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An energy autonomous house equipped with a solar PV hydrogen conversion system

Paolo Giuseppe Mura[a*], Roberto Baccoli[a], Roberto Innamorati[a], Stefano Mariotti[a]

[a]*University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy*

Abstract

The use of RES in buildings is difficult for their random nature; therefore the plants using photovoltaic solar collectors must be connected to a power supply or interconnected with Energy accumulators if the building is isolated. The conversion of electricity into hydrogen technology is best suited to solve the problem and allows you to transfer the solar energy captured from day to night, from summer to winter. This paper presents the feasibility study for a house powered by PV cogeneration solar collectors that reverse the electricity on the control unit that you command by a PC to power the household, using a heat pump, an electrolytic cell for the production of hydrogen to accumulate; control units sorting to the utilities the electricity produced by the fuel cell. The following are presented: The Energy analysis of the building, the plant design, economic analysis.

Keywords: RES in buildings; the conversion of electricity into hydrogen; hydrogen storage;

1.Introduction

Integrating the use of RES into buildings means being able to integrate the solar collectors into their structure in a rational and harmonious way, to meet the electricity and heating demands. The civil sector and the construction subsector use a fraction more than 30% of the end use of the Annual National Energy Budget in Italy of 2013, also its value has remained at around 49 Mtoe [1], even during the years of the economic recession; Therefore the contribution that RES can make is very important; what's more the solar collectors integrated into building structures help to avoid the use of land destined for agriculture or for the natural cycles of the Environment.

Since the year 2006solar PV has reached significant penetration in the construction industry thanks to the financial mechanism of the "tariff" and of the "metering" systems, but two limiting conditions remain: a) the building unit does not generally reach self-sufficiency with the PV system; b) as they are plants connected to the National Transmission Grid (NTG), they use it as an "improper accumulator " and they download to the grid a quantity of power which in recent years has become very large.

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* Corresponding author. Tel.: +39-070-675-5269; fax: +39-070-675-5263.
E-mail address: murapg@gmail.com

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The non-programmable RES, which primarily input, can introduce power surges that can destabilize the regional and national network and interfere with the regime of the base thermoelectric power stations. This risk exists if one takes into account that the PV power installed and connected to the national network in 2013 amounted to 17.5 GW [2], with respect to the maximum power value demand of 56 GW! As a concrete example we can report the data for the month of April 2013: during a public holiday, the peak demand was 32 GW, the thermoelectric power network was at about 11 GW, while the solar PV power was 12 .4 GW between the hours of 12 and 3pm. [2]. Therefore it is important to avoid burdening the electric power generated by the PV system on small regional networks or on the national network. The PV system proposed in this paper, equipped with a hydrogen accumulator and an electricity generator with the Fuel Cell can contribute to the successful integration of RES both in buildings and in the national grid.

2. General functional description of the system

This system is intended to meet the energy requirements, thermal and electrical, of a particular home type.

The home type is made up of detached independent house, with a covered area of 120 m^2 on two floors (60 m^2 surface in the plan), inhabited by 4 people and located in the province of Cagliari. It is hypothesized that such a house is equipped with all the typical accessories, in particular an invertible system heat pump cycle for winter heating, and summer cooling. The main elements of the system are: solar photovoltaic cogeneration, electrolytic cell, fuel cells, a DC/AC inverters, hydrogen storage system, electrochemical storage system, thermal accumulator system and a control system. The system that we aim to achieve is schematically represented, in its stand-alone configuration, in fig.1. A scale model of such a system, connected to the power grid "Grid connected" can facilitate the testing of components and simulations and be a valuable test bed for experimentation. The operation of the system in "stand-alone" (in Fig.1), can be schematically summarized as follows: the electricity from the PV collectors will be used to directly power the consumption when it is in the solar radiation phase and to produce hydrogen using the electrolytic cell. The electric accumulators have the main task of ensuring the leveling of the fluctuations of the electrical power input to the home network. In periods of low availability of solar energy, the energy required for consumption will be generated by a fuel cell that will use hydrogen accumulated in the previous phases. The system is structured so as to interact with all the elements that generate thermal energy, namely solar collectors, fuel cells and the heat pump (inside the building); in particular, via a buffer tank, the system will handle the thermal energy generators, so as to meet the needs of the consumer to maximize the overall efficiency.

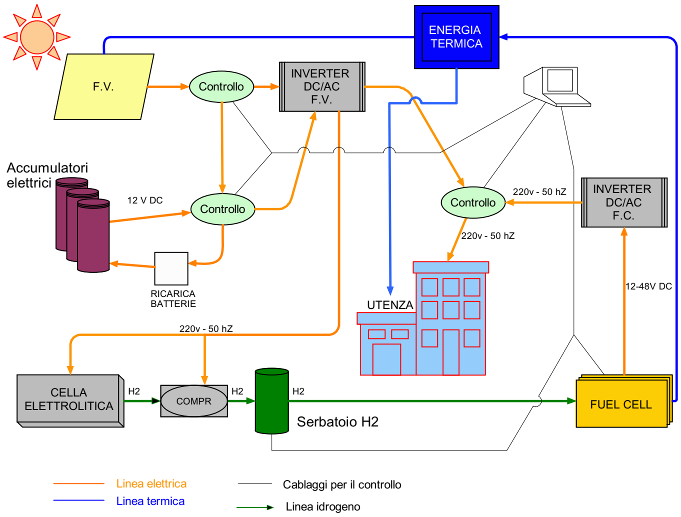

Fig. 1: Schematic representation of the system in its stand-alone configuration

In the operation mode "grid-connected", the electricity generated by the sensors will be fed into the grid, and the same network will pick up the necessary energy for hydrogen production and for the operation of the systems, the other functions are similar to the "stand-alone" scheme. The "grid-connected" operating mode is more suited to the functions of a test bed for research purposes, it allows you to run tests on components, evaluate the actual production of heat and power from sensors, and, as already mentioned, evaluate the possibility of grid-connected PV systems with the accumulation of hydrogen, which can reduce the excess instantaneous "non-programmable" power fed into the regional and national network.

3. Description of the main components of the system

Photovoltaic cogeneration collectors perform the conversion of the radiant energy of the sun into electricity and heat. Inverter: to convert into AC 220 V, 50 Hz the DC electrical energy produced by the collectors and the fuel cell. Electrochemical accumulators: necessary to level the input power to the home network in short-term fluctuations. Electrolytic cell for the production of Hydrogen: The element which has the task of producing hydrogen from water. Hydrogen compressor: This is necessary to compress the hydrogen produced to the pressure of accumulation. Hydrogen tank: the size depends on the amount of hydrogen needed for autonomy and on the pressure of accumulation. Fuel cell: Electricity and heat generation system that takes advantage of the H2 produced.

4. Analysis and choice of technologies

As can be seen in detail in the following paragraphs, the choices made were affected mainly by the basic costs of the various elements, but also by considerations of obstacles, security, ease of installation and use, the running costs.

4.1. Solar collectors

As explained previously, the PV cogeneration collector has been chosen for its energy peculiarities; with their hybrid configuration they can in fact take advantage the Exergy of solar radiation, producing electric and heat Exergy. An alternative would have been to buy thermal and photovoltaic solar collectors separately; the choice was made to insert an element of new technology into the system that is to be developed.

4.2. Electrolytic cell for the production of hydrogen

With regards to the production of hydrogen the following alternatives can be taken into account: 1)Steam reforming of light hydrocarbons; 2) non-catalytic partial oxidation of hydrocarbons; 3) Water electrolysis. The first two alternatives are both responsible for the problem of the production of carbon dioxide (CO_2), the main cause of the "greenhouse" effect. Therefore in the proposed plant we adopt the water electrolysis cell.

4.3.The Physical Properties of Hydrogen.

Density at normal "p" and "T" 0.084 kg/m^3; HCP = 141.86 MJ/kg; LCP = 119.93 MJ/kg; critical point: p_c= 1.31 kPa, T_c = 32.98 K; triple point: T_3 = 13,96K, p_3 = 7.3 kPa. Normal boiling temperature: T_{eb} = 20.39K.

4.4. Hydrogen storage

Currently the most important methods of storing hydrogen are the following: 1) chemical hydrides; 2) Carbon based systems; 3) Crystal microspheres and other systems. 4) Metal hydride systems. 5) A liquid hydrogen; 6) A compressed gas hydrogen. The first three are experimental technologies and therefore are not used in this system. The systems of metal hydrides are already widely tested, available in the market and have certain qualities, such as security and reliability. This storage system, however, presents high costs; requires complicated control systems with refrigeration and heating for the entry and extraction of the gas; it also has low density energy volumes. The liquefaction processes use a complex multi-stage cooling machine to obtain the desired cooling; the Joule-Thomson coefficient uses the hydrogen in the thermodynamic states (p,T) where it is $(dT/dp)_h>0$. This process is therefore complicated and requires expensive equipment, and continuous refrigeration to maintain at a low temperature T <20K the liquid hydrogen. The process of hydrogen compression follows the law ($pv = RT$) of ideal gases; the technology is simpler because the necessary equipment is a compressor and a tank of adequate size with composite materials; it is therefore safe, reliable and cheap.

4.5. Hydrogen powered fuel cells

The fuel cells can be divided according to the type of electrolyte used: a) AFC, Alkaline Fuel Cell, using potassium hydroxide as the electrolyte; b) PEFC, Polymer Electrolyte Fuel Cell; c) Phosphoric Acid cells (PAFC);

d) Molten carbonate cells (MCFC); e) Solid oxide cells (SOFC, Solid Oxide Fuel Cell); f) DMFC, Direct Methanol Fuel Cell, with very high unit costs. For the proposed plant PEMFC type polymer electrolyte cells were chosen , for several reasons. First, the cost of these systems is the most competitive with conventional systems, due to the relative simplicity of construction and the fact that systems of small size are already available on the market (from 1 to 25kW) [3]. Modularity is another merit of these systems: a stack of cells may be composed of more elementary units, connected in series/parallel; this particular construction allows to change the rated power of the system without having to change radically.

5.Analysis of the stand alone energy system and dimensioning

In this section a summary of the feasibility study is presented, with particular reference to the analysis of the Energy "Building and Plant System" referring to the system diagram "stand alone" (Fig.1), consists of cogeneration PV solar collectors, hydrogen system storage and fuel cell, in addition to the storage of hot water.

5.1. Method of calculation of the energy analysis of the "Building and Installation System"

The need for thermal energy for heating the building is calculated with software type MC4; on an hourly basis the energy content of the accumulation is verified and when this is not sufficient electrical energy is taken directly from the circuit PV, then by the electrochemical accumulators up to the limit set; if the supply is low the demand is satisfied by the Fuel cell that powers the heat pump with electric power. The build-up to 1000 liters is "recharged" from the thermal photovoltaic panels. The demand for heating energy is converted into electrical energy by considering a CoP of the heat pump average of 3. To the electricity needs of the heat pump are added up, moment by moment, the needs of the other domestic loads such as lights, washing machine etc. In this way, by reverse calculation the amount of hydrogen needed to meet the electricity requirements is deduced. At the same time the thermo photovoltaic system is working and the electrical energy produced by it goes to recharge the batteries, and if these are "charged" the PV electricity production goes to produce hydrogen to be accumulated for subsequent use.

5.2. Estimation of the thermal energy needs

The estimate of the energy needs for heating of this house has been performed in accordance with the requirements of the law 195/'05 and 311/06 (and subsequent modifications and integrations) according to UNI/TS 11300/1-2. The area of the house (about 60 m^2 on two levels) will be used for PV cogeneration collectors. The heating system is of the type with fan coils powered by water at 45°C, with a 1000 liter water buffer tank. The production of sanitary hot water, evaluated separately, involves an average requirement of 1200 MJ/month, to produce 150 kg per day of water at 80°C, calculated only in the winter months, at other times there is an excess of thermal energy. The results of the software type MC4 and TERMUS are shown in Tab.1 Summary.

Table 1. Requirements of thermal energy for winter heating [MJ] - [Source: "Lex 10 professional"]

	November	December	January	February	March	Totale
Qh	1.187	4.407	5.471	4.287	3.032	18.384
Qhvs	1.187	4.407	5.471	4.287	3.032	18.384
Qhr	1.187	4.407	5.471	4.287	3.032	18.384
Qp	1.187	4.407	5.471	4.287	3.032	18.384
Q	1.099	4.081	5.066	3.969	2.807	17.022

Table 2. Symbols of Table 1

Qh:	Usable Energy requirements in continuous operation output
Qhvs:	Usable Energy requirements in real operation
Qhr:	Usable Energy requirements useful in real conditions
Qp:	Thermal energy provided by the production system
Q:	Primary Energy Requirement

5.3. Estimate of electricity needs

For the power consumption required, the following were taken into account- commonly used electrical devices, the time of daily use from which the demand for daily energy results, monthly and annual basis; the electricity for summer air conditioning was also added. The total value of 4064 kWh / year is greater than the statistical average of 3660 kWh/year provided by ENEA for Sardinia. Here are the results: Electricity consumption obliged: a) daily, 9 kWh; b) weekly, 63 kWh; c) Monthly, 273 kWh; d) Annual 3270 kWh. The results of electricity are in Table 3.

5.4. Cumulative solar radiation data

We used the average monthly solar radiation data provided by the website of the SAR, Sanluri Station (Tab.4) [4]. The tables below show all the results obtained and the values extracted from the different sources.

Table 3.Electric Power consumption of the housing unit [kWh]

Month	Forced	Summer Conditioning	Total	Month	Forced	Summer Conditioning	Total
January	272		272	July	272	300	572
February	272		272	August	272	200	472
March	272		272	September	272	150	422
April	272		272	October	272		272
May	272		272	November	272		272
June	272	150	422	December	272		272
TOTAL	annual						**4064**

5.5. Yields of the elements of the system and fundamental calculation parameters

S_c = 40 m^2 gross area of the absorbing surface; h_{fv} = 0.155 Average yield of photovoltaic sensors;
h_s = 0.45 Solar-thermal conversion yield; $h_{t\ fc}$ = 0.3 Average Thermal yield of the fuel cell;
h_{sincro} = 0.85 Yield for the lack of simultaneity between thermal loads required and the availability of solar radiation;
h_{acc} = 0.7-0.9 Yield of electric accumulators, variable in the range of 0.7-0.9 depending on the download speed.
h_{fc} = 0.45 Average Electrical yield of the fuel cell
η_c = 0.50, Average yield of the electrolytic cell. Please refer to the full study for further investigation.

Table 4. Average monthly cumulative Solar radiation for the province of Cagliari [MJ/m^2] (data refers to the horizontal surface).

Month	S.R [MJ/m^2]	Month	S.R. [MJ/m^2]
January	200	July	750
February	270	August	640
March	430	September	450
April	510	October	340
May	600	November	200
June	700	December	180

Using these values, for the 12 months of a calendar year, all the monthly flows of energy were calculated. It was assumed that in the non-winter months (months in which it is not necessary to heat the living spaces), all electrical demands are met by the solar source, when available, and by electric accumulators. As a simplifying assumption, it was assumed that in the months from November to February, for space heating, electricity produced by photovoltaic collectors is not used to produce hydrogen, but only to satisfy the needs of the user. The results are in Table 5.

Table 5. Hydrogen flows produced and used - Annual flows of hydrogen [kg]

month	Produced [kg]	Consumed [kg]	month	Produced [kg]	Consumed [kg]
March	1.75	0	September	.5	0
April	3.33	0	October	.36	0
May	4.56	0	November	0	-1.62
June	4.51	0	December	0	-7.55
July	3.54	0	January	0	-10.39
August	3.19	0	February	0	-0.1
Annual balance		2.08			

6. Dimensioning of the main components

In the analysis carried out, the size of some components were left out; here we add the size of the other components. *a) Absorbing surface area*: is bound to the production of hydrogen; a gross area of 40 m^2 is chosen, sufficient to produce in terms of solar radiation of 1000 W/m^2 electric power equal to 6 kWp. *b) Power of the electrolytic cell*: is bound to the maximum output of the PV collectors; a power consumption of between 6 kW is adopted. *c) Fuel cell power:* this value is to be determined according to the time diagram of the electric power demands, the ability of electric accumulators to compensate for peak demands and system reliability; we believe appropriate the power of 4.5 kW. *d) Compressor and storage tank of H_2*: The compressor must be able to develop a flow rate equal to the provision of maximum H_2 of the electrolytic cell of about 1 Nm^3/h. The tank must be dimensioned so as to be able to contain all the H_2 produced with an increased coefficient for safety. Supposing that one wants to store 25kg of H_2, the volume required is a function of the storage pressure according to the ideal gas law, as shown in Table 6. On the basis of the available space and acceptable costs by adopting the nominal pressure of 200 bar, the total volume of the tanks is 1.5 m^3. *e) Electric accumulators* are sized to give the system the autonomy of 48 hours to the required demands; therefore the energy to accumulate is 18 kWh. Assuming accumulators of 125 Ah are installed (1500Wh / 100h), 15 are used considering that the accumulators should never get to discharge levels of above 70%.

Table 6. Tank volume as a function of storage pressure for 25 kg of H_2

Pressure [bar]	Volume required [m^3]	Pressure [bar]	Volume required [m^3]
100	3	300	1
150	2	400	0,75
200	1,5		

Table 7. Cost analysis of the system

Item	**Quantity**	**Unit price**	**Total**
Solar kit 3000Wp 20m^2 - including the control unit and Inverter	2	€ 13.900	€ 27.800
Inverter Layer 4.5 kW per cell to fuel	1	€ 1.200	€ 1.200
Electrolytic cell 1Nm^3/hr	1	€ 15.200	€ 15.200
Fuel cell type PEMFC 4,5kWe	1	€ 26.400	€ 26.400
Hydrogen storage tank 200 bar 1 m^3	2	€ 8.000	€ 16.000
Hydrogen compressor	1	€ 2.500	€ 2.500
Batteries + charging device	1	€ 5.000	€ 5.000
Miscellaneous	1	€ 2.000	€ 2.000
TOTAL			€ 96.100

7. Comment Result

From the point of view of the analysis of Energy, the analysis yielded positive results, as demonstrated by the monthly flows of H_2 shown in table 5. The annual analysis closes with a positive reserve of energy in the form of 2 kg of H_2. We can therefore say that it is possible to realize energy autonomy for the "stand alone" plant for a single building at least in the Mediterranean areas where the flow of solar energy is similar to that of Sardinia. This analysis, however, cannot be considered complete and exhaustive; in fact, considering the instantaneous electric power, it must be considered that, in the absence of a renewable source, the electric accumulators will not always be able to meet the demands; the intervention of the fuel cell will therefore be necessary that will produce electric energy with lower yields than nominal levels because the operation time is small and of low power. With regards to the economic analysis, it is evident that the cost is high, comparable with the basic cost of the house; the costs are high because the components are available on the market, but not readily and widespread available.

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