Development and implementation of a prototype pilot hydrogen generation plant using solar energy in rural areas

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Abstract

Background

Worldwide, hydrogen is being regarded as a fuel of the future due to its abundance and the byproducts generated by its combustion. However, mass production of hydrogen gas is a problem complex, since it entails large energy costs. In this work, three prototypes, based on standard and low cost materials, for the production of hydrogen were used, varying the way of generating hydrogen by electrolysis and the way of using the hydrogen produced, either by storing it or to be use in burners in kitchen.

Results

It was found that the operating temperatures oscillate between 60 to 90 degrees Celsius. The system of rectangular plates with bipolar dry cell electrolyzer obtained a H_2 generation of $0.1 \text{ m}^3/\text{hr}$ with an energy consumption of $553.6 \text{ [kW/m}^3 \text{ H}_2\text{]}$ operating at 2 [atm], on the other hand, the unipolar collector with points generated $0.02 \text{ m}^3/\text{hr}$ 20/60 standard liters per H_2 with a consumption of $144 \text{ [kW/m}^3\text{]}$ operating at 1 [atm] this was the most efficient device with a 26 % efficiency considering the solar energy used.

Conclusion

A low cost prototype was created which allows the use of solar energy, allowing the energy storage in the form of H_2 . It can be used in a rural area to be injected in kitchen burners, reducing LPG (liquefied petroleum gas) consumptions and contributing to the sustainable development.

1 Introduction

As the world faces unprecedented energy challenges, many countries seek to include smart energy solutions as an effort to achieve a sustainable future. Hydrogen energy systems have the potential to become part of a clean, reliable, affordable, safe and sustainable portfolio of smart energy solutions. A key advantage of hydrogen is that it can be produced from a variety of sources, including fossil fuels, nuclear power, biomass and renewable energy. [1][2] These potential reserves allow hydrogen to be obtained in several ways, with gasification [3] [4] [5], steam reforming [6], and thermolysis [7] [8] being among the most common. However, these processes generate a negative impact on the environment due to the emission of toxic gases into the atmosphere, such as monoxide, carbon dioxide or volatile compounds [9]. It is for this reason that electrolysis is the best option to produce hydrogen [10] [11], since it is an environmentally friendly process that generates clean fuel without the emanation of CO_2 , thus decreasing the carbon footprint.

Electrolysis is based on the production of H_2 and O_2 by applying an electric current to water and has been gaining attention in recent years, since it can produce high purity hydrogen [2] as well as being compatible with renewable energies [2], and providing an infinite supply of energy [12]. This is why

hydrolysis is considered as one of the most promising technologies for the small-scale production of hydrogen [13] [14].

Nowadays there are different techniques to efficiently extract hydrogen through electrolysis, one of these methods is hydrogen production by aqueous methanol electrolysis, decreasing the operating voltage when using this mixture and also the cost of production [2]. Another technique is the use of commercial aluminum anodes [13] since they are good energy stores.

The transport of supplies to produce hydrogen or the transfer of the product itself for the processes mentioned above increases the carbon footprint, so that the use of hydrogen as a clean and non-polluting energy source is lower due to its high economic value compared to the use of a traditional fuel.

In fact, the production of hydrogen by electrolysis is suitable for systems based on solar energy, since it generates the product very quickly and efficiently [15] [13].

Faced with such problems, it is proposed to use solar energy to generate hydrogen, which can be produced anywhere outside or inside a city, stored as gas and then combusted when energy is required. The identification, comparison and selection of technologies for the generation of hydrogen through electrolysis connected to solar panels are addressed. The equations that govern the generation of solar hydrogen are established with fundamental models of electrochemistry and gas-liquid equilibrium, which allow the design of a domestic prototype. A prototype unit to generate solar hydrogen is designed and built, which allows to establish the performances and design parameters, for its subsequent scaling.

2 Materials And Methods

To carry out the generation of hydrogen, the principle of electrolysis was used. The design of this equipment (See Figure 1) was based mainly on the natural conditions of water and gases seeking optimization through the interaction of water-gas temperature and the relation of conductivity of hydrogen, electromagnetic field movement, tip-shape effect and electrification equipment, electric current intensity, accessibility to maintenance, suitable materials such as copper and stainless steel 316, plastics and borosilicate glass, industrial glues and tin-copper and silver-copper solders, arc welding, tic, blowtorch, tin, plastic welding. All these applications and combinations of materials are necessary to be able to design and build the gas generating equipment. The construction material, was based in low cost commercial components (tanks, piping, tubes).

The flow chart presented in Figure 1 corresponds to the base scheme, since three prototypes were made changing the area of the gasifier that is presented in the diagram, in order to find the most feasible and viable production solution. The prototypes are described below:

2.1 Design s hydrogen generator and solar collector

The first point to be analyzed is the tip-shape effect. This consists of a natural condition of the current, which models the energy in a specific direction. This is focused on the tip of the electrical conductor

which receives most of the energy, this effect was put to the test and it was discovered that the increase of 1.76 [cm³] to 11.6 [cm³] of H₂ in 12 hours of electrification, not only generates the electrostatic wind produced by the tips, but also polarizes the water molecules and amplifies the production of hydrogen inside an electrode.

The electrifier-gasifier equipment specifically separator, is based on previous experiences in which the combination of the proximity of the poles in direct current, the metals that compose it as stainless steel 316 TI and copper, PVC (Polyvinyl Chloride) pipes with perforations in all its contour to bring the poles closer in function of a diaphragm and at the same time prevent them from coming into contact, acrylic that performs the same function as PVC but makes it visible to the observer, stainless steel meshes and to conserve the electrical conductivity it was necessary to weld the electrical connections with silver and argon.

2.1.1 Design of the gasifier

The gasifier stores the hydrogen coming from the electrifier in relation to what it produces. First, it is pre-stored in the suction cup storage (See Figure 2), once it is full it releases the gas to the gas seal and to the gasometer.

The gasometer together with sunlight prevents the hydrogen from mixing with air or oxygen maintaining the quality of the gas. The objective of this design is used in the accumulation of molecular hydrogen to subsequently store it temporarily in a water seal.

The water seal and the suction cup storage together are a single device and are an essential part of the hydrogen plant. In Figure 3, the gas outlet system is not installed, but it is in the design.

The criteria for obtaining a hydrogen gasifier begin with the characteristics of the gas itself. The H₂ molecule is the smallest found in the table of chemical elements, since it is so small, special care must be taken so that no leakage occurs, all seals must be interchangeable, it should also be taken into account the ground inclination with respect to the gasifier, Henry's law, gasifier height, container material, sealant glues, water seal effect, safety conditions (distance from switches or sparks).

2.1.2 Solar collector design

The aim of the solar collector is to heat the water with the sun, which favors the dissociation of gas from water. These collectors are made of a material called boro-silicate which is transparent and black which allows the sun's rays to enter the collecting pipe, but does not let it come out which increases the temperature quickly. It's design is shown in Figure 4.

Care must be taken that the water does not increase its temperature beyond 90 ° C due to its evaporation, which damages the concentration of hydrogen, so in the worst case it results in hydrogen with water vapor.

To increase the collection of solar rays it is necessary to install an aluminum mesh from which the beam of light bounces off, being projected into the solar collector, as shown below.

2.1.3 Gas compressor

Equipment sought in the market to meet the needs of the pilot solar hydrogen plant. The characteristics to select it were the maximum pressure that it reaches, 200 [psi], and an average temperature of 43°C. In relation to the Van der Waals equation, storage should be at a maximum of 90 [psi] since hydrogen performs self-ignition at 530°C. The compresor is recycled form domestic refrigerators.

2.1.4 Hydrogen gas storage cylinder

The hydrogen gas cylinder of the solar hydrogen plant is a reinforced stainless steel cylinder capable of safely storing 250 [psi]. This cylinder is from the AGA company in its special gases division.

This cylinder is ideal for the storage and transport of pressurized hydrogen gas, which is why it is used as a fundamental part of the pilot solar hydrogen plant. This cylinder has a capacity of 10 liters of gas at atmospheric pressure and 205 liters or 100 [psi] at maximum pressure as the maximum safety pressure.

2.1.5 Electrified water output

The output water of the equipment has a high concentration of iron oxide in it, so it is necessary to store it as industrial waste.

2.2 Prototype N°2 Cylindrical plates of 2 mm thickness and H-Cut

This equipment does not separate hydrogen from oxygen so a gas called HHO (oxyhydrogen) is obtained with it. This gas has a trace of oxygen and one of hydrogen mixed, these can be pressurized and ignite a conical flame capable of reaching a temperature of 900°C. We can see the diagram of the prototype in the Figure 5.

2.2.1 Cylindrical electrified plates

This equipment has the facility of working with photovoltaic panels as well as with common batteries used in the automotive industry and it is more focused on the production of more efficient gas in a small predesigned cylindrical space. To start operating, it needs direct current and at an amperage of 0.1 [A] the electrolysis process begins to be observed. The design of the plates are shown in Figure 6.

2.3 Prototype N°3 Rectangular plates of 1 [mm] thickness

This equipment has an efficiency of 0.07% with respect to natural energy, which complicates the option of storing hydrogen in a pressurized gas cylinder. The advantage of this configuration and geometrical shape is the contact area of the fluids since being the same size as the previous electrolyzers, it has a contact area of 0.286 [m²]. This area is much higher than the previous more efficient equipment that had

an area of contact of 0.08 m^2 so it needs a higher power intensity and a lower voltage. What does improve in this design is the continuity of the fluid that enters and exits.

Figure 7 shows the constituent parts of the gas generating plate equipment. It has a rubber composed of bi-teflon that performs the task of pressure seal and separator between plates. It has a stainless steel plate and a lid that has a fluid exchange system.

The equipment built is 25% smaller than the one in the 3D diagram, this is due to lack of materials with the ideal dimensions.

2.3.1 Design of a family plant

This plant is oriented to the villages of the interior, specifically to a family composed of four members, and the objective is to implement a substitute product to the LPG used in homes, namely pressurized gaseous H_2 .

For the calculation of the initial investment, the sums of the investments in civil works and pieces of equipment were taken. The sum of all of them results in a total investment of US\$31,000 per family of four people.

Indirectly, as the demand for hydrogen grows, the carbon footprint of those who choose this technology for their home decreases proportionally. So in the best of scenarios it is possible to raise prices due to the reduction of the carbon footprint and the sale of carbon credits by our customers.

The carbon ratio that is no longer produced is 59% of the mass of LPG gas, so 70.8 kg of coal are no longer emitted per year, evaluated in US\$310 and tradable emissions of US\$30.

The location of the headquarters of the company would be in the city of Calama preferentially, due to its greater proximity to the towns of the interior and its great amount of solar electromagnetic energy.

Typical housing with three rooms for a family of four inhabitants, a bathroom and parking. In the backyard there are civil works for the installation of gas generation equipment for a household (Figure 8)

Unlike previous equipment, it has a water heater and electrifier in one single container, thus improving the commercial aesthetics of the possible equipment to be installed in the altiplanic zones of the province of El Loa.

3 Theory And Calculations

3.1 Energy generated

In the general calculation it is necessary to clearly identify the need for energy in the area, identifying values such as energy demand and energy generated in order to know the real seasonal energy needs. To

obtain the amount of energy generated by the hydrogen obtained by electrolysis, Faraday's law for gases is used (Equation 1).

$$m_f = \frac{M}{F * n^0} * I * t \quad (Equation1)$$

$$PV = nRT \quad (Equation2)$$

$$n = \frac{m}{M} \quad (Equation3)$$

Where:

V = Volume

R = Constant of ideal gases

I = Intensity of current

T = Temperature

t = Time

F = Faraday's constant

P = Pressure

n = Number of moles

M = Molecular weight

n^0 = Oxidation state

m_f = Deposited mass

Replacing Equation 3 in Equation 2, Equation 4 is obtained.

$$PV = \frac{m}{M} * R * T \quad (Equation 4)$$

Then Equation 1 is replaced in Equation 4, obtaining Equation 6:

$$PV = \frac{\frac{M}{F * n^0} * I * t * R * T}{M} \quad (Equation 5)$$

$$V = \frac{R * I * t * R * T}{n^0 * F * P} \quad (Equation6)$$

3.2 Storage pressure

To be able to store the amount of gas required by households, it is necessary to pressurize the hydrogen at room temperature, to determine the pressure at which it is compressible, the Van der Waals equation was used (Equation 7).

$$\left(P + n^2 \frac{a}{V^2}\right) \left(\frac{V}{n} - b\right) = RT \quad (\text{Equation 7})$$

Isolating the pressure from Equation 6, we obtain Equation 8, which is used to determine the pressure:

$$P = \frac{RT}{\left(\frac{V}{n} - b\right)} - n^2 \frac{a}{V^2} \quad (\text{Equation 8})$$

Then to determine the adiabatic temperature of the flame in the H-cutting, the heat of reaction is considered. The generated hydrogen can also be used for H-cutting. For this there are two options. The first is the adiabatic temperature of the H₂ flame without excess oxygen and with excess oxygen.

According to the oxidation reaction

Where a, b, c and d correspond to the amount of moles.

According to the energy balance of the reaction, there is the enthalpy of the product and the reactants.

$$\Delta H_{\text{product}} = N_C \left(\int_{T_{\text{ref}}}^T C_{PC} dt + \Delta H_{fC} + \Delta H_{\text{phase change}} \right) + N_D \left(\int_{T_{\text{ref}}}^T C_{PD} dt + \Delta H_{fD} + \Delta H_{\text{phase change}} \right) \quad (\text{Equation 10})$$

$$\Delta H_{\text{reactants}} = N_A \left(\int_{T_{\text{ref}}}^T C_{PA} dt + \Delta H_{fA} + \Delta H_{\text{phase change}} \right) + N_B \left(\int_{T_{\text{ref}}}^T C_{PB} dt + \Delta H_{fB} + \Delta H_{\text{phase change}} \right) \quad (\text{Equation 11})$$

With T as the unknown.

3.3 Hydrogen Thermal conductivity

To determine the water conductivity, the following correlation is used, which is obtained from Figure 9.

$$\text{Hydrogen thermal conductivity} = 0,0404 * T [K] + 5.3646 \quad (\text{Equation 12})$$

We can also see the Graph of Water Thermal Conductivity versus Temperature in Figure 10.

4 Results

The operating pressure is variable according to the design. The first was designed so that no piece reaches a pressure different from the atmospheric pressure inside the electrifier, for the other equipment it was necessary to increase the pressure in relation to the design and utility. All the data of materials and operating values are shown in Table 1.

Table 1: Difference in hydrogen production at different conditions and equipment. Source (Own elaboration)

Test equipment	Solar collector and tips	Cylindrical plates of 2 mm thickness	Rectangular plate of 1 mm thickness
Type of Hydrogen generator	Unipolar with solar heating	Electrolyzer	Dry bipolar electrolyzer
Diaphragm	Polypropylene or PVC or Acrylic	Without diaphragm	Without diaphragm
Operating temperature (°C)	60-75	50-60	75-90
Operating pressure (atm)	1	6	2
Current density (mA/cm ²)	2,4	17	32
Volume of H ₂ in an hour (m ³ /h)	0,02	0,09	0,1
Cell voltage (V)	12	12	1,73
Energy consumption (kW/m ³ H ₂)	144	415,6	553,6
Efficiency with respect to available solar energy (%)	25,5	14,6	0,6
Efficiency with respect to solar energy (%)	3,6	2,1	0,07

5 Discussion

5.1 Comparison of prototypes

The difference of the equipment constructed in this work is discriminated in relation to the natural solar energy present in the area of the Province of El Loa.

The gas generation efficiencies were analyzed in relation to natural energy and available energy, the latter is what the photovoltaic panel provides, which compared to the natural one is approximately 18%.

The energy consumption is different in the three prototypes due to important design differences such as the diaphragm and the current density delivered by the electrolysis equipment.

The number of poles is the difference in cell configuration. Unipolar cells are those that have a parallel connection and have only one electrification cell. And the bipolar is the one that is connected in series with other electrification cells that work together.

Each of the equipment types has important differences at the time of electrolysis and production of hydrogen gas. Differences produced by electrode configuration (series and parallel), contact area and design.

The large amount of energy produced by the electrolysis of water is useless without an industrial utility, so it is proposed to burn the hydrogen using it as an oxygen cutting equipment using H_2 to replace the LPG.

6 Conclusion

When comparing hydrogen generation technologies, two independent variables were identified that directly influence the generation of hydrogen, these are; geometry of the wet area of the electrodes and electrolysis temperature. Due to this it was considered to heat the water with solar collectors and experiments were made with the tip-shape effect and rectangular as well as cylindrical plates.

Hydrogen gas generation prototype units were designed and built, obtaining efficiencies of 25.5% compared to the available solar energy.

Three prototypes for hydrogen generation using tap water and solar energy were designed and evaluated. Obtaining an efficiency in the conversion of natural solar energy to pressurized hydrogen of 3.4%. Producing 0.89 Kg-year/m²-panel.

In the construction of the electrodes, a considerable improvement was observed when using stainless steel 316-l, so the scaling to a larger plant would be built with this material.

A low cost prototype was created which allows the use of solar energy, allowing the energy storage in the form of H_2 . It can be used in a rural area to be injected in kitchen burners, reducing LPG consumptions and contributing to the sustainable development.

7 Abbreviations

H_2 : Hydrogen

O_2 : Oxygen

CO_2 : Carbon Dioxide

LPG: Liquefied Petroleum Gas

PVC: Polyvinyl Chloride

HHO: Oxyhydrogen

8 Declarations

Ethics Approvals and Consent to Participate: All authors consent to participate and declare that there are no ethical issues in this article.

Consent for Publication: All authors give their consent for publication of this article.

Availability of Supporting Data: All data supporting this study is provided in the manuscript

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Figures

Figure 1

Schematic of electrochemical flow of the solar hydrogen pilot plant.

Figure 2

Hydrogen suction cup storage.

Figure 3

Water seal built with waste materials such as the lid of a Coleman and 20 liters of water container.

Figure 4

Solar collectors installed in the electrifier-gasifier device with an aluminum mesh to increase solar collection.

Figure 5

Cutting equipment with hydrogen and 2 mm thick plates gas generator.

Figure 6

Disk electrifier.

Figure 7

Electrifier of rectangular plates of 1mm thickness with connection to voltage regulator and photovoltaic solar energy.

Figure 8

Distribution of the hydrogen generating equipment for a household 2.

Figure 9

Temperature versus hydrogen thermal conductivity. Source (Perry 2006)

Figure 10

Graph of Water Thermal Conductivity versus Temperature. Source (Perry 2006)