BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

FACULTY OF TRANSPORT AND ENGINEERING OF VEHICLE

FINAL THESIS

STUDY OF TECHNICAL AND ECONOMIC VIABILITY OF A SUSTAINABLE PLAN FOR THE INTRODUCTION OF HYDROGEN VEHICLES IN THE AUTOMOTIVE MARKET OF VALENCIA

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Budapest, May 2023

MŰEGYETEM 1782

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

RESUMEN

La contaminación global por la dependencia energética de los combustibles fósiles es uno de los principales problemas que enfrenta nuestra sociedad ante la búsqueda de conservar y mantener el entrono.

Al estudiar esta problemática, no se puede pasar por alto el papel de la industria de la automoción, causante de mas del 30 % de las emisiones globales de CO_2, lo que nos clarifica el fuerte problema de los combustibles fósiles, ya que son una fuente de energía no renovable y muy contaminante.
Por tanto, se han de buscar alternativas, entre las que destaca el Hidrogeno como una opción mas sostenible y verde.

El mercado automovilístico de Hidrogeno ya cuenta con distintos modelos en comercialización, pero todavía se encuentra en sus primeras fases de desarrollo.
Este, plantea distintos desafíos como la obtención verde del hidrogeno, su transporte y su viabilidad económica.

En este trabajo, se analizará el mercado automovilístico del hidrogeno, y se estudiará la viabilidad económica y funcional de la implementación de un plan de introducción en la sociedad del vehículo de hidrogeno, analizando el suministro necesario, así como la producción verde del hidrogeno requerido a través del estudio de una planta de producción de dicho gas a partir de energía solar.
De esta forma, se obtendrá un visón sobre el futuro de las tecnologías de hidrogeno aplicadas a la automación, y sobre su posible introducción en la sociedad.

Palabras clave: Hidrogeno, Vehículo, Coche, Electrolisis, Pila de combustible, Energía solar, Combustibles.

ABSTRACT

Global pollution due to energy dependence on fossil fuels is one of the main problems facing our society as we seek to conserve and maintain the environment.

When studying this problem, we cannot overlook the role of the automotive industry, which is responsible for more than 30% of global CO2 emissions, which clarifies the serious problem of fossil fuels, since they are a non-renewable and highly polluting source of energy.
Therefore, alternatives have to be found, among which Hydrogen stands out as a more sustainable and green option.

The hydrogen automotive market already has several models in commercialization, but it is still in its early stages of development.
This market presents different challenges such as the green hydrogen production, its transportation and its economic viability.

In this research, the hydrogen automotive market will be analyzed, studying the economic and functional feasibility of the implementation of a plan for the introduction of hydrogen vehicles in society, analyzing the necessary supply, as well as the green production of the required hydrogen through the study of a plant for the production of this gas from solar energy.
In this way, a vision will be obtained about the future of hydrogen technologies applied to automation, and about its possible introduction in society.

Key words: Hydrogen, Vehicle, Cars, Electrolysis, Fuel cell, Solar energy, Fuels.

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1.INTRODUCTION.

One of the most recurring themes in current society is the pollution and sustainability of our planet and environment.
In studying it, we cannot overlook the determining role of the automobile industry in this problem.

When analyzing the impact of vehicles for personal use on the environment, we find alarming data: private cars generate 18% of CO_2 emissions, the main gas causing the greenhouse effect. In addition, vehicles not only emit CO_2, but they also generate other types of polluting gases and particles that have a negative impact on air quality and public health, including nitrogen oxides, carbon monoxide and fine particles.

Therefore, we must think about improving the impact of automotive pollution on our planet by working on reducing vehicle emissions, where decarbonization will play a key role in achieving this.

In this sense, one of the most promising and increasingly viable solutions is the implementation of hydrogen cars in our society. These vehicles use fuel cells that convert hydrogen into electricity, which means that they emit no polluting gases. Moreover, hydrogen is a renewable and abundant resource on our planet, which makes it a sustainable option in the long term.

However, despite the advantages of hydrogen cars, their implementation in society presents significant challenges, such as the need for infrastructure for hydrogen production, storage, and distribution.

Therefore, in this work, the hydrogen automotive market will be analyzed, studying the economic and functional feasibility of the implementation of a plan for the introduction of hydrogen vehicles in society, analyzing the necessary supply, as well as the green production of the required hydrogen through the study of a plant to produce this gas from solar energy.
In this way, a vision will be obtained about the future of hydrogen technologies applied to automation, and about its possible introduction in society.

2.HYDROGEN

Hydrogen is the most abundant element on the planet, is found in 75% of matter, but we can't find it alone, as it is found with other compounds such as oxygen or carbon forming organic compounds.

Given its abundance, it is a very promising option as a clean fuel for generating thermal or electrical energy, and it also has many environmental advantages since it can be used without emitting polluting or greenhouse gases, and it has a high energy density.

After the worrying environmental situation of our planet, hydrogen is the main solution towards decarbonization, but we must understand the concept of green hydrogen.

This green hydrogen is obtained through a process free of emissions, which is the key to the fight against climate change, so, to obtain green hydrogen we must use electricity from solar, wind or hydraulic sources, and through the process of electrolysis, which will be explained later.

2.1 Hydrogen methods production

Today, 90% of hydrogen production comes from fossil energy sources: natural gas and oil, and a very small proportion comes from biomass derived from wood. There are three industrial methods for obtaining hydrogen: molecular transformation, coal gasification and water electrolysis. We will briefly explain what these three methods consist of:

The first method is the use of chemical reactions to obtain hydrogen from natural gas from oil fields. High-temperature steam is used to break up the carbon particles that are together with the hydrogen particles that make up the natural gas.
The second method is coal gasification. This consists of the use of a reactor to increase the temperature of the coal, in this increase of temperature we proceed to a combustion of coal where many gases are released, two of these gases are the ones that interest us: carbon monoxide and hydrogen.
The third method, which is what interests us in our work, uses the electrolysis of water to generate hydrogen. This obtaining of hydrogen from the electrolysis of water makes the procedure of obtaining hydrogen the environmentally cleanest of the three methods. But we must point out that this happens when in the electrolysis process the corresponding energy that we use comes from non-polluting energies, an alternative energy to produce hydrogen, since in many cases we are told that the method is cleaner than the others, but a circumstance is ignored; obtaining the main energy to generate

the electrolysis is also given by polluting fuels. Thus, electrolysis is an interesting process if we use a green method in the generation of the energy needed for it.

After knowing the different methods of obtaining hydrogen, in this work we will focus on the method of electrolysis with obtaining the energy through solar energy, so that we will obtain a green hydrogen without polluting emissions.

2.2 Electrolysis

This is a hydrogen generation technique, discovered in 1799, which has great potential today.
The main attraction of this technique is that no CO_2 or other greenhouse gases are generated during its operation. This makes it an environmentally friendly and CO2-free method of generating hydrogen in combination with renewable energy sources.
In addition, it is an easily scalable process, allowing it to be used in installations of very different capacities.

Going into more detail, a direct electric current is applied by means of a pair of electrodes connected to an electrical power supply and immersed in the solution. The electrode connected to the positive pole is known as the anode, and the one connected to the negative pole is known as the cathode.
Each electrode attracts ions of opposite charge. Thus, negative ions, or anions, are attracted and move toward the anode (positive electrode), while positive ions, or cations, are attracted and move toward the cathode (negative electrode). The energy needed to separate the ions and increase their concentration at the electrodes is provided by the power supply. Electron transfer occurs at the electrodes between the electrodes and the ions, producing new substances. The negative ions or anions give up electrons to the anode (+) and the positive ions or cations take electrons from the cathode (-) (Figure 1).
After completion of the process, oxygen and hydrogen are released and electrolysis process is completed.

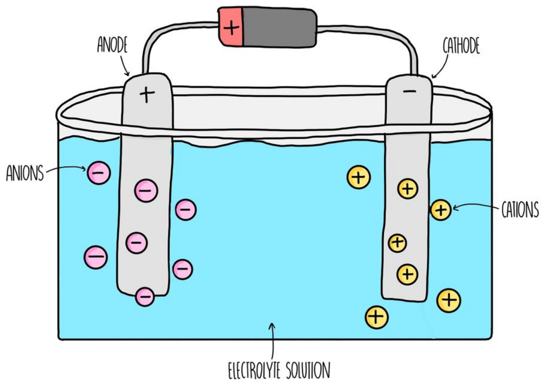


Figure 1. Electrolysis process

Source [5]

2.2.1 Types of electrolyzers

To carry out the electrolysis process we use an electrolyzer, its role will be fundamental in our project, as well as in the development of hydrogen technologies in the future. There are different types of electrolyzers in the market, as well as many new prototypes in research, because the improvement of them, getting more efficient products, will be the necessary impulse for hydrogen technologies to be implemented on a large scale in different technological sectors.

There are three main types of electrolyzers: proton exchange membrane (PEM), solid oxide and alkaline.

2.2.1.1 Alkaline electrolyzer

Conventional alkaline electrolysis is the most developed method of electrolysis and is already in an advanced commercialization process.

Among its main benefits is its simple technology, since the absence of noble metals makes it an inexpensive, low-maintenance and highly stable technology.

However, it has certain disadvantages compared to its alternatives, since in order not to produce a mixture between hydrogen and oxygen, it works within certain operating limits, obtaining low current densities and therefore losing part of the energy produced. In addition, they require the coupling of an external battery due to its high response time, so it is a good option for plants connected to the grid, but for our study we discarded it, because the variability provided by a supply generated by solar energy does not make it compatible with this study. The next figure shows how it works (Figure 2).

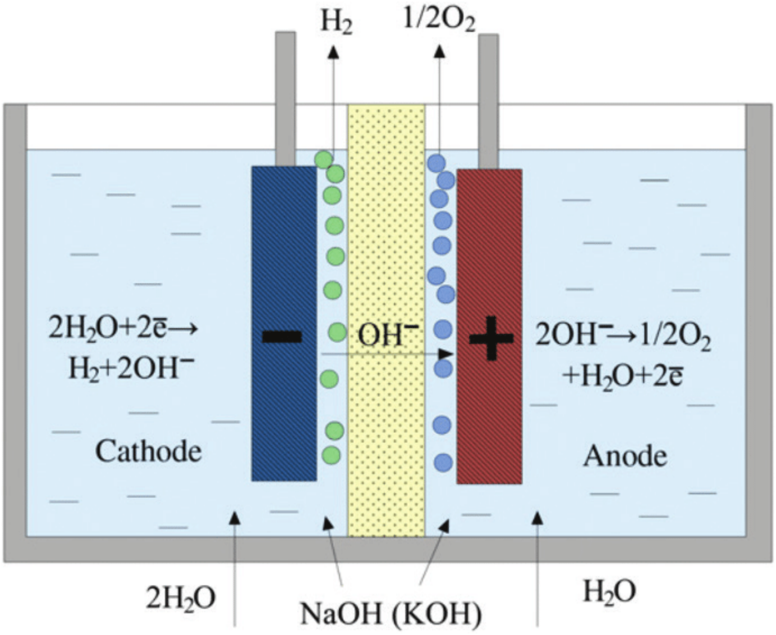


Figure 2. Alkaline electrolysis process

Source [6]

2.2.1.2 Solid oxide electrolyzers (SOE)

The solid oxide electrolyzer, unlike the two previous ones that were classified as low temperature electrolyzers (LTE), is considered a high temperature electrolyzer (HTE). This technology is under development and is not yet commercialized but has several advantages such as high thermal and energy efficiency.

It is a solid system that works at high temperatures (500-1000 °C) and the electrolyte is a conductor of oxygen ions (O_2-), elaborated with ceramic materials what reduces the production costs. The energy efficiency is practically 100%, it does not need noble metals, it can work at high pressure, and it is reversible to a fuel cell.

However, due to its high temperatures there are still problems regarding the durability of its components.
The process is shown in the next figure (Figure 3).

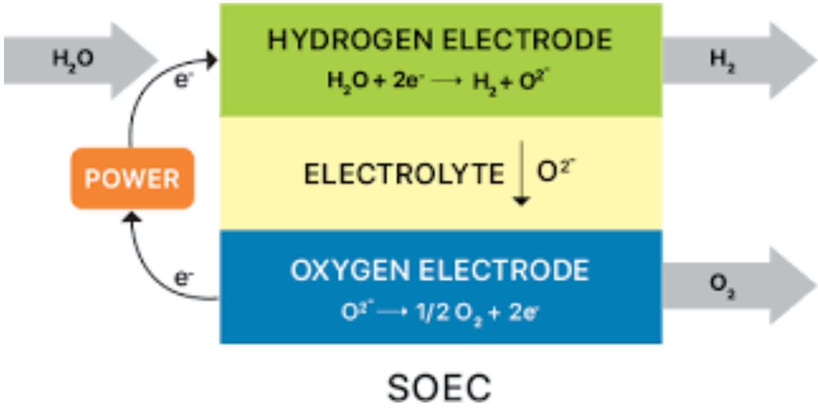


Figure 3. Solid oxide electrolysis process

Source [7]

2.2.1.3 Proton exchange membrane (PEM)

PEM electrolyzers are a newer model, although they are already commercially available although still under development.

It is a type of electrolysis where the electrolyte is a solid polymeric membrane that conducts H+. It is fed with pure water, the hydrogen produced is very pure (99.999 %) and is pressurized directly in the system.

As plus points, we can find that in this case the current densities are high, and their response is fast, so they work well for renewable energy systems where the power supply is very variable.

On the other hand, it also has certain negative aspects such as its high price and the scarcity of materials since its electrodes are made of noble metals and its bipolar plates contain titanium.

PEM electrolyzers are more suitable for small and medium plants, especially those with a variable output, while alkaline electrolyzers are clearly better for large plants that are connected to the power grid. The following figure shows a representation of the process (Figure 4).

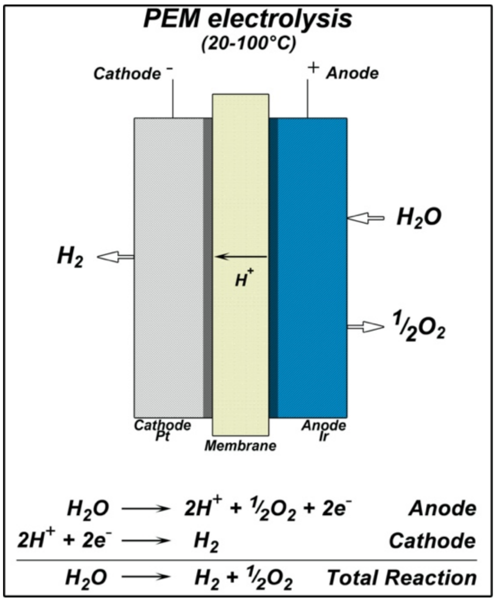


Figure 4.Proton exchange membrane electrolysis

Source [8]

2.2.1.4 Comparation between electrolyzers

In the next table (Table 1) a visual comparison can be observed between some technical requirements of the electrolyzers mentioned above.

	Alkaline electrolyzer			PEM Electrolyzer			Solid oxide Electrolyzer		
	Now	2030	Long term	Now	2030	Long term	Now	2030	Long term
Electric efficiency	63-70	65-71	70-80	56-60	63-68	67-74	74-81	77-84	77-90
Operation pressure (bar)	1-30	-	-	30-80	-	-			-
Operation Temperature (ºC)	60-80	-	-	50-80	-	-	650-1000	-	-
CAPEX ($/kWe)	500 - 1400	400 - 850	200 - 700	1 100 - 1 800	650 - 1 500	200 - 900	2 800 - 5 600	800 - 2 800	500 - 1 000

Table 1. Techno-economic characteristics of different electrolyzer

Source [-]

2.3 Hydrogen fuel cells

Hydrogen fuel cells are electrochemical devices capable of directly transforming the chemical energy of a fuel into electrical energy. They supply electrical energy from the oxidation and reduction reaction undergone by the fuel (hydrogen) and oxidant (oxygen) circulating inside them. After this process, the only products obtained are electricity in the form of direct current, water and heat.
Polymeric membrane fuel cells (PEM) are so called because the electrolyte is a polymeric membrane that separates the anodic and cathodic parts of a cell. This membrane behaves as a proton conductor by allowing the passage of H+ ions but acts as a physical barrier to other substances.
The fuel cell has 3 distinct zones: the cathodic zone where the negatively charged electrode is located, the anodic zone where the positively charged electrode is located and between both zones is the electrolytic membrane that separates the gases on both sides.
The electrochemical reactions described above can be formulated as follows, and the process can be observed in the following figure (Figure 5).

Anode: H_2 > 2H++ 2e-

Cathode: 1⁄2 O_2+ 2H++ 2e-> H_2O

Global reaction: H_2 + 1⁄2 O_2 > H_2O

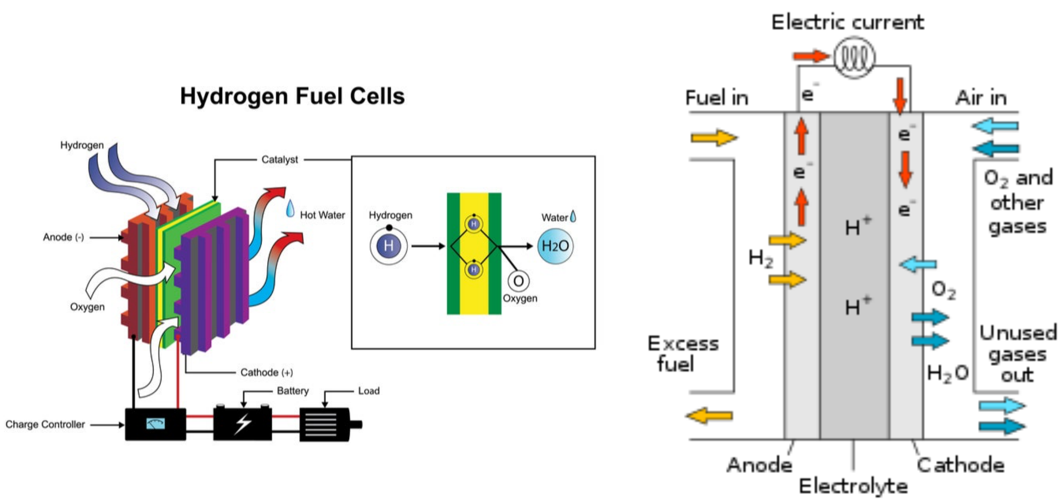


Figure 5. Hydrogen fuel cells.

Source [9]

3.HYDROGEN AUTOMOTIVE MARKET

Given the problem of the high pollution emitted by fossil fuels, hydrogen vehicles are one of the most promising alternatives.

Their operation is characterized by zero emissions, since they only expel water vapor. In addition, this technology has a greater autonomy than electric cars and a faster refueling.

However, it has certain negative points on which work must continue, such as its costly manufacture due to the high cost of producing fuel cells, as well as the implementation of hydrogen refueling stations.

To better understand this type of vehicle, its operation will be explained in basic terms. The hydrogen fuel cell car is essentially an electric car but with the difference that it produces its own electricity. To do this, the vehicle stores hydrogen in a tank to which oxygen is injected through fuel cells to produce an electrochemical reaction. This generates electricity that is stored in the car's battery and drives the electric motor.

3.1 Current situation of the hydrogen vehicle market

The hydrogen vehicle market is continuously growing and is currently in its development stages.

An analysis of the numbers for the year 2021 shows data characteristic of a market in its early stages of development, with sales still small compared to other vehicle markets. Global sales data reached 15,500 units internationally in 2021, which despite being a modest figure, is very promising as demand increased by 84% over the previous year, which shows the strong growth in which this market is immersed.

In the Figure 6, the yearly hydrogen production during the lasts years can be observed.

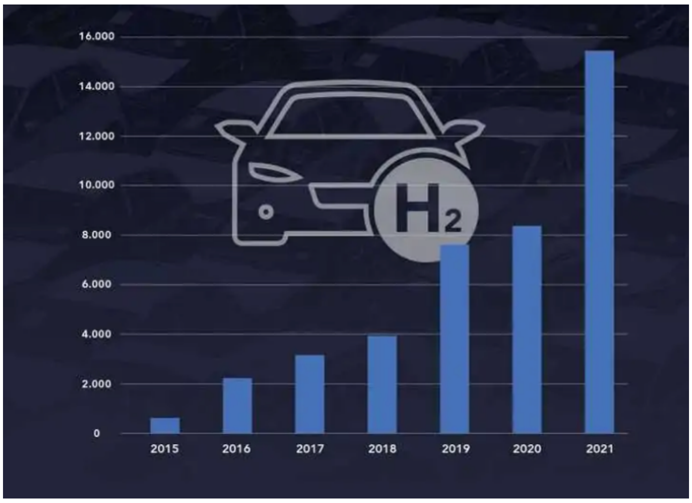


Figure 6. Hydrogen yearly international production.

Source [10]

3.1.1 Overview of existing vehicle technologies in the market

It is extremely rare to see a hydrogen car on the streets, its high price and, above all, the lack of infrastructure are the main reasons for these low figures, added to the few options offered right now.

Little by little, the market is adapting and over the next few years a very high growth is expected.

Even so, in the current market there are different options, among which the Toyota Mirai and the Hyndai Nexo stand out, occupying a 98% share of global sales of hydrogen cars.

Focusing on the Spanish market, these two models are the only ones marketed.

Hyundai is one of the companies that are betting most strongly on the future of the hydrogen car. The Nexo (Figure 7) already uses a second-generation fuel cell and last year achieved the record range for a hydrogen car, reaching 778 km on a single full charge, and is the first mass-produced hydrogen fuel cell vehicle. It can be purchased from 72,850 €.

Figure 7. Hyundai Nexo

Source [11]

The Toyota Mirai (Figure 8) can be purchased from 68,900.08 € and has, as a curiosity, a revolutionary air purification system, which eliminates harmful pollutants such as sulfur dioxide and nitrogen oxide in its path outside.

Figure 8. Toyota Mirai.

Source [12]

For the study to be carried out in this paper, we must look at certain technical specifications of the hydrogen vehicles that dominate the market. For this study it will be of vital importance to know the consumption of these vehicles for further analysis. Thus, we have consumptions of 0.9 kg/100 km in the Hyndai Nexo, reaching consumptions of 0.7 kg/100 km in urban areas, and 0.76 kg/100 km on average for the Toyota Mirai, dropping to 0.69 kg/100 km in urban areas.

In addition, continuing with the analysis of the different models, several brands and manufacturers continue to develop hydrogen-powered vehicles. This is the case of BMW, which has already announced the release this year of its hydrogen-powered X5. On the other hand, Honda already developed the FCX Clarity in 2008, although it is no longer marketed. The Jaguar Land Rover group is working on a hydrogen version of the Land Rover Defender. Ineos, Europe's largest operator of electrolysis plans to begin testing an Ineos Grenadier, and Renault, through its subsidiary Hyvia, hopes to launch a hydrogen version of its commercial model Master

3.1.2 Analysis of current infrastructure for hydrogen vehicles

Currently, given the early stage of development of this technology, there is a shortage of hydrogen stations where these vehicles can be charged.

There are currently five stations in Spain. Two of them are for the exclusive use of buses. Another, located in Aragon, is publicly accessible, but serves hydrogen pressurized to 35 bar, which is incompatible with the two hydrogen car models discussed above, which require a pressurization of 700 bar in their tanks.

This means that, for the moment, of the five hydrogen stations available in Spain, two of them have to be discarded because they are exclusively for buses and one of them, the only one that serves hydrogen publicly to individuals, is not compatible with the fuel cell vehicles mentioned previously.

There is a compatible station for these two vehicles in Madrid, operated by Enagas, but it is not publicly accessible. The only alternative in the whole country is the station of the National Hydrogen Center in Puertollano (Ciudad Real), which is public and serves pressurized hydrogen at 700 bar.

3.2. Future of hydrogen automotive market

3.2.1 Growth potential of hydrogen vehicles in Valencia.

Hydrogen vehicles have a high growth potential, this is due to the various advantages they will bring.
As mentioned above, their advantages are zero emissions, greater autonomy compared to electric cars and their ease and speed of refueling, in a process very similar to that of a traditional fuel car and in approximately 5 minutes for a full charge.

In addition, the estimated refueling cost is lower than that of current fuels and its maintenance is also lower, since its components are less complex than current electric and gasoline vehicles.

Today hydrogen is sold at hydrogen plants at a price of between 8 € and 10 € per kilogram, using the Toyota Mirai as an example, filling its three tanks would cost between 44 € and 55 € with the current selling price, with which we could travel about 650 km. Compared to an equivalent gasoline car, we would be saving 2 € per 100 kilometers, and all this without taking into account the decline in hydrogen prices in the coming years due to economies of scale.

Moreover, since hydrogen production by electrolysis requires only energy and water, countries with the potential for wind and solar power generation have a large capacity to produce clean hydrogen. Following a study by the International Energy Agency, Spain is among these countries with high potential, being able to obtain values in the future of a hydrogen production cost of 2.5 euros/kilo.

These advantages are very attractive and compared to conventional vehicles would make a big difference by providing a better environmental and economic performance, so its implementation is very attractive.

3.2.2 Potential challenges and barriers to overcome for widespread adoption

This technology also presents several problems, which will have to be addressed in order to achieve full implementation of hydrogen vehicles. These problems lie mainly in the high cost of manufacturing the cars and the implementation of hydrogen stations.

Another drawback is the method of obtaining hydrogen. In this project, the electrolysis method will be studied because of its non-polluting character. This process involves a high consumption of water and electricity, which should always come from renewable sources for the hydrogen car industry to be truly 100% clean.

There is also a negative perception about the safety of hydrogen tanks, as it is a highly flammable gas. However, manufacturers insist on the safety of their tanks, and their actual risk is not much different from that of conventionally fueled vehicles.

Moreover, although hydrogen is highly flammable, it is also highly volatile, so that in the event of a tank leak, it would dissipate easily without becoming concentrated in sufficiently hazardous quantities.

These challenges, along with the uncompetitive actual cost of hydrogen production and distribution, will be studied and improved upon with the development of this technology, and its implementation with economies of scale will make this technology a very competitive option in less than 10 years.

3.2.3 Government initiatives and policies supporting hydrogen vehicles

In order for hydrogen technologies to be implemented in society, the government published the Hydrogen Roadmap in which it sets out its plan to deploy green hydrogen in pursuit of emission neutrality no later than 2050.

To achieve this, the intention is to have a minimum of between 100 and 150 hydroline stations by 2030, with the intention of reaching these figures, different measures are proposed by the government, among which the following stand out among others

First, a specific plan dedicated to the progressive penetration of fuel cell-based solutions in urban public passenger transport will be developed.
In line with this measure, in 2019 and 2020, the MOVES I Plan and MOVES II Plan respectively, have incentivized the acquisition of alternative energy vehicles including battery electric vehicles and hydrogen-powered fuel cell electric vehicles. The MOVES II Plan is endowed with €100 million.

In addition, to support the Spanish automotive industry and favor the production of hydrogen-powered fuel cell electric vehicles, a measure has been promoted for industrial innovation in renewable H2, development of new technologies and prototypes aimed at new models for the domestic market and anticipation of the needs of export markets. This measure is endowed with 25 M€.

Also, specific legislation has been developed for hydrogenators stations, which specifies the administrative requirements and delimits the permits necessary for their construction and management, and last hydrogen dispensers can be introduced now in existing service stations.

Finally, support will be given to R&D&I of renewable hydrogen value chain technologies, through measures such as creating an exclusive line of financing for renewable hydrogen value chain projects, or strengthening the role of the National Hydrogen Center (CNH2) as a public R&D&I center of reference, or promoting the national development of high-power electrolyzers by promoting their mass production.

4.HYDROGEN CONSUMPTION

4.1. Hydrocarbons fuel consumption in the province of Valencia

In order to analyze the real fuel consumption in the province of Valencia and develop a sustainable plan for the introduction of hydrogen vehicles in society, we must know the real data of hydrocarbon consumption in Spain.
For this, we can obtain the consumption in two different ways, which are described in the next two points below.

4.1.1. Data analysis of consumptions

The first way to obtain the consumptions is based on data provided by CORES, a non-profit public law corporation supervised by the Ministry for Ecological Transition and the Demographic Challenge in Spain.

In this way, we can know the different fuel consumptions in the province of Valencia during the 2021 year, specified in the nest table (Table 2) on a monthly basis.

2021 FUEL CONSUMPTION(Tons)				
	95 Gasoline	98 Gasoline	Gosaline	Diesel
January	15.872	736	16.609	75.330
Febrary	15.179	724	15.904	78.963
March	20.803	996	21.799	94.919
April	20.517	971	21.487	89.202
May	22.190	1.039	23.229	94.425
June	25.376	1.226	26.602	104.349
July	28.122	1.309	29.431	107.861
Agoust	26.661	1.203	27.864	95.547
September	25.648	1.129	26.777	102.325
October	24.597	1.020	25.617	99.244
November	23.048	873	23.922	99.265
December	22.303	1.038	23.341	89.118
Total	270.318	12.264	282.582	1.130.549

Table 2. Fuel consumptions at Valencia (2021)

Source [13]

When observing the data, we are struck by the large quantities of diesel consumed, but this is due to the important role of heavy transport in our country, so we must correct the data obtained to know the actual consumption data for private vehicles.

In order to do this, we must make an estimation to obtain a value close to the real value, calculating it as follows on the equation 1:

$$Anual\ diesel\ consumption = Anual\ gasoline\ consumption * \frac{Diesel\ consumption}{Gasoline\ Consumption} * \frac{Diesel\ cars}{Gasoline\ cars}$$

Equation 1

To make these calculations we have taken the consumption of a standard gasoline car as 6 l/100 km and the consumption of a diesel car as 4.5 l/100 km. Also, we need to know the ratio of diesel and gasoline vehicles, for that we have consulted the number of diesel and gasoline vehicles that we have in Spain for the year studied, obtaining data of 14.9 million diesel vehicles compared to 9 million gasoline vehicles.

Knowing this, we must transform the above data table, changing the diesel consumption cell. Results can be observed in Table 3.

2021 FUEL CONSUMPTION(Tons)					
	95 Gasoline	98 Gasoline	Gosaline	Diesel	
January	15.872	736	16.609	20.623	
Febrary	15.179	724	15.904	19.747	
March	20.803	996	21.799	27.067	
April	20.517	971	21.487	26.680	
May	22.190	1.039	23.229	28.843	
June	25.376	1.226	26.602	33.031	
July	28.122	1.309	29.431	36.544	
Agoust	26.661	1.203	27.864	34.597	
September	25.648	1.129	26.777	33.248	
October	24.597	1.020	25.617	31.807	
November	23.048	873	23.922	29.703	
December	22.303	1.038	23.341	28.982	Total fuel
Total	270.318	12.264	282.582	350.872	633.454

Table 3. Fuel consumption for private vehicles (2021)

Source [13]

Thus, we can conclude that through the data provided by CORES, we can obtain an approximate fuel consumption of 633454 Tons per year in the province of Valencia.

4.1.2. Estimation with average distance

Another way of estimating fuel consumption is through the average kilometers traveled by a standard citizen and calculating from the consumption of the vehicles the amount of fuel needed to feed the fleet of cars during a year.
Thus, following surveys carried out by the National Statistics Institute (INE), we can take as a reference a value that indicates that an average vehicle in Spain makes 12562,9 kilometers per year.

Furthermore, also referring to the INE, in the year 2021 in the province of Valencia there were a total of 1293340 vehicles for private use.

With this, we can obtain the amount of fuel needed at the province of Valencia for one year following the Equation 2:

$$Anual\ fuel\ consumption = number\ of\ cars * anual\ average\ kms * average\ consumption$$

Equation 2

Also, we must calculate the average car consumption according to the equation below.

$$Average\ consumption = \frac{diesel\ consumption * nº diesel\ cars + gasoline\ consumption * nº\ gasoline\ cars}{total\ nº\ cars}$$

Equation 3

$$Avearge\ \ consumption = \frac{4{,}5*14{,}9*10^6+6*9*10^6}{23{,}9*10^6} = 5{,}0649\,\frac{l}{100km} = 3{,}98\,\frac{kg}{100km}$$

Equation 4

$$Anual\ fuel\ consumption = 1293340 * 12562{,}9 * 3{,}98 = 646.674{,}42\ Tons\ \text{of fuel}$$

Equation 5

After these calculations, we obtain an annual expense of 646.674,42 tons.

4.2 Equivalent hydrogen consumption

As part of our plan to introduce the hydrogen vehicle into Valencian society, we need to calculate the necessary supply of hydrogen that will be needed to power all the vehicles, for this, we must obtain the energetic equivalent of hydrogen for knowing the hydrogen supply that will be required.

	Comsumption (l/100km)	Density (kg/l)	Consumption (kg/100km)
gasoline	6	0,832	4,992
diesel	4,50	0,75	3,375
HC	5,0649	0,78	3,98
H_2	-	-	0,7

Table 4. Fuel consumptions

Source [14]

As we can see in the table 4, the different consumptions have been calculated both in liters and kilograms for each type of vehicles, being HC vehicles the weighted average between diesel and gasoline vehicles.

Thus, having both consumptions in kg/100km we can compare them and obtain the consumption relation as follows (Equation 6):

$$Cosnumption\ relation = \frac{HC\ consumption}{H_2\ consumption} = \frac{3{,}98}{0{,}7} = 5{,}6913$$

Equation 6

After this, we can calculate the Hydrogen supply needed for our project as follows (Equation 7):

$$H_2\ consumption = \frac{HC\ consumption}{5{,}6913}$$

Equation 7

Knowing this, we already know the cost of H2 that we would need to supply 100% of the vehicles in the province of Valencia, obtaining amounts of 111302 Tons of H_2 with the data analysis calculation, and 113625 Tons of H_2 in the average distance traveled way.
As a result, we can see that both values are very similar, with a difference of only 2.19%.

5.IMPLEMENTATION PLANS FOR H_2 VEHICLES

5.1. Plans description

In view of the serious problem of combustion cars, the European Commission has proposed certain measures to decarbonize the automobile industry.
These measures consist of reducing CO2 emissions by 55% from 2030 compared to 2021 emissions, and to reduce them to zero by 2035, which implies a ban on combustion vehicles from 2035 onwards.

The European Parlament, also aware of Hydrogen cars potential, has developed a plan for which hydrogen reporting stations will be installed every 100 km, and this proposal is to be implemented by 2028, which shows us the potential of this technology, and how its implementation is no longer something distant, but will grow by leaps and bounds over the next few years.

All this leads us to think about a plan to introduce this vehicle in the Valencian automotive market.

For this, we have assumed three different rates of introduction in order to study from a more unfavorable case in which the implementation of this technology is done more gradually, to
the most favorable case in which we assume sales of hydrogen cars after 10 years of almost a third of new vehicle sales.

To design these plans, we must know the number of new cars registered in the province of Valencia, for this purpose, resorting again to the data studied by the INE, we can conclude that during the year 2021, our year of study, the new registrations were 32,386 vehicles.

Knowing this, the following table (Table 5) shows the three plans designed for the introduction of hydrogen vehicles, all of them estimating a certain percentage of hydrogen vehicles with respect to new annual registrations.

Total cars at valencia	1293340
New registered cars at valencia	32386

YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7	YEAR 8	YEAR 9	YEAR 10
0,5%	1,5%	2,5%	3,5%	4,5%	5,5%	6,5%	7,5%	8,5%	9,5%
0,5%	2,0%	3,5%	5,0%	6,5%	8,0%	9,5%	11,0%	12,5%	14,0%
0,5%	2,5%	4,5%	6,5%	8,5%	10,5%	12,5%	14,5%	16,5%	18,5%

New H_2 cars									
162	486	810	1134	1457	1781	2105	2429	2753	3077
162	648	1134	1619	2105	2591	3077	3562	4048	4534
162	810	1457	2105	2753	3401	4048	4696	5344	5991

Total H_2 cars									
162	648	1457	2591	4048	5829	7935	10364	13116	16193
162	810	1943	3562	5668	8258	11335	14898	18946	23480
162	988	2544	4903	8147	12362	17646	24107	31861	41039

Table 5. Introduction plan data.

Source [14]

In the tables, we can see how in the upper part we find the percentage of new registered vehicles that will be hydrogen vehicles.
According to the plan, each year this percentage increases by 1,1,5 or 2% respectively.
In the second table, we observe the total number of new cars with hydrogen technology that we will implement annually, and finally in the last table the values refer to the total number of hydrogen cars, meaning the new cars sold that same year and those of previous years.

Therefore, if we follow the first plan with a medium rate of introduction of vehicles, in the tenth year we will obtain a total of 16,000 vehicles in circulation in the province of Valencia, while if we follow the last plan, with a very high rate, we will obtain about 41,000 H2 vehicles in 10 years.

5.2 Hydrogen supply and consumption required

After knowing the different plans for the incorporation of hydrogen vehicles, we must estimate the necessary supply of hydrogen to refuel these cars, so, from the number of hydrogen cars that we have calculated above, and knowing the amount of hydrogen needed to feed all vehicles in the province of Valencia we can calculate it, following the next equation (Equation 8):

$$Anual\ H_2\ consumption = Consumption\ 100\%\ H_2\ cars * \frac{Total\ H_2\ cars}{Total\ cars\ valenica}$$

Equation 8

Applying this to the consumption data obtained after the cores data analysis, we obtain the following results (Table 6).

YEAR 1	Total H_2Cars	H_2 amount(kg)	H_2 amount/day	H_2 amount/day and station	H_2 amount/day and station
0,5%	162	13935	38	0,1	0,4
0,5%	162	13935	38	0,1	0,4
0,5%	162	13935	38	0,1	0,4
YEAR 2					
1,5%	648	55741	153	0,3	2
2,0%	810	69677	191	0,3	2
2,5%	972	83612	229	0,4	2
YEAR 3					
2,5%	1457	125418	344	0,6	3
3,5%	1943	167224	458	1	5
4,5%	2429	209030	573	1	6
YEAR 4					
3,5%	2591	222965	611	1	6
5,0%	3562	306578	840	1	8
6,5%	4534	390190	1069	2	11
YEAR 5					
4,5%	4048	348384	954	2	10
6,5%	5668	487737	1336	2	13
8,5%	7287	627090	1718	3	17
YEAR 6					
5,5%	5829	501672	1374	2	14
8,0%	8258	710703	1947	3	19
10,5%	10687	919733	2520	4	25
YEAR 7					
6,5%	7935	682832	1871	3	19
9,5%	11335	975474	2673	4	27
12,5%	14736	1268116	3474	6	35
YEAR 8					
7,5%	10364	891862	2443	4	24
11,0%	14898	1282052	3512	6	35
14,5%	20905	1799053	4929	8	49
YEAR 9					
8,5%	13116	1128763	3093	5	31
12,5%	18946	1630435	4467	7	45
16,5%	28339	2438824	6682	11	67
YEAR 10					
9,5%	16193	1393534	3818	6	38
14,0%	23480	2020625	5536	9	55
18,5%	37165	3198315	8763	15	88

Table 6. Hydrogen consumptions with CORES data

Source [14]

In order to compare and contrast the results obtained, we again carried out the process of obtaining the annual fuel consumption for each plan, but this time calculating it based on the average distance traveled by a standard vehicle as its showed in the equation 9.

$$Anual\ H_2\ consumption = Total\ H_2\ cars * anual\ average\ kms * \left(\frac{0{,}7}{100}\right)$$

Equation 9

YEAR 1	H_2 amount	H_2 amount/day(kg)	H_2 amount/day and station	H_2 amount/day and station
0,5%	14240	39	0	0
0,5%	14240	39	0	0
0,5%	14240	39	0	0
YEAR 2				
1,5%	56961	156	0	2
2,0%	71201	195	0	2
2,5%	85441	234	0	2
YEAR 3				
2,5%	128162	351	1	4
3,5%	170882	468	1	5
4,5%	213603	585	1	6
YEAR 4				
3,5%	227843	624	1	6
5,0%	313284	858	1	9
6,5%	398725	1092	2	11
YEAR 5				
4,5%	356004	975	2	10
6,5%	498406	1365	2	14
8,5%	640808	1756	3	18
YEAR 6				
5,5%	512646	1405	2	14
8,0%	726249	1990	3	20
10,5%	939851	2575	4	26
YEAR 7				
6,5%	697768	1912	3	19
9,5%	996812	2731	5	27
12,5%	1295856	3550	6	36
YEAR 8		0		
7,5%	911371	2497	4	25
11,0%	1310096	3589	6	36
14,5%	1838406	5037	8	50
YEAR 9				
8,5%	1153454	3160	5	32
12,5%	1666100	4565	8	46
16,5%	2492173	6828	11	68
YEAR 10				
9,5%	1424017	3901	7	39
14,0%	2064825	5657	9	57
18,5%	3268276	8954	15	90

Table 7. Hydrogen consumptions calculated with average distances

Source [14]

In both tables, we obtain the values of the annual hydrogen expense necessary to implement each plan, as well as the daily consumption and the consumption per hydroline station, considering two possible cases:

The first one, with 600 hydroline stations, assuming that all the gas stations in the province of Valencia would implement the necessary technologies for the hydrogen refueling, and a second case in which we consider the possibility of bringing this technology to 100 gas stations.

6.HYDROGEN GREEN PRODUCTION

6.1 Photovoltaic solar energy

The implementation of the hydrogen vehicle in society is a technological challenge that mainly lies in the production and transportation of the necessary hydrogen, therefore, as part of our plan we must think of a sustainable and economically viable method of hydrogen production for our plan to work.

In this regard, solar photovoltaics has emerged as one of the key technologies for clean and efficient hydrogen generation.
This technology is attractive because solar energy is renewable and abundant in many parts of the world, particularly in Valencia, making it a promising option for large-scale hydrogen production. In addition, solar photovoltaic energy produces no greenhouse gas emissions or other pollutants, making it a clean and environmentally friendly energy source.

Photovoltaic solar energy is obtained from the incidence of the sun's radiation on a panel called a photovoltaic panel, formed by cells of a semiconductor material capable of transforming this radiation into direct current electrical energy.
The operation of these cells is based on the use of doped semiconductors. This doping consists of adding foreign atoms to the semiconductor to modify its crystalline structure and generate an excess or defect of electrons in it, which modifies its electrical properties.
The panels are made up of two layers of silicon; the first, where the solar radiation directly hits, is N-type doped (with an excess of electrons) and the second is P-type doped (with a defect of electrons).
When these panels receive solar radiation, it strikes the first N-type silicon layer, exciting the excess electrons and jumping to the second P-type layer, which attracts them due to its lack of electrons. This generates an interlayer potential difference and, if an external circuit is connected, an electric current.

6.2 Sizing solar power plant for hydrogen production

After analyzing the potential of photovoltaic solar energy, we chose this as the way to produce the hydrogen needed for the different plans.

Therefore, we will perform the necessary calculations to establish the dimensions of a photovoltaic power plant with the capacity to generate the necessary energy to obtain the necessary quantities of hydrogen calculated in the previous sections.

To do this, we must know certain parameters that will affect our calculations, and to know them we must conduct a study of solar energy and the different technologies of solar panels that we can use.

In order to have a quick overview of the dimensions that our solar plant should have, calculations were made by adopting typical values for parameters such as the efficiency of the panels, the energy needed for electrolysis and the hours and radiation of the sun in Valencia. These parameters are specified in table 8.
Then, as we go into the design of the plant in depth, we will analyze and calculate these values more precisely.

electrolysis energy for 1 kg H_2	50 kWh/kgH_2
rend solar panel	0,21
solar radiation vlc	5,23 kWh/m2

Table 8. PV installation data

Source [14]

$$Electrolysis\ energy(kWh) = \frac{Electrolysis\ energy}{kgH_2} * H_2\ amount = 50 * H_2\ amount$$

Equation 10

$$Sun\ energy(kWh) = \frac{Electrolysis\ energy}{\varepsilon} = \frac{Electrolysis\ energy}{0{,}21}$$

Equation 11

$$Area(m^2) = \frac{Sun\ energy}{solarradiation\ vlc} = \frac{Sun\ energy}{5{,}73}$$

Equation 12

$$Instalated\ power(kW) = Solar\ radiation(\frac{kW}{m^2}) *\ \varepsilon * area = 1 * 0{,}21 * area$$

Equation 13

Following these steps, the table below (Table 9) shows the results obtained for the CORES data prediction.

YEAR 1	kWh(electrolysys)	kWh(sun)	area(m2)	powinst(MW)
0,5%	1909	9090	1738	0,37
0,5%	1909	9090	1738	0,37
0,5%	1909	9090	1738	0,37
YEAR 2				
1,5%	7636	36361	6952	1,5
2,0%	9545	45451	8690	1,8
2,5%	11454	54541	10429	2,2
YEAR 3				
2,5%	17181	81812	15643	3,3
3,5%	22907	109083	20857	4,4
4,5%	28634	136354	26071	5,5
YEAR 4				
3,5%	30543	145444	27810	5,8
5,0%	41997	199985	38238	8,0
6,5%	53451	254527	48667	10,2
YEAR 5				
4,5%	47724	227256	43452	9,1
6,5%	66813	318159	60833	12,8
8,5%	85903	409061	78214	16,4
YEAR 6				
5,5%	68722	327249	62571	13,1
8,0%	97357	463602	88643	18,6
10,5%	125991	599956	114714	24,1
YEAR 7				
6,5%	93539	445422	85167	17,9
9,5%	133627	636317	121667	25,6
12,5%	173715	827212	158167	33,2
YEAR 8				
7,5%	122173	581776	111238	23,4
11,0%	175624	836302	159905	33,6
14,5%	246446	1173550	224388	47,1
YEAR 9				
8,5%	154625	736310	140786	29,6
12,5%	223347	1063558	203357	42,7
16,5%	334086	1590884	304184	63,9
YEAR 10				
9,5%	190895	909024	173810	36,5
14,0%	276798	1318085	252024	52,9
18,5%	438125	2086311	398912	83,8

Table 9. PV calculations for area and installation power

Source [14]

7.DESIGN OF A SOLAR PLANT FOR HYDROGEN PRODUCTION

In this point of the study, we will design in more detail a solar production plant to produce green hydrogen of 10MW, analyzing and calculating the required dimensions as well as the necessary equipment for its design.
This plant has a power capable of supplying the hydrogen necessary for the above mentioned plan during the first 7 years in the most pessimistic case, or during 4 and a half years in the most optimistic case.

The plant will be located in the province of Valencia, as its main function will be to supply the hydrogen needed for the hydroliners required to refuel hydrogen vehicles.

7.1 Location and irradiation study

The solar radiation incident on Spain makes photovoltaic technologies a very favorable option for energy production in this country. As we can see, is one of the countries with the best solar conditions in the European Union, with an average of 1800 kWh/m2 (Table 9).

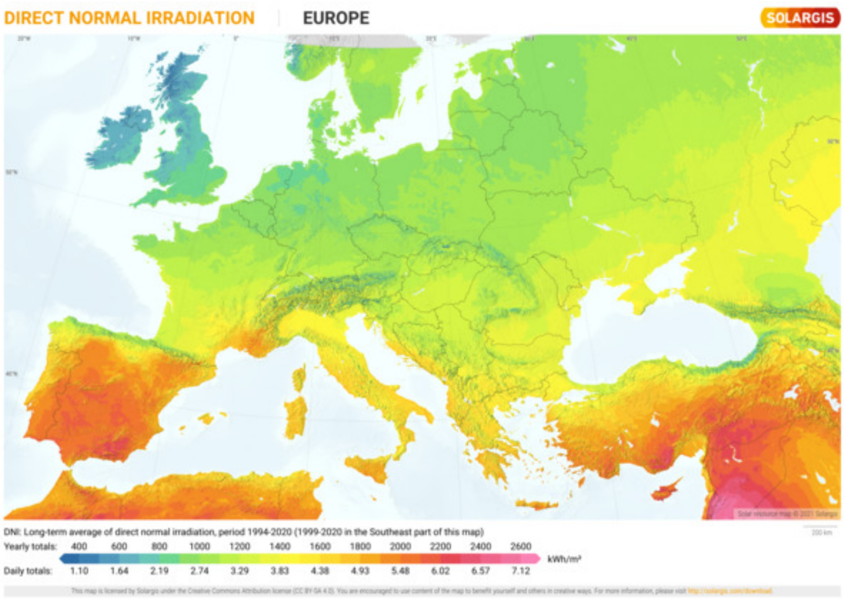


Figure 9. Irradiation map

Source [15]

Our plant will be located in the province of Valencia, since its purpose will be to supply the different hydrogen reporting stations in this province.
More specifically, it will be located in La Pobla de Vallbona, in a land surrounded by orange groves which will favor the absence of shadows that may harm our installation.

The study of solar irradiation is necessary for the sizing of our solar plant, and to do so it is necessary to correctly understand the concept of peak sun hour.
Peak sun hours are a way of measuring the amount of sunlight a location receives.
A peak sun hour is defined as an hour in which the intensity of sunlight (solar irradiance) reaches an average of 1,000 watts per square meter, its unit is kWh/m2 per day.

Using a peak sun hours calculator, we obtain the following values for our plant design site (Figure 10):

5.23 peak sun hours per day

Your monthly averages:

- January: 4.19
- February: 4.72
- March: 5.28
- April: 5.44
- May: 5.77
- June: 5.91
- July: 6.33
- August: 6.11
- September: 5.75
- October: 4.99
- November: 4.35
- December: 3.93

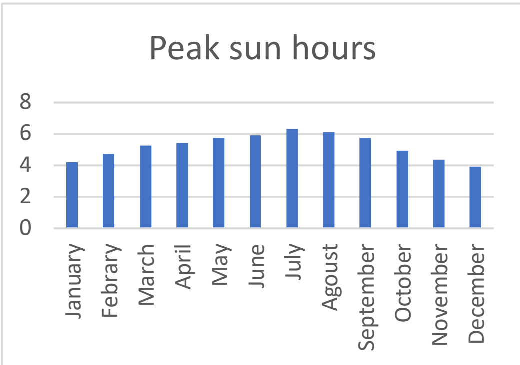


Figure 10. Monthly peak sun hours analysis

Source [16]

Knowing this, and having an installed capacity of 10 MW, we can calculate the maximum possible hydrogen production of our plant.
This will occur during the month of July, where we will have the maximum number of peak sun hours.
To make the calculation we will proceed in the same way as before, and we will obtain results of 1266 kg of H_2.

$$Kg\ of\ H_2 = \frac{6{,}33 * 10000}{50} = 1266\ kg/day$$

Equation 14

Knowing this, we know the maximum flow requirements with which to design our installation, for the design of certain components it will be easier if we handle the data in Nm3/h, so we must convert the data to these units, obtaining 587 Nm3/h.

$$\frac{1266kg/dia}{24h/dia * 0.0899\frac{kg}{m^3} *} = 587Nm^3/h$$

Equation 15

7.2. Study of hydrogen yearly production

To know the productive capacity of our hydrogen plant we must calculate the monthly production in a same way as in the previous section, studying each month separately because the average monthly irradiation is variable and there will be months like winter in which the production will be lower. The next figures represent these calculations (Figure 10).

	Peak sun hrs	H_2 kg
January	4,19	25978
Febrary	4,72	26432
March	5,28	32736
April	5,44	32640
May	5,77	35774
June	5,91	35460
July	6,33	39246
Agoust	6,11	37882
September	5,75	34500
October	4,95	30690
November	4,35	26100
December	3,93	24366
Average	5,23	31817
Total	62,73	381804

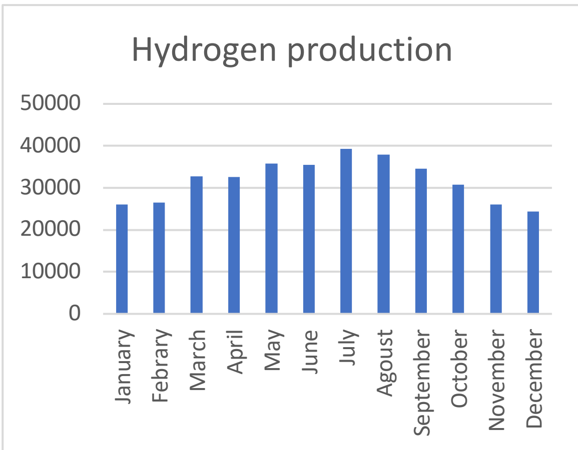


Table 10. Monthly production analysis and Figure 11. Graph of monthly production analysis

Source [14]

Therefore, with a 10 MW plant, approximately 381 tons of hydrogen will be produced. Also, we can measure it in other units that will be interesting for later calculations, being the annual production of 177,000 Nm3.

7.3. Installation components

To study the feasibility of our plan we need to know if the production of green hydrogen is technically and economically feasible, so we must know the different components of the plant in order to determine if functionally we can find the equipment that suits the technical requirements, and also to know approximately the investment needed to develop the project.
This second part, the economic analysis will be done by analyzing the costs of the main components of the plant, which will approximate the real value of the necessary investment.

7.3.1. Selection of solar modules

To cover the selected power, solar modules have to be installed, for which the 545W JA Solar Mono PERC model has been selected.

The production data of the 545W JA Solar Mono PERC solar panel is as follows:

- Peak Power (PMAX): 545W
- Voltage at maximum power (VMPP): 41.80V
- Intensity at maximum power (IMPP): 13.04A
- Voltage at open circuit (VOC): 49.75V
- Short circuit current (ISC): 13.93A
- Module efficiency: 21.1%.
- Dimensions: 2279 x 1134 x 30mm
- Solar Panel Warranty: 25 years

Knowing the technical data of the module used, we can calculate the number of panels needed to obtain 10 MW of installed power.

$$Number\ of\ solar\ panels = \frac{required\ power}{panel\ power}$$

Equation 16

Operating in this way, we obtain a total of 18349 solar panels.

After this and knowing the dimensions of each panel we can calculate the total surface of panels and size our plant, obtaining a total area of solar panels of 47500 m^2.

An important fact is the unit price of the panel, which is 216.24 euros for every panel.

7.3.2 Electrolyzer

For the production of hydrogen, we need an electrolyzer, this is the device with which we can carry out the electrolysis process, which consists of separating the hydrogen and oxygen molecules using electricity.

Going into more detail, an electrolyzer consists of the stacking of conductive electrodes separated by a membrane where a high voltage and intensity is stacked, thus generating an electric current in the water from which we get to decompose more hydrogen and oxygen molecules.

There are different types of electrolyzers, such as alkaline electrolyzers, proton exchange membrane electrolyzers (PEM) or solid oxide electrolyzers (SOEC).
For our plant, we have focused on PEM electrolyzers, as they are the most popular, as their benefits include the production of high purity hydrogen and ease of cooling. They use a proton exchange membrane and a solid polymer electrolyte, and when current is applied to the battery, the water splits into hydrogen and oxygen and the hydrogen protons pass through the membrane to form hydrogen gas on the cathode side.
On the downside, the use of precious metals as catalysts makes them somewhat more expensive

To suit the size of our plant, the EL600N electrolyzer from H2B2 has been selected, with the following technical specifications:

Hydrogen gas production:

- Max. nominal hydrogen flow: 600 Nm^3/h (1,290 kg/day)
- Hydrogen flow range: 10 – 100%
- Operating pressure: 15 – 40 barg (217-580 psig)
- Hydrogen purity (before gas purification): > 99.9%; < 25 ppm O_2; H_2O saturated
- Hydrogen purity (after gas purification): 99.999%; < 5 ppm O_2; < 5 ppm H_2O

Electrical requirements

- Voltage: 3 x 400 VAC ± 10% (3Ph+N) / 3 x 480 VAC ± 10% (3Ph+N)

Frequency: 50 Hz ± 5% / 60 Hz ± 3%
Power (BoP + Stacks): 3,100 kW
Stack consumption: 4.7 kWh/Nm^3 H_2
AC power consumption (BoP + stack): 5.1 kWh/Nm^3 H_2

Feed water requirments
Consumption: < 1 L/Nm^3 H_2
Temperature: +5 ºC to + 40 ºC (+41 ºF to +104 ºF)

In addition, a control system is included to manage the working process of the electrolyzer with a PLC, fully automated and unattended with 15” color touch screen and a Modbus TCP/IP or Profinet (RJ45 port) communication.

Other specifications that might be mentioned, are the dimension and weight, having a size of 12m x 2.4m x 2.9m, an approximated weight of 45,000 kg.

In the figure 12, the electrolyzer EL600N can be seen.

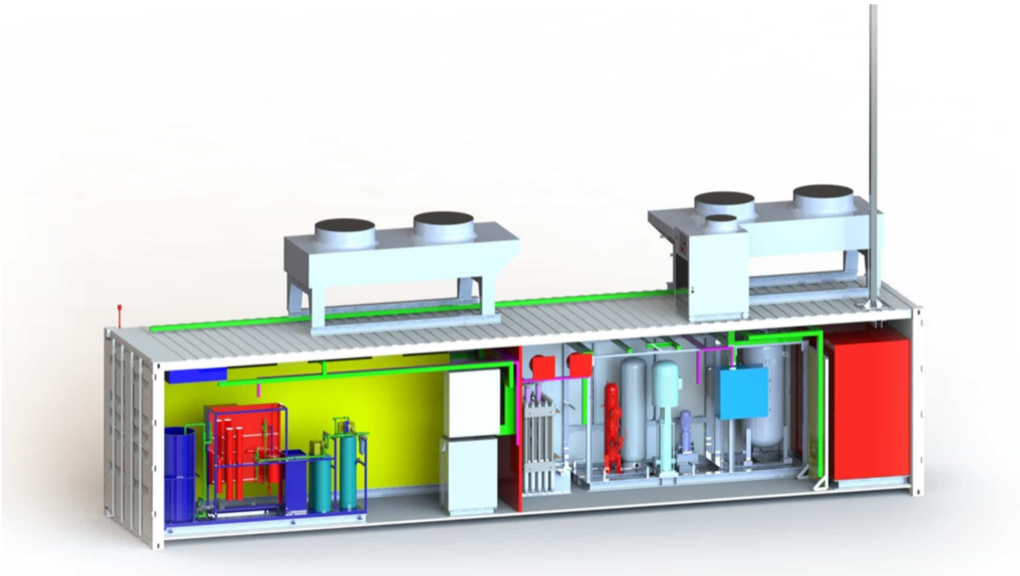


Figure 12. Electrolyzer

Source [18]

7.2.3 Compressor

Another vital element for the installation is the compressor because to transport the hydrogen we will have to do it at high pressures, higher than 700 bar, which is the pressure required in the hydrogen stations for vehicles.

To achieve this, we will have two compressors, one low pressure and one high pressure. In this way, the low-pressure compressor will raise the pressure to 160 bar and the high-pressure compressor to 900 bar.

Therefore, the path that the hydrogen will follow in its compression process will start at the beginning of the electrolyzer, from where it will be conducted to the low-pressure compressor and after the compression process it will be stored in the low-pressure tank at 60 bar. After this, the hydrogen will pass to the high-pressure compressor and will be stored in the high-pressure tanks from where it can be distributed to the different hydroline plants in the province of Valencia.

Knowing this, we know the pressure requirements that our equipment will need, in addition, the compressor must be able to work with a hydrogen flow higher than the maximum flow provided by the electrolyzer, so we must look for a compressor that operates correctly with flows up to 485 Nm^3/h.

For this, we would select among all the compressors on the market the Hiperbaric brand, selecting the model 1KS 50 for the first stage of compression and the model 1KS 95 for the second stage.
Thus, knowing the specifications of the hydrogen compressors we will need two compressors for the low-pressure stage due to the high hydrogen flows, and one for the high-pressure stage.

Technical specifications of 1KS 50 Compressor (Figure 13) :

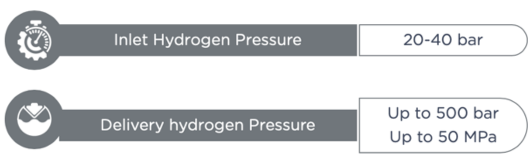


Figure 13. 1KS 50 Compressor specifications

Source [19]

Technical specifications of 1KS 95 Compressor (Figure 14):

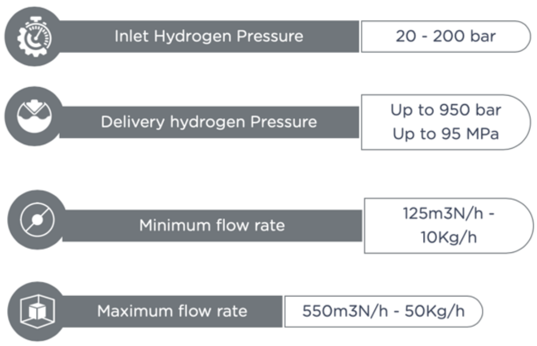


Figure 14. 1KS 95 Compressor specifications

Source [19]

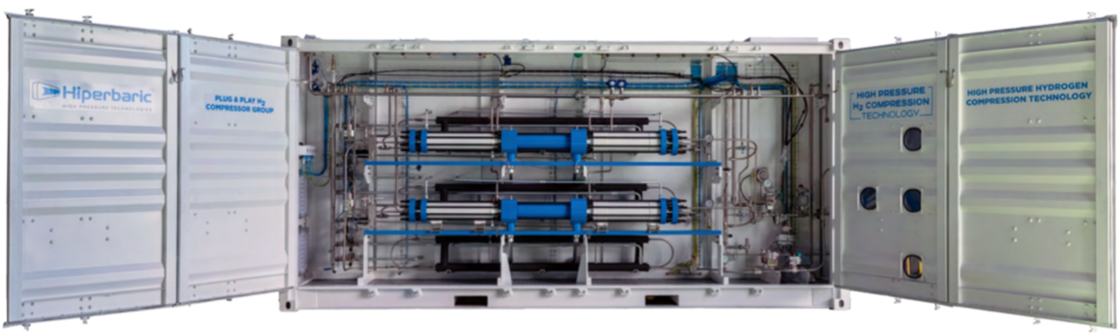


Figure 15. Compressor

Source [19]

7.2.4 Low-pressure tank

Another main component of the installation is the low-pressure tank where the hydrogen is stored after the first compression stage.
To know its capacity, the daily hydrogen production must be estimated.
Assuming a production at 100% of the electrolyzer capacity to obtain an upward estimate, which will not occur because the solar energy obtained in the most favorable month is not enough for that level of production, a value of 1290 kg of H2 per day is obtained.

Since the pressure at the outlet of the first compression stage will be 160 atmospheres, the required tank volume can be obtained by following the equation below (Equation 17):

$$V = \frac{n * R * T}{P} = \frac{m * R * T}{M * P}$$

Equation 17

Each value being:

- V is the volume (l)
- m is the hydrogen mass (Kg)
- R is the ideal gas constant ($atm\text{-}l/k\text{-}mol$)
- T is the temperature of hydrogen (Kelvin)
- M is the molecular mass of H2 (Kg/mol)
- P is the hydrogen pressure in atmospheres.

$$V = \frac{1290 * 0{,}082 * 298}{0{,}002 * 160} = 98507{,}6\ l$$

Equation 18

With this volume, the LH 100H tank manufactured by LAPESA SL (Figure 16) will be installed, with the following technical specifications:

- Nominal volume (m3) =100
- Outer diameter D (mm)=3000
- Overall length L (mm)=15.350
- Unladen weight (Ton)=34,7
- Price (€) = 253.100

Figure 16. LAPESA Hydrogen tank

Source [20]

7.2.5 High-pressure tank

Finally, the last component that will be considered for the economic estimation of the project will be the high-pressure tank, where the hydrogen will be stored ready for distribution.

For this purpose, the required dimensions of the tank are calculated in the same way as in equation 17, obtaining a value of 17.512,5 l.

After that, the LH 25H model is selected, with the following technical data:

- Nominal volume (m3) =25
- Outer diameter D (mm)=2200
- Overall length L (mm)=7850
- Unladen weight (Ton)=10,1
- Price (€) = 98.900

8. ECONOMIC VIABLITY OF HYDROGEN VEHICLE INTRODUCTION PLAN

In order to be able to study the feasibility of this project, we must analyze it from an economic point of view.

For this, we must analyze the different types of costs that the implementation of the hydrogen production plant would carry and study the income that would be generated by the sale of the hydrogen in the different points of distribution and sale to the public.

8.1 Economic study of costs and income

Direct costs are those that are directly linked to production and the product these must be distinguished between fixed and variable costs.
The first are those that do not vary with the level of production, which means that they are independent of the amount of hydrogen produced, and the second are variable costs, and depend exclusively on production, being higher as production increases.

Firstly, we will analyze the different fixed costs, which will be mainly the investment in the equipment necessary for the construction of the hydrogen production plants. In addition, other fixed costs will be the purchase of the building and the land.
These costs are represented in the Table 11:

Fixed costs			
Equipment [eur]	Units [eur]	Unit price [eur]	Amount [eur]
Solar panels 545W JA Solar Mono PERC	18349	216,24	3967788
Electrolyzer EL600N H2B2	1	10000000	10000000
Compressor 1KS50	2	500000	1000000
Compressor 1KS95	1	600000	600000
Low-pressure tank	1	98900	98900
High-pressure tank	1	253100	253100
Land and warehouse purchase	1	300000	300000
		Total	16219788

Table 11. Equipment Budget

Source [14]

Secondly, variable costs will be those derived from the water consumption demanded by the electrolyzer, and the maintenance and service costs of the installation.

To be able to calculate the cost of the water supply required by the electrolyzer, the price of water supplied by the Valencia network will be taken as a reference, which is regulated by the government and has been 1.97e/m3 for the last few years.

Therefore, with our production level (381 Tons), we can calculate the water yearly costs as follows (Equation 18) , obtaining a value of

$$\frac{1l}{Nm^3H_2} * Nm^3H_2 * \frac{1m^3}{1000l} * \frac{1{,}97e}{m^3} = 750 \ e$$

Equation 19

Since the amortization period is 20 years, the variable costs associated with the water will be 15000 euros.

Once we know the direct costs of our project, we must establish a small percentage of them destinated to the complementary direct costs, so that these include concepts that are difficult to quantify. Thus, we will establish 1% of direct costs.

Indirect costs are execution costs that are not attributable to specific units of work, but to the whole or part of the project, for these, we establish a 4% of the direct costs. An example of these costs would be plant maintenance.

After this, we can already know the Budget for Material Execution and calculate the Investment Budget applying the different standardized rates (Table 12).

Equipment [eur]	Units [eur]	Unit price [eur]	Amount [eur]
Solar panels 545W JA Solar Mono PERC	18349	216,24	3967787,76
Electrolyzer EL600N H2B2	1	10000000	10000000
Compressor 1KS50	2	500000	1000000
Compressor 1KS95	1	600000	600000
Low-pressure tank	1	98900	98900
High-pressure tank	1	253100	253100
Land and warehouse purchase	1	300000	300000
Water yearly supply	20	750	15000
Equipment and material budget	16234787,76		
Complementary direct costs (1%)	162347,8776		
Indirect costs (4%)	649391,5104		
(1)Budget for Material Execution (1)	17046527,15		
(2) Overhead Expenses (0,13*1)	2216048,53		
(3) Industrial Profit (0,06*1)	1022791,63		
(4)Contract execution budget (1+2+3)	20285367,31		
(5)Value added tax (0,21*4)	4259927,13		
(6)InvestmentBudget (4+5)	24545294,44		

Table 12. Investment budget.

Source [14]

The investment budget amounts to twenty-four million five hundred forty-five thousand two hundred ninety-four euros and ten cents.

The income that the hydrogen plant can generate will come from the sale of hydrogen to the different hydrogen sales points, so, in order to estimate it properly, we must study the selling price of each kilogram of hydrogen.

When studying the selling price of hydrogen nowadays, the production and distribution costs associated with hydrogen remain relatively elevated, rendering it a pricier alternative compared to conventional fuels. Nevertheless, with advancing technology and the realization of economies of scale, industry experts project a substantial decline in hydrogen prices over the upcoming decade. Enhanced hydrogen production techniques, expanded infrastructure development, and governmental incentives are anticipated to contribute to this transformative trend. Consequently, a more fiercely competitive and economically viable hydrogen market is foreseeable, thereby facilitating widespread adoption of hydrogen-fueled vehicles and propelling the transition towards a sustainable transportation paradigm.

Due to the current uncertainty about the price of hydrogen, to study the feasibility of our study instead of setting a specific price for the sale of hydrogen, we will calculate from what price our project starts to be profitable.

Graphically this can be understood as the intersection between the cost and benefit curve and the point of the intersection is called the break-even point (Figure 17).

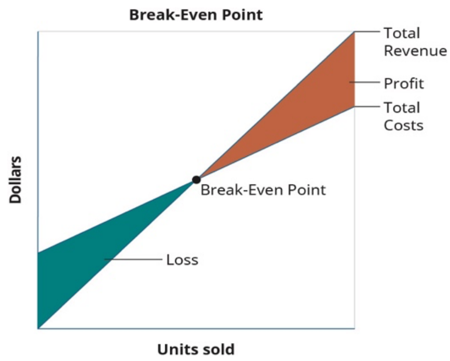


Figure 17. Break-even point graph

Source [21]

As we can see, if we are above the break-even point, we obtain a profitable situation, since revenues would exceed costs, while if we are below the break-even point, the situation would be one of losses, since costs would be higher than revenues.

To translate this to our work situation, we must draw both curves from our data.

First, the cost curve can be approximated to the fixed costs, since the variable costs only include the water supply and their cost is insignificant with respect to the investment budget, so we will take the cost curve as a straight line with the value of the investment cost.

In addition, due to the lack of data on the residual value of the components of the installation, we will be in the most unfavorable situation in order not to fail in the feasibility study, and we will take the residual values of the acquired equipment as 0.

Second, the income curve is studied. This has a higher complexity since the sale price of hydrogen as mentioned above is very uncertain for the coming years and it is expected that with economies of scale it will be reduced considerably.
Therefore, we cannot determine the slope of the income curve and plot the situation to find the break-even point.
Due to this, the minimum average sale price of hydrogen will be calculated so that the investment is recovered in the 20 years of useful life of the project, and it will be studied if it fits with the predictions that exist, or on the contrary it is an unreal price and

therefore the project of the construction of the plant to supply green hydrogen for the plan of introduction of vehicles would not be viable.

$$Income\ curve = H_2\ production * H_2\ price$$

Equation 20

To calculate this, we must proceed according to the following equations :

$$Costs\ curve = Income\ curve$$

Equation 21

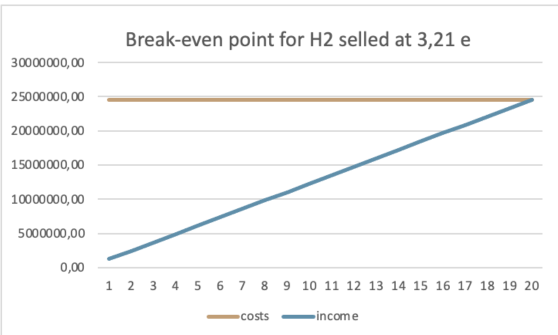
$$Costs\ curve = 20 * H_2\ yearly\ producion * H_2 price$$

Equation 22

$$22869626{,}10 = 20 * 381804 * H_2 price$$

After carrying out these calculations, we obtain an average sale price of hydrogen of 3,21 euros from which the investment will be recovered in 20 years.

Knowing this, the following graphs represent the break-even curves for a price of 3,21e/khH_2 and 5e/kgH_2, with the amount in euros on the y-axis, and the years since start-up on the x-axis. 100% production capacity of the plant is assumed, so that 381 tons of H_2 are produced each year (Figure 18).



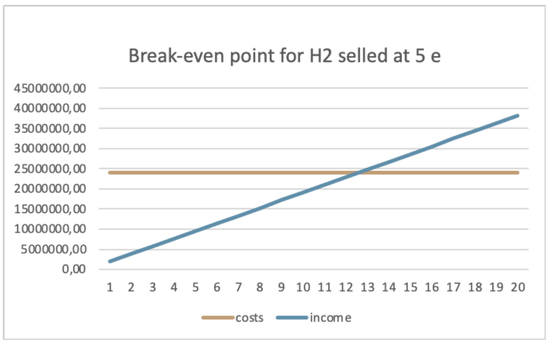


Figure 18. Break-even graph for H2 price of 3,21 and 5 euros

Source [14]

As can be seen in the first graph, if the plant operates at 100% and the average selling price of hydrogen during the study period is 3,21 euros, the investment will be recovered in year 20, while if the price of H2 is increased to 5 euros, the investment will be recovered in year 12, and the useful life of the plant will end with an approximate profit of 15 million euros.

Considering the hydrogen market and the predictions we found about its price in the future, we can see that currently its selling price is 8 to 10 euros, but due to economies of scale there will be a considerable reduction in the prices of fuel cells and storage tanks, which will bring about a 70% reduction in the cost of hydrogen production over the next 10 years.

In addition, for hydrogen technology to become viable for the automotive industry, its selling price should be less than 5 euros, and for it to be very competitive it should be less than 4 euros per kilo.

The economic study carried out for our work places the selling price within the range required to be able to implement the plan, so the creation of a plant with the above characteristics to cover the production of the hydrogen needed for the introduction of the hydrogen car in Valencia is economically feasible.

8.2 Economic comparation of energetic equivalence with conventional fuels price

To get a different perspective on the selling price of hydrogen, and whether it would be attractive to the market, a comparative analysis between hydrogen and other conventional fuels can be analyzed.
For this, we will calculate the costs of the equivalent amount of energy in terms of autonomy in both cases, thus studying the percentage difference between the two prices.

As seen in section 5.3 of the paper, the energy equivalent between the two compounds can be calculated as follows (Equation 22):

$$Cosnumption\ relation = \frac{HC\ consumption}{H_2\ consumption} = \frac{3{,}98}{0{,}7} = 5{,}6913$$

Equation 23

Next, the price of an energy unit for both fuels can be analyzed. This will be done based on the price of 1 kg of hydrogen, which will cost between 3.21 and 5 euros, and obtaining its energy equivalence (Equation 23), and operating with the units (Equation 24), since the price of conventional fuels is known in liters, the economic comparison will be obtained.

$$1kg\ H_2 = 5{,}6913\ kg\ HC$$

Equation 24

$$\frac{5{,}6913\ kg\ HC}{0{,}78\frac{l}{kg}\ HC} = 7{,}2965\ l\ HC$$

Equation 25

After these calculations is known that the energetic equivalent of 1 kg of H_2 is 7,2965 liters of traditional fuels, and setting an average price of 1,795 euros/l we have total price for this amount of energy of 13,1 euros, a value much higher than that obtained for hydrogen in the study, which put its selling price of that amount of energy between 3.21 and 5 euros.
Speaking in percentage terms, hydrogen would provide us with a 62% cheaper form of energy to power vehicles.

This saving can be observed in a clearer way when the price is analyzed in function of the kilometers traveled, acting in this way, the price to travel 100 kms with an H_2 vehicle and considering a high consumption value for hydrogen vehicles, would oscillate between 3,21 and 5 euros due to the range of sales prices with which we have been working in this study, while using a conventional fuel would be 9.1 euros per 100 km.

Some interesting data that can be obtained by continuing with the price analysis would be the fuel savings that would be obtained with the implementation of the hydrogen vehicle introduction plan that has been formulated in this work.

To do this, using the consumption of hydrogen in kilograms of each period of time, we must estimate the equivalent cost of traditional fuels, and then subtract the price of that hydrogen. This process is shown in the equation 25:

$$kg\ of\ H_2 * 7{,}2965\ l\ HC/kg\ of\ H_2 * 1{,}795\ eur/l - kg\ of\ H_2 * 5$$

Equation 26

Thus, with the creation of the hydrogen production plant, which would supply the necessary hydrogen during the first 5 years of the plan and making these calculations assuming a hydrogen sales price of 5 euros per kilo, placing us in the most unfavorable situation of the price range, would help to save between 6 and 11 million euros depending on the plan to be implemented between the medium, high, or very high-rate plans.

In addition, the implementation of the full plan would result in savings of between 43 and 88 million euros in fuel consumption over the ten-year implementation period.

9. ENVIRONMENTAL VIABILITY OF HYDROGEN VEHICLE INTRODUCTION PLAN

We can also address the benefits of the implementation of the studied plan from an environmental point of view. In this area, given the renewable nature of the energy sources used for the generation of the energy required for the electrolysis, and the green character of this process, the generation of the hydrogen necessary to supply autonomy to the first cars to be launched on the market in the province of Valencia will be totally non-polluting, with totally zero levels of polluting emissions.

For this, when analyzing the reduction of pollutant emissions, only the previous emissions of vehicles with conventional fuels should be calculated, since the saving will be 100%.

After the analysis of environmental data on vehicle emissions during the year 2021, it is known that vehicles emit an average of 2.45 kg of CO_2 per liter of fuel, so knowing the liters of fuel that will be saved with the implementation of the plan can be known the savings of CO_2 emissions into the atmosphere.

After these simple calculations, we obtain values of a reduction of CO2 emissions close to 200,000,000 kilograms after the 10-year duration of the plan.

This saving in CO_2 emissions would be the equivalent of planting 1.000.000 trees or a 20 hectares forest, knowing each of the trees would absorb an average of 20 kg of CO_2 per year.

Lastly, the economic value of these emissions can be determined. The price of CO2 emission allowances during the year 2021 reached an annual average of 53.55 euros/ton, so we multiply this value by the calculated emissions to obtain the economic value, being this of 10.710.000 euros.

10.CONCLUSION AND RESULTS DISCUSION

In conclusion, after the study of the sustainable plan for the introduction of hydrogen vehicles in the province of Valencia, it has been possible to show the strong advantages that can bring the implementation of hydrogen technologies in the automotive industry, and which are the barriers to be dealt with.

Mainly, it has been proposed a plan that covers from the sale of hydrogen vehicles and the calculation of the required hydrogen fuel supply to the sustainable production of hydrogen fuel, showing the necessity of the progressive electrification of the automotive market and the consequent evolution of hydrogen production systems to supply this change in the market.

After this study, the feasibility of this project has become clear, after analyzing the approximate investment cost of a fully green hydrogen production plant, the implementation of which will be a key point in the course towards the use of sustainable hydrogen.

Also, the economic and environmental benefits of this change in the vehicle market have been discussed, and the beneficial character of the introduction of the studied plan has been evidenced.

In addition, it must be emphasized the stage of development of the hydrogen market, and how economies of scale will make hydrogen prices even more competitive, a technology whose future will undoubtedly be very promising.

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