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Hydrogen from renewable energy: A pilot plant for thermal production and mobility

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Abstract

In the mainframe of a research contract, a feasibility pre-design study of a hydrogen-fuelled Laboratory-Village has been carried out: the goals are the design and the simulation of a demonstration plant based on hydrogen as primary fuel. The hydrogen is produced by electrolysis, from electric power produced by a mix of hydroelectric and solar photovoltaic plants. The plant will be located in a small remote village in Valle d'Aosta (Italy). This country has large water availability from glaciers and mountains, so electricity production from fluent water hydroelectric plants is abundant and cheap. Therefore, the production of hydrogen during the night (instead of selling the electricity to the grid at very low prices) could become a good economic choice, and hydrogen could be a competitive local fuel in term of costs, if compared to oil or gas. The H_2 will be produced and stored, and used to feed a hydrogen vehicle and for thermal purposes (heating requirement of three buildings), allowing a real field test (Village-Laboratory).

Due to the high level of pressure requested for H_2 storage on-board in the vehicle, the choice has been the experimental test of a prototype laboratory-scale high-pressure PEM electrolyzer: a test laboratory has been designed, to investigate the energy savings related to this technology.

In the paper, the description of the dynamic simulation of the plant (developed with TRNSYS) together with a detailed design and an economic analysis (proving the technical and economical feasibility of the installation) has been carried out. Moreover, the design of the high-pressure PEM electrolyzer is described.

Keywords: Renewable energy; Zero emission mobility; High-pressure PEM electrolyzer; Solar energy

1. Introduction

In the very particular natural context of a little village in the North-Western Italian Alps, the design of an energy system based on the local production and utilization of hydrogen has been developed. From meteorological and geographical point of view, the Village is located on the left side of the Valtournanche, on an ample plateau at 1800 m. The site is facing South, wide open at South and West direction. Temperature, horizon and shadings, and solar irradiance have been investigated (Table 1) for detecting the thermal energy request for residential heating and for the design and estimation of the energy production from a photovoltaic system.

Concerning the vehicle mobility, the village is not connected to the main road network and the vehicle transit is strictly regulated, with only 3 or 4 cars or little trucks allowed to circulate for tourist and working material transportation.

The village is electrically connected to the Valle d'Aosta electricity grid; here the alpine configuration and the large availability of water are turned into a wide utilization of water for electricity production, by means of seasonal (with dam) and daily reservoir plants, and open-flume plants, as reported in Table 2.

In Italy, the power system market is regulated by a tariff system, in which prices are divided in four daily levels: the higher is the national electric power request, the higher is the price at which it is possible to sell the energy. From the hydroelectricity company point of view, the impossibility to regulate the water flow in the 73.6% share of the installed power (that generates the 80% of the total annual energy) and consequently, the impossibility to sell

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Table 1
Temperature and irradiance distribution along the year in the location

	January	February	March	April	May	June	July	August	September	October	November	December	Average
Temperature data: monthly mean													
Village temperature (°C)	−7.2	−4.3	−0.2	4.1	7.8	11.8	13.6	12.5	9.0	3.4	−2.1	−6.1	3.5
	January	February	March	April	May	June	July	August	September	October	November	December	Total year
Meteonorm data: montly mean daily irradiation													
Beam irradiation ($kWh\,m^{-2}$)	54	73	128	155	180	173	186	162	125	90	55	45	1425
Diffuse irradiation ($kWh\,m^{-2}$)	24	31	48	66.8	76.5	80.2	77.8	70.6	56.9	39	24	22	615.4

Table 2
Hydro power plants in Valle d'Aosta by typology

Plant regulation	Installed capacity (MW)	Total annual production (MWh)
Seasonal	200	500,000
Daily	330	1,000,000
Open flume	230	1,000,000
Total	760	2,500,000

the energy at the maximum tariff value, is a great loss of money.

This particular boundary conditions generate some interest in a system that can store the energy produced by hydroelectric plants during low cost hours (selling the electricity just during high price hours) in a high value form: hydrogen. To investigate this system, a real plant has been scheduled where to test and monitor different components for using and producing H_2, from both technical and economic points of view. This pilot plant will be located in the village described above, which, for its particular location, is particularly concerned with the preservation of its environment: therefore, the integration of renewable sources and hydrogen could be a interesting local solution.

The aim of an energy system based on renewable energy sources (RES) and H_2 is to supply the whole energy request (electric power, heating ant transportation) without the integration of traditional systems based on exhausting resources. In fact, hydrogen-based technologies could offer an efficient alternative to traditional RES storage devices (e.g., batteries). Over the past decade, several RES–H_2 plants have been discussed in literature, both in technical and economic terms [1–6], for different power size: from domestic applications to national systems. Lessons learned are that the technology is potentially interesting, but it needs larger efforts in research and development. Some experiences have been developed through demonstration projects: SAPHYS project (I) [7], SCHATZ Solar Hydrogen Project (USA) [8], Markus Friedly Residential House (CH) [9]. Nowadays, the most important project is the reorganization of the transport sector in Iceland in a RES + H_2 fuel system before 2040 [10]. More recent studies are focused to the development of control strategies for renewable energy systems with hydrogen storage for small scale systems (up to 10–50 kW peak power) [11], and for residential applications [12]. They represent "black box" optimization problems, that the authors solve using heuristic or genetic algorithms: the control system for distributed power system is committed to the operation of the system and to the optimization of the economic parameters; it is devoted to regulate the hydrogen production during off-peak electricity from renewable energy sources. Other authors are investigating economics aspects of the integration of hydrogen energy technologies in renewable energy power systems [13], and some studies compare cost–benefits of different distributed generation systems, considering also fuel cells and "green" H_2 [14]. These papers agree about the technical feasibility of the hydrogen renewable energy system, but remark the high costs related to this option.

A particular insight of the project described in the present paper is the application and test of a direct high-pressure electrolyzer. The direct production of hydrogen at high-pressure is an interesting improvement in the storage problem, because it allows to reduce or even eliminate the compression of the hydrogen gas. Gas compression, and in particular hydrogen compression, is characterized by high energy and components cost. As a result, it has been developed a laboratory for the test of the electrochemical and thermal behavior of a high-pressure proton exchange membrane (PEM) electrolyzer that can produce hydrogen at 70 bar; in a second phase, a small direct high-pressure electrolyzer will be tested and monitored in the Village. In the paper, the laboratory test is described and some first considerations about high-pressure electrolysis are drawn.

2. Description of the Laboratory-Village

As described in [15], the primary energy sources of the plants are hydroelectricity and photovoltaic electricity, devoted to two hydrogen utilisations: the photovoltaic field-area is designed to supply the electricity needs of the vehicle refuelling station, while the hydrogen supplying the heating request is produced from hydroelectricity. Two vehicle typologies are taken into account: an off-road vehicle with internal combustion engine, and a proton exchange membrane fuel cell (PEMFC) vehicle. Three different average daily travelling distances are considered: 100, 50, 35 km day^{-1}. Two scenarios of hydrogen production have been evaluated (Fig. 1): (a) the H_2 for both heating and automotive is produced by a single electrolyzer; all the hydrogen produced is stored in a single low-pressure tank; the gas

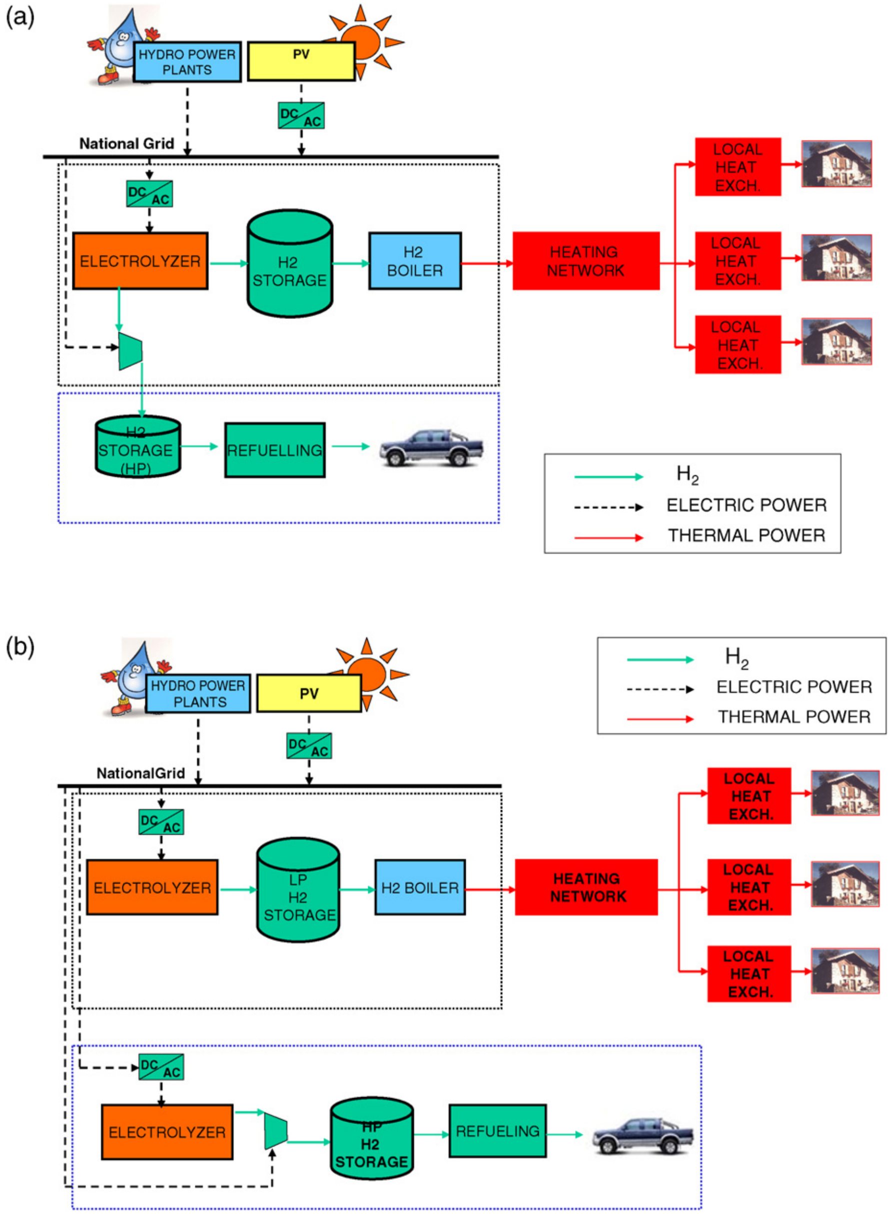

Fig. 1. Schemes of the plant. (a) Single electrolyzer. (b) Electrolyzer devoted to mobility.

needed to supply the refuelling station is compressed by a membrane compressor and stored in a high-pressure tank; (b) the hydrogen is produced in two separate plants, with two different electrolyzers and two different tanks, one devoted to supply the heating requirements (low hydrogen pressure), and the other one committed to the refuelling station (high hydrogen pressure).

The technical and economic analysis allow to exclude some cases. In the particular application of the Laboratory-Village, the scenario with a common hydrogen production is always less convenient, in economic terms, compared to the scenario with separated hydrogen production. In fact, in the scenarios with a single electrolyzer, the membrane compressor is very expensive due to the particular construction and to the high volume flow of H_2, and the yearly electricity consumption of the whole plant is higher than in the scenarios with two electrolyzers. The production and storage for the mobility has been therefore separated from the production and storage for the stationary use.

3. The mobility requests

The energy request related to the mobility service of the local community and for tourists and luggage transport have been investigated. Due to the mountain location, courses are off-road and often snowy or icy and the vehicle must fulfil particular requirements: 8/9 seats; high clearance from the ground; possibility to carry people, luggage, working material; easy access; available space for H_2 tanks. Table 3 shows the estimate energy needs, related to the different scenarios. A maximum number of km year^{-1} and km day^{-1} have been supposed, to size the hydrogen production and storage plant, the refuelling station and the on-board tank.

3.1. Fuel cell vehicle

An electric vehicle, powered with a proton exchange membrane fuel cell, is the most efficient solution for mobility use, in terms of energy savings. But for this particular application, added to common problems (lifetime, costs, etc.), others topics are relevant: the vehicle will be exposed to very low temperature (and this situation can generate freezing and breaking of the membranes), and it will be stressed by vibrations due to off-road use, that can generate fracture of graphite elements. For this reasons a FC vehicle has been discarded.

Table 3
Energy needs for the vehicle (underlined the covered distance)

	km day^{-1}		
	$\underline{100}$	50	35
H_2 (Nm^3 day^{-1})	66	33	23
Energy[a] (kWh day^{-1})	323	161	108
	km year^{-1}[b]		
	$\underline{3000}$	1500	1000
H_2 (Nm^3 year^{-1})	2000	1000	660
Energy (kWh year^{-1})	9800	4900	3267

[a] LHV of H_2: 119.93 MJ kg^{-1}.

[b] Under the hypothesis of 30 full days use at 100 km day^{-1} for 1 year.

Table 4
ICE vehicle data

Vehicle	
Engine capacity (l)	4.02
Power output (hp)	140
Maximum torque (Nm)	15
Interior tank (l)	541
Exterior tank (l)	2 × 240
Tank material	Composite fiber
Maximum operating pressure (bar)	340
Average consumption (km l^{-1})	10
Range (km)	340
Cost (€)	35,000/50,000

3.2. ICE vehicle

It is possible to adapt a internal combustion engine (ICE) to gaseous fuels, as hydrogen, and this is common with LPG or CH_4 conversions. Some suitable off-road vehicle are available on the market, deriving from conversion of existing ones. Specification data are reported in Table 4. These vehicles and their relative converted versions are characterized by high fuel consumption rates.

3.3. Refuelling station

The considered refuelling station is supplied by ILT-PIEL (Italy); it is composed of electrolyzer, purifier, compressor, storage tank, as reported in the data sheet in Table 5. The energy for the mobility is produced from a solar photovoltaic plant, made of 94 m^2 of multicristalline silicon modules, that can deliver 10,100 kWh year^{-1}. The purchasing cost is €63,000, the expected life is 25 years, for an average energy cost of €0.24 kWh^{-1}, without any financial subsidy.

Table 5
Piel station data

Electrolyzer	
Number of stack	1
Number of cells	200
Cell dimensions (cm)	20 × 20
Maximum current (A)	52
Maximum production flow (Nm^3 H_2 h^{-1})	4.04
Electric power (kW)	22.5
Compressor	
Electric power (kW)	2.2
Specific consumption (kWh Nm^{-3} H_2)	0.55
Electrolyzer and compressor	
Specific consumption at 180 bar (kWh Nm^{-3} H_2)	6.15

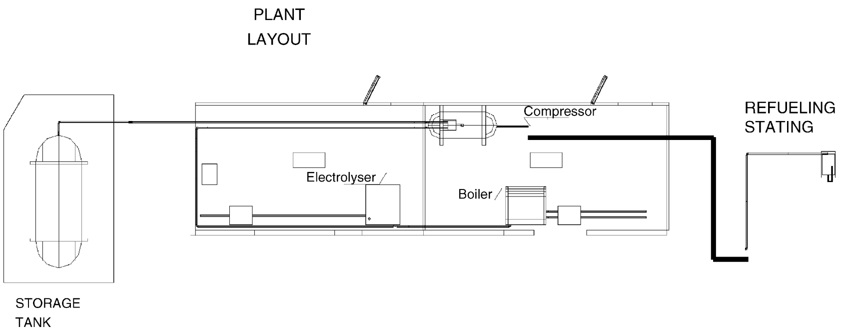

Fig. 2. Plot of the site: position of production, storage and refuelling devices.

4. Plant layout

Figs. 2 and 3 show the components of the hydrogen system, in the design with a centralized H_2 burner. The refuelling station is equipped with a dedicated group made of electrolyzer and compressor. The main electrolyzer devoted to H_2 production for heating purposes (Table 6) is fed with demineralized water and hydroelectricity, and the H_2 produced is directed toward the burner if heat is required from the heating network, or stored in the storage tank at 25 bar. In case of necessity, it will be possible to supply H_2 to the high-pressure storage tank in the refuelling station from this low-pressure storage tank, through a multi-compression stage. The high-pressure tank is directly fed by another electrolyzer, that produces and compress a dedicated mass flow of H_2; this solution has been preferred after the economic analysis. Security components, as pressure and flow control valves, sniffers and gas extraction hood are provided, to prevent dangerous H_2 concentration.

Table 6
Characteristics of the electrolyzer devoted to heating requests

Vanderborre	
Electrolytic solution (% of KOH)	20–30
Maximum volume flow ($Nm^3\,h^{-1}$)	60
Maximum output pressure (bar)	25
Cell area (cm^2)	1000
Production for single stack in series ($Nm^3\,h^{-1}$)	4–15
Specific consumption ($kWh\,Nm^{-3}$)	4.03
Auxiliary consumption ($kWh\,Nm^{-3}$)	0.06

5. Simulation of the system performance

On the basis of the of the main energy flow of the plant (Fig. 4), the hourly operation of the plant, during a whole

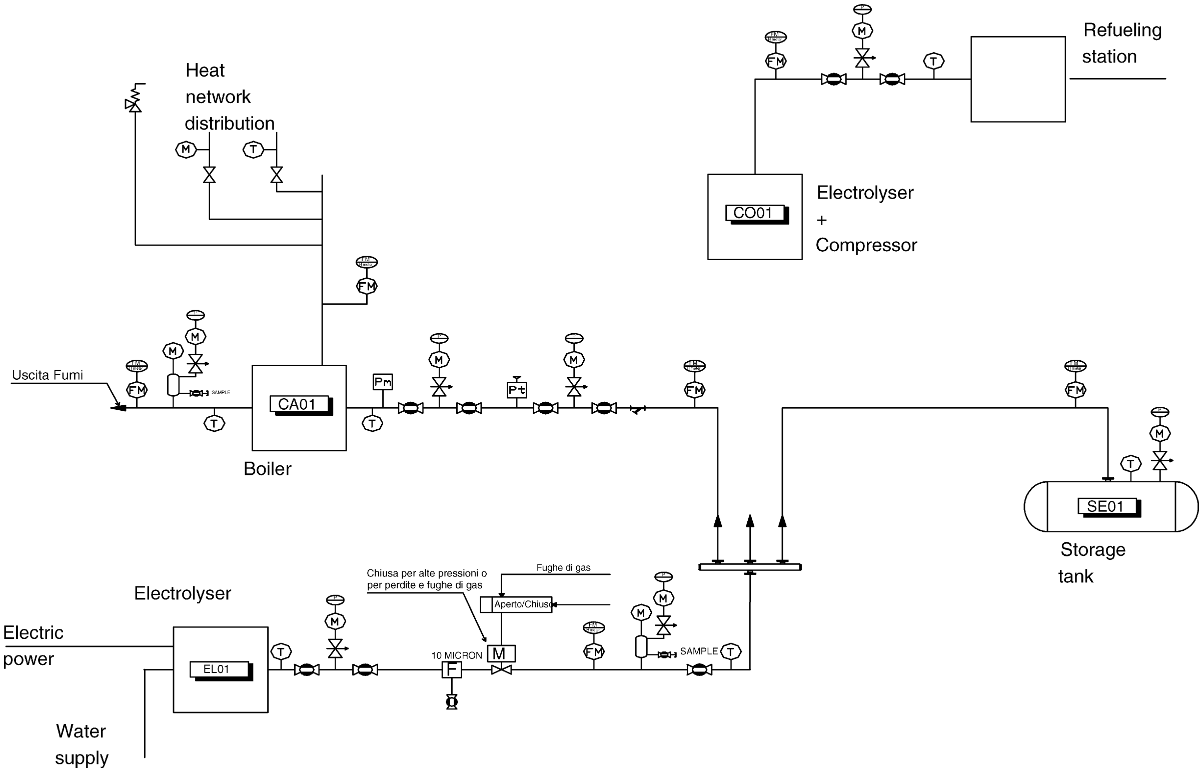

Fig. 3. Scheme of the plant components.

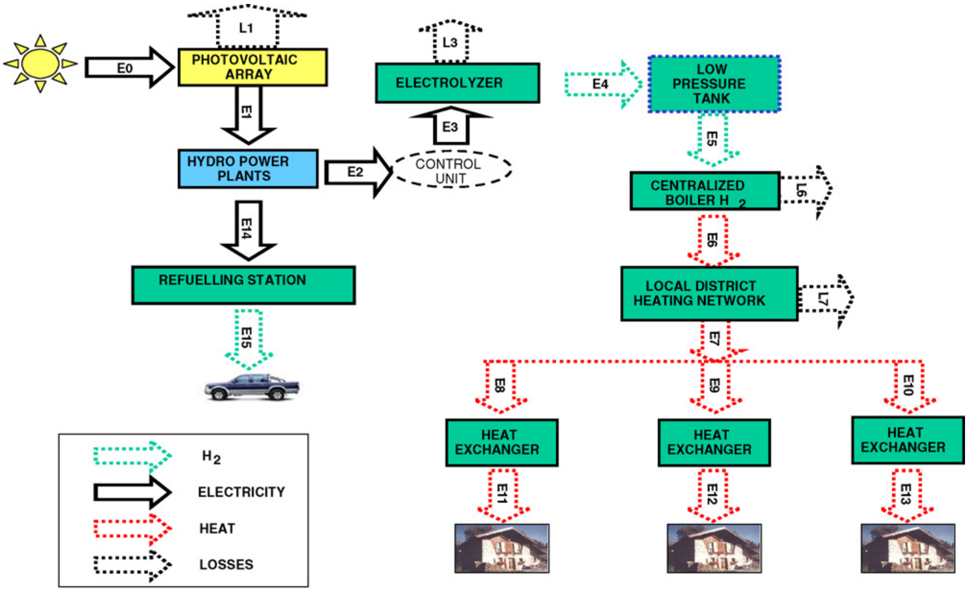

Fig. 4. Scheme of the main energy flow of the plant.

year, has been simulated with TRNSYS®. Fig. 5 shows the month cumulative energy flows of the plant. The annual-average energy efficiency of the main components of the system and some significant subsystems are: 8% (photovoltaic array), 61% (electrolyzer), 35% (electricity-heating requests), 50% (electricity-vehicle fuel), 5% (solar irradiance-H_2). The annual heating request (E7) is $400\,\mathrm{MWh\,year^{-1}}$; the electricity consumption for H_2 production is $1200\,\mathrm{MWh\,year^{-1}}$ (E3). This value corresponds to $244{,}440\,\mathrm{Nm^3\,year^{-1}}$ of H_2 produced with a total energy content of $733\,\mathrm{MWh\,year^{-1}}$ (E4). The total irradiance received by the photovoltaic array is $126\,\mathrm{MWh\,year^{-1}}$ and the electricity produced is approximately $10\,\mathrm{MWh\,year^{-1}}$, which is used as input of the refuelling station to produce $1980\,\mathrm{Nm^3\,year^{-1}}$ ($\approx 6\,\mathrm{MWh\,year^{-1}}$) of H_2, necessary to cover $3000\,\mathrm{km\,year^{-1}}$. The total electricity consumption is shared 99% for the heating and 1% for the mobility requests. This is also the ratio of the electric consumption from hydropower plant and photovoltaic –array.

Fig. 6 represents the trends of the electricity produced by the photovoltaic array and the electricity input to the refuelling station during the year. The time-integral of the curves is equal, but the distribution of the values of the two trends is different. As described in the economic analysis, the advantage of the adoption of the feed-in tariff is based on this difference.

The performances of the single components and of the subsystems can vary depending on producers, quality, temperature levels, ambient conditions; therefore, a sensitivity analysis has been performed, varying the efficiency of each component in a range of values (representative of typical operating parameters) derived from data on existing models. As an example, the data sheets of market electrolyzers indicate specific consumption varying between 4 and $5.5\,\mathrm{kWh\,m^{-2}}$, considering electrolyzer and ancillary, that results in efficiency from 0.55 to 0.75. The values adopted in the economic analysis described below, and the upper and lower value for the sensitivity study are indicated in Table 7; Table 8 indicates the efficiency of the whole systems, and Fig. 7 shows the indicative efficiency range for the main components and results on the total efficiency of the system.

The transformation chains indicate the total path to convert the energy from the indicated initial source to the energy vector needed by the final user. As an example, to convert solar radiation to high-pressure H_2 to be delivered to the vehicle it is

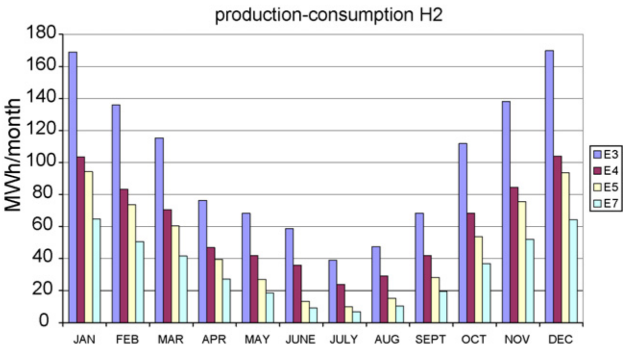

Fig. 5. Monthly energy flow of the system.

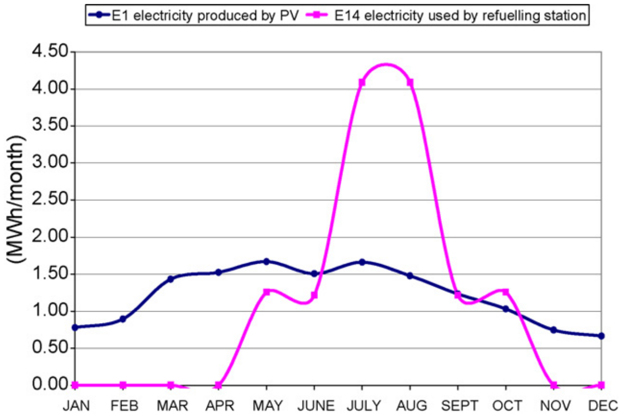

Fig. 6. Monthly energy flow of the PV-mobility system.

Table 7
Indicative efficiency range for the main components of the plant

Component	Efficiency of single components, η		
	Typical value	Lower value	Upper value
Photovoltaic system	0.12	0.08	0.15
Electrolyzer + ancillary	0.61	0.55	0.75
High-pressure compressor	0.7	0.63	0.77
H_2-boiler	0.6	0.54	0.66

Table 8
Indicative efficiency range for the main energy transformation chains

System	Efficiency of energy transformation chain, η		
	Typical value	Lower value	Upper value
Electricity to heat	0.37	0.30	0.50
Electricity to vehicle fuel	0.43	0.35	0.58
Solar radiation to H_2	0.073	0.044	0.113

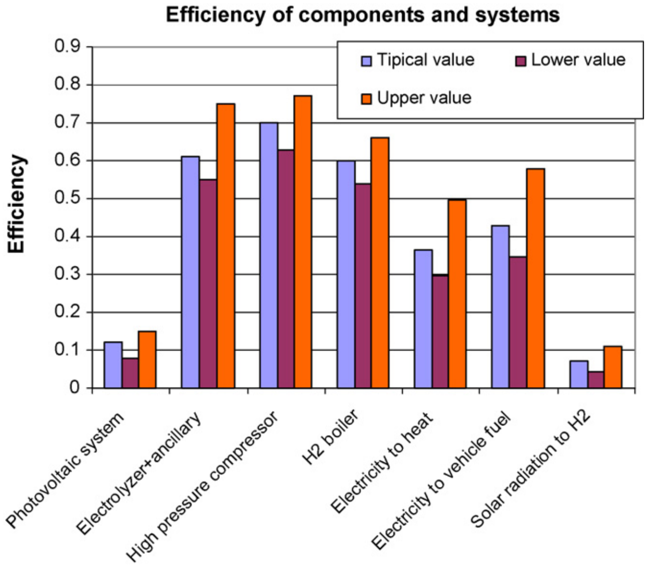

Fig. 7. Indicative efficiency range for the main components and results on the total efficiency of the system.

necessary to convert solar energy into electric power thorough solar modules and dc/ac converter; electric power is then used in the electrolyzer to produce H_2, which is compressed in the storage tank by the electric compressor. The sensitivity analysis indicate a wide variation in the total efficiency of transformation chains (from 40 to 60%), where many subsystems are involved. This can result in an wide variability of the economic results, if poor quality components are used, or operating conditions affecting the efficiency are neglected. To minimize this uncertainty and to keep a safety factor for the economic analysis, the average values have been considered.

6. The economic analysis

A current net value analysis (CNV) has been carried out. The initial investment of the plant is around €791,000. The cash flow discount rate is 7.8%. The life span of the plant is estimated to be 20 years (optimistic for the electrolyzer and compressor). The cash flow is composed by two positive flows: oil cost avoided (OCA) and solar energy reward (SER). The first represents the avoided cost of oil, due to the use of the hydrogen as a fuel. The second positive term represents the income obtained producing electricity with the photovoltaic array if the feed-in tariff is applied (it was under debate in Italy at the moment of the study, it is applied now); a price of €0.63 kWh^{-1} has been assumed.[1] The CNV's of the investment is negative: €−428,000. This result underlines that the investment is not profitable. The negative flows are due to the return of the finances (FC, finances costs), and the operational costs (MC, maintenance costs and EC, electricity costs), as shown in Fig. 8.

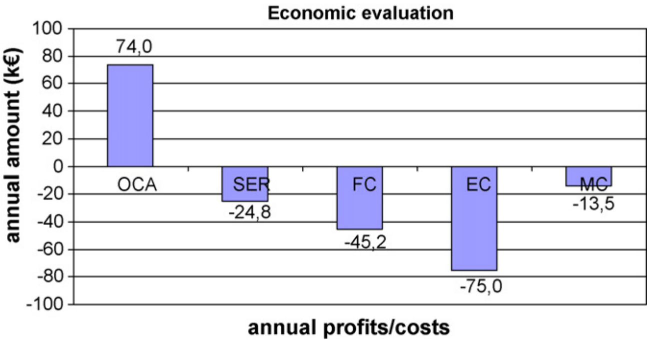

Fig. 8. Components of the cash flow.

It must be focused that also a system based on traditional fossil fuels as oil, LPG, or methane, does not have a positive income because it is used to cover the user requests and not to sell energy to gain a profit. Therefore, in the case under study, the concept of NPV is not particularly indicated as a decision index to determine whether to invest or not in a technology. It could be used the concept of investment cost of the components: but at present the technologies using hydrogen are at the level of alpha or beta prototypes, and cannot be compared with technologies developed in the last century, for burning coal, oil or natural gas. Therefore, another possibility to compare the systems could be to compare the cost of the fuels: the hydrogen produced by the system is around €0.24 Nm^{-3}, or €0.022 MJ^{-1}, while CH_4 is at €0.6 Nm^{-3} (this is the total cost for residential user), or €0.018 MJ^{-1}. The cost calculated for H_2 produced is in accordance with cost indicated by other authors [13], taken into account the differences between the reference systems and the particularly favourable conditions for purchase and sale of electric power in the Laboratory-Village. Moreover, the cost of the hydrogen produced is comparable with the cost of natural gas, with a difference of €0.004 MJ^{-1}. Due to the dynamic of the international costs of the hydrocarbon fuels, that are continuously raising, it is predictable that, in the medium term, the self-produced hydrogen will become competitive with natural gas coming from abroad. In this case, energy systems such as

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[1] This value (€0.60 kWh^{-1}) is suggested by Gruppo Imprese Fotovoltaiche Italiane (GIFI) to obtain the return of the investment of the solar plant in a period of 7/8 years.

the one here discussed could become profitable in the medium term even in terms of cost.

7. The DHPHP: direct high-pressure hydrogen production

H_2 energy density at ambient pressure is extremely low; the upper heating value is 3.54 kWh Nm^{-3} (to be compared to 9300 kWh l^{-1} for UHV of gasoline). Especially in the mobility sector, high energy density of the fuel (that means high-pressure H_2) is a crucial problem: for a given space of the fuel tank in the vehicle, rising the pressure it is possible to obtain a longer path covered. This is clearly visible in Fig. 9 where different mass content in a 0.33 l storage are indicated for pressure varying from 20 to 200 bar.

In some cases (as for transformation from gasoline to gas in an already existing vehicle), large volume vessels can invalidate the use of the rear seats and/or the luggage store, producing unacceptable discomfort and cost in comparison with usual fuels. Recent researches are oriented in developing very high-pressure storages (from 400 to 700 bar), using as lighter as possible vessel (made of carbon fiber, or better aluminium fiber), as reported in [16,17].

The request of H_2 at high and very high-pressure can be satisfied in two ways:

- H_2 production at low-pressure and subsequent compression.
- H_2 production directly at high-pressure.

State of the art electrolyzers produce high mass flow (up to 120 Nm^3 h^{-1}) with delivering pressure at 4–20 bar. The electrolyzers are often used coupled with multi-stage compressors, to obtain the requested final pressure: H_2 compressors must be of particular construction, and have high investment costs. In many plants, membrane compressors are used, that have the following characteristics and specifications:

- membrane compression: extremely low leakage (it is possible to reach 10^{-8} mbar l s^{-1}), avoided contact between the gas and oils or contaminants, no need of gas purification after the compressor;
- multi-stages: it is possible to obtain high compression rates;
- high performances materials: stainless steel, Hastelloy, Cr–Ni alloy (to prevent embrittlement, to guarantee high mechanical performances).

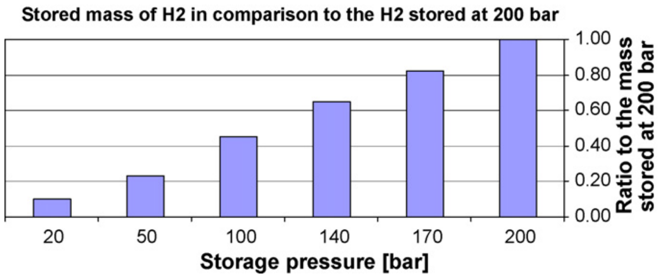

Fig. 9. Stored H_2 mass vs. storage pressure for a 0.33 l volume.

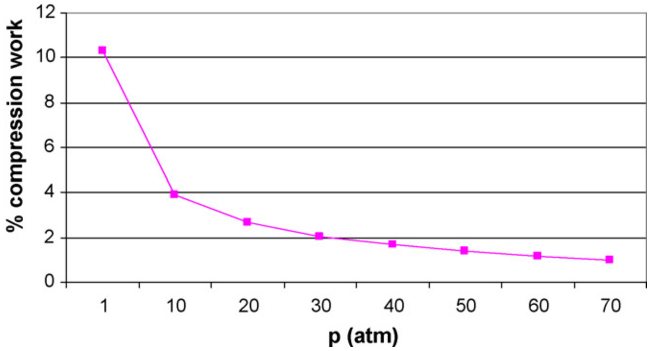

Fig. 10. Compression energy (in % on the total energy for mobility) to deliver H_2 at 200 bar vs. compressor inlet pressure.

H_2 compression requires power and energy use: in the Laboratory-Village plant the energy consumption added for the compression from 4 to 200 bar is near 3% of the total energy requested for the mobility (estimated in 10 MWh year^{-1}).

In Fig. 10 it is possible to see the influence of the compression work, on the total energy needs, for different compressor inlet pressure (different compression ratios): for compression ratio of 200:1, energy need is 1011 kWh, decreasing to 97 kWh for compression ratios of 200:70 (2.86) (calculations done assuming $\eta_{\text{iso}}\eta_{\text{mech.}} = 0.7$).

During last years, some papers have been presented about the production of H_2 by electrolysis directly at high-pressure [18–21] using both alkaline and PEM technologies. Alkaline electrolyzer experimental plants have been realized in medium power scale (up to 100 kW, as reported in [19]), and deliver H_2 at pressure around 100 bar. This technology implies that the whole stack is kept in a pressure vessel and the feeding water is pumped to the same pressure of the produced H_2. This means that there is no pressure difference between the inside and the outside of the stack, and between the anode and the cathode side; the pressure across the separation walls is balanced.

As in the fuel cell sector, PEM technology is also applied and PEM electrolyzers have been developed for spatial and submarine applications, initially with balanced pressure stacks: the anode and cathode sides are kept at the same pressure, with low stress for the membranes.

New applications, in very small sizes (less than 0.1 kg h^{-1}) [21–23] are provided by some American producers. This systems present unbalanced pressure: the anode side is at ambient (or neat ambient) pressure, while the cathode side is maintained at the delivering pressure of hydrogen. Unbalanced pressure systems cause higher stress for the membrane, but generate a cost reduction of the system, because the feeding water for the reaction and the relative piping and components (valves, pumps, sensors, . . .) do not need pressurization.

It is possible to describe the working parameter of the stack with the equation of the stack voltage (polarization curve):

$$V = V_{\text{OC}} + \eta_{\text{act,a/c}} + \eta_{\text{ohm}} + \eta_{\text{conc,a/c}} \tag{1}$$

where V is the terminal voltage, V_{OC} the open circuit voltage, $\eta_{\text{act,a/c}}$ the activation overpotential, η_{ohm} the ohmic overpotential

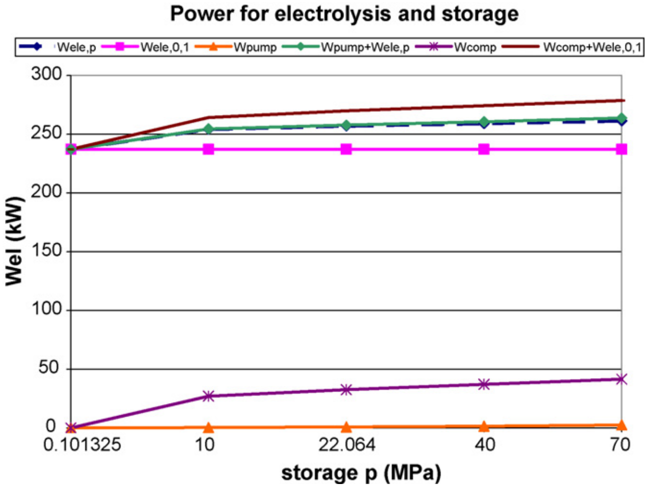

Fig. 11. Power needs for hydrogen gas storage vs. storage pressure.

and $\eta_{\text{conc,a/c}}$ is the concentration overpotential. For the study of electrolyzer power consumption it is important to investigate the variation with pressure of the single terms of the equation.

The Nernst equation (under hypothesis of ideal gases) express the direct influence of the pressure on the open circuit voltage:

$$V_{\text{OC}} = E_0(T, p_{\text{ref}}) - \frac{RT}{2F}\ln\left(\frac{(p_{\text{H}_2\text{O}})}{(p_{\text{H}_2})(p_{\text{O}_2})^{0.5}}\right) \qquad (2)$$

It is possible to see that open circuit voltage raises with pressure (and consequently the power consumed for the electrolysis).

But, in terms of power needs for the complete reaction (from power to high H_2 stored), the total power requested from the system is lower in the case of high-pressure electrolysis (even in the case with water pumping) in comparison with the case with low-pressure electrolysis and H_2 compression. Fig. 11 (obtained from a study developed by Onda et al. [18]) represents and compares the two paths: (1) $W_{\text{ele,p}}$: power for the high-pressure electrolysis at different hydrogen outlet pressure; W_{pump}: power to pump water in the high-pressure electrolyzer; $W_{\text{pump+ele,p}}$: total power to pump the water and for the high-pressure electrolysis; (2) $W_{\text{ele,0.1}}$: power to electrolyze water at 0.1 MPa; W_{comp}: power to compress the hydrogen gas; $W_{\text{ele,0.1+comp}}$: total power to electrolyze at 0.1 MPa and to compress the hydrogen gas.

It is possible to observe that the electrolysis power raises with the pressure, in accordance with the Nernst equation, but the total energy savings obtained in the high-pressure electrolysis process (with water pumping), compared with the low-pressure electrolysis + compression of H_2 gas are 4 and 5%, respectively, at 100 and 400 bar.

Some authors [18,24] indicate DHPHP as a field of promising interest without differences between alkaline and PEM electrolyzers, for the possible reduction in terms of energy consumption per H_2 produced, and for the interesting cost reduction and plant simplification, due to the elimination of the compressor. Industries and research centers are also investigating this field, as reported in some notices [25,26] and articles [20,21,29,30] and books [28]. Other authors are skeptical about the convenience of DHPHP in terms of electrical energy efficiency [27], due to the increase of the reversible voltage; only in small applications pressurized electrolyzers might be preferable. Nevertheless, according to [18,28], direct high-pressure hydrogen production seems to be a potential promising field, both for alkaline and PEM electrolyzer.

8. Development of the laboratory scale prototype

To investigate the performance of the process, and in particular the total electricity-to-H_2 efficiency and the influence of the pressure on the different terms of the polarization curve, a laboratory scale PEM electrolyzer test station has been designed (Fig. 12) and is now under construction at the DENER laboratory in the Politecnico di Torino (Italy). The stack is provided by Giner Electrochemical Systems LLC., that developed it in the frame of a DOE Hydrogen Program [22,23].

The peculiarity of the system is that pressures between anode and cathode side are unbalanced: purified water is fed at atmospheric pressure to the anode side of the stack for the electrolysis reaction and thermal conditioning, while H_2 is produced at the cathode side at a imposed high-pressure value. A variable current is provided to the stack to simulate an unpredictable source (as PV panels and some micro-hydro turbines plants), and high-pressure H_2 is produced at the cathode side, where it is vented or stored in storage tanks. Water is circulating at the anode side by means of an ac circulator; the produced O_2 at the anode side is separated by water and vented to the atmosphere.

The stack is made of 12 cells, with an active area of 160 $\text{cm}^2\ \text{cell}^{-1}$; it will be operated at around 50 °C. The anode side is normally at 1 bar, while the cathode side can reach 35 bar for some hours of operation, and a maximum of 68 bar for some minutes. The maximum hydrogen production rate is fixed at 0.1 kg h^{-1}, with related current of 224 A (1.4 A cm^{-2}), and voltage of 25 V (at 35 bar): the total power is therefore rated at 5.6 kW. Low voltage and current are recommended for continuous operation.

Future work will be carried on regarding the characterization of the stack, for the comprehension of the influence of the main

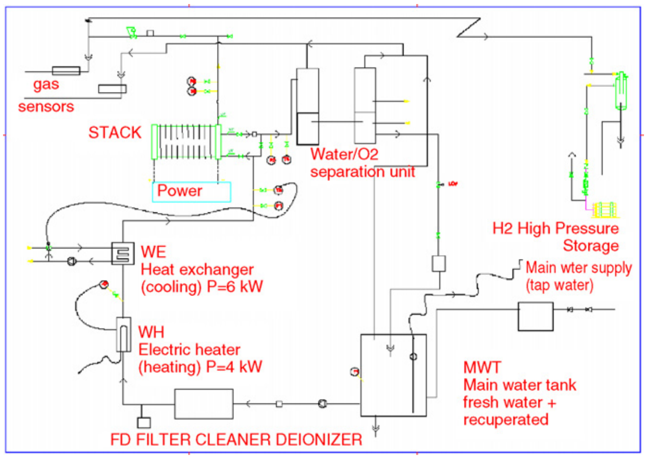

Fig. 12. Schematic of the laboratory high-pressure PEM electrolyzer test station.

operation factors (in primis, pressure) on the different terms of the polarization curve, especially the activation overvoltage (kinetic term) and the concentration overvoltage (mass diffusion mechanisms).

9. Conclusions

This study has shown that H_2 production for mobility in a village in Valle d'Aosta using RES could be feasible and nearly profitable. According to the feasibility study, the cost of the produced H_2 is around €0.24 Nm^{-3}. The cost of energy from H_2 is €0.022 MJ^{-1}, that must be compared to, e.g., imported natural gas at €0.018 MJ^{-1}. This value results under the hypothesis that H_2 is produced by power bought from the grid during low-cost hours. To feed the heating request, the most suitable option is a local district network with a centralized H_2-boiler, and to feed the mobility needs a dedicated refuelling station separated from the other utilization. Taking into account the external costs of fossil fuels as well as the expected improvements in efficiency and decreasing in costs of some technologies (as PV cell, electrolyzers and H_2-boilers), a H_2 system as the one here described could become financially competitive.

For application in the mobility sector, a direct high-pressure hydrogen electrolyzer is interesting both for energy savings and possible investment cost reduction, but operating parameters, larger components and improvement in materials life have to be developed. A laboratory test for a alpha prototype direct high-pressure PEM electrolyzer (produced by Giner LLC.) is under development by the authors, to characterize the technology and explore the pressure effect on the various terms of the polarization curve with experimental data. The first results will be available soon.

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