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Viability analysis of centralized hydrogen generation plant for use in mobility sector

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ABSTRACT

Nowadays, the use of renewable energy sources is one of the keys to achieve the sustainable development of societies. The intensive use of fossil fuels has caused effects in the environment and the human health. Greenhouse gas emissions and the carcinogenic effect of diesel are widely demonstrated. The production of clean energy based on renewable sources and the use of hydrogen as an energy vector in general and as an alternative fuel in particular represent a technically feasible reality. However, it is necessary to study the economic variables of centralized or distributed production of hydrogen as an alternative fuel. The aim of this paper is to analyze the technical and economic viability of a centralized generation hydrogen plant for mobility use. It was performed a sensitivity analysis of main parameters such as size of hydrogen production plant, operating hours of the plant, investment costs of the main equipment and electricity price. A NPV of 1,272,692 and a 9-year pay-back were obtained for a centralized hydrogen production plant of 2 MW, considering commercial values of the main evaluation parameters. The sensitivity analysis determines that the main variables affecting the NPV are the price of electricity and the operating hours of the plant. With 95% of confidence, the NPV will be positive with an 80.19% of certainty. Therefore, centralized hydrogen production represents a technically viable, environmentally friendly and economically attractive process that can rapidly position hydrogen as an alternative fuel for mobility.

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Introduction

The era of fossil fuels is already coming to an end. The sustainable development of societies requires the development of energy strategies that are technically feasible, economically viable and environmentally friendly. Therefore, the development of the hydrogen energy vector based on a renewable energy production can meet these requirements via water electrolysis [1–3]. Other methods, such as steam reforming, water-gas-shift reaction, pyrolysis, plasma reforming and biomass gasification, have been used for hydrogen production [4–11].

The transport sector is one of the main consumers of diesel; at the same time, this sector is responsible for greenhouse gas emissions (GHG) and problems of air quality of the main cities of the world. Nowadays oil dominates the fuel mix that meets the world's transport needs. Gasoline and diesel account for 96% of the total fuel consumption and 21% of the global carbon emissions. Then, the use of Alternative Fuel Vehicles (AFV) like Fuel Cell Vehicles (FCV) to replace vehicles powered by internal combustion engines is a clear alternative of road transport that may provide security in the energy supply [12,13], reduction in the GHG emissions and improvement of the air quality in cities in the long term [14,15].

Many works have been focused on technical aspects to produce H_2 via alkaline water electrolysis, high pressure polymer electrolyte membrane electrolysis and others [16–19]. Additional economic studies have been reported. To a central production facility with a H_2 capacity of 50,000 kg H_2/d, Genovese et al. [20] reported a price around 3.00 USD/kg H_2. For the same capacity of H_2 production, Ainscough et al. [21] estimated a cost of 5.12 USD/kg H_2. Therefore, the technical aspects of hydrogen production have been consolidated in the last decade; now the main objective is to find a competitive consumer price. Then, the problem is to define how this hydrogen should be produced to deliver the best price. The first option is a centralized hydrogen production plant, transporting the hydrogen up to different Hydrogen Refueling Stations, and the second one is to set different hydrogen production plants in which the hydrogen production is done on-site in the Hydrogen Refueling Station.

The aim of this paper is to analyze the technical and economic viability of a centralized generation hydrogen plant for mobility use. The hydrogen generation technology analyzed will be the polymer electrolysis. It was performed a sensitivity analysis of main parameters such as size of the hydrogen production plant, operating hours of the plant, investment costs of the main equipment and electricity price.

Methods

Hydrogen production plant description

The design considered in this paper is focused on a centralized renewable hydrogen generation plant using the hydrogen generation technology of polymer electrolysis, the storage at generation pressure in large Type-I reservoirs, the compression by membrane compressor and the supply of hydrogen compressed to tube trailers for its distribution to the consumption points. The hydrogen cost obtained from the technical-economic study and the feasibility studies does not include the transport cost; id est, it includes the filling of the tube trailer but not the deployment, as this cost depends directly on the distance to the final consumption point.

The main equipment part of the centralized hydrogen production plant (see Fig. 1) is the following:

- Polymeric electrolyzer. This equipment requires 2.2 MW of electricity, which comes from renewable energies in this case (the stack has a consumption of 2 MW and the remaining 0.2 MW corresponds to the plant balance), and 15 L of raw water per kg of generated hydrogen. The electrolyzer will produce 863 kg of hydrogen per day at 35 bar of pressure and a purity of 99.999%, 3350 kg of oxygen per day at 35 bar and a purity of 99.95% and 21.6 MWday of residual thermal energy with an outlet temperature of 65 C and an inlet temperature of 50 C. Both oxygen and residual heat are byproducts of the polymer electrolysis process that can be evaluated, although they are not considered in the present paper; therefore, the use of these byproducts will improve the obtained results.
- Hydrogen Storage. The generated hydrogen is stored at the generation pressure in order to reduce the CAPEX and OPEX of the storage system and to simplify the installation, as the space is considered to be enough to install the necessary hydrogen tanks. It is considered necessary to have a capacity equivalent to 48 h of full load operation of the polymeric electrolyzer, which allows some flexibility and margin to uncouple the hydrogen generation and the supply of the mentioned hydrogen to the final consumers. The storage system will consist of 4 tanks with a capacity of 150 m^3 of an equivalent volume of water, which can store about 450 kg of hydrogen per tank. All these tanks will be interlinked to the same inlet manifold and the same outlet manifold, so that it can be managed as a single storage.
- Hydrogen Compressor. In order to supply hydrogen to the tube trailers, it is necessary to compress the hydrogen, for which it is also necessary to use a compressor. A membrane compressor has been selected in this case, given that they are the most indicated ones when working with high purity hydrogen. The compressor will have the capacity to compress up to 400 Nm^3/h of hydrogen from 10-bar pressure to 250-bar pressure (a compressor that can reach up to 250 bar must be selected so that it can overcome the load losses and can supply hydrogen to the tube trailer at 200 bar at least). It is necessary to consume 130 kWh of renewable energy to carry out this work, generating 70 kWh of residual thermal energy with an outlet temperature of 65 C and an inlet temperature of 50 C. This residual heat can be used for different applications. In this case, the use of the residual heat is not considered in the study.
- Tube trailers. It is necessary to use tube trailers at 200-bar pressure in order to transport the hydrogen between the centralized generation point and the consumption points. The tube trailers considered for this paper are formed by 4 cages of bottles, each of which is formed by 68 bottles of 85-L capacity. Thus, the tube trailer has a transport capacity of approximately 367 kg of hydrogen.

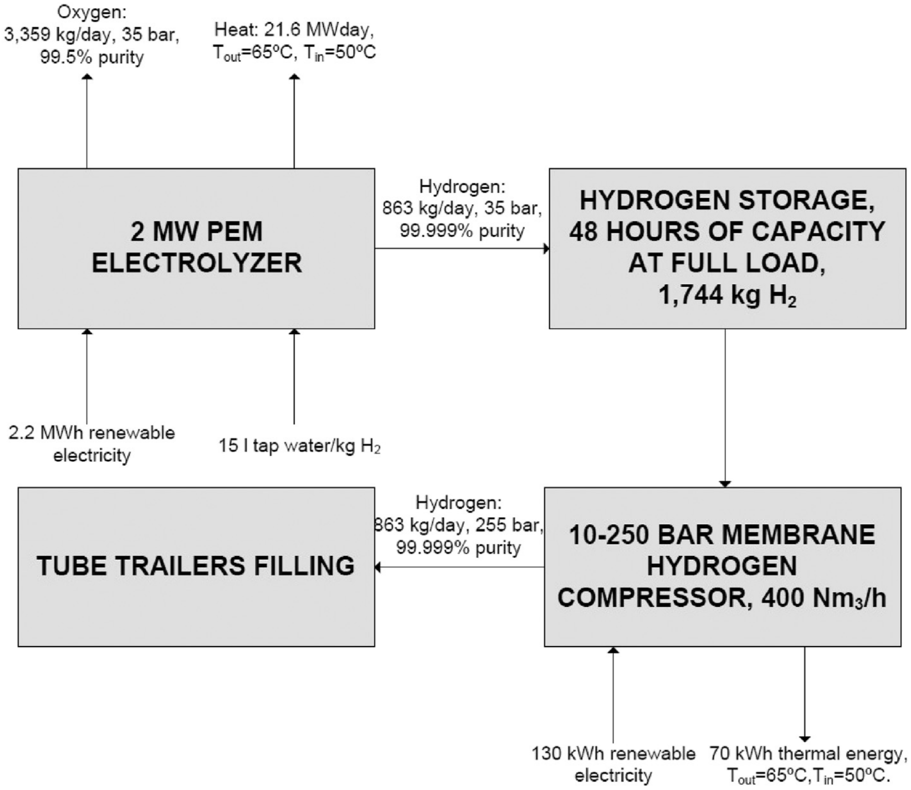

Fig. 1 – Hydrogen production plant and filling of tube trailers.

Cost estimation and sensitivity analysis

The total estimation of production costs is based on the amount of capital costs (CAPEX) and operating costs (OPEX) of the plant to be studied. Capital costs include hydrogen production equipment, storage, compression, ancillary equipment and civil works, while operational costs include electricity, water, equipment maintenance, staff costs and land leasing costs. The estimation of NPV, IRR and pay-back was calculated following project evaluation methods [22–24]. The cost of the main equipment considers values of the main European manufacturers. An acceptable minimum internal rate of 7% and an evaluation horizon of 25 years are considered in the evaluation.

The sensitivity analysis considered two stages. The first stage evaluates the individual analysis of the following parameters: electricity price, electrolyzer cost, plant operating hours, hydrogen generating plant size, sales price and hydrogen production cost. Subsequently, a sensitivity analysis was performed with the Oracle Crystal Ball tool in order to determine the aggregate effect of the following variables over the net present value: size of the hydrogen production plant, plant operating hours, investment costs of the main equipment and electricity price. In these simulations, 10,000 iterations were performed.

Considerations adopted for the realization of the technical-economic study

For the realization of the technical-economic study, the following considerations have been made:

- 8000 h of electrolyzer operation every year.
- Efficiency of the electrolyzer variable from 76.5% to 70%, considering a degradation of the stack of 2 μV per hour. This degradation means that the electrolyzer will need more electric energy to generate the same amount of hydrogen or that it will generate less amount of hydrogen every year.
- According to the above considerations, the electrolysis stack will be replaced after 80,000 h or after 10 years of use. The considered replacement cost of the stack has an initial cost of 30% of the investment cost, and it will decrease at a rate of 1% per year from the first year to the final year of the study.
- The economic evaluation will not consider the revenues of the byproducts, oxygen and heat, generated in the electrolyzer and the compressor of the plant.
- 30% of the investment on the centralized generation plant will be made with in-house resources; the remaining 70% will be made through a 10-year loan, considering the French payment method.
- The CAPEX and OPEX data of the main equipment (part of the centralized generation plant) are the following:
  - Polymeric electrolyzer. CAPEX: €1000/kW of stack power. OPEX: 1.5% of the initial investment cost. Replacement of the stack: 80,000 h or 10 years.
  - Membrane compressor. CAPEX: €863/Nm^3. OPEX: 1.5% of the initial investment cost.
  - Hydrogen Storage CAPEX: €300/kg of stored hydrogen. OPEX: 1.5% of the initial investment cost.
  - Cost of other facilities and civil works. 30% of the cost of the main equipment summation. (Civil work 10% (fire protection walls, cimentations, industrial room, etc.),

chemical integration 10% (hydrogen pipelines, oxygen pipelines, compressed air facility, nitrogen production plant facility, deionized water system), instrumentation and control system 5% and safety and security systems 5%).

- The total investment cost of the hydrogen production plant is 3,740,000.
- Electricity costs: €50/MWh.
- Gross Water Cost: €2.5/m^3.
- Staff cost: €400,000/year.
- Land leasing cost: €100,000/year.
- WACC: 8%.
- Inflation rate: 1.5% per year.
- 25-year life cycle of the centralized hydrogen generation plant.

Results

Results of the technical-economic study

Based on the centralized hydrogen generation plant defined above and represented in Fig. 1, the considerations adopted to carry out the technical-economic study and a cost of hydrogen sales of 7 €/kg, the study results are as follows:

- Net Present Value: €1,272,692.
- Internal Rate of Return: 14%.
- Return period of the investment (years): 9.

In Fig. 2, the Net Present Value curve can be observed over time. As can be seen, the amortization is carried out in year 9. On the other hand, it is also shown that in year 10 there is a small decrease in the Net Present Value due to the replacement of the electrolysis stack, which implies an increase in maintenance costs.

Sensitivity studies of the main parameters done independently

It is vital to carry out sensitivity studies of the main parameters, so that the impact of these parameters on the economic profitability of the centralized hydrogen generation plant can be quantified. The parameters to which the sensitivity study is going to be performed are the following:

1. Net Present Value variation based on the electricity price.
2. Variation in the hydrogen production cost (regardless the depreciation and the staff costs) depending on the electricity price.
3. Variation of the return period of the investment according to the electrolyzer cost.
4. Net Present Value variation according to the operation hours.
5. Hydrogen sale price variation maintaining the same internal rate of return, based on the size of the centralized hydrogen generation plant.
6. Hydrogen production cost variation based on the stack degradation over the life cycle of the centralized hydrogen generation plant.

Each of the sensitivity studies before mentioned is developed below:

Net present value variation based on the electricity price

Keeping constant the other parameters considered in the technical-economic feasibility study, the electricity price varies from €5/MWh (in the case of free energy that would otherwise be lost, whose cost would only be the payment of tolls) up to €100/MWh. As can be seen in Fig. 3, the hydrogen generation plant would not be feasible in case of electricity costs above €60/MWh. In the same way, the higher the Net Present Value is, the lower is the electricity cost.

Variation in the hydrogen production cost (regardless the depreciation and the staff costs) depending on the electricity price

Keeping constant the other parameters considered in the technical-economic feasibility study, the variation in the hydrogen production cost (regardless amortization and staff costs) compared to the electricity price, has been analyzed, taking into account that the electricity cost varies between 5/MWh (in case of free energy that would otherwise be lost, the only cost corresponding to the payment of tolls) and 100/

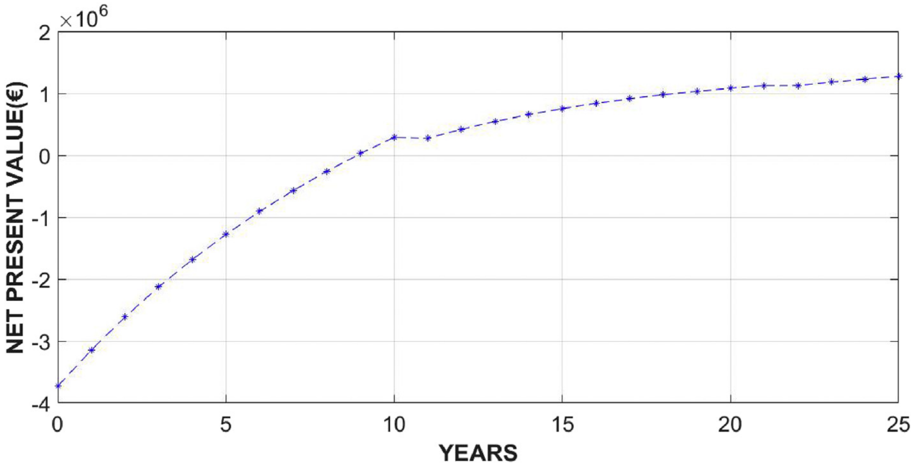

Fig. 2 – Net present value VS year.

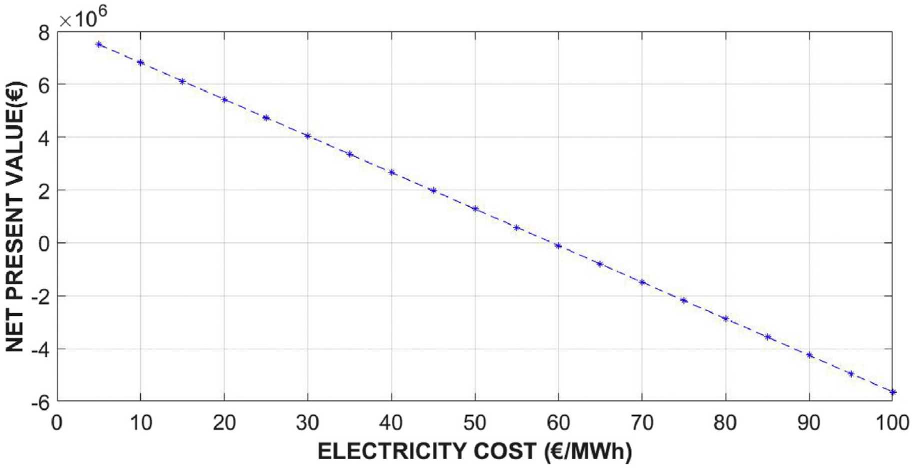

Fig. 3 – Net Present Value VS electricity cost.

MWh. As can be seen in Fig. 4, the electricity cost increases as the hydrogen production cost (regardless amortizations or staff) is higher, showing that the electricity cost has a very important impact on production costs and therefore on the economic viability of the centralized hydrogen generation plant too.

Variation of the investment return period according to the electrolyzer cost expressed in €/kW

Keeping constant the other parameters considered in the technical-economic feasibility study, the electrolyzer investment costs vary from 500/kW up to €1150/kW. As can be seen in Fig. 5, the lower the electrolyzer investment cost is, the lower the return period of the inversion. The electrolyzer cost is used to make the sensitivity study, since it is the equipment that has a higher cost and, therefore, it is the one that has the most impact from the economic point of view.

Net present value variation according to the operation hours

Keeping constant the other parameters considered in the technical-economic feasibility study, the hours of operation of the centralized hydrogen generation plant vary from 3000 h/year to 8500 h/year. As can be seen in Fig. 6, the more the annual operating hours increase, the more the Net Present Value increases. In the same way, it can be observed that it is necessary that the centralized hydrogen generation plant of 2 MW operates for 6500 h per year at least, so economic losses can be avoided.

Hydrogen sale price variation maintaining the same internal rate of return, based on the size of the centralized hydrogen generation plant

Keeping constant the other parameters considered in the technical-economic feasibility study, the size of the centralized hydrogen generation plant varies in MW, from 2 MW to 10 MW, taking into account that the internal rate of return has to remain constant.

As can be seen in Fig. 7, as long as the size of the centralized hydrogen generation plant increases, the hydrogen can be sold at a lower price.

This happens because the hydrogen production plant size in the study is considered, since the cost of a 10 MW electrolyzer is lower expressed in €/kW) than the 2-MW electrolyzer cost, thus having an exponential relationship.

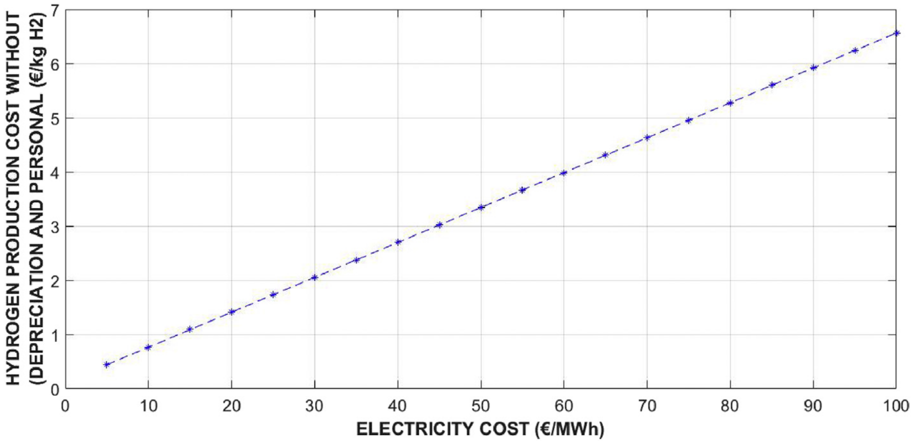

Fig. 4 – Cost of hydrogen production (regardless amortizations or staff) VS electricity cost.

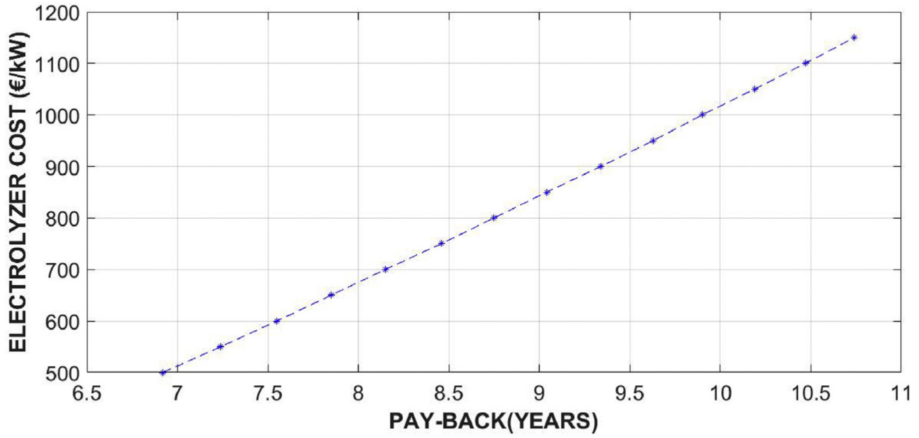

Fig. 5 – Investment Return period VS electricity cost.

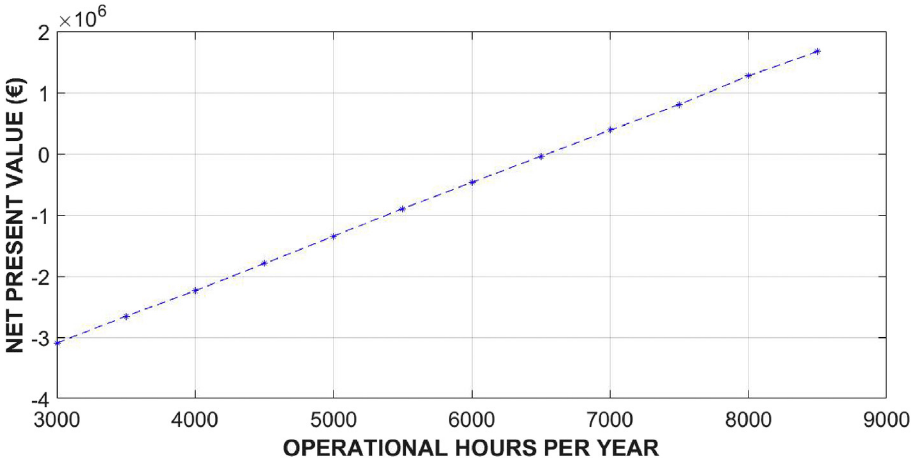

Fig. 6 – Net Present Value VS annual operating hours.

Hydrogen production cost variation based on the stack degradation over the life cycle of the centralized hydrogen generation plant

This analysis examines how the stack degradation affects the hydrogen production costs and therefore the profitability of the centralized hydrogen generation plant. As can be seen in Fig. 8, more energy is needed to generate the same amount of hydrogen while the electrolyzer has more operational hours, which means higher production costs for the same amount of hydrogen. A stack change is considered in this paper including every 80,000 operating hours or every 10 years. However, it may be interesting to replace the stack before 80,000 operating hours or 10 years as it will allow us to generate cheaper hydrogen. On the other hand, if the stack is changed more frequently a higher maintenance cost is produced.

It has been conducted a study of how many operational hours are the ideal ones to carry out the stack change, taking into account these two ideas: the greater the number of working hours of the electrolyzer stack, the greater the production cost; the greater the number of stack replacements, the greater the maintenance costs.

In the same way, it has been considered that the stack replacement costs, currently representing 30% of the equipment cost, are going to be reduced by around 1% annually, which implies that the stack change is going to be more and more economical every time; this can make it interesting to replace the stack before 80,000 h or 10 working years. In Fig. 9, it is shown that the ideal degradation percentage to perform the stack change is 8%, as it is the value that maximizes the investment Net Present Value. Changing the stack when the degradation reaches an 8% implies that it is ideal to make 2 stack changes over the project life cycle, as shown in Fig. 10.

Combined sensitivity studies of the main parameters

In this study, the Oracle Crystal Ball tool [25–27] was used to analyze the effect of the following parameters on the Net Present Value: size of the hydrogen production plant, operating hours of the plant, investment costs of the main equipment and electricity price.

From the base case being studied, which describes a Net Present Value (NPV) of €1,272,692, simulations were done in order to estimate the success probability of the project. Fig. 11 shows that, with a 95% of certainty, the Net Present Value will be greater than zero for 80.19% of the studied cases.

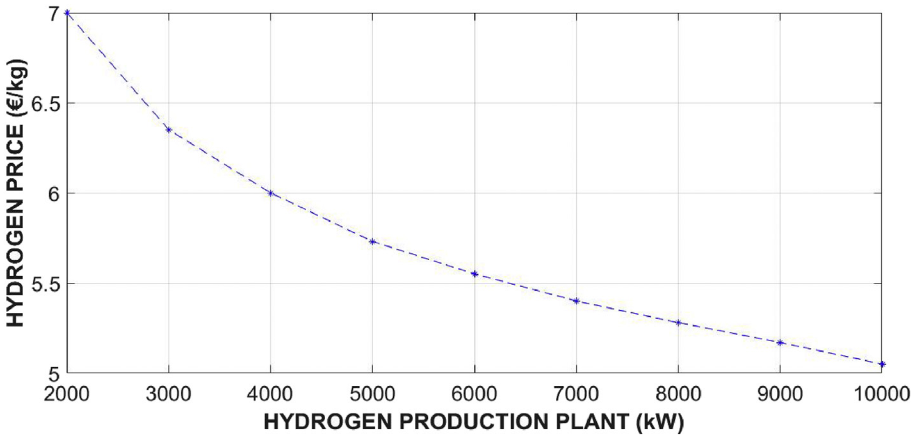

Fig. 7 – Hydrogen sales price VS size of the centralized generation plant.

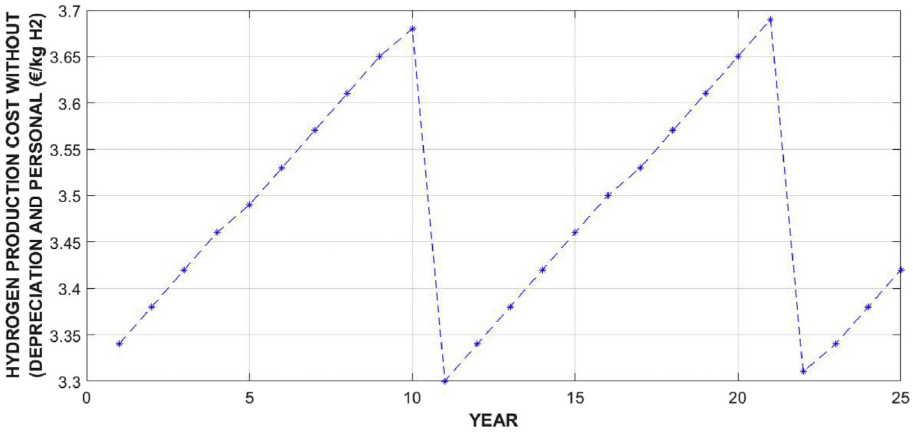

Fig. 8 – Hydrogen production cost (regardless amortizations or staff) VS operational years.

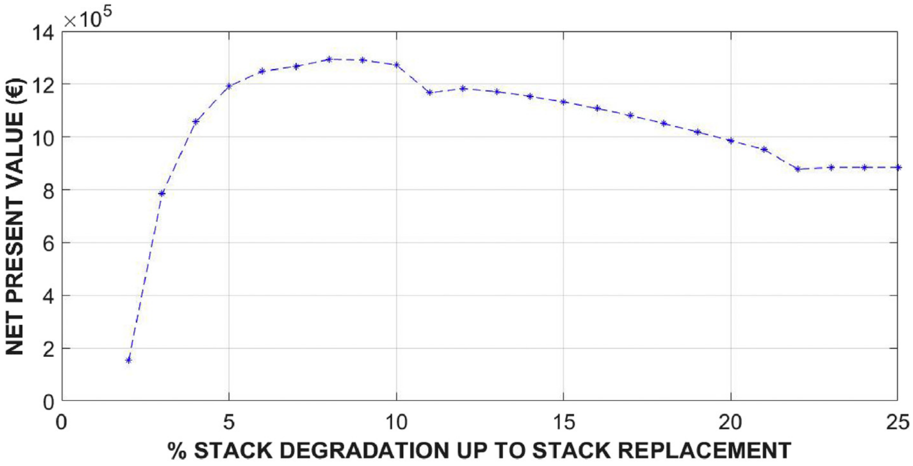

Fig. 9 – Net Present Value VS stack degradation at the time of the change.

In Table 1, the electricity cost explaining in a 62.92% the Net Present Value variance is described. Then, the size of the hydrogen generation plant has a significant effect on the Net Present Value (36.77%). These results are consistent with previous analysis carried out independently. The NPV is positively correlated with the operating hours, while the correlation is negative regarding the electricity price.

From the results obtained, it can be observed that the hydrogen sales price, maintaining fixed parameters of profitability, depends on the size of the hydrogen generating plant

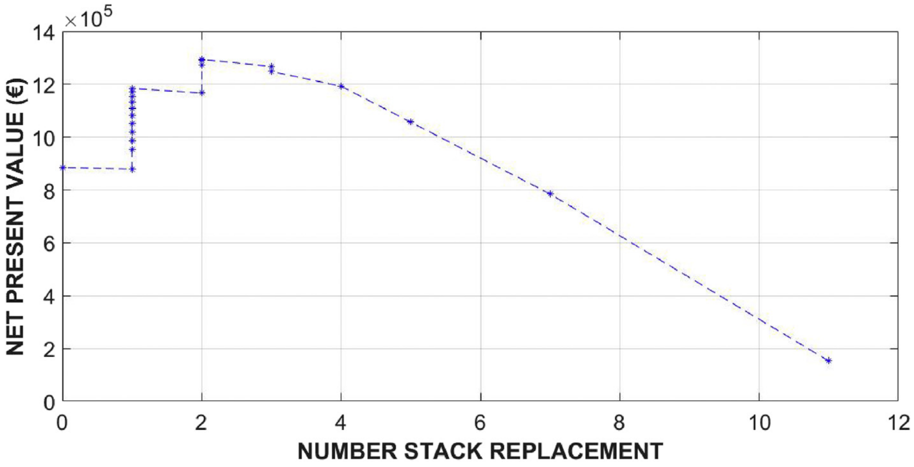

Fig. 10 – Net Present Value VS number of stack changes.

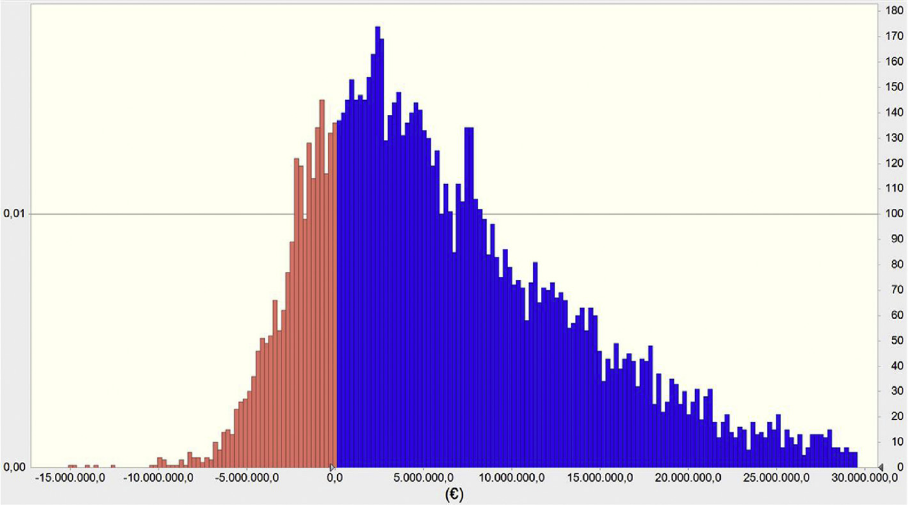

Fig. 11 – Probability distribution of the NPV sensitivity analysis.

to a great extent, varying between 7 and 5 €/kg for plant sizes of generation of 2 and 10 MW respectively. These values are in line with the hydrogen production prices obtained in the bibliographic references [28–33].

Likewise, it can be observed that the electricity cost is a key parameter for the viability of the plant, showing that the centralized hydrogen production plant is not profitable for costs in excess of €60/MWh, being the profitability higher as the cost of electricity is lower. These results agree with the results of Fuel Cells and Hydrogen Joint Undertaking (FCH) [33].

Table 1 – Analysis of the sensitivity to Net Present Value.

Assumptions	Contribution to variance (%)	Rank correlation
Electricity Cost (€/MWh)	62.9	−0.76
Hydrogen Production Plant Size (kW)	36.7	0.58
Electrolyzer Cost (€/kW)	0.30	−0.05
Operational hours per year	0.00	0.01

The study developed in the present paper focuses on the hydrogen production for the mobility sector centralized from renewable energies through polymer electrolysis, obtaining that the hydrogen can be sold at €/kg and having a positive Net Present Value, an Internal Rate of Return of 14% and a Pay-Back of 9 years. All these parameters are acceptable from the investor point of view. This hydrogen sale price for its subsequent transport and sale in a hydrogen station is of the same order as those obtained in the study carried out by Viesi, Crema and Testi [31].

Conclusion

The main parameters affecting the economic evaluation are the electricity cost and the number of operational hours for a centralized hydrogen production plant. The electricity cost is a fundamental parameter as the lower the electricity cost, the lower the hydrogen production cost; therefore, there is a possibility to sell cheaper hydrogen while maintaining the same benefit or to obtain greater profit while maintaining the hydrogen sale price. The number of operational hours is a parameter that has a significant impact on the profitability of the centralized hydrogen production plant as the fewer operational hours, the less the hydrogen production and therefore the less the revenue; besides, the greater the number of operational hours, the greater the hydrogen production and therefore the higher the revenue.

Another parameter of interest is the scale factor that positively influences the viability of the centralized hydrogen generation plant because the costs are reduced as the plant size increases. This CAPEX reduction makes the hydrogen sale price potentially lower or, on the contrary, makes that the hydrogen generation plant could obtain a greater profit by keeping the hydrogen sale price at a constant value. The cost of replacing the stack is an important point, which is why we must pay particular attention to the evolution of that cost: a drastic reduction in the next few years can mean that the stack may be changed with lower degradation % instead of waiting to have an 8% stack degradation (the optimal point between hydrogen production costs and maintenance cost); this will increase the plant efficiency and allow a significant cost reduction.

The possibility of using the oxygen and the residual heat of the electrolyzer and the compressor can lead to additional income in the profit and loss account of the hydrogen generation plant. This will have a positive impact, allowing the payback of the investment to be lower or to have the possibility to sell hydrogen at more economical prices while maintaining the initial pay-back.

Therefore, the centralized hydrogen production represents a technically viable, environmentally friendly and economically attractive process (with a positive NPV with 80.19% certainty), which can rapidly position hydrogen as an alternative fuel for mobility and other applications.

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