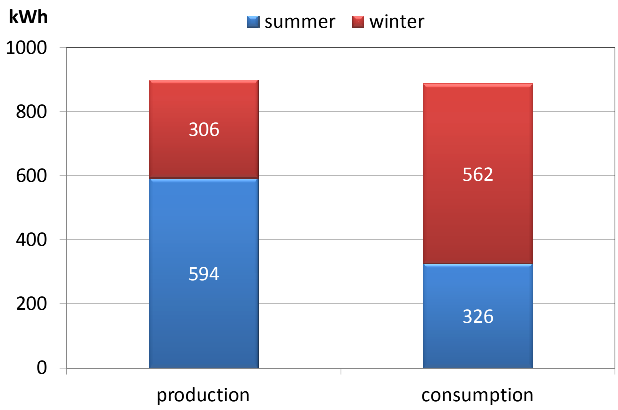

Fig. 4. Daily average energy stored in the form of hydrogen.

Finally, it has been possible to evaluate the electrical power of the fuel cells, from the knowledge of the alimentation supplied by the energy provider and the efficiency of the cells themselves.
Considering that the energy provider furnishes an alimentation equal to 0,5 MW and that PEM fuel cells have been used, having a conversion efficiency of 40%, the maximum power to be supplied to the cell system using hydrogen resulted equal to 1.25 MW.
From the knowledge of the specific energy amount of the carrier (3 kWh/Nm^3) the gas flow required in order to get maximum instantaneous power has been determined (417 Nm^3/h).
Further important parameter, the necessary input air flow to the fuel cell, has been determined from the knowledge of the rate at which oxygen is present in atmospheric air (21%), obtaining an average value of 385 m^3/h.

B. *Economic analysis*

The cost of the whole system resulted equal to € 1.300.000.
The evaluation of its production cost has been carried out taking into consideration the economic benefits provided by the Italian Government for energy production from renewable source (*Conto Energia)*.
Figure 5 reports the simulated cash flow of the proposed system: as it is possible to see, a payback time of about 15 years, with annual proceeds nearly equals to € 107.000 have been obtained; the global profit, at the 20^{th} year, approximately will be equal to € 495.000.
According to these evaluations, the cost of the global plant per kWp resulted equal to € 5.700/kWp, about 50% greater than the cost of the only photovoltaic system.

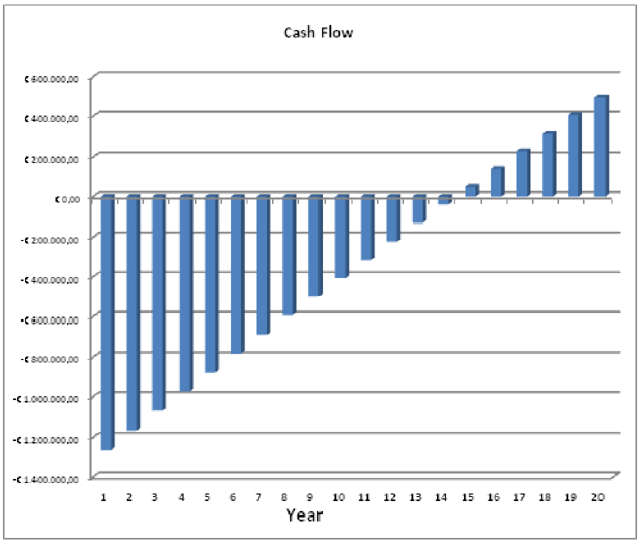

Fig. 5. Cash flow of the proposed system

C. *Environmental analysis*

Another important feature of the system is the greenhouse gas emission reduction and, in general, the atmospheric pollution reduction.
In Table 2 the yearly avoided emissions are reported in relation to a same amount of electrical energy yearly consumed and produced by fossil fuels.

Tab. II. Yearly avoided pollutant emissions

CO_2 (t)	NO_x (kg)	SO_2 (kg)	Dusts (kg)
246.6	143.2	146.2	17.8

4. Conclusions

In the paper an innovative plant to be used in a building of *Regional Agency for Environmental Protection of Calabria* (*ARPACAL*), located in the Southern Italian town of Reggio Calabria, has been proposed,
In order to overcome the intrinsic discontinuity of renewable sources and to efficiently satisfy building energy demand using an auto-sufficient plant, an integrated system for electric energy and hydrogen

production, the gas storage and its use in fuel cells is proposed.
In particular, the system integrates a photovoltaic plant for the conversion of solar energy into electric energy, an electrolyser for hydrogen production, a pressure tank for the gas storage and fuel cells for electric energy production from hydrogen.
The energy behavior of the PV system has been simulated by means of the PVSOL software on a daily, monthly and annual basis.
The results obtained from the analysis confirm that the cost of the energy unit stored in hydrogen volumes is greater than the cost of 1 kWh produced using only photovoltaic systems.
Consequently, also the starting fund of the proposed integrated system results very high, as it implies, in addition to the cost of the photovoltaic panels, those due to the electrolyser, the tank and the fuel cells, with a total, additional average cost per kWp equal to about 50% of the cost of the only photovoltaic system.
In addition, among the disadvantages of the proposed solution must be cited, at the moment, both the global efficiency of the production process, which is not very high (the process *hydrogen production - electricity from fuel cell* shows global efficiencies equal to 25%), and the requirement of big hydrogen volumes in order to satisfy the energetic demand, unless high pressures are used in order to obtain acceptable occupations.
Anyway, the economic analysis of the system design, when carried out taking into account the incentivizing fares provided by the Italian Government, encourages the production of pressurized hydrogen, that in such case not only shows to be sustainable, but also represents an interesting investment, with good capital returns for the investors, obtainable in about 15 years.
Consequently, at the moment, in the aim to obtain a quick, effective penetration of the carrier into the market, it is urgently necessary to enact incentivizing policies, attributing to hydrogen production fares able to cover its additional costs due to its electrolytic production and storage.
Finally, analysing the results obtained from an environmental point of view, encouraging evaluations can be effected, as the study shows that the adoption of the energy production system allows to save the emission of about 250 t CO_2/year.
The evidence of such an environmental advantage might encourage, in the next future, a widespread use of hydrogen also in the transport sector, thus appreciably limiting pollution in urban areas and globally, markedly reducing greenhouse gas emissions into the atmosphere and risks of global change for the planet.
Obviously, it should be underlined, that in a possible hydrogen economy, in order to give an effective contribution to the improvement of both urban and planetary environmental conditions, in compliance with both the provisions of the Kyoto Protocol and the the so-called “20-20-20 Objective” recommended by EU Directives, the gas must be produced from renewable energy sources, like in the proposed system.

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