



Techno-economic Assessment of Hydrogen Production Using Solar Energy

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Abstract. Concerns related to climate change, environmental pollution and security of energy supply have led several countries to reconsider their means of energy production and examine their dependence on other countries. Portugal was the first country in the world to assume the goal of being carbon neutral in 2050. Renewable energies will play a very significant role in our energy future. However, most renewable energy sources are intermittent by nature and the production from such sources can be difficult to forecast with great accuracy. From this perspective, hydrogen can assume a central role, being simultaneously presented as an efficient option to promote, and facilitate the energy transition and at the same time present several opportunities for economic, scientific, and technological development. In this paper, a study is presented that makes it possible to identify the main costs associated with the production of hydrogen, through the electrolysis process using solar energy as a source of electrical energy production. The study makes it possible to evaluate different scenarios, taking into account the uncertainties associated with the evolution of electricity prices, the evolution of costs associated with electrolyzers and the electrolyser load factor. For each of the scenarios, the hydrogen production costs in €/kg H₂ are identified, allowing the assessment of the attractiveness of the investments, and helping investors in their decision.

Key words. hydrogen production, solar energy, uncertainties, economic assessment.

1. Introduction

One of the most important challenges today is the decarbonization of the global economy. The increase in the global average temperature has caused environmental catastrophes and accelerated the melting of glaciers. This increase in temperature results in extreme climatic and meteorological events such as heavy rains, acid rains or, on the contrary, periods of severe droughts. All these changes will negatively affect all ecosystems. However, the cause of climate change is the emissions of greenhouse gases (GHG), namely carbon dioxide (CO₂), methane (CH₄), perfluorocarbons (PFC's), among others [1].

In this context, several energy strategies have emerged from the European Commission in order to act in different areas to reduce the impact of climate change. Thus, the Climate Energy Package 2030 (PNEC, 2019) emerges. In the European Union (EU), the goals for 2030 are [2], [3]:

- 40% reduction in greenhouse gas emissions;
- 27% of energy will come from renewable sources.
- 27 to 30% increase in energy efficiency;
- 15% of electrical interconnections, that is, transfer of electricity between European Union (EU) countries.

Portugal's strategy has been highlighted in the path defined in the sense of reaching increasingly high levels of incorporation of renewable sources in the various sectors, having achieved a total share of incorporation in final energy consumption well above the European average and on a growing trajectory in the last years. In the electricity production sector, Portugal has reached values around 60% in terms of the incorporation of renewable energy [4]. Portugal has committed to basing its energy production on renewable sources, incorporating 47% of final energy consumption by 2030 and achieving carbon neutrality by 2050 [2]. In order to ensure the neutrality of GHG emissions by 2050, it is necessary to decarbonise the electricity production system, industry and transport. In these sectors, total electrification is not an economically or technically viable alternative. In this way, Portugal implements the National Strategy for Hydrogen (EN-H2), which aims to incorporate and use renewable gases in the energy sector. Thus, it is expected to replace fossil fuels with green hydrogen, that is, hydrogen from renewable sources, in order to complement the electrification strategy. This strategy also aims to promote and boost the supply and consumption of hydrogen, in various sectors of the economy, starting with those that cannot be electrified, creating the necessary conditions for a real hydrogen economy in Portugal. One of the objectives is to ensure, in the long term, the decarbonization of the natural gas network and consumption of power plants, also

contributing to the decarbonization of the transport and industry sectors [5].

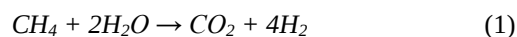
Hydrogen is being considered as an important future energy carrier, which means it can store and deliver energy in a usable form. Hydrogen's high energy density makes it particularly interesting for system-wide energy balancing, it can be produced from several sources, such as hydrocarbon fuels, biomass, boron hydrides, water, and chemical elements with hydrogen [1]. The presented study focuses on the production of hydrogen through the water electrolysis process using a renewable energy source. This hydrogen production process has a number of advantages, including: increase the integration of renewable energy sources in final energy consumption, reduce CO₂ emissions, reduce energy dependence on fossil fuels, contribute to a better flexibility of the National Electric System and increase its efficiency. Hydrogen can be used in the power generation sector. Hydrogen can be collected, transported in natural gas network and re-electrified in gas turbines, or fuel cell power plants. Modern gas turbines can be operated with a mix of hydrogen and natural gas [6].

In this paper, the main objective was to incorporate different sources of uncertainties in investment assessment. This analysis is relevant because there is a wide number of factors affected by uncertainty, that can contribute to turn an investment project very risky and so be discouraged for some classes of investors. This kind of studies is also important in terms of the development of competitive mechanisms in the hydrogen sector leading to a more volatile environment so that the investment decisions have to be taken in view of the uncertainties, evaluating the risks.

2. Solar Hydrogen Production

Hydrogen is a high potential energy source. It can be used in different ways and in different sectors of activity. For example, it can be injected into natural gas pipelines, used as fuel in the transport sector, or even used to produce electricity through fuel cells. However, storage and transportation, as well the production costs are still the main constraints and adversities to the technology. Hydrogen is the most abundant element in the universe and the lightest. A high Higher Heating Value, HHV, is another particularity, ie, a high energy density per mass (141.6 MJ/kg), and a low energy density per volume (8.491 MJ/L). This means that 1 kg of hydrogen contains a huge amount of energy. On the other hand, 1 liter of hydrogen contains 8.491 MJ, which requires more storage capacity. In summary, very specific conditions of pressure and temperature need to be guaranteed for the storage and transport of hydrogen [1], [7].

There are several technologies available in the market and related to the hydrogen production. These can vary from thermal processes or through the electrolysis of water. There are processes that release carbon dioxide, CO₂, into the atmosphere, such as steam reforming, which consists of the reaction of hydrocarbons with water, generating CO₂ and H₂ (1).



On the other hand, there are clean processes, obtaining green hydrogen. In this case, no CO₂ is released into the atmosphere, as is the case with water electrolysis. This process consists of the dissociation of a water molecule, resulting in oxygen, O₂, and hydrogen H₂ (2).



Water electrolysis is a process that requires electrical power to supply energy to the electrolyser, and water to generate hydrogen. The electrolyser is composed of an anode and a cathode separated by an electrolytic membrane, where the oxidation-reduction reactions take place. Oxidation takes place at the anode and reduction at the cathode [1], [8].

There are different types of electrolyzers:

- Alkaline Water Electrolysis (AEL);
- Proton exchange membrane (PEM);
- High Temperature Electrolysis (HTEL ou SOEL).

The electrolytic of the AEL electrolyser is an aqueous solution, such as Potassium Hydroxide (KOH). On the other hand, the PEM electrolytic uses an acidic solid polymer, the most common is the Nafion polymer. Finally, the HTEL electrolyser, despite having a higher performance, it works at extremely high temperatures, which makes it an adversity to the technology due to the temperature conditions that the materials are subjected to. In this general context, water electrolysis and more specifically polymer electrolyte membrane (PEM) water electrolysis is expected to play an increasing position. PEM water electrolysis is an efficient, durable, and very flexible technology that can sustain successive power on/off cycles and that is therefore well suited for water splitting using intermittent power sources [9]. The general features of a PEM water electrolysis are represented in Figure 1 [10].

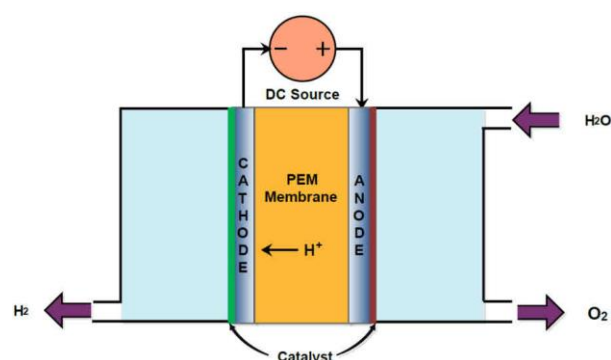
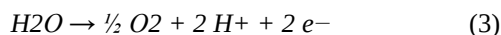


Fig.1. Schematic of polymer electrolyte membrane (PEM) [10].

In PEM cells, there is no liquid electrolyte, for this reason, PEMs are highly reliable because of their non-corrosive polymeric electrolyte. The central component of the PEM is a thin membrane of a proton-conduction polymer electrolyte. On both sides of the membrane, two porous catalytic layers are coated. These catalytic layers are connected to an external DC power source that provides electrical energy for the reaction. In this

process, DC current is used to split liquid water into gaseous oxygen and protons at the anode (3). Due to the electric field established through the cell, hydrogen will be released at the cathode (4).



The major disadvantage of this process is the large amounts of electrical power that it requires to dissociate a water molecule. In this way, the technology only becomes environmentally advantageous when the electrical power comes from renewable energies. Using photovoltaic solar energy is an effective solution, by powering the electrolyser and making it to produce H_2 (Figure 2).

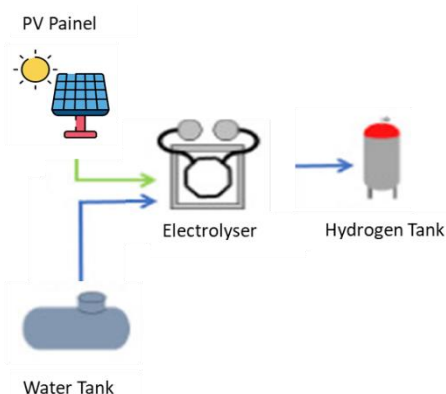


Fig. 2. Ilustração de um sistema solar fotovoltaico na produção de hidrogénio [11].

In order to make better use of renewable energies, in particular solar energy, hydrogen production from electrolysis presents rather interesting features. There is broad consensus in considering that water electrolysis is probably the most environmentally friendly hydrogen production technology combined with renewable energy generation. It is indeed a suitable technology for renewable energy sources as it can adapt its power consumption to available input power. It also offers the advantage of being a fully scalable technology, allowing systems in the range of a few kilowatts to several tenths of megawatts [12].

The system shown in Figure 3 represents a scheme in which the electrical energy produced in the photovoltaic system is used directly by the electrolyser to produce hydrogen. This system has the following advantages: it improves efficiency in the operation of the photovoltaic system, delivers access to energy at more competitive prices, eliminates the costs associated with the use of the transport and distribution network and reduces energy losses in the networks.

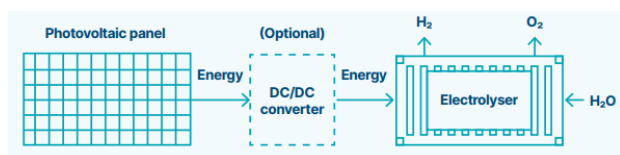


Fig.3. Direct use of photovoltaic production [13].

Figure 4 shows a system in which the electrical energy comes from the electrical system. In this system there is the possibility of using electrical energy from different sources including photovoltaic energy. In this case, the hydrogen production system will be able to: define its operating profile according to the variations in electricity prices on the market, be used to help maintain a balance between production and consumption and also contribute to the stability of the electrical power system.

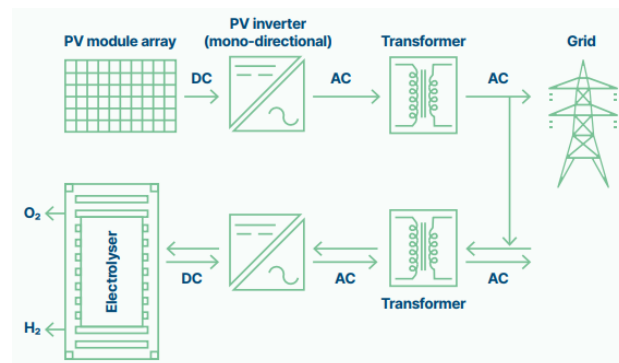


Fig.4. Photovoltaic system and electrolyser connected to the electrical grid [13].

3. Hydrogen production cost

The hydrogen production costs from electrolysis are influenced by the capital costs of the electrolyser, its load factor and the electricity purchase price during the time of operation [6], [14]. For the economic assessment of the system, Levelized Cost of Hydrogen (*LCOH*) is estimated. The *LCOH* is the discounted lifetime cost of building and operating a production system, expressed as a cost per quantity unit of hydrogen produced ($\text{€}/\text{kg } H_2$). The *LCOH* was calculated by determining the ratio of the total discounted costs for the life of the system to the total amount of hydrogen expected to be produced over the system's lifetime. The main cost components are capital expenditures (C_{CAPEX}) that include construction and equipment costs, other expenses are operating cost (C_{COPEX}) including electricity, electrolyser replacement and maintenance costs, which are set into relation to the annual amount of production hydrogen P_H . A discount rate r is assumed over n years economic lifetime. In this process it is possible to include the installed capacity of the system, the expected load factor, and its efficiency. The *LCOH* is determined through the expression 4.

$$LCOH = \frac{\sum_{t=0}^{t=n} \frac{C_{CAPEX} + C_{OPEX}}{(1+r)^t}}{\sum_{t=0}^{t=n} P_H} \quad (4)$$

The developed tool allows to evaluate the cost associated with the production of hydrogen considering:

- the costs associated with the electrolyser;
- efficiency rate;
- electrolyser load factor;
- costs with the installation of electrolysers;

- costs associated with project financing;
- costs of the electric energy.

From the parameters mentioned, it is possible to identify that there are many uncertainties related to its evolution. To ensure that the model results are relevant for a longer period of time, we use a range of costs and explore the sensitivity of the *LCOH* to these values. This information is important to obtain data that allows investing agents to have the most complete perspective possible of the different scenarios that may occur.

Regarding the cost of the electrolyser, the forecasts are that it will have a significant decline in the coming years [14]. Another relevant factor is the cost of electricity, which is directly influenced by the technology used. For the photovoltaic system, the Figure 5 shows a significant cost reduction between 2010 and 2020 [15]. Also in this aspect, forecasts indicate that prices will continue to decrease in the upcoming years, making the technology increasingly competitive. In other words, more and more effective systems have been developed, contributing to the competitiveness and costs reducing related.

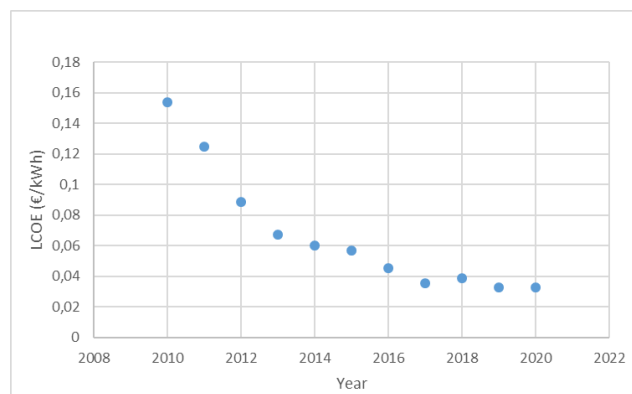


Fig.5. Evolution of production costs of Photovoltaic Solar System

It is expected that the current prices in the market, for hydrogen production through renewable energies, will decrease in the future, with the potential to become a more economical solution when compared to using fossil fuels [16].

4. Case Study

A case study was developed aiming to analyze the evolution of the hydrogen cost production in a more concise way. Based on that, different scenarios were developed, aiming to observe the behavior of the hydrogen cost production, such as:

- Influence of the load factor of the electrolyser;
- Influence of the electrical power costs;
- Influence of the cost of the electrolyser.
- Influence of the costs variation related to the project (C_{CAPEX} and C_{COPEX}).

In this project it was considered a PEM electrolyser with an efficiency of 42 kWh/kg H₂. For the base scenario

associated with the project, the technical-economic parameters presented in Tables I and II were considered.

Table I. – Technical Operating Parameters and Specifications

Operating Capacity Factor (%)	86,00%
Plant Design Capacity (kg of H ₂ /day)	50 000
Plant Output (kg of H ₂ /day)	43 000
Plant Output (kg of H ₂ /year)	15 695 000

Table II. – Financial Parameters

Length of Construction Period (years)	1
% of Capital Spent in 1st Year of Construction	100%
Plant life (years)	30
Depreciation Schedule Length (years)	20
Interest rate on debt, if applicable (%)	3,70%

For this case, it was considered a Capital Expense (C_{CAPEX}) of 82953872.64 €. This amount includes depreciable and non-depreciable costs, costs related to land, commissioning and engineering costs and electrolyser acquisition costs. Operation and maintenance costs are 79 063 112.64 €. These expenses include fixed costs, like, costs related to labor and maintenance, and variable costs, which include the cost of electricity (0.077 €/kWh), electrolyser replacement and the costs of non-energy products, such as water supplied to the electrolyser. For the base case, a value of 5.13 €/kg H₂ was obtained for *LCOH*.

In order to evaluate the influence of the electrolyser load factor on the evolution of *LCOH*, a sensitivity study was carried out. The results presented in Figure 6 show that the load factor has a very relevant impact on the cost of hydrogen production. It is possible to verify that the cost decreases with the increase of the load factor. However, for load factor values greater than 50%, *LCOH* tends to stabilize. This information is very relevant, particularly for the evaluation of the investment and definition of possible strategies for the operation of the hydrogen production system.

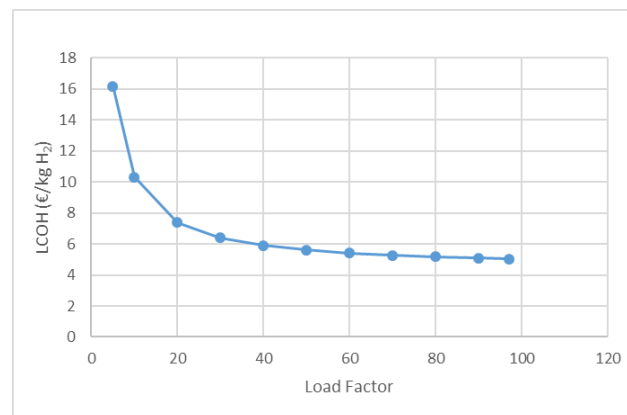


Fig.6. Influence of electrolyser load factor on hydrogen production cost.

Considering the uncertainties associated with the evolution of electricity production costs, a set of simulations was carried in order to identify the influence of these costs on the evolution of *LCOH*. The results presented in Figure 7 demonstrate that there is a very direct and proportional relationship between the evolution of electricity prices and the evolution of the *LCOH*. For an electricity cost of 0.025 €/kWh (equivalent to 25 €/MWh) the *LCOH* value is 2.3 €/kg H₂, which represents a value that is considered competitive. However, it is possible to verify that for an electricity cost of 0.15 €/kWh (equivalent to 150 €/MWh) the *LCOH* value increases to 9.6 €/kg H₂, which represents a very high and uncompetitive value. This analysis is very important given the current situation, in which prices in the electricity market are very high, which have increased significantly in recent months. Although forecasts indicate that the costs of producing electricity through photovoltaic systems will decrease in the upcoming years, it is important to realize that, in a competitive market, electricity purchase prices can increase significantly, and consequently it will have its impact on the cost of hydrogen production.

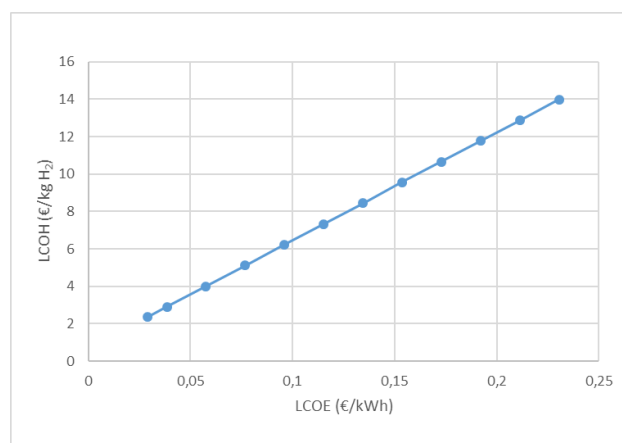


Fig.7. Influence of the cost of electricity on the hydrogen production cost.

As mentioned, it is expected that, considering the evolution of technology and the increase in installed capacity in electrolysers, their costs will decrease. In this perspective, Table III presents the *LCOH* values for the scenario in which the cost of the electrolyser is reduced by 50% and 60%. In this case, for a 50% reduction in the cost associated with the electrolyser, there will be a reduction of approximately 5% in the value of the *LCOH*.

Table III. – Influence of cost of the electrolyser on the hydrogen cost production

<i>C</i> _{CAPEX}	<i>LCOH</i> (€/kg H ₂)
0%	5,13
50%	4,92
60%	4,88

Considering that there are many uncertainties in the parameter values considered in the project evaluation, Table IV shows the evolution of the *LCOH* value, as a

function of the variation of the total costs associated with the implementation and operation of the hydrogen production system.

Table IV. – Influence of *C*_{CAPEX} and *C*_{OPEX} variations on the hydrogen cost production

Total Costs	<i>LCOH</i> (€/kg H ₂)
-20%	4,98
-15%	5,02
-10%	5,05
-5%	5,09
0%	5,13
5%	5,16
10%	5,19
15%	5,22
20%	5,26

The results obtained, allow to identify that the factors that most influence the cost of hydrogen production are: the load factor of the electrolyser, the cost of electricity and the cost of the electrolyser.

5. Conclusion

The environmental impact caused by significant GHG emissions from fossil fuels represents an increasingly urgent issue that must be addressed, and the development of sustainable alternatives is vital. Hydrogen is a very versatile fuel with great potential to replace fossil fuels, thus contributing to a more sustainable future. Regarding the production of hydrogen, there are already several well-established technologies, and electrolysis through renewable energies is presented as the best solution given the current environmental problems. In addition, another issue of great importance is the costs associated with the production of hydrogen through the electrolysis process using solar energy as a source of electrical energy production. These are essentially influenced by the cost of the electricity and the load factor and the electrolyser cost. However, the forecast for the near future is that this technology will become increasingly competitive, presenting significant reductions in the costs of electrolysers. Additionally, it is considered that the costs associated with electricity will become competitive, especially for electricity produced through renewable sources, such as photovoltaic energy. These two aspects are considered essential in the production costs of the hydrogen.

The sensitivity analysis results confirm what can be observed in the *LCOH* repartition: the impact of cost of electricity and load factor are of paramount importance on the *LCOH*, by far greater than *C*_{CAPEX}. Considering the results presented, it is expected that the price of hydrogen will decrease in the coming years. However, any investment in a hydrogen production project should be evaluated considering possible scenarios that imply higher electricity costs.

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