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Abstract

Cost is a key issue in the spreading of any technology. In this work, the cost of hydrogen is analyzed and determined, for hydrogen obtained by electrolysis. Different contributing partial costs are taken into account to calculate the hydrogen final cost, such as energy and electrolyzers taxes. Energy cost data is taken from official URLs, while electrolyzer costs are obtained from commercial companies. The analysis is accomplished under different hypothesis, and for different countries: Germany, France, Austria, Switzerland, Spain and the Canadian region of Ontario.

Finally, the obtained costs are compared to those of the most used fossil fuels, both in the automotive industry (gasoline and diesel) and in the residential sector (butane, coal, town gas and wood), and the possibilities of hydrogen competing against fuels are discussed. According to this work, in the automotive industry, even neglecting subsidies, hydrogen can compete with fossil fuels. Hydrogen can also compete with gaseous domestic fuels. Electrolyzer prices were found to have the highest influence on hydrogen prices.

1 Introduction

1.1 Hydrogen costs

Fuel cell costs have been widely analyzed, but in order to have affordable hydrogen systems, both the fuel cell and the hydrogen consumption must have, for end users, competitive prices: similar or lower than those of current motors and fossil fuels.

Depending on the method used for hydrogen obtaining, different costs of infrastructure, energy and raw materials should be considered. Hydrogen production by electrolysis is an interesting option for the long term, because it does not need fossil fuels and the energy needed by the electrolysis can be obtained from renewable sources.

The global hydrogen cost as an addition of several costs has already been done for some areas, such as the West Danish area [1].

1.2 Energy costs

Unlike most of the products, electric power costs are not constant. They depend significantly on time [2]. Depending on the ratio between the required energy and the rate of energy obtaining (power), the energy would be bought only in the times when it is cheaper, or should be bought in every time. This depends basically on the power of the hydrogen generation system (in our case, an electrolyzer), which depends mainly on its costs: if the cost per unit of power is high, low powers will be used, in order to optimize the global cost.

1.3 Electrolyzer costs

Electrolyzer costs are significantly dependant on the technology. The large majority of current commercial electrolyzers are alkaline or PEM. Alkaline electrolyzers are considered the most commercially affordable option for hydrogen production [3], due to their lower costs. For this electrolyzer type, the main costs to be considered are the electrolyzer itself and power costs [4]. Although water is used in large quantities, its costs are not significant for the cost of the produced hydrogen. Their durability is estimated in 15-20 years.

2 Data

2.1 Electric energy prices

The prices of the electric energy were taken from official webpages. Five sets of data were obtained and used later for the calculations: Germany-Austria, France, Switzerland, Spain and Ontario.

The prices for Germany, France, Austria and Switzerland were taken from the European Energy Exchange (EEX) webpage [5]. Three sets of data were obtained from this page: one for Germany and Austria, another for France and a final one for Switzerland. The Spanish prices were obtained from the webpage of the Spanish Energy Commission [6]. The prices from Ontario were found on the IESO (Independent Electricity System Operator) webpage [7].

2.2 Electrolyzer prices

Most electrolyzer prices are given after demand on the electrolyzer. However, some studies summarize these costs. On one of them, the cheapest industrial electrolyzers are found to be about 100.000 $ per kg/h. Assuming a 60% efficiency at nominal conditions, that is approximately 1.300.000 €/MW [8]. Literature costs were lower, but this is often associated to mass production costs, which are not available yet.

2.3 Fuel cell data

The possibility of adding a fuel cell to the system was considered. This fuel cell may be useful for selling electricity back to the electric system, obtaining profits and reducing hydrogen costs. The fuel cell cost and durability were considered to be 55 €/kW and 2000 hours [9].

3 Procedure

3.1 Assumptions

Several assumptions were taken for this work:

- A system formed by a fuel cell and an electrolyzer is considered. The electrolyzer is used for obtaining hydrogen. The fuel cell is considered to sell energy back to the electric market, in case the price of the electricity in the market is above the price of the hydrogen needed to produce it.

- The performances of system electrolyzer and fuel cell are linear with the current and, therefore, with the hydrogen consumption. This is not exact, because the performance changes more for low currents than for high current, but is an acceptable hypothesis, since both the electrolyzer and the fuel cell would work mostly on the linear region.

3.2 System behavior

For each situation a given price of the hydrogen was calculated or assumed. For each hour of the year a decision was taken about electrolyzing water, consuming hydrogen or neither of them. The following cases were considered:

- If the hourly electricity price divided by the hydrogen price is below the maximum efficiency of the electrolyzer, hydrogen was produced by electrolysis. Hydrogen was produced with an efficiency that was the average between this price ratio and the maximum efficiency, with the limit of the minimum efficiency of the electrolyzer (the hydrogen production efficiency could not be below that minimum). This average optimizes the total profit of the hydrogen production, which is proportional to the hydrogen production and also to the difference between the production efficiency and the price ratio (which is proportional to the difference between incomes and hydrogen production costs).

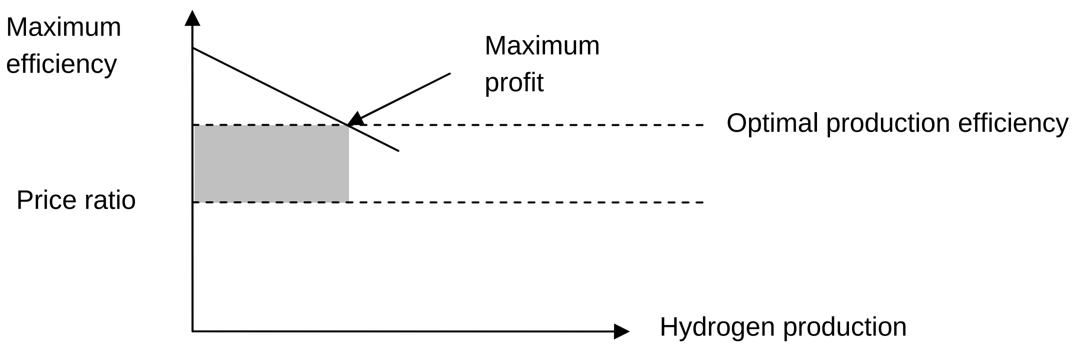

Figure 1: Optimal point for hydrogen production. The profit is proportional to the grey area: it is proportional to the hydrogen production and to the difference between the production efficiency and the price ratio.

- If a fuel cell is considered and the hydrogen price divided by the hourly electricity price is below the maximum efficiency of the fuel cell, hydrogen is consumed by the fuel cell to produce power. To maximize profits, the fuel cell efficiency is the average between the maximum efficiency and the previously mentioned price ratio.
- If none of the two previous cases is happening, the system does not consume or produce hydrogen.

3.3 Calculation of the total hydrogen costs

To calculate the total hydrogen cost, four different components were considered: the electricity price, the electrolyzer price, the fuel cell price and the net profit of the facility due to the energy interchange with the electric market. The last component was negative: this energy interchange profit could absorb part of the electrolyzer costs, decreasing the part of this cost that should be charged to the hydrogen price. The fuel cell price is optional: it was only added if it produced a decrease on the total price (increasing the negative contribution of the net profit).

Both the electricity price and the fuel cell price were optimized. Higher electricity price imply that hydrogen is produced in more hours and consumed in less, so the net production of hydrogen increases, decreasing the electrolyzer costs per unit of produced hydrogen. Higher fuel cell prices and powers cause a higher profit through interchange with the electric market. In both cases, the trade-off between both variables was found.

4 Results

The results were first calculated for a base case, where the costs and the maximum and minimum efficiencies were assumed to have a certain value. Later, a sensitivity analysis is performed to study the effect of changes in these variables.

4.1 Base case

In the base case, the minimum and maximum electrolyzer efficiencies were assumed to be 0.6 and 0.8. The latter one belongs with an approximate voltage of 1.5 V, which is approximately the minimum current at which alkaline electrolyzers begin to produce a significant amount of hydrogen. The minimum electrolyzer efficiency belongs with a voltage of 2 V, which is approximately in the middle of the electrolyzer nominal-voltage range.

A maximum fuel cell efficiency of 0.7 is considered, which corresponds with an approximate voltage of 0.85 V. Although fuel cell voltages can usually be higher, this voltage is close to the intersection of the extrapolation of the linear region with the zero-current axis, so it is useful for modeling this linear region.

The price results are shown in Figure 2:

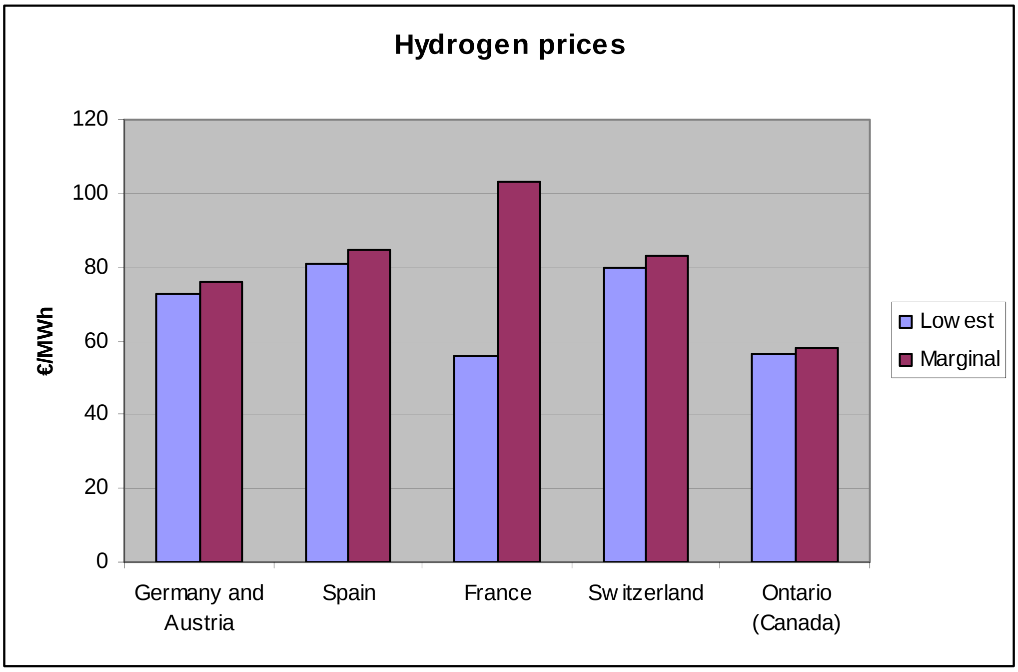

Figure 2: Lowest and marginal hydrogen prices for different countries. The lowest price is the minimum profitable price. The marginal price is the price that the system internally gives to the hydrogen, in order to electrolyze or not.

The lowest and marginal hydrogen prices are quite close for most of the countries. Excluding France, the difference is always below 6% of the marginal cost. The final base cost of hydrogen may be closer to the lowest or the marginal cost, depending on the competence of the market. Excluding France, the lowest cost is below the marginal cost because most of the hydrogen is produced with a cost below the marginal one. The reduction of the electrolyzer costs per unit of produced hydrogen may justify producing hydrogen, in some cases, with a cost slightly higher than the price at which it will be sold, in order to increase hydrogen production.

In the case of France, there are significant differences between both prices because the hydrogen energy storage system may be profitable by itself (reselling later the energy to the electric system with a fuel cell). If the ratio between the yearly income and the yearly outcome of the system is maximized, the marginal cost of the hydrogen would be about 103.1 €/MWh (and 256.2 MW of fuel cell would be used per MW of electrolyzer). However, hydrogen energy storage systems can be profitable with a marginal cost as low as 55.83 €/MWh (and 13.97 MW of fuel cell per MW of electrolyzer).

For all the other countries but France, the addition of a fuel cell to the system, even if it was small, was not profitable.

All the hydrogen prices are between 55 €/MWh and 104 €/MWh. If these values are calculated per unit of mass or per unit of weight, the results would be between 2.2 and 4.1 €/kg or between 0.19 and 0.37 €/Nm^3, respectively. The prices could be also compared with those of current fuels for automotive applications. From each gasoline liter approximately 2.4 kWh of mechanical energy are obtained and for each diesel liter, approximately 3.2 kWh [10]. Assuming a fuel cell plus electric motor system to power a car, a 0.5 average fuel cell efficiency and a 0.9 average motor efficiency, each MWh of hydrogen would yield 450 kWh. Therefore, the hydrogen base prices (before taxes and commercial benefits) are between 0.29 € and 0.55 € per equivalent to a gasoline liter and between 0.39 € and 0.74 € per equivalent to a diesel liter. This ranges are approximately centered in the current values of gasoline and diesel: which were 0.44 €/l and 0.55 €/l in 2008 [11] (the latest available information at the time when this work was done).

Wood has costs about 0.12 €/kg and a heating power about 5 kWh/kg, which makes a cost per unit of energy of 0.024 €/kWh, which is 24 €/MWh. Coal costs about 0.10 €/kg and has a heating power of approximately 9 kWh/kg, so the cost per unit of energy is 0.011 €/kWh, 11 €/MWh. Butane prices are about 0.94 €/kg and its heating power is about 13 kWh/kg, which yields a cost per unit of energy of 0.072 €/MWh, which is 72 €/MWh. The cost of town gas is about 0.07 €/kWh, 70 €/MWh.

4.2 Sensitivity analysis

A sensitivity analysis was performed, changing different variables to study their effect on the hydrogen cost. The most influencing variables was the electrolyzer cost. Figure 3 shows its influence:

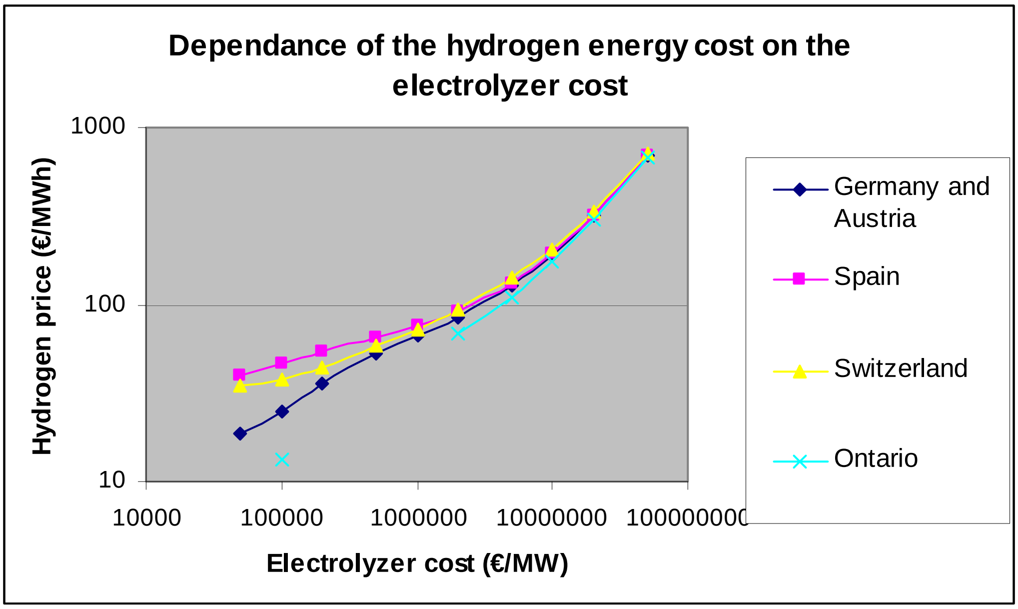

Figure 3: Influence of the electrolyzer cost on the hydrogen cost.

The electrolyzer costs influence clearly the hydrogen cost. For low cost, this influence is smaller and there are significant differences on the hydrogen costs among countries, as most of the hydrogen costs depends on the energy. For high electrolyzer costs, the influence is clear and the hydrogen costs among countries are close in relative terms.

The dependence of hydrogen costs on other variables was also studied. Fuel cell costs only influenced costs in France and Canada, where high electricity prices during some hours make fuel-cell energy generation profitable. If fuel cell costs are low, hydrogen generation costs may decrease in these countries to 38 €/mWh in Ontario and 49 €/Mwh in France. However, if fuel cell costs are high, energy generation from the fuel cell is no longer profitable, and hydrogen prices climb to 76 €/mWh in France and 56 €/Mwh in Ontario.

A change of the maximum electrolizer efficiency from 70% to 90% had an effect on the hydrogen costs between 2% and 5%. A change of the minimum electrolyzer efficiency from 50% to 70% changed the hydrogen costs about 25%. This is probably attributed to a higher hydrogen production (the ratio between maximum production and cost is being changed). In both cases, logically, higher efficiencies resulted in lower costs. The effect of the fuel cell performance was studied for France, where the addition of a fuel cell was profitable. A change from 60% to 80% of the fuel cell efficiency changed the minimum hydrogen price in about 10%.

5 Conclusions

The main conclusions that can be extracted from the current work are:

- Under the base case, the base cost of hydrogen energy for automotive applications would be equivalent to that of current fuels.
- For domestic applications, hydrogen can only compete with gaseous fuels (such as butane and town gas), which have similar costs. Solid fuels (such as wood and coal) have significantly lower costs.
- Electrolyzer cost is the variable with a highest influence on hydrogen costs. This influence is specially significant for high electrolyzer costs.
- In some countries, like France, hydrogen systems could already be profitable interchanging energy with the electric system, due to the very high energy prices during some hours.

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