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Electrolytic hydrogen production from renewable source, storage and reconversion in fuel cells: the system of the “Mediterranea” University of Reggio Calabria

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Abstract

Nowadays a redesign of cities, amid the others from an energetic point of view, is taking place. It increasingly addresses the smart city model, an organic system in which infrastructures, services and technology are organized in order to achieve friendly and livable cities, combining in a single urban model environment protection, energy efficiency and economic sustainability.

In smart cities buildings are nZEB and equipped with domotics applications, energy grids are smart, transports are electric, lighting is high-efficiency, hydrogen is used for energy storage, ecc.. As concerns this latter, in the last periods hydrogen has increasingly shown to be particularly fit as an energetic carrier, being not pollutant, versatile, allowing production at all scales and, compared to electric battery, not requiring time consuming recharging. Anyway, due to the present relevant starting funds of its technology, its quick, effective penetration into the market still requires the necessary economic breakthroughs.

Within this frame, in the paper a system aimed at hydrogen production through electrolysis from renewable source (provided by both PV and wind generators), its storage and reconversion in fuel cells is presented. The system is installed at the Mediterranea University of Reggio Calabria. Particularly, in the paper the global process taking place in the system is described, evaluating the hourly hydrogen stored amount, the power autonomy provided and the global efficiency of the process.

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Keywords: hydrogen; storage systems; smart grids; renewable energy.

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1. Introduction

Nowadays among economists and scientists the concern is widespread that new economic paradigms are required in order to put to use emission reduction policies, driving a transition towards carbon free models. This means abandoning the present, centralized-hierarchical, energy management model, under the aegis of a wide resource federalism. The new energetic regime, distributed and collaborative, will be based on renewable energy, buildings converted in productive centrals, smart grids, electric mobility, energy storage and Hydrogen [1-10].

Within this frame, a city redesign from the energetic point of view is presently taking place, addressing towards the *smart city*, a urban model in which infrastructures, services and technology combine in an organic system conjugating energy efficiency, economic sustainability and environment protection.

In the new model, Hydrogen will perform a more and more significant role, showing to be particularly fit as an energetic carrier [11-12]. Thanks to its energetic properties, in the next future it could be one of the main candidates to replace conventional fuels, being not pollutant, versatile, allowing production at all scales and, compared to electric battery, not requiring time consuming recharging. Among fuels, it shows the highest mass energy content and a very high combustion efficiency, thanks to which it is now regarded as the preeminent future fuel. Nevertheless, its low volumetric energy content must be cited as one of its main weak points.

From an environmental point of view, water is the only product of its combustion in pure Oxygen, that is free from pollutant emissions. In air combustion, nitrogen oxides (NO_x) are the only byproducts and no greenhouse gases, particularly CO_2, are produced. Combined with methanol, ethanol, gasoline and natural gas, it markedly contributes to emission reduction.

Unfortunately, its cleanest production method, electrolysis, totally free from environmental impacts, requires large electricity amounts that make it convenient only when energy cost is not high, as in case of surplus or renewable source production. Moreover, its storage is not very easy and infrastructures completely lacking.

Consequently, at the moment, due to the relevant starting funds of its technology, a quick, effective penetration into the market still requires the necessary economic breakthroughs. As that, a transition towards an Hydrogen-based energy model only gradually can take place, extending its present industrial applications to widespread uses as a fuel.

Within this frame, in the paper, as a contribution to research concerning its use for energy storage, a system aimed at Hydrogen production through electrolysis from renewable source (PV and wind generators), storage and reconversion in fuel cells, of the *Mediterranea* University of Reggio Calabria is presented. Particularly the components of the system, its functioning principles and the global process are described, together with its efficiency assessment.

2. Components of the system

The system consists in the following elements (Fig. 1):

- renewable energy power generator;
- inverter;
- deionized water tank;
- electrolyzer;
- hydrogen analyzer and purifier;
- storage tank;
- fuel cell;
- control system.

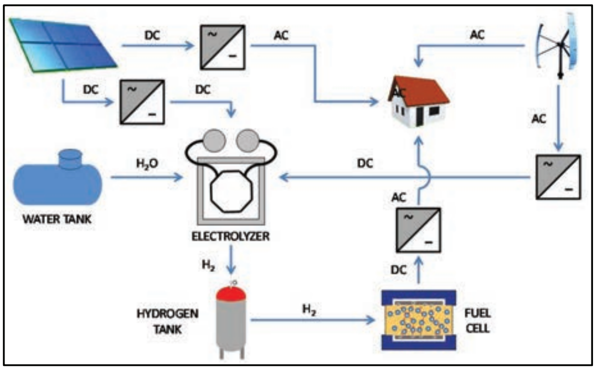

Fig. 1. Sketch of the whole system

On the whole, the system can be considered consisting in *a Process unit*, governing water electrolysis, hydrogen storage and reconversion in electric energy, and a *Power supply unit*, supervising, together with the *Programmable Logic Controller* (*PLC*), the control of all the system parameters, thus guaranteeing the correct process functioning.

Renewable energy power generator

The renewable energy power generators, at the moment partially available, are (Fig. 2):

a) a photovoltaic plant, with a peak power of 10 kW
b) a photovoltaic plant equipped with solar tracker, with a peak power of 2 kW
c) a vertical axis wind turbine, with rated power of 30 kW
d) two vertical axis wind turbines, with rated power of 1 kW and 3kW;

Fig. 2. RES Power Generators

Inverter

The electrolyzer requires electrical energy as DC current, so that the electronic converter is AC/DC only if energy source is wind or solar thermoelectric, whereas, in case of photovoltaic source, the system is equipped with a DC/DC converter, in order to optimize the energy flow, adapting it according to the voltage level of the system.

Deionized water tank

The electrolyzer requires deionized water, that is stored in a tank.

Electrolyzer (stack)

The electrolyzer consists of bipolar electrolytic cells and produces Hydrogen and Oxygen (this latter liberated into the atmosphere) under pressure, without use of a compressor (Fig. 3). In order to increase its efficiency, water is made highly conductive by adding Potassium hydroxide (KOH). The efficiency of the system is 0.75; Hydrogen output has purity of 99.8% and pressure of 20 bar.

Hydrogen analyzer and purifier

The process is carried out using various filters, having the following tasks:

a) deoxidize hydrogen in a reactor;
b) recover the residual KOH;
c) absorb the residual water.

At the end of the process Hydrogen purity reaches 99.99%.

Storage tank

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

Fuel cell

A fuel cell with a rated power of 1.7 kW allows to produce electric energy using a pair of RedOx reactions. Particular attention must be paid to the separation membrane that, in order to ensure operability and reliability, requires a high purity level in Hydrogen input (99.99%).

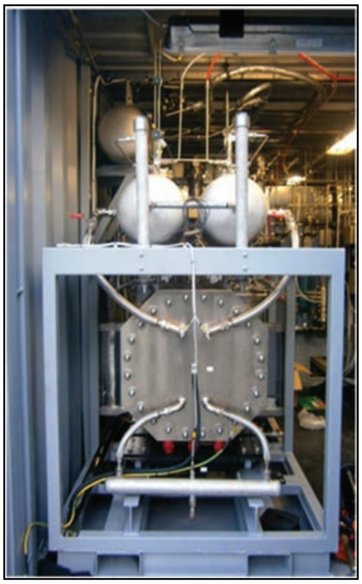

Fig. 3. Stack and separator tanks

The output current is DC and requires an inverter. There are also auxiliary systems:

- fuel cell controller, which manages the interface and communication of the cell with other units;
- accumulators, operating as buffers to regulate the output power and as backup unit if electrical current is absent;
- inverter, which in addition to DC/AC transformation, is also used to manage the charge state of accumulators;
- valve block, in which the input power supplies are connected to the cell;
- wiring area, namely the wiring scheme composed by circuit breakers.

Control system (PLC)

A control system, remotely manageable via specific software, is responsible of ensuring the system safety, efficiency and correct functioning; moreover, it allows to operate without manual operation, except for the starting and shutdown phases. The controller is programmed to regulate and monitor all process parameters and, in case of deviation from standard values, to immediately stop gas production, emitting specific alarms.

The purity of hydrogen and oxygen is monitored by gas analyzers. Alarms are activated if the percentage of Oxygen into Hydrogen (or vice versa) is close to the minimum limit, in order to avoid the explosion of the mixture. In particular, three security control systems are present:

- pressure transducers, constantly controlling pressure values;
- mechanical safety valves, that automatically depressurize the machine if 30 bar pressure is reached;
- Hydrogen leak detectors, that switch off the system if the gas percentage exceeds a preset threshold

In addition, the electrolyzer is provided with an analyzer of O_2 in H_2, equipped with two alarm contacts at the concentrations of 1.1% and 1.6%. The second one blocks the process and gradually let the gas escape, in order to avoid gases mixing; when the pressure is close to the atmospheric one nitrogen is automatically entered to inert the separator tanks.

3. Phases of the process

The process evolves through eight phases, which take place inside the described devices.

1) System inerting

In order to minimize every possible hazard, before being switched on and after being switched off, the system is made inert by inflating approximately 0.46 kg of Nitrogen at low pressure. This action allows air, Oxygen and Hydrogen to be eliminated from the plant and from the tanks. Pressure, monitored by the control system, is lowered to 5-10 bar at the electrolyzer inlet, and to 1 bar at the analysis sections.

2) Pre-start

During the pre-start phase (60 s long) a solution of demineralized water (yielded at a rate of 8 l/h by means of cation or anion exchange resins, that eliminate all present ions) and electrolyte KOH, in concentration of 25-30%, flows through the electrolyzer. KOH increases the electrolysis efficiency and prevents detonations, as the Oxygen and the Hydrogen separating tanks communicate through a U-pipe. At this stage, Nitrogen is still circulating in the plant. At the end of the phase, the system pressure decreases below 0.3 bar.

3) Purging

During the purging phase, which lasts 7 minutes, whose purpose is the removal of the residual Nitrogen, the electrolyzer stack is powered and the production of Hydrogen and Oxygen begins. In order to minimize energy demand, the control system keeps the supplied power at 20% of the maximum value.

Hydrogen and Oxygen produced are directed to the separating tanks and hence to each corresponding breather to be discharged outside as Nitrogen contaminated. The breathers are provided with silencers.

4) Pressurization and hydrogen production

Pressurization starts automatically after the purging phase: the control system increases the supplied power until the selected settings are reached. Usually the power is kept at 70% of its maximum value.

Electrolysis takes place and Hydrogen and Oxygen produced are directed to the separating tanks where the pressure rises. For stoichiometric reasons, Hydrogen production is higher than the Oxygen one and a pressure unbalance would arise: in order to prevent it and the two gas blending, causing detonation, compensation actions are required. The process consumes demineralized water which is automatically restored by a pump.

5) Gas processing

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

6) Gas analysis and purification

Hydrogen is directed to a tank, named *bubbler*, where, flowing through a pipe, equipped with porous filter and submerged in demineralized water, it produces babbles. There it is purified from the residual KOH electrolyte, which is retrieved and directed to the stack. The same purification regards Oxygen before its discharging into the atmosphere.

The following process aims at the elimination of the residual Oxygen from Hydrogen and occurs inside a deoxidizing reactor, consisting of a tank containing palladium and a thermistor. Here part of the Oxygen reacts with Hydrogen producing water; Hydrogen is hence cooled flowing through a heat exchanger, where condensation is removed by a coalescing filter. Finally, it is then sampled and tested to gage the percentage of residual O_2, in order to prevent the formation of explosive mixtures: if O_2 concentration greater than 1.6% (law limit) is detected, the plant is immediately depressurized. The analyzer is equipped with a sensor able to detect the lack of flow at the inlet section.

After being depurated by the residual water by means of two alumina dryers operating alternatively (one being regenerated, while the other dries the gas), the produced Hydrogen reaches a purity level of 99.9%.

7) Hydrogen storage

Purified Hydrogen is stored in a tank which is located in a dry and cool environment, well ventilated and shaded from direct solar radiation. Inlet flow is 2 Nm^3/h. The tank storage capacity is 0.75 m^3. At a pressure of 20 bar Hydrogen volume is approximately 15 Nm^3.

8) Power production in the fuel cell

The valve block of the fuel cell needs to be initially powered to open the general circuit breaker; furthermore the cell is activated when the tank pressure exceeds 5 bar, even though a pressure of 10 bar is recommended in order to ensure a long operability. The energy generated by the fuel cell charges the batteries up to a voltage of 55 V; once reached this level, the cell goes on a standby state. When the battery voltage lowers below 49 V, the fuel cell automatically starts energy production to charge again the battery. The process continues until the plant is switched off and the control system handles the Hydrogen flow in order to meet the load power demand.

The fuel cell is equipped with a self-diagnostic system which is able to verify the proper operation mode also after long periods of inactivity (one month at least) and to ensure an efficient lifetime to the proton exchange membrane.

4. Analysis of the global process

The system has been dimensioned with reference to the maximum input power to the electrolyser, equal to 10 kW, that is provided by several renewable energy power generators. At a pressure p = 1.01325 bar and temperature t = 0°C, the maximum hourly Hydrogen production of the electrolyser, $\dot{V}_{H_2}$, is 2 Nm^3/h. As Hydrogen density, ρ_{H_2}, is equal to 0.0899 kg/Nm^3, the hourly produced mass, $\dot{m}_{H_2}$, will be:

$$\dot{m}_{H_2} = \dot{V}_{H_2} \times \rho_{H_2} \times \tau = (2\,\mathrm{Nm^3/h}) \times (0.0899\,\mathrm{kg/Nm^3}) \times (1\,\mathrm{h}) = 0.18\,\mathrm{kg/h}$$

Hydrogen volume, V_{H_2}, that can be stored in a tank of V = 0.75 m^3, at a pressure p = 20 bar and temperature t = 0°C, can be determined using the ideal gas law:

$$V_{H_2} = \frac{M_{H_2}}{\rho_{H_2}} = pV\frac{PM_{H_2}}{\rho_{H_2}RT} = $$

$$= 20 \times 10^5\ \mathrm{Pa} \times 0.75\ \mathrm{m^3}\ \frac{2.016\ \mathrm{kg/kmol}}{0.0899\ \mathrm{kg/Nm^3} \times 8314\ \mathrm{J/Kkmol} \times 273\ \mathrm{K}} = 14.8\ \mathrm{Nm^3} \tag{1}$$

Considering Hydrogen lower calorific value, pci_{H_2} = 3 kWh/Nm^3, and the fuel cell efficiency, ε_{FC} = 0.4, the stored volume allows to produce an amount of electric energy given by:

$$E_{FC} = \varepsilon_{FC} V_{H_2} pci_{H_2} = 0.4 \times 14.8\ \mathrm{Nm^3} \times 3\ \mathrm{kWh/Nm^3} = 17.8\ \mathrm{kWh} \tag{2}$$

In the system design, one of the most important parameters concerning the fuel cell is its autonomy in absence of energy from the solar and wind generators, given by the ratio between the stored Hydrogen volume, V_{H_2}, and the hourly input flow of the fuel cell at the rated power, $\dot{C}_{H_2}$.

$$A = \frac{V_{H_2}}{\dot{C}_{H_2}} \tag{3}$$

where: $$\dot{C}_{H_2} = \frac{P_{FC}}{\varepsilon_{FC} \times pci_{H_2}} = \frac{1.7\,\mathrm{kW}}{0.4 \times 3\ \mathrm{kWh/Nm^3}} = 1.42\ \mathrm{Nm^3/h} \tag{4}$$

in which P_{FC} is the fuel cell rated power. Consequently:

$$A = \frac{V_{H_2}}{\dot{C}_{H_2}} = \frac{14.8\ \mathrm{Nm}^3}{1.42\ \mathrm{Nm}^3/\mathrm{h}} = 10.4\,\mathrm{h}$$

As concerns the global process efficiency, considering that $\varepsilon_{electrolyser} = 0.75$, and $\varepsilon_{FC} = 0.40$,

$$\varepsilon_{tot} = \varepsilon_{electrolyser} x \varepsilon_{FC} = 0.75 \times 0.40 = 0.30 \tag{5}$$

5. Conclusions

Effective policies aimed at emission reduction cannot disregard the adoption of new economic paradigms, giving up the present energy management model, centralized and hierarchical, in favor of a distributed and collaborative one, based on renewable energy, buildings converted in productive centrals, smart grids, electric mobility, energy storage and Hydrogen. This configures a *smart city* model, in which infrastructures, services and technology effectively conjugate energy efficiency, economic sustainability and environment protection.

In this frame, Hydrogen has increasingly shown to be particularly fit as an energetic carrier, being not pollutant, versatile, and, compared to electric battery, not requiring time consuming recharging. Anyway, the present relevant cost of its technology still requires the necessary economic breakthroughs for a quick, effective penetration into the market. Moreover, its storage is not very easy and infrastructures for its supply completely lacking. In addition, fuel cells, although showing many advantages with respect to combustion engines (lack of environmental impact, low operative temperature, fast response to load variation) and autonomy limited only by the tank size (as for vehicles), today exhibit a high cost of both hydrogen and Platin used at the electrodes. Further limitation, they do not tolerate fuel impurities and require very pure Hydrogen, produced by water electrolysis or purified after reforming.

Within this frame, in order to carry out a detailed analysis of both the components and the process taking place in systems aimed at electrolytic Hydrogen production from renewable source, storage and reconversion in fuel cells, in the paper a system installed at the *Mediterranea* University (Reggio Calabria), is presented. Through the study the hourly hydrogen stored amount, the power autonomy and the global process efficiency are assessed.

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