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MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

WHAT WILL BE THE ROLE OF HYDROGEN IN THE SPANISH ENERGY DEMAND? A MODELLING APPROACH FOR THE 2050 HORIZON

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Director: José Carlos Romero Mora
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Madrid
Agosto de 2022

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What will be the role of hydrogen in the Spanish energy demand? A modelling approach for the 2050 horizon

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RESUMEN DEL PROYECTO

Este documento analiza la literatura actual con respecto a los vehículos de hidrógeno y proporciona una estimación de los costes para los vehículos de carga ligera, mediana y pesada de celdas de combustible para el año 2050. Además, el coste estimado para los vehículos ligeros tanto eléctricos como de hidrógeno es introducido en un modelo matemático del sistema energético español con el fin de analizar el impacto que ambas tecnologías podrían tener en el mix energético para el año 2030.

Palabras clave: Vehículos Eléctricos de Pila de Combustible, hidrógeno, sistema energético español

Como resultado de los avances tecnológicos actuales, el aumento de las energías renovables y la urgente necesidad de descarbonización, el hidrógeno está creciendo como un potencial vector de energía eficiente y económico. Sus métodos de producción, explorados en este artículo, son múltiples, pero la electrólisis es la solución más prometedora a largo plazo, no solo porque es limpia sino también porque puede resolver los problemas derivados de la intermitencia de las fuentes de energía renovable (IEA, 2021). Su almacenamiento sigue siendo un gran desafío debido a su alto coste y complejidad. Si bien se están explorando múltiples soluciones nuevas en este campo, como la mezcla con materiales líquidos o el almacenamiento sólido, aún es necesario lograr avances técnicos (Tarhan & Çil, 2021). Aun así, el hidrógeno como vector de energía proporciona una solución sostenible en múltiples sectores. Dentro del sistema energético, se puede utilizar como almacenamiento de energía, aumentando la flexibilidad de los sistemas y reduciendo la brecha entre oferta y demanda (Yue, y otros, 2021). En aplicaciones domésticas e industriales, puede sustituir a los combustibles fósiles en la producción de calor (Kovač, Paranos, & Marciuš, 2021). Por último, en el sector de la movilidad, en el que se centra este trabajo, tiene el potencial de impulsar todo tipo de vehículos, desde el transporte ligero al pesado por carretera, pasando por trenes y carretillas elevadoras, gracias a la tecnología de celda de combustible, e incluso reducir drásticamente la huella de carbono de barcos y aviones gracias a los combustibles sintéticos.

En comparación con los vehículos eléctricos, los vehículos de hidrógeno comparten muchas características, pero cada uno posee sus propias ventajas y desafíos. Los vehículos de celda de combustible pueden recorrer distancias más largas, repostar más rápido y proporcionar mayor potencia, lo que los convierte en una solución ideal para vehículos pesados y de largo alcance, mientras que los vehículos eléctricos seguirán probablemente siendo la mejor solución para aplicaciones de corto alcance (Hydrogen Council, 2020). Los principales desafíos que enfrentan los vehículos de hidrógeno son los altos costes, la escasa infraestructura y la falta de políticas claras y de apoyo, que dificultan el crecimiento esta tecnología en el mercado (Ajanovic & Haas, 2021). Sin embargo, con suficiente planificación, incentivos políticos e investigación, los vehículos de hidrógeno podrían convertirse en una alternativa competitiva en la década actual. Se espera que las flotas de vehículos, como autobuses o taxis, logren antes la paridad de costes con los vehículos eléctricos, debido al uso más eficiente de los recursos con una infraestructura centralizada.

A través de un profundo análisis de la literatura, en esta tesis se obtienen estimaciones de costes para vehículos de celdas de combustible de carga ligera mediana y pesadas para el momento actual, representada bajo el título REAL, y para los años 2020, 2030 y 2050, para los cuales se asumen tasas de fabricación de 100,000 a 500,000 unidades por año. Las diferencias de precio entre la estimación actual (REAL) y la de 2020 se deben a dos motivos: primero, debido al retraso existente entre que una tecnología se desarrolla y llega al mercado, haciendo que los costes actuales sean los de la tecnología de aproximadamente 5 años atrás; y segundo, debido a que en el contexto actual las tasas de fabricación son de alrededor de 1,000 a 3,000 unidades al año, muy lejanas a las asumidas en la estimación de 2020. Los resultados de las estimaciones aparecen resumidas en la siguiente tabla:

VEHÍCULO	REAL	2020	2030	2050
LDV	$60.807	$41.944	$34.285	$31.234
MDV	$213.593	$172.714	$143.311	$120.058
HDV	$443.972	$345.458	$256.600	$215.772

Table 1 Resumen de costes estimados para vehículos ligeros de celda de hidrógeno

A continuación, los datos relativos a los vehículos ligeros se incorporan al MASTER.SO, un modelo matemático del sistema energético español para el año 2030. Este modelo proporciona el mix energético óptimo que aporta el máximo bienestar social, es decir, el mínimo coste del sistema teniendo en cuenta los costes asociados a indicadores de sostenibilidad como el coste de las emisiones de CO2. Se realiza un análisis de sensibilidad utilizando un escenario optimista y pesimista, donde los costes de los vehículos de hidrógeno son un 20 % mayores o menores a los estimados, respectivamente. Los resultados son resumidos en la siguiente tabla:

	ESCENARIO		
PARAMETRO	**BASE**	**OPTIMISTA**	**PESIMISTA**
Coste total (G€)	298,80	296,91	301,48
Emisiones CO2 (MTCO2)	164,12	162,91	162,91
%ACT LVL(<500KM) FCEV	12%	12%	0%
%ACT LVL (>500KM) FCEV	42%	94%	42%
%ACT LVL (<500KM) BEV	0%	0%	12%

Table 2 Resumen de resultados del modelo para 2030

Con los parámetros estimados, los vehículos de hidrógeno representan un 12% del nivel de actividad de transporte para viajes de hasta 500km y un 42% de los de mayor rango, mientras que la actividad de los coches eléctricos es nula. En el escenario optimista, el coste total del sistema se reduce un 0,63%, las emisiones de CO2 disminuyen un 0,74% y el porcentaje de actividad de transporte compuesta por vehículos de hidrógeno en el rango superior a 500km aumenta hasta el 94%. En el escenario pesimista, el coste total del sistema aumenta un 0,9% y las emisiones de CO2 aumentan un 1,31%. En este escenario, se produce el denominado "penny switching effect", lo que da lugar a que los vehículos eléctricos ocupan el lugar de los de hidrógeno, cubriendo el 12 %

de la demanda, mientras que los de pila de combustible solo cubren el 42 % de la demanda por encima de los 500 km.

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WHAT WILL BE THE ROLE OF HYDROGEN IN THE SPANISH ENERGY MIX? A MODELLING APPROACH FOR 2030 HORIZON

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ABSTRACT

This paper analyzes the current literature with regards to hydrogen vehicles and provides a cost estimation for light, medium and heavy duty fuel cell vehicles for the year 2050. In addition, the estimated cost for electric and hydrogen light duty vehicles is introduced into a mathematical model of the Spanish energy system in order to analyze the impact which both technologies could have on the energy mix for the year 2030.

Keywords: Fuel Cell Electric Vehicles, Hydrogen, Spanish energy system

As a result of current technological advances, the increase of renewable energy and the urgent necessity of decarbonization, hydrogen is growing as a potential lean and affordable energy carrier. Its production methods, explored in this paper, are multiple, but electrolysis is the most promising long term solution, not only because its clean but also because it can solve the problems arising from the intermittency of renewable energy sources (IEA, 2021). Storage is still a major challenge due to its high cost and complexity. While multiple new solutions are being explored in this field, such as blending with liquid materials or solid storage, technical advances still need to be reached (Tarhan & Çil, 2021). Still, hydrogen as an energy carrier provides a sustainable solution across multiple sectors. Within the energy system, it can be used as energy storage, increasing the systems flexibility and reducing the gap between supply and demand (Yue, y otros, 2021). In domestic and industrial applications, it can substitute fossil fuel in the production of heat (Kovač, Paranos, & Marciuš, 2021). Lastly, in the mobility sector, which is the focus of this work, it has the potential to power all types of vehicles ranging from light to heavy road transportation, trains, and forklifts thanks to the Fuel Cell technology, and even drastically reduce the carbon footprint of ships and planes thanks to synthetic fuels.

When compared to electric vehicles, hydrogen vehicles share many characteristics, each of which containing its own advantages and challenges. FCEVs can run longer distances, refuel faster and provide higher power, which makes them an ideal solution for long range and heavy vehicles, while electric vehicles will likely remain the better solution for short range applications (Hydrogen Council, 2020). However, the main challenges are the high costs, the scarce infrastructure and the lack of clear and supportive policies, which hinder the growth of hydrogen vehicles into the market (Ajanovic & Haas, 2021). However, sufficient planning, investment policies and research, hydrogen vehicles could become a competitive alternative in the present decade. Vehicle fleets, such as buses or taxis, are expected to achieve cost parity with electric vehicles earlier, due to the more efficient use of resources with a centralized infrastructure (Hydrogen Council, 2020).

Through an in-depth analysis of the literature, this thesis provides cost estimates for light medium and heavy duty fuel cell vehicles for the current time, represented under the name REAL, and for the years 2020, 2030 and 2050, for which manufacturing rates of 100,000 to 500,000 units per year are assumed. The differences in price between the current estimate (REAL) and that of 2020 are due to two reasons: first, due to the delay between a technology being developed and reaching the market, which makes the current costs of the technology those of approximately 5 years ago; and second, because in the current context the manufacturing rates are around 1,000 to 3,000 units per year, very far from those assumed in the 2020 estimate. The results of the estimates are summarized in the following table:

VEHICLE	REAL	2020	2030	2050
LDV	$60.807	$41.944	$34.285	$31.234
MDV	$213.593	$172.714	$143.311	$120.058
HDV	$443.972	$345.458	$256.600	$215.772

Table 3 FCEVs cost estimates summary

Then, the data regarding LDVs is incorporated into the MASTER.SO, a mathematical model of the Spanish energy system for the year 2030. This model provides the optimal energy mix which provides the maximum social welfare, this is, the minimum system cost taking into account expenses associated with sustainability indicators such as CO2 cost of emissions. A sensibility analysis in conducted using an optimistic and a pessimistic scenario, where FCEVs costs are 20% above or below the estimation, respectively. The results are summarized in the following table:

	SCENARIO		
PARAMETER	BASE	OPTIMISTIC	PESIMISTIC
Total Cost (G€)	298,80	296,91	301,48
CO2 Emissions (MTCO2)	164,12	162,91	162,91
%ACT LVL(<500KM) FCEV	12%	12%	0%
%ACT LVL (>500KM) FCEV	42%	94%	42%
%ACT LVL (<500KM) BEV	0%	0%	12%

Table 4 Model results summary for 2030

With the estimated parameters, hydrogen vehicles represent a 12% of the transport activity level for trips up to 500km and 42% of those with higher range, while BEVs activity is zero. In the optimistic scenario, the total cost of the system is reduced by 0,63%, the CO2 emissions decrease by 0,74%, and the percentage of transport activity met by hydrogen vehicles in the range higher than 500km increases to 94%. In the pessimistic scenario, the total cost of the system is increased by 0,9% and the CO2 emissions rise by 1,31%. In this scenario, the “penny switching effect” takes place, making BEV take the place of FCEVs, covering 12% of the demand while FCEVs only meet 42% of the demand above 500km.

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INDEX

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

As far back as 1874, the English writer Jules Verne imagined the use of hydrogen as a fuel in its work *The Mysterious Island* in which he wrote “I believe that water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable” (Verne, 1874). On top of that, already in 1923, the scientist J.B.S. Haldane prophetically wrote about the potential of the hydrogen in combination with renewable energy: “there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen”.

Almost one hundred years later, hydrogen is finally gaining momentum as one of the most promising technologies for the decarbonization of the energy system. The EU has stablished ambitious targets towards the reduction of carbon emissions and the green transition. Hydrogen, as an energy carrier, is seen as a potential solution for achieving carbon neutrality, especially in those hard-to-abate sectors. In the transportation category, fuel cell vehicles could become an affordable clean alternative in the following decades.

However, many challenges still remain, and the development of the technology in the following years will likely decide the future of hydrogen. For it to succeed, large investments need to be made with regards to hydrogen infrastructure and research. Right now, governments and companies face the decision of whether to start taking action towards the development of this technology or focus on other sustainable alternatives. Accurate decision making and planning will be essential in order to reach the EU sustainability objectives for the following decades.

In this context, the aim of this thesis is to provide relevant information which could help decide the future of the technology. With that objective, this paper provides an estimation for the future costs of the hydrogen fuel cell vehicles up until the year 2050. Secondly, the estimated costs are introduced into a model of the Spanish electric system in order to analyze the effect which hydrogen transportation can have into the energy mix. A comparison between the costs and benefits of battery electric vehicles and fuel cell electric vehicles is also performed, and how the relative cost changes the optimal mobility solution.

The work will be organized as follows: first, the current state of the art of hydrogen will be reviewed, briefly exploring the types of hydrogen, the production, storage and transportation methods, its safety and its main applications. Next, the applications of hydrogen in transport are delved into, reviewing current technology, the challenges it faces, as well as the main applications and their role with respect to electric vehicles. Following that, the most recent literature regarding the costs of the main components of fuel cell vehicles will be analyzed in depth, which will be used to estimate the costs of hydrogen vehicles. Afterwards, the model used in this work is described, clarifying the formulas and parameters used. Next, the results of the model are analyzed and a sensitivity analysis is presented. Finally, the conclusions of the model are highlighted.

2. STATE OF THE ART

Hydrogen, it is an odorless, colorless, tasteless, flammable gas and it is composed of the lightest of all known molecular configurations: one proton and one electron (Jolly, 2020). Many could consider it a boring element, and it is, in fact, the most abundant element in the whole universe, even three times the abundancy of the second most common element, the helium (Jolly, 2020). However, hydrogen has a property that has made it one of the most promising solutions for the environmental and sustainable energy crisis of the XXI century, it burns when combined with oxygen, producing water. Not without reason it was given the name hydrogen, from the Greek hudro- ‘water’ + -genēs ‘-born, meaning water maker (Oxford Advanced Learner's Dictionary, 2022).

2.1. BRIEF HISTORY

The official discovery of hydrogen took place in 1776, when the British chemist and physicist Henry Cavendish identified it when combining zinc with acid and presented its discovery to the Royal Society of London (Jonas, 2009). However, the history of hydrogen goes as back as the 16th century when a physician and alchemist named Paracelsus found it experimenting with dissolving a metal into acid, although he mistook it with other existing flammable gases (Jolly, 2020). In 1788, the father of modern chemistry, Antoine Lavoisier, gave hydrogen its current name (Jonas, 2009).

The first known production of this gas through electrolysis took place in 1800, in an experiment conducted by Nicholson and Carlisle (Dawood, Anda, & Shafiullah, 2019). Later, in 1838 the chemist Schönbein discovered that mixing hydrogen with water could produce an electrical current, a discovery that Sir William Grove used to create the first gas battery in 1845 (Jonas, 2009). Then, in 1889 James Dewar managed to liquefy it for the first time (Dawood, Anda, & Shafiullah, 2019). Since then, thanks to its abundancy and low density, hydrogen was used for different transportation methods which required lifting, like hydrogen balloons, invented by Ferdinand von Zeppelin in 1900 (Dawood, Anda, & Shafiullah, 2019) or even trans-Atlantic dirigible flights in 1937 (Jonas, 2009). One of these dirigible flights, the Hindenburg, resulted in an accident which occurred the 6 of May of 1937 and resulted in the death of 35 people (Webster, 2017). Although the cause of this accident was never determined, many studies indicated that it might have been due to the paint used being inflammable (Webster, 2017). Still, this accident contributed to create a negative image of hydrogen as a fuel, and hydrogen use for dirigibles was eventually stopped, being replaced by helium, a safer but more expensive option (Granger, 2019). Other uses of hydrogen during these years were the adapted vehicles and submarines, made by the engineer, Rudolf Erren in the 1920s. After that, in 1958 the foundation of NASA took place, which saw the massive energy resulting from the combination of liquid hydrogen and oxygen as an opportunity to power their space shuttles. They eventually became the largest hydrogen user, mainly for the propulsion of rockets and the manufacturing of fuel cells (Jonas, 2009).

During the 1970s the concept of "hydrogen economy" started to take shape. It was first used in 1970 by General Motors (Dunn, 2002), followed by the publication of the first paper about it in 1972 and several meetings in 1973 and 1974 (Bockris, 2013). The rise of oil prices in 1973 led many to the belief that the era of cheap oil was over, boosting the research on alternative fuels like hydrogen, which received funding from various governments like US, Europe and Japan (Dunn, 2002). However, the interest in hydrogen research dropped back after oil prices plummeted to historical lows in de following decade (Dunn, 2002).

Figure 1. Crude oil barrel prices inflation-adjusted, 1946-2022

Source: Macrotrends (2022)

Subsequently, other waves of interest in hydrogen energy have surged, but sustainable investment in the sector has never been reached. Different initiatives involving research in the area have occurred, driven by the increased concerns about climate change and rising interest in renewable cleaner energies, like Japan's JP¥4.5 billion funding for international hydrogen trade in 1993 or the European Commission and Quebec's CAD $33 million investment for the research on hydrogen storage and case uses (IEA, 2019). Nevertheless, over the last decades, different factors such as low oil prices, high promises of new nuclear plants and later the surge of electric vehicles, which have lower initial investment costs, have relegated the interest on further research to a secondary plane (IEA, 2019).

Today, hydrogen's situation is much different. The energy crisis, coupled with the urgent need to reduce carbon emissions into the atmosphere, have created a picture where hydrogen is emerging as one of the solutions with the greatest potential for the next few decades. The range of possibilities and the extent of political interests are leading different countries around the world to the stablishing of ambitious goals with hydrogen as one of the main pillars. However, the lack of investment in the past has left large gaps in the development of this technology, and there are still many challenges which need to be solved for hydrogen to become a viable solution for the energy transition.

2.2. TYPES OF HYDROGEN

Hydrogen is the most occurring element, making up more than 90% of the matter in the universe. Not only it is common, but also has the highest calorific power of all the known fuels, of about 120 to 140 MJ/kg, compared to the 47.2 MJ/kg of Natural Gas or the 45.8 of Gasoline (Rodrigue, 2020). On top of that, it is very light, can be transported in containers and its use is completely free of carbon emissions or any polluting agents, as its only byproduct is water. These characteristics place hydrogen as one of the potentially best energy sources available on Earth.

However, although being so abundant, the biggest drawback of hydrogen is that it can't be found on Earth as an independent element. While other celestial bodies like the Sun or Jupiter have a very high concentration of hydrogen, on Earth, hydrogen is lighter than air and any other element, so any amount of this gas contained in the atmosphere quickly leaves the planet into outer space (Royal Society of Chemistry, 2022), which is the reason why hydrogen can only be found rather combined with other elements like water, biomass or fossil fuels. In contrast with other sources of energy such as natural gas or petroleum, hydrogen needs to be separated from these other elements in order to be used as a fuel, a process which usually requires high amounts of energy. For this reason, hydrogen, rather than an energy source, is more accurately referred to as an energy carrier, such as electricity (IEA, 2019).

Hydrogen has been widely presented as a clean fuel. However, similarly to electricity, hydrogen's sustainability is also conditioned by the source of its production. While being completely clean during its usage, hydrogen's production methods can be high in carbon emissions or, on the contrary, be completely sustainable. To address this, it's become popular to classify hydrogen using a color scale depending on the sustainability of the technology used for its production. These are the main types:

- Grey hydrogen: Refers to the hydrogen produced from fossil fuels such as natural gas commonly obtained through a process called Steam Methane Reforming (SMR) or coal gasification. Due to its availability and low price, it's currently the most common type of hydrogen, making up for 96% of the total production (World Energy Council, 2019). However, this type of production emits high quantities of CO2 to the atmosphere, which makes it an unfeasible long-term solution for the climate crisis.
- Blue hydrogen: Very similar to grey hydrogen, with the exception that the CO2 emitted is captured and stored, usually underground in salt caverns or depleted gas reservoirs. This technology captures between 85-95% of carbon emissions (IRENA, 2020), with the drawback of significantly increasing the cost of production. Although it's being explored as a potential solution for future decarbonisation, some studies have shown that blue hydrogen footprint is actually quite high, with emissions only 9-12% lower than of grey hydrogen and a greenhouse gas footprint even higher than directly burning natural gas (Howarth & Jacobson, 2021), without taking into account the risks associated with storing the CO2. Nonetheless, blue hydrogen is easy to implement and could be a potential initial solution for the transition period of hydrogen production to cleaner methods (IRENA, 2020).
- Green hydrogen: It is produced using renewable energies resulting in low or zero-emissions hydrogen. The most common method to produce it is through electricity obtained from

renewable energies, which is used to perform electrolysis to water, splitting H2O into H2 and oxygen. Apart from being sustainable, green hydrogen production might be useful at providing flexibility to an energy system increasingly composed of renewable sources. Green hydrogen is conceived as the best production method for a sustainable energy transition. For the moment, it only makes up to a small percentage of total hydrogen production, as it is the most expensive alternative, but the production costs have decreased in the last years and global policies are aiming for the further implementation of this technology.

Apart from these, there are other less common types of hydrogen, like pink hydrogen, produced through electrolysis but using nuclear electricity, or turquoise hydrogen, a novel alternative which uses pyrolysis to produce hydrogen and solid carbon form methane, so there is no need to capture the carbon (FSR, 2021). It is also worth mentioning golden hydrogen, a new technology recently developed by researchers in Spain which can produce hydrogen from NH3, CH4, and biogas using stacked proton ceramic reactors with 99% recovery efficiency (Clark, y otros, 2022). Apart from the high efficiency, its attractiveness lays on its capacity to remove CO2 from the atmosphere while using renewable energies, leading to negative greenhouse emissions and circular economy, which is the reason why it’s received the name of golden hydrogen. On top of that, the production costs of this method are comparable to those of green hydrogen, or even lower if the negative CO2 emissions are considered (Hurtado, Soria, & Pinilla, 2021).

2.3. PRODUCTION

There are three factors that can vary when choosing the method used to produce the hydrogen: the source of the hydrogen, which can be hydrocarbons or non-hydrocarbons; the energy source, which include thermal, electrical and bioenergy (Martino, Ruocco, Meloni, Pullumbi, & Palma, 2021); and the catalyst. These factors, together, determine the Hydrogen Production Pathway (HPP) and affect the cost, the efficiency, the cleanness and the overall feasibility of the process.

2.3.1 THERMAL METHODS

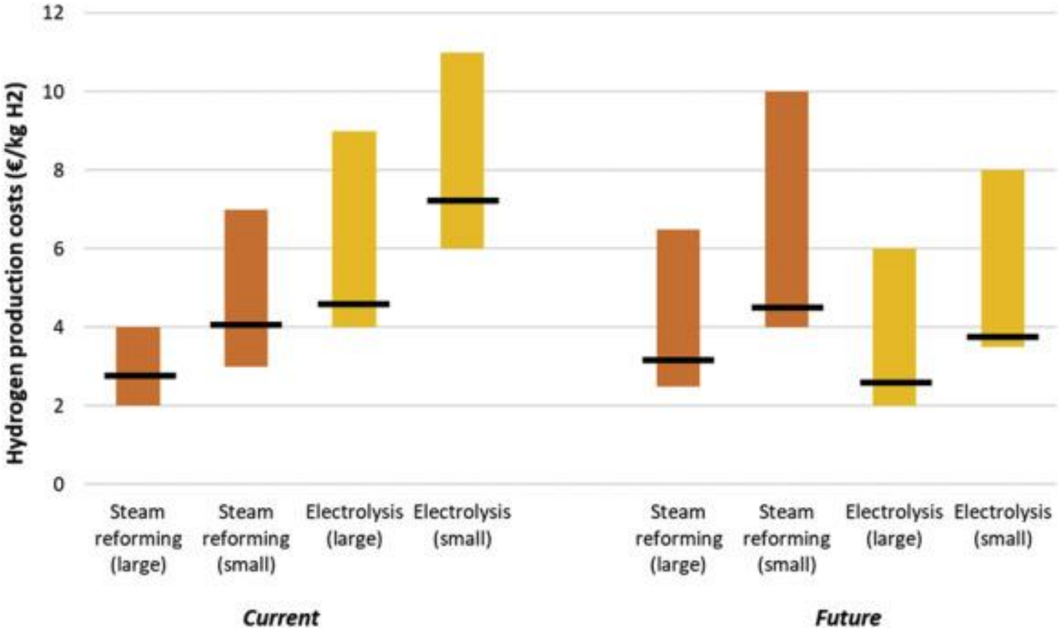
Thermal methods are the most common type of hydrogen production and involve using heat to split hydrogen from other matter. Among this group, Steam Reforming (SR) is the most popular technology, which combines steam and a hydrocarbon to produce hydrogen (Martino, Ruocco, Meloni, Pullumbi, & Palma, 2021). The main hydrocarbon used is methane obtained from natural gas, which reacts with steam at 700-1000ºC to make syngas, a mixture of hydrogen, carbon monoxide and carbon dioxide, so further treatment is required (Dawood, Anda, & Shafiullah, 2019). Currently, hydrogen produced from natural gas accounts for about three thirds of the hydrogen production and takes up 6% of natural gas global use (IEA, 2019). Other less used sources for SR include biomass, methanol or ethanol. In contrast to SR, Partial Oxidation is a method that uses the oxygen in the air as an oxidant (IEA, 2019). Another interesting alternative is Autothermal Reforming (ATR), which combines both previous methods. ATM uses the excess heat from partial oxidation, which is exothermic, combined with steam and air, to produce steam reforming (Martino, Ruocco, Meloni, Pullumbi, & Palma, 2021). Studies estimate that this technology could capture up to 94.5% of carbon emissions (H-Vision, 2019). Apart from these methods, gasification is another thermal option which uses carbonaceous materials such as carbon or biomass, which are transformed into syngas when combined with an oxidizing agent at high temperatures. Biomass gasification efficiency (35-50%) is low when compared to coal gasification (74-85%) or steam reforming (60-85%) (Dawood, Anda, & Shafiullah, 2019), but can be performed with different feedstocks such as algae or food waste, which are highly available.

2.3.2 ELECTRICAL METHODS

Electrical methods mainly refer to electrolysis, a process by which an electric current is run through water to split the H2O molecule into H2 and O2, producing high purity hydrogen (Abdin, y otros, 2020). This process currently represents only about 2% of the global hydrogen production, and most of it comes from the chlor-alkali electrolysis which produces hydrogen as a byproduct (IEA, 2019). Only 0.1% of it comes from dedicated hydrogen production, but this number is expected to grow in the next years in combination with renewable energies as a mean to produce clean hydrogen (IEA, 2019). The electric consumption of this method is quite high, with an efficiency that goes from 60% to 81% (IEA, 2019). There are multiple different electrolysis technologies, but the main ones are Alkaline Electrolysis (AE) and Proton Exchange Membrane (PEM), both of which have high maturity levels (Dawood, Anda, & Shafiullah, 2019). Recently, a new technology called Solid Oxide Electrolyzer Cells (SOEC) has gained some attention, as it seems to provide higher efficiencies (IEA, 2019).

The main drawback of hydrogen production through electrolysis is the high cost, which is two to three time more expensive than that of steam methane reforming methods (IRENA, 2020). Available technology for big scale electrolysis is limited, and so is hydrogen demand, which holds back the implementation of this method (IRENA, 2020). Still, the demand is expected to grow in the future and multiple high scale projects are expected to take place, which would increase the capacity (IRENA, 2020). On top of that, renewable energies are developing rapidly, and many progresses are being made in the hydrogen sector such as improvements in storage, which could increase the feasibility of this method (Tong, Michalek, & Azevedo, 2017). Hydrogen generation through water electrolysis could be used to solve the intermittency of the renewable sources, serving as an alternative energy carrier for the energy surplus and also providing additional stability to the variability of the grid. Furthermore, experts anticipate future electrolysis production costs to decrease, becoming cost competitive with steam reforming. The IEA data reflects that electrolysis will become cheaper than SR by 2030 (IEA, 2021). Figure 2 below shows the cost comparison for both production methods.

Figure 2 Main hydrogen production methods current and future cost range



Source: (Ajanovic & Haas, 2021)

2.3.3 BIOLOGICAL METHODS

There are also a wide variety of biological methods which use microorganisms to convert biomass into hydrogen. These processes include bio-photolysis, dark-fermentation, photo-fermentation and CO gas-fermentation (Akhlaghi & Najafpour-Darzi, 2020). Photolysis captures solar energy through microalgae and microbacteria to produce hydrogen from water and CO2 (Akhlaghi & Najafpour-Darzi, 2020). Dark fermentation, on the other side, uses anaerobic organisms to produce hydrogen from organic materials in absence of light (Martino, Ruocco, Meloni, Pullumbi, & Palma, 2021). Photo-fermentation uses light energy and PNS bacteria. Lastly, CO gas-fermentation uses photosynthetic bacteria to bioconvert CO and H2O into hydrogen (Akhlaghi & Najafpour-Darzi, 2020). Among these methods, studies have shown that, although dark fermentation is the most cost effective, it's uncompetitive and better suited for local production, while photo-fermentation has the highest hydrogen production and efficiency, making it the most promising solution (Martino, Ruocco, Meloni, Pullumbi, & Palma, 2021)

Most biological methods are still in the early stages and haven't reached maturity yet, so the efficiency could still increase. However, the high complexity of these processes increases the production price of hydrogen, and the supply for affordable sustained biomass is limited (IEA, 2019), which decreases the feasibility of these technologies. On top of that, biological methods produce carbon emissions, so they would need to be combined with carbon capture methods in order to be considered a suitable solution in the future.

2.4. TRANSPORTATION AND STORAGE

Hydrogen has still to prove its feasibility as one of the main energy solutions for the transition. Nowadays, hydrogen is used and stored at a much smaller scale, mainly in gas or liquid tanks. In the future, however, hydrogen is expected to represent a bigger portion of the world's energy mix and, therefore, transportation and storage will likely play an increasingly larger role in hydrogen's future development. In order for that to happen, it will be necessary to develop appropriate means to store large quantities of this gas for long periods of time and also the necessary infrastructure to carry it for long distances (IEA, 2019). In this context, the capabilities and costs of this technology will affect the competitiveness of hydrogen against other alternatives.

With respect to storage, the most adequate solution might depend on different variables such as the required availability of the fuel, the storage period, the volume stored and the geological characteristics of the country (IEA, 2019). For short-term and lower quantities, the preferred option is the usage of tanks, while geological storage is used to store hydrogen in bigger quantities over long periods due to the lower operational and land costs (IEA, 2019). These geological caves include former gas and oil reservoirs, aquifers or salt cavern, each of which present different advantages. Depleted reservoirs are usually bigger than salt caverns, but contaminate the hydrogen, which then needs to be purified, while aquifer use is not a mature method and there are concerns about its sustainability (IEA, 2019). Although geological storage is a feasible solution for large-scale storage, for smaller scale and short-term applications tanks are a better solution given the required size, pressure and availability (IEA, 2019). Tanks have high efficiency (around 99%) and are widely available and easy to discharge.

Hydrogen's properties, mainly its low density, make it hard for it to be stored and transported. In order to solve these complications, different hydrogen storage methods have been developed, which include the three states of matter: gas, liquid and solid. Storing hydrogen as compressed gas is the most stablished technology and allows for rapid fill and discharge. However, it requires of low temperatures or high pressures (usually 700 bar). Even then, the gas density achieved is still low, which means that these tanks need to be about seven times the size of those for conventional fuels to store the same energy (Tarhan & Çil, 2021).

If temperature is low enough (-253ºC), hydrogen can be stored in liquid form even at low pressure, resulting in high energy density and storage efficiency. However, the low boiling point of hydrogen creates the need of cooling systems which consume about 30% of the energy produced and increase the risk of boil-off (Tarhan & Çil, 2021). As an alternative, hydrogen can be combined with larger molecules, which simplifies the transportation requirements, is more cost-effective and results in smaller loses for long-distance transportation, with the drawback that hydrogen often needs to be liberated from these molecules for consumption, a process which increases the costs (Tarhan & Çil, 2021). The two main ways of doing this are through ammonia (NH3) and organic compounds (LOCH), both of which require energy in order to combine the hydrogen with the molecules. In the case of LOHC, additional energy is needed to transform them back into pure hydrogen. Ammonia can be transported at much higher temperature than liquefied hydrogen (-33ºC) and has an energy density 1,7 times higher (IEA, 2019), making it the cheapest and the most energy efficient of the three liquid methods (Tarhan & Çil, 2021). However, ammonia is toxic and presents the risks of polluting the air, and some applications require conversion into pure hydrogen (IEA, 2019).

In third place, the solid storage method involves combining hydrogen atoms with other substances, which can be nanostructured materials or hybrids. It is the least mature technology for hydrogen storage and transportation, but some experts believe it's a good candidate for the future. The research in this matter develops in two main directions: absorption, by which hydrogen is combined to formulate chemical compounds that retain the hydrogen, and adsorption, which uses porous materials to physically store it (Yue, y otros, 2021). For absorption, multiple experiments are being conducted with different materials which include complex, chemical, metal and magnesium-based hybrids (Tarhan & Çil, 2021). However, although each combination presents some advantages, there is yet no material which can fulfill all requirements for viable application (Chen, y otros, 2021). For now, metal hybrids have been recognized as the most feasible solution, although they generally have low kinetics, small release at low temperatures and limited storage (Fan, Tu, & Chan, 2021). So far, one of the most promising materials is Palladium, which can absorb 900 times its own volume of hydrogen at room temperature and atmospheric pressure (Yue, y otros, 2021).

Regarding the transportation method, there are once again multiple options whose feasibility depend on the circumstances. As with storage, hydrogen's low density increases transportation costs, which can be three times as much as production costs for long distance trips (IEA, 2019). In this scenario, the availability of a cost-affordable, wide and reliable transportation network will be essential for the development of hydrogen. In smaller scale transportation, the use of trailers is the preferred option, either with compressed or liquefied hydrogen. Compressed gas containers are more cost-effective, and the further development of this technology is oriented toward cheap light materials that can allow for the transportation of high quantities while maintaining high pressure and safety (Faye, Szpunar, & Eduok, 2022). On the other side, if the hydrogen is liquefied, higher quantities can be transported per trip, but this method faces the problem of high costs and the complications of thermal insulation.

For larger scale applications, pipelines are considered the best option as they are the most cost-effective, in addition to being safe, dependable and environmentally friendly (Demir & Dincer, 2018). On top of that, there is already a large existing infrastructure of natural gas pipelines which could potentially be used to transport the hydrogen. However, hydrogen’s low density requires it to be compressed in order to improve pipeline transportation speed. Besides, it is smaller and more diffusive than natural gas, and therefore the use of conventional pipelines would result in higher losses and some operational and safety issues (Faye, Szpunar, & Eduok, 2022). As a solution to this problem, the blending of hydrogen with natural gas (methane) is being studied. If the blend has low hydrogen concentrations of less than 5% to 15% by volume, then the pipeline modifications required would be low, and pure hydrogen could be delivered by using separation and purification technologies (Witkowski, Rusin, Majkut, & Stolecka, 2018). For higher hydrogen concentrations, bigger problems arise and the benefits of the method need to be weighted. On the other side, the hydrogen-methane blend can also be used as fuel by itself, without separating both elements. The hydrogen addition boosts the combustion performance, improving flammability limitations and therefore increasing efficiency and reducing CO2 emissions (Abohamzeh, Salehi, Sheikholeslami, Abbassi, & Khan, 2021). However, the blending would also have negative effects on the natural gas delivery such as reduction in energy content, increase in price, and different effects on safety (IEA, 2019). On top of that, not all applications tolerate the use of this mix as a fuel and there are multiple regulations regarding the maximum blending accepted which would need to be addressed (IEA, 2019).

2.5. SAFETY

Although hydrogen has started to gain popularity in the recent years, there are still some concerns about the future safety of its implementations. In the past decades, since the development of the first applications, a wide number of hydrogen accidents have taken place, which have risen doubts in the public opinion, starting with the Hindenburg fire in 1937 but also a number of more recent incidents such the leaks in a hydrogen chemical plant in California and in a hydrogen station in Oslo in 2019 which resulted in an explosion (Genovese, Blekhman, Dray, & Fragiacomo, 2020).

Hydrogen properties, such as its high flammability, lack of color and odor, fast diffusion through the air, low ignition energy and rapid flame spreading rate, make hydrogen’s safe utilization a key issue in the development of hydrogen technology (Wei, y otros, 2022). During storage and transportation, materials face the risk of embrittlement, a process by which hydrogen penetrates metals causing mechanical damage (Karlsdóttir, 2012), which could result in degradation and cracking. Moreover, hydrogen is very small, so material permeability is an important factor to take into account, an issue which increases with material degradation, increasing the risk of leakage (Abohamzeh, Salehi, Sheikholeslami, Abbassi, & Khan, 2021). The significant dangers associated with hydrogen leakage, which include explosion and fire, rise the importance of the development of reliable containment and detection systems (Kovač, Paranos, & Marciuš, 2021). When hydrogen is released into the air, it dissipates quickly due to its lightness, which reduces the risk of explosion in open spaces. On top of that, hydrogen isn't toxic so a leakage to the atmosphere wouldn't have any negative impact on the environment (Hosseini & Butler, 2019). The main safety concerns arise, however, in confined spaces, where it can reach higher concentration, which is why some regulations impose the use of safety sensors when performing indoor fueling operations (Buttner, Post, Burgess, & Rivkin, 2011). Even then, hydrogen explosions are much less likely to occur than quick burning fires, which can happen in the presence of a spark even at low concentrations, although the heat radiation of the flame is low, and therefore only objects very close to the flame are under risk of being burnt (Hosseini & Butler, 2019). In the case of vehicles transporting or using hydrogen as fuel, it is usually stored at very high pressure, which presents high risk of exploding, and therefore thermally activated pressure relief devices (TPRD) are used, which release the hydrogen if temperature is high. To prevent the hydrogen release to risk drivers and other people, a rotatable TPRD which allows to adjust release direction has been designed (Li & Sun, 2020) In any case, the understanding of these risks and the implementation of the sufficient safety analysis and practices constitute essential elements for the safe use of hydrogen, and experts believe that as more demonstrations succeed people will increase their confidence in the safety of hydrogen (Dawood, Anda, & Shafiullah, 2019).

2.6. MAIN APPLICATIONS

Hydrogen is a versatile element. Although the international push for its integration in the energy mix is relatively recent, hydrogen has been widely used in oil refining and industrial applications for many years. The petroleum refining process represents the largest consumption (IEA, 2021), where hydrogen is used to reduce the sulfur content of crude oil. For industrial use, chemical industry is the biggest consumer, mainly for the production of ammonia, which is a key element of agriculture fertilizers and cleaning products, and methanol (IEA, 2021).

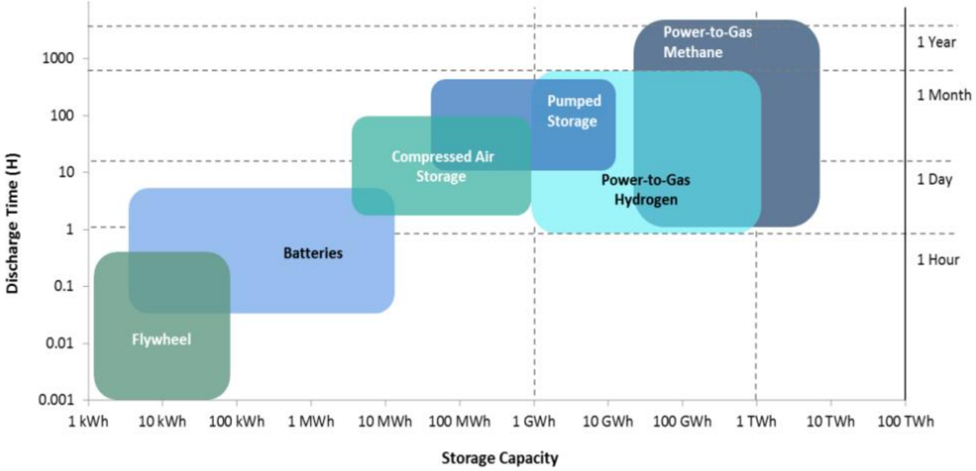
In the recent years, hydrogen has grown momentum, not as an ingredient for refining and chemical processes, but rather as an energy carrier with a relevant role in the energy system. Although the technology is still in development and faces many challenges, both technical and economic, hydrogen as an energy carrier brings new opportunities for the energy industry. So far, electricity has been the main alternative energy carrier to fossil fuels, allowing for energy transportation through power lines, storage through batteries and application through electric motors and heaters. However, electricity-based networks are highly flow based, where demand and supply must be balanced as energy storage is not feasible at large scale.

Hydrogen and electricity share many common characteristics. They are both energy carriers which can be obtained from multiple different sources and technologies and both provide a big range of flexibility in its application. Furthermore, neither of them have a negative impact to the environment when converted into other forms of energy and their carbon footprint depends on the cleanness of the energy and technology used for their production. However, while electricity uses electrons to carry the energy, hydrogen is a chemical energy carrier which uses molecules. As a result, there are some applications where electricity-based applications face major technological and economical drawbacks, but where hydrogen can provide sustainable solutions. These include large scale energy storage, steel and iron production, industrial and residential heating, chemical manufacturing or heavy transport. The urgency to decarbonize these sectors is increasing and political and financial organisms are reaching for solutions. Hydrogen, as an energy carrier, can be burnt, stored, transported and mixed in several ways, which makes it a prominent choice for lowering carbon use in these hard-to-abate emission sources (IEA, 2019).

2.6.1 ENERGY STORAGE AND PRODUCTION

Due to its chemical properties, one of the main benefits of hydrogen is the possibility to store it for long periods of time with relatively low cost and loses compared to traditional electrical batteries. On top of that, hydrogen can be transported in containers without the need of a connected network and later be burnt or combined to produce fuels (IEA, 2019). Its discharge time is also very fast, allowing for flexible use of the energy stored. Figure 3 bellow shows the comparison between hydrogen's capacity and discharge time with respect to other storage methods.

Figure 3. Energy discharge time and storage capacity methods comparison



Source: (California Hydrogen Business Council, 2015)

For these reasons, hydrogen is gaining popularity as a method for storing energy, mainly for long-term and high capacity purposes. In the current global scenario, the presence of renewable energy systems is rapidly growing in the power sector, which is leading to an increased imbalance between supply a demand and to larger amounts of excess energy. In this sense, hydrogen storage could be combined with renewable energy generation, aiming to solve the problems arising with their intermittency and lack of flexibility and facilitating the transition to a more sustainable and resilient economy. Hydrogen is expected to have two main roles in the energy system: first, by storing the excess energy produced by renewables when demand is low and using it to produce energy when needed, and secondly, by compensating the energy seasonality of renewables storing energy between seasons (Yue, y otros, 2021). Excess renewable energy is transformed into hydrogen mainly through water electrolysis, which is a mature technology that produces no CO2 emissions. However, the investment costs for electrolysers are high, so in order for them to be economically feasible, a minimum number of operation hours must be reached, which implies that there must be sufficient excess energy from renewables (Ajanovic & Haas, 2021). If these challenges are met, hydrogen will not only enhance the security of power supply by increasing the flexibility of the renewable technologies, but it could also improve the economic feasibility of renewable energies, encouraging more investments in the sector (Ajanovic & Haas, 2021). Some other advantages of the hydrogen flexibility include, for instance, the mitigation of power line congestions, stabilization of energy prices by storing and releasing energy, frequency regulation purposes or voltage support (Yue, y otros, 2021). On top of that, some countries could highly benefit from the importation of hydrogen in order to achieve the zero emissions objective. In Japan, for instance, where the access to renewable sources is limited and investment in other alternatives such as nuclear is low, zero-emission thermal power generation through imported hydrogen is presented as a good alternative (Matsuo, y otros, 2018).

After hydrogen is stored, there are different pathways by which this hydrogen can be reintegrated into the energy systems. For instance, hydrogen can be transformed back into electricity using hydrogen combustion engines, although their efficiency is around 20-25%, which is lower than conventional combustion engines due to the low volumetric energy (Yue, y otros, 2021). Stationary fuel cells are a preferred option, as they convert the chemical energy directly into electricity, which leads to 60-80% efficiencies (Yue, y otros, 2021). The same process can be applied to transport, where hydrogen can be used to run Fuel Cell Electric Vehicles (FCEVs), or be converted into other fuels like ammonia for the use of heavy transport such as ships. Hydrogen can also be used as a gas either by blending it with the natural gas grid or through its conversion into methane. Lastly, instead of reconverting the hydrogen into energy, it can be used directly as an ingredient for the production of chemical compounds (Maestre, Ortiz, & Ortiz, 2021).

2.6.2 DOMESTIC AND INDUSTRIAL USE

Hydrogen technologies present some new opportunities in the domestic and industrial sector, where there is often demand for heat and electricity. For the domestic use, hydrogen could be used as a low-carbon alternative for fossil fuels, which currently accounts for most part of residential heating (IEA, 2019). PEM or Alkaline electrolyzers generate low to medium temperature heat which could be applied for the heating of buildings, although its feasibility is still restricted to many factors such as building type, location or supply methods which affect the final cost (Kovač, Paranos, & Marciuš, 2021). Its use is being explored, although its application is currently limited to studies, demonstrations and localized operations like in Europe, where over 1000 cogeneration cells have been installed between 2012 and 2017 (Yue, y otros, 2021). Blending with natural gas and direct use for heat are currently the two main opportunities, followed by indirect heating through local district energy networks (IEA, 2019). One of the ways to improve hydrogen's energy efficiency is to apply it to combined energy systems such as co-generation and tri-generation, which use the excess energy that otherwise would be lost. Cogeneration usually refers to Combined Heat and Power (CHP), where the excess thermal energy obtained from the combustion of hydrogen is used to generate electricity, so that both heat and electric needs can be met simultaneously, reaching efficiencies up to 95% (Yue, y otros, 2021). When cooling is also produced as a third outcome then it is referred to as tri-generation.

For industrial applications, electricity falls short with regards to heat generation. According to a study by McKinsey (Roelofsen, Somers, Speelman, & Witteveen, 2020), with the available technology, almost 50% of the global energy demand could be met using electricity. However, for high temperature generation processes (>1000ºC), which represent about 30% of fuel consumption, there isn't any mature technology which allows for electrification, so heat is usually obtained with fossil fuels. Hydrogen, through the use of Solid Oxide Fuel Cells (SOFCs), can produce great amounts of heat which could help reduce CO2 emissions and fossil fuel dependence in high-temperature applications such as the steel and iron industry (Kovač, Paranos, & Marciuš, 2021). In this industry, the use of hydrogen or hydrogen-rich gases at competitive prices would improve energy and production efficiency, and could be applied in pellet and sinter production, palletizing processes and ladle and furnace heating (Liu, y otros, 2021). The steel and iron industry already constitutes the fourth greatest source of hydrogen demand, where it's widely used as an agent in blast furnace and direct reduced iron processes for the production of steel, an activity which is expected to continue growing (IEA, 2019). With the aim of reducing carbon emissions, many hydrogen-related projects are being conducted all over the world. Anyhow, changes in this sector usually occur very slowly, so practical applications are not expected to be implemented in the near future (Liu, y otros, 2021).

2.6.3 VEHICLES

According to the US Environmental Protection Agency, in 2021 the transportation sector was responsible for 53% of national carbon monoxide emissions, 53% of nitrogen oxide emissions and 15% of total volatile organic compounds in the U.S. (2022). Globally, transportation is accounts for 37% of CO2 emissions according to IEA (2022), an impact which they say is likely to continue rising as transportation remains highly reliable on fossil fuels. In order to reach the Net Zero Emissions by 2050 objectives, these emissions need to be reduced and countries all over the world are developing policies which encourage the shift to more sustainable alternatives. In this scenario, hydrogen is considered one of the major opportunities for the achievement of a reliable and low-carbon transportation infrastructure. Although hydrogen had already been considered for this purpose in the past, some factors like high investment costs and the introduction of electric vehicles slowed down the development of hydrogen transportation, which is at the moment very small, and only 13.000 Fuel Cell Vehicles are currently in operation globally (Ajanovic & Haas, 2021). The transition to a hydrogen-based mobility still faces many challenges such as weak price competitiveness, the need of a wide distribution structure, high storage and production costs or the lack of steady regulations (Silvestri, Micco, Forcina, Minutillo, & Perna, 2022). However, with the recent advances in hydrogen technologies, the increase in renewable energy sources and the increase in political support towards sustainable technologies, hydrogen's research projects are experiencing a record high and its number is expected to increase even more rapidly soon, which could lead to a reduction in the costs of production, storage and distribution (Kovač, Paranos, & Marciuš, 2021).

3. HYDROGEN-FUELED MOBILITY

Transportation continues to represent a major contribution to the climate change, being responsible of 29% of EU greenhouse emissions in 2018 (Buysse & Miller, 2021). In order to meet the EU objectives in global emissions, a change in paradigm in the transportation sector needs to take place. The urge of change is evident and multiple countries, including Spain, have already announced to ban pure internal combustion engines by 2040 (Petroff, 2017). While other technologies can only act as bridge for the energy transition, hydrogen offers a route to for complete decarbonization of the sector, providing an emission free solution for the wide range of transportation technologies, especially for heavy and long-range transport.

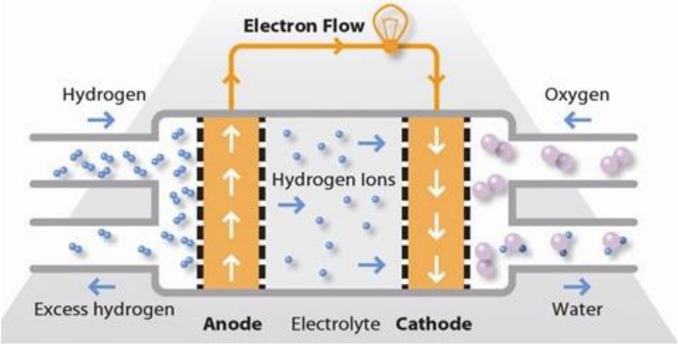
Hydrogen is considered the most attractive sustainable technology for heavy transport such as trucks, buses, trains, ships and large cars (Fuel Cells and Hydrogen Joint Undertaking, 2019). The overall environmental impact of hydrogen vehicles is subject to the emissions created in the production of hydrogen, which nowadays is mostly done through fossil-based production methods. Nevertheless, a study has shown that, even when hydrogen is produced using Steam Reforming from fossil sources, the final well-to-wheel greenhouse gas emissions is still about 15%-45% lower compared with conventional ICE vehicles (Liu, y otros, 2020). Otherwise, when hydrogen is produced from renewable sources, the reduction can be up to 50% of life cycle greenhouse emissions (Ajanovic & Haas, 2021).

Some prototypes of hydrogen vehicles were already manufactured 200 years ago, although its commercialization never took place. However, things have changed in the recent years, and there are now new opportunities for this sector. A combination of political incentives, industrial implication and technological advances has resulted, for the first time, in large-scale manufacturing of fuel cells, and some hydrogen vehicles have already started to be commercialised.

3.1. CURRENT TECHNOLOGY

Hydrogen mobility became possible thanks to the invention of fuel cells, which is the component that converts the chemical energy of hydrogen into electricity. There are different types, but Alkaline Fuel Cells (AFCs) and Proton Exchange Membrane Fuel Cells (PEMFCs) are the two most mature and extended types, being the latter the most widely used in vehicle applications due to the fast start-up time, low working temperature range and high specific energy (Fan, Tu, & Chan, 2021). PEMFCs are made up of three main parts: an anion, a cation, and an electrolyte. When operating, hydrogen is electrochemically oxidized in the anode thanks to the catalyst, producing cations and free electrons. The cations travel to the cathode through the membrane, while free electrons flow there through the outer circuit, which creates an electric current. When electrons and cations meet at the cathode, they react with the oxygen producing water and heat.

Figure 4 PEMFC diagram



Source: (FuelCellWorks)

The electrolyte located in the middle consists of a Polymer Electrolyte Membrane, also known as Proton-Exchange Membrane, as its function is to conduct the protons. These membranes require having good proton conductivity and overall durability, which is currently achieved mainly through Nafion-based membranes manufactured by DuPont, although the market price of these membranes is expensive, and multiple efforts are being put in the development of cheaper and better alternatives (Fan, Tu, & Chan, 2021). Another key element of the PEMFC is the catalyst layer, where the electrochemical reaction occurs. Currently, the most common material for its manufacture is platinum, due to its chemical properties and stability, although its rarity makes it expensive, which is why other alternatives are also being studied (Fan, Tu, & Chan, 2021).

Apart from standard Fuel Cell Vehicles, there are two other ways to utilize hydrogen's energy and use it for mobility. One of these is the production of synthetic fuels from hydrogen with low carbon content, such as methanol or ethanol, from renewable sources, which could be directly used in

ICEs increasing the efficiency while reducing CO2 emissions and consumption (Hosseini & Butler, 2019). The use of these synfuels is mostly considered for airplanes and ships. The second alternative are Hydrogen-fueled Internal Combustion Engine Vehicles (HICEVs), which are a modified version of conventional internal combustion engines which can run with hydrogen instead of gasoline. While FEVs use an electrochemical process, HICEVs use combustion. When comparing both alternatives, studies have shown that HICEVs only reach efficiencies up to 20-25%, in contrast to the 60% that can be achieved through FCVs (Hosseini & Butler, 2019). On top of that, although HICEVs don't produce carbon-based pollution such as CO2 or CO, they produce nitrogen oxides, which is an atmospheric pollutant. For these reasons, HICEVs haven't had as much development as FCVs, which are currently considered the best pathway for hydrogen mobility. However, hydrogen and electric vehicle technologies still face many challenges, and the global uptake on these alternatives will likely still take some years. While FCVs are still a relatively new technology which lacks infrastructure and development, conventional ICEs can be modified with relatively low complication to be run on hydrogen, which constitutes a feasible and environmentally viable solution for the period of transition from fossil fuel vehicles (Anisits, 2021). On top of that, hydrogen combustion engines can be fueled with non-pure hydrogen, potentially reducing hydrogen production costs. Furthermore, contrary to electric and fuel cell vehicles, this solution does not require the use of scarce and costly minerals like rare earth metals and would provide a sustainable escape for the conventional ICEs which are already in operation and are not likely to be replaced soon. With some adjustments, HICEs can benefit from all the already existing ICEs manufacturing and supply infrastructure and know how, as well as securing jobs at the automotive industry. Nevertheless, HICEs drawbacks can't be overlooked. The straightforward conversion from gasoline to hydrogen engine results in mechanical problems which include backfiring, knocking, pre-ignition problems, low volumetric performance as well as compression losses, which ultimately affect the engine durability and efficiency (Onorati, y otros, 2022). The low efficiency translates into more hydrogen required per km, and therefore the travel range per tank is reduced. Moreover, when compared to FCV and electric cars, combustion engines usually face more mechanical problems which result in overall higher maintenance costs. To avoid these mechanical challenges, several technological solutions need to be implemented implying the design of an engine specific for hydrogen combustion. These solutions include direct injection, sophisticated combustion modes, laser ignition, higher boost pressures and a specialized after-treatment to remove NOx emissions (Onorati, y otros, 2022).

In the long run, due to the higher efficiency, the lack of greenhouse emissions and their low noise, FCVs are currently considered the cleanest car alternative. Not only they don't produce greenhouse gases, but they also don't emit any pollutants, which contributes to reach better air quality in cities (Turoń, 2020).

3.2. CHALLENGES

For hydrogen vehicles to reach a competitive position in the automotive industry, there are still several challenges which must be overcome. These challenges can be classified in three categories: costs, infrastructure and policies.

3.2.1 COSTS

Currently, hydrogen FCVs cannot compete economically with neither BEV nor conventional cars. Its high price, which averages \$60k to \$70k, is around 50% higher than the equivalent electric or gasoline fueled alternative (Turoń, 2020). Although some of this price difference is due to the production rate, which is currently very low and almost limited to niche markets and demonstrations, a significant portion of the price difference is caused by the high cost of the fuel cell, which can account for 50% of the FCV cost structure (Ajanovic & Haas, 2018). On top of that, the other main challenge is the development of economically viable storage systems. Studies have shown that purchase price is a major pushback for the penetration of FCVs into the market, although in a recent study conducted in Spain (Rosales-Tristancho, Brey, Carazo, & Brey, 2022) 46.2% of respondents affirmed they would be willing to pay up to €3000 extra over the price of a conventional car for a zero emissions vehicle.

On top of the vehicle price, the overall hydrogen mobility cost is also affected by other factors such as operating and maintenance costs, energy efficiency, vehicle lifetime, number of kilometers travelled per year, as hydrogen fuel prices, or interest rates (Ajanovic & Haas, 2021). However, many of these prices are expected to decrease with the development of cheaper materials, technological breakthroughs, reduction in hydrogen production costs and the advance of the technological learning curve, while the prices of conventional cars are a mature technology where no major cost reductions are anticipated.

3.2.2 INFRASTRUCTURE

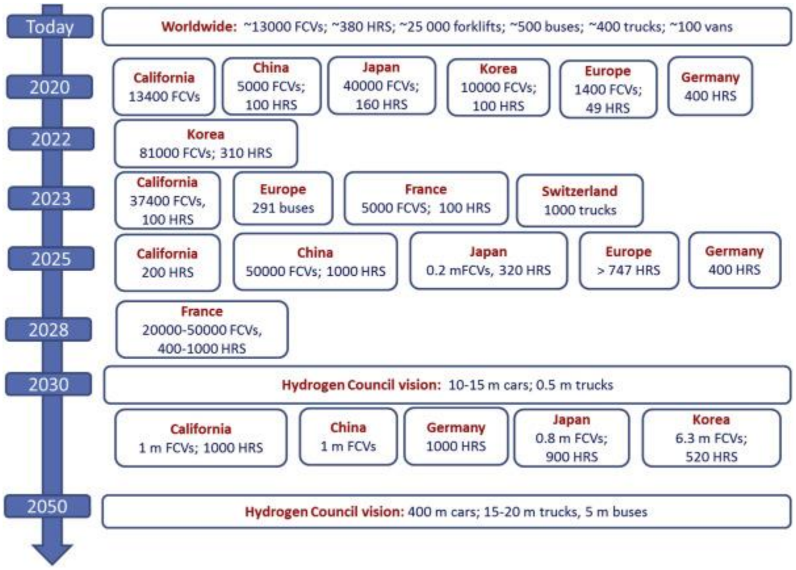
Another one of the main impediments for the development of HV is the lack of a developed hydrogen supply infrastructure. So far, only 376 refueling stations operate around the globe and there are only five countries that possess more than 20 stations (Ajanovic & Haas, 2021). In Spain, there are only 9 hydrogen refueling stations (glpautogas, 2022), which are private, in comparison to the more than 29.000 electric vehicle connectors scattered through the Spanish territory (Electromaps, 2022). Multiple initiatives have already been revealed for the extension of the hydrogen refueling network such as the Naturgy project for the construction of 38 stations by 2025 (Naturgy, 2021). For hydrogen vehicles demand to increase, the number of stations should be enough to fulfill the demand and make travel convenient and hydrogen prices should be comparable to gas on a price per kilometer travelled. Different surveys have been performed on this matter. A survey by Martin et. al. (2009) showed that 89% of individuals would be willing to deviate more than 5 minutes from their normal route to refuel a FCV while only 29% would accept more than 15 min. deviation. In Brey et al. (2017) results also showed high acceptance for deviations less than 10 min., and that if hydrogen fuel where to be available in 20% of conventional stations offering, acceptance rates could be higher than 50%. One of the main advantages of hydrogen refuelling stations over electric charging stations is the refuelling time, which is about 10 to 15 times faster (Fuel Cells and Hydrogen Joint Undertaking, 2019). This not only implies less waiting time for consumers, but also that a much smaller amount of stations is required to meet the demand, which ultimately implies smaller investment. On top of that, BEV chargers are a huge burden for the electric grid, adding high energy demands at peak times, when traffic is higher. Hydrogen refuelling stations, on the contrary, can play an important role in balancing the energy network, allowing for energy storage through daily and seasonal imbalances. When comparing investment costs, hydrogen refuelling is half as capital intensive as fast charging (Fuel Cells and Hydrogen Joint Undertaking, 2019).

The scarce network is not the only problem, but also the lack of utilization in the early stage, which can impact the viability of the refueling stations, for which financial support might be necessary. Currently, only 10 to 90 cars utilize each station on average (IEA, 2019), although this number is expected to reach 2.500-3.500 vehicles per station as the number of vehicle increases (Robinius, y otros, 2018). For that reason, during the early stages of the development of hydrogen vehicles, the infrastructure cost of hydrogen refueling stations (HRSs) is expected to be about 4.000€ per vehicle, compared to 2.000€ of electric stations. As hydrogen utilization increases, prices of both stations are expected to stabilize at around 2,500€ per vehicle (Fuel Cells and Hydrogen Joint Undertaking, 2019). Until that, refueling stations for vehicle fleets represent the easiest expansion path, since the centralized usage ensures high utilization.

3.2.3 POLICIES

As hydrogen vehicles transition from niche applications to the market, policy support will be essential to ensure the market penetration of these technologies. Most studies conducted conclude that the successful development of hydrogen will be very influenced by the implementation of consistent and predictable policies by the government (Ajanovic & Haas, 2021). The policies introduced by the different countries must set a clear long term vision for the expansion of hydrogen. For this vision to be effective, the main opportunities must be identified, followed by the announcement of a concrete set of objectives and support measures. State funding could play an essential role, financing research and development projects, pushing for the development of a wide and reliable infrastructure, supporting the progressive creation of hydrogen demand and launching financial incentives to stimulate the transition. Among the different countries, the lack of coordinated standards and regulations could hinder the expansion of new projects, and therefore an international regulatory framework in combination with coordinated actions should be stablished (Ajanovic & Haas, 2021). According to the Hydrogen Energy Roadmap in Europe (2019), the lack of consolidated efforts in Europe would lead to adoption rates of HFCV significantly lower, undermining EU's competitiveness and impeding the achievement of climate goals. The Figure 5 bellow shows the announced targets and visions set up by main regions around the globe in relation to hydrogen vehicles.

Figure 5 Announced targets and visions for fuel cell vehicles



Source: (Ajanovic & Haas, 2021)

With sufficient planning, investment policies and research, hydrogen vehicles could soon become a competitive alternative. Rosales-Trintacho et al. (2022) analysed the adoption barriers for zero emission vehicles in Spain and concluded that purchase incentives of 12.000€ along with the development of a refuelling station infrastructure of no more than 15min apart could lead to a market penetration of 2.75% of HFCVs. The cost of a basic HRS infrastructure along EU would cost the less than a tax of 1 cent per liter of gasoline and diesel for three years (Fuel Cells and Hydrogen Joint Undertaking, 2019).

3.3. APPLICATIONS

Hydrogen can provide high flexibility in the transportation sector. For that reason, there are multiple different applications where hydrogen could end up playing a relevant role. These applications include passenger vehicle, buses, trucks, and special vehicles such as forklifts. Currently, the only commercially available options are passenger vehicles, buses and forklifts, although there are prototypes for heavy-duty and mining trucks.

3.3.1 LIGHT DUTY VEHICLES

Vehicles are commonly classified in classes according to their weight, going from class 1 to 8. Light Duty Vehicles (LDV) includes those whose weigh is less than 10.000lbs (classes 1 and 2) and which are commonly used to transport passengers and cargo such as cars or vans. Commercial hydrogen LDVs first appeared in the market with the introduction of the Toyota Mirai in 2014, a car which is currently still commercially available in its second-generation version (Gutierrez, 2021). Since the launching of the first vehicle, hydrogen passenger vehicles have achieved very small sales in comparison to electric vehicles, accounting for just a few thousand vehicles sold globally, mainly in Korea, Japan and United States (IEA, 2020). The Toyota Mirai, the Hyundai Nexo and the Honda Clarity Fuel Cell account for the greater part of the sales, although the Clarity FC will stop being produced in 2022 (Wyatt & Gear, 2022). The two main remaining competitors, Toyota and Hyundai, experienced an 82% increase in sales in 2021, a growth partly impacted by the large government spending, which resulted in discounts of 50-65% in the price of the vehicles (Collins, 2022).

3.3.2 MEDIUM DUTY VEHICLES

Following LDVs, the Medium Duty Vehicles (MDVs) category includes those vehicles with a weight up to 26.000lbs. (classes 3 to 6), such as buses or delivery trucks. Most MDVs meet the characteristics for being a suitable application for fuel cell technologies as they require medium travelling range and carry heavy duties. On top of that, many of them operate through a centralized infrastructure, which optimizes the use of hydrogen storage and refueling stations. Furthermore, buses are typically publicly operated, which makes them an ideal way to publicly promote hydrogen vehicles as a green and reliable transportation option. As with LDVs, hydrogen MDVs could contribute to decrease CO2 emissions, pollution and noise inside cities.

In comparison to battery electric buses, fuel cell electric buses (FCEBs) are more costly for smaller fleets as they require higher initial investments, but as the fleet size increases, they become a more affordable alternative as battery electric fleets require additional expensive infrastructure modifications to support the load (Wyatt & Gear, 2022). Even though their market share remains low, latest global objectives and investments suggest a mass transit to hydrogen in the sector (Ajanovic & Haas, 2021). Currently, China owns the vast majority of FCEBs with a fleet of over 5.300 vehicles, while the second holder, Japan, has only 100 (IEA, 2020). In Europe, there are over 150 FC buses, and 240 are planned to be implanted in the following years (Yorke, 2021).

3.3.3 HEAVY DUTY VEHICLES

In third place, Heavy Duty Vehicles (HDVs) are those with a weight higher than 26.000 lbs. (classes 7 and over). This group is mainly composed of long-haul heavy trucks and city transit buses, where the application of electric solutions is highly limited by the heavy loads and the necessity of long driving ranges. For that reason, heavy transportation is believed to be a promising segment for the application of fuel cell technologies. Apart from the longer driving range, another advantage of HDVs is the much faster refueling rate in comparison to electric vehicles, which is essential to minimize the downtime operation time. On the downside, these vehicles are mostly privately operated and travel through extended locations. Therefore, for them to be viable, a reliable and extended refueling infrastructure is needed, a scenario which is currently very far from being a reality. Still, if their use were to popularize, and in combination with clean produced hydrogen, they would highly contribute to reduce CO2 emissions and pollution.

3.3.4 TRAINS

Fuel Cells Trains (FCTs) are expected to play a significant role in the railway sector in the future, particularly for longer ranges and higher power demand. Ruf et. Al (2019) showed that FCTs can perform as well as diesel trains and have the potential to become cost-competitive with them in the short run, making it possible that by 2030 one in five new train purchases could be hydrogen powered. Although many barriers still exist regarding the technology, they constitute an optimization challenge rather than a fundamental limitation, and therefore can be solved with future R&D (Ruf, y otros, 2019). Multiple hydrogen-fueled regional trains have already been placed into service in Europe, and it is anticipated that they will soon account for up to 30% of all diesel fleets. (Yue, y otros, 2021)

3.3.5 SHIPS

Approximately 80% of global trade's volume is carried through maritime transport which is highly reliable of highly polluting hydrocarbons. As a result, it accounts for around 2.5% of total global greenhouse gas emissions and 13.5% of all greenhouse emissions from transport (EEA; EMSA, 2021). The volume of global shipping is expected to increase in the following years (UNCTAD, 2021), which could cause an increase in global emissions of 90-130% the amount of 2008, a scenario which would strongly collide with the EU's Paris Agreement of emission reduction (IMO, 2020). The European Commission recently highlighted the crucial role of hydrogen based synthetic fuels in sectors such as aviation and maritime, where decarbonization is hard reach (European Comission, 2021).

While for other transportation methods hydrogen use is mainly predicted to be performed through fuel cells, in the case of maritime transport the main usage will likely be hydrogen combustion. While some fuel cell ships prototypes have been developed, such as the HySeas III ferry in Scotland or the Hydra-Ship in Norway, this type of application is mainly limited to small passenger fleets (Hoecke, y otros, 2021). For large cargo ships, the decarbonization of the sector is more complicated as these require long travelling distances with very heavy loads and high power. As a result, electric alternatives are not very suitable as they would require too many batteries, heavily increasing the price and weight of the vessel. Instead, the use of combustion engines is believed to be a better option as it allows for the construction of larger more powerful ships and requires smaller modifications of the existing designs. In order to achieve cleaner transportation, the two main alternatives being considered are biofuels, whose production is limited, and hydrogen, either through the combustion of pure hydrogen or synthetic fuels. Still, some challenges still need to be addressed regarding fuel production, storage and safety.

3.3.6 PLANES

Regarding aviation, the technological scenario is very similar that of maritime transport. Either electric or fuel cell applications lack the necessary power density the application of these fuels and therefore synfuels are considered the most feasible alternative. One of the main challenges associated with the decarbonization of this sector is the large amounts of time which would take for new cleaner emissions to be implemented. This is due to the low turnover rate of planes and the large number of regulations, testing and approvals needed for new designs to get into operation, which can take more than 45 years (Bruce, y otros, 2020). For this reason, the main focus is set on the development of achievable measures which can be applied to current fleets, such as the development cleaner and more efficient fuels. While the use of pure hydrogen is used in other applications, for aviation transport this still requires further R&D (IEA, 2019), and therefore the most feasible applications are biofuels or synthetic fuels, both of which could be applied with none to very few modifications to current planes. Synthetic fuels can be produced combining hydrogen from electrolysis and CO2 from carbon capture. Still, a report by the CSIRO showed that scaling the synfuel industry will require large coordinated efforts, government intervention and aid, careful resource planning and the further development of renewable and hydrogen technologies, and even then, the cost of these fuels would be higher than conventional jet fuel, which is a major drawback in an industry where fuel costs represent a large share of the total cost (Bruce, y otros, 2020).

3.3.7 FORKLIFTS

While most hydrogen mobility applications are still in very early stages of development, for material handling equipment such as forklifts the case is different, as they are already widely commercially available. Some of its advantages include the long operation hours and low refueling times in comparison with electric alternatives. The extended commercialization of these forklifts, which is estimated to be 25.000 globally (IEA, 2019), helps improve hydrogen technologies and extend the market penetration of fuel cells.

3.4. COMPARISON WITH ELECTRIC VEHICLES

Battery electric vehicles (BEVs) are currently considered the main alternative for achieving the transition to a carbon free mobility. While hydrogen vehicles are still far behind in technology development, this could change in the following years as commercially available vehicles are starting to make its way into the market. Both technologies can potentially decarbonize the road transport and decrease urban pollution. In this context, it is likely that in the future these two technologies will coexist and represent a relevant portion of the vehicle market.

However, both technologies present certain barriers for the widespread adoption by the public. For the FCEVs, as previously presented, these barriers mainly include the high price of fuel cells and storage, the lack of refueling infrastructure and the need of supportive and steady policies. While electric vehicles already have an extended charging infrastructure, FCEVs still lack refueling stations. On top of that, electricity generation is already extended and becoming cleaner thanks to RES while hydrogen generation is still mainly produced from fossil fuels. Another major hydrogen's drawback is the higher energy lost resulting from the multiple energy transformations that involve hydrogen's pathway: first, when it's produced through electrolysis; and secondly, when it's transformed back to electricity to be used in the electric motor of the car.

For the BEV, the barriers are mostly technological. Batteries are the main limiting factor, due to their high price and weight, which makes the driving range of BEV very limited. The energy storage system weight for a FCV with a range of 500km is around 125kg, while for a BEV of that range the battery weight can reach 830kg (Brinkman, Eberle, Formanski, Grebe, & Matthé, 2012). On top of that, weather conditions, especially the cold, can have a high negative impact on the battery's performance, heavily decreasing the driving range. These limitations make long-range driving a difficult option for BEV. Additionally, electric vehicle batteries take up multiple hours to be charged while FCVs have very short refueling times which range between 3 and 5 minutes (Turoń, 2020). According to a study, hydrogen is the best decarbonisation solution for long-range purposes, while electric cars are the better option for shorter distances (Hydrogen Council, 2020).

In the end, both vehicles have their own drawbacks. BEVs face technological barriers which might forever limit their capacity to meet certain objectives in terms of range, weight, price and application, while FCEVs challenges are still far from being overcome. However, the cause of FCEV barriers barriers is mainly economic, and therefore overcoming these challenges might be more attainable.

4. COST ESTIMATIONS

In this section, the future price of fuel cell vehicles will be studied. In order to do that, information has been gathered regarding hydrogen technologies which is used to estimate the cost of each of the components of the vehicle. The cost estimations will not only be useful for the study of future hydrogen vehicles feasibility in the market but will also be implemented into the data of the Spanish system model.

Regarding the scope of the estimation: four different year scenarios have been selected:

- Real: Accounts for the real current price of the vehicle based on low production rates of the different components. Latest advances in vehicle technology don't immediately reach the automotive manufacturing industry, so a delay of approximately five years exists between laboratory and on-road technology. This means that vehicles being produced in 2020 still have the technology and costs of 2015, approximately.
- Years 2020, 2030, and 2050: For these years manufacturing rates of 100k to 500k units per year are assumed resulting in cost reduction due to economies of scale.

For the cost estimation three different vehicles have been selected:

1. LDV: Based on the 2nd generation Toyota Mirai, which has a 128kW FC (108 kWnet), a storage capacity of 5,6kg and a battery of 1.24kW (310V and 4Ah) and 31.5kW peak power (Toyota, 2020), and a 134kW motor generator.
2. MDV: There is a wide spectrum of characteristics for MDV. According to the US Department of Energy (DOE), storage values range from 10 to 30kg and fuel cell representative value $160kW_{net}$ (James, 2019). For battery capacity, it varies widely depending on the model. A 36kWh battery and a 190kW motor have been selected, which are representative values for a FC bus.
3. HDV: Similar to MDV, existing prototypes vary enormously, so illustrative values have been selected. According to DOE storage values range from 60 to 100kg and fuel cell representative value $300kW_{net}$ (James, 2019). For heavy trucks, a 50kWh and a 350kWh are assumed for a $300kW_{net}$ bus (Zhao, Wang, Fulton, Jaller, & Burke, 2018).

Vehicle specifications				
Vehicle type	FC system (kWnet)	H2 Tank (kg)	Battery (kWh)	Electric motor (kWh)
LDV	108	5,6	1,6	134
MDV	160	20	36	190
HDV	300	72	50	350

Table 5 FCEVs specifications summary

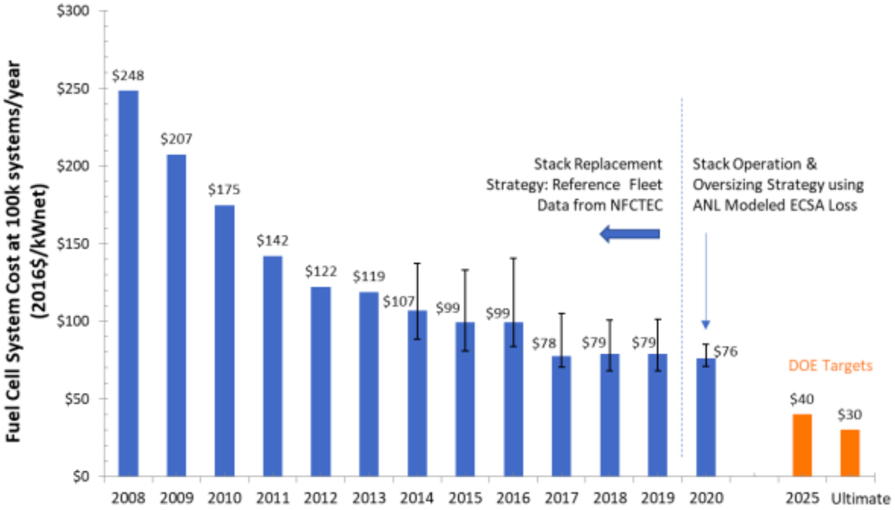
Hydrogen Fuel Cell Vehicles manufacturing cost is determined mainly by five principal components: Fuel Cell System, Hydrogen Storage, Battery, Electric Motor and Glider.

4.1. COST COMPONENTS

4.1.1 FUEL CELL

According to the DOE, the manufacturing cost for a LDV 80kW$_{net}$ PEM FC system cell with a production of 100.000 units per year is \$76/kW$_{net}$, and sets targets for price reduction down to \$40/kW$_{net}$ in 2025 and \$30/kW$_{net}$ as its ultimate price (James, 2021 DOE Hydrogen and Fuel Cells Program Review Presentation. Fuel Cell Systems Analysis, 2021).

Figure 6 DOE 80-kWnet PEM fuel cell cost at 100k units/year



Source: (US DOE, 2021)

Previous DOE estimations reported lower cost estimates of $52\$/\mathrm{kW}_{net}$, but changes were made to better incorporate durability into the model (James, 2021).

Currently, manufacturing rates for FCEV are still far from reaching the values considered in the prediction, standing at a just a few thousand units per year, leading to higher production costs. The DOE estimates fuel cell systems costs to be $\$159/\mathrm{kW}_{net}$ for a production of 1,000units/year and $\$113/\mathrm{kW}_{net}$ at 3,000units/year (Elliot Padgett, 2020). Still, due to the delay between laboratory advances and real manufacturing application, the current cost of the commercially available vehicles , such as the Toyota Mirai, is estimated to be \$165/kW at 3,000 units per year (Elliot Padgett, 2020). Other studies, like the James et al. (2018) report, present similar cost estimates ranging from $\$168.18/\mathrm{kW}_{net}$ with 1000units/year to $\$41,6/\mathrm{kW}_{net}$ with mass production of 500k units/year, which could go down to 37,21 by 2025.

Regarding MDVs, the DOE estimates FC costs to be \$170/kWnet in 2021 and \$125/kWnet by 2025 at 100k units/year. For HDVs, DOC estimates the cost of fuel cell system for HDV at 100k units per year production to be \$185/kWnet in 2021 and predicts it come down to \$129/kWnet by 2025. The DOE also sets targets of \$80/kWnet for 2030 and an ultimate target of \$60/kWnet, although predicts these objectives will be hard to meet (James, 2021). The James et al. (2018) report present similar cost estimates, ranging from \$291,29/kWnet with 1000units/year to \$85,69/kWnet with mass production of 100k units/year, which could go down to 75,46 by 2025.

Vehicle type	Specific cost (\$/kWnet)				Capacity (kWnet)
	Real	2020	2030	2050	
LDV	159	76	40	30	108
MDV	246	170	125	60	160
HDV	246	185	129	80	300

Table 6 Fuel Cell assumptions

4.1.2 HYDROGEN STORAGE

Due to the high energetic density of hydrogen by weight, only 4kg of it are necessary for a FCV to reach the 400km range, or 8kg if in case of a hydrogen ICEV (Schlapbac & Züttel, 2010). However, due to the low volumetric density, large containers are needed to contain that quantity, and the materials composing that storage must meet a set of characteristics which include high hydrogen density, quick charge and release, strong and tight atomic packing or sufficient thermal conductivity (Hosseini & Butler, 2019). On top of that, they must be light, durable and exist in sufficient quantities to meet the demand, which makes it difficult to find a material which meets all of these characteristics while maintaining a low price.

The representative sizes of hydrogen storage tanks for Light, Medium and Heavy Duty Vehicles is vehicles are 5,6kg, 20kg and 80kg, respectively (James, 2019).This hydrogen is commonly stored at 700bar tanks systems, for which the DOE estimates the costs to be $14,19/kWh with a potential future cost of $8,29 when production is 500k units/year (James, 2019). The IEA report annex details similar hydrogen tank costs of $15/kwh in the short term and $9/kWh in the long term (IEA, 2019). A study by Whiston et al. suggests these targets will not be met and instead anticipated costs to be $13,5 and $10,53/kWh for 2035 and 2050, respectively, according to expert analysis (Whiston, Azevedo, Litster, Samaras, & Whitacre, 2021). In Brooker et al. (2021) storage assumptions are $21, $11 and $8/kWh for 2020, 2030 and 2045, respectively.

For HDVs, storage assumptions are $42, $25 and $8/kWh in 2021, 2027 and 2050 respectively (Brooker, y otros, 2021). Another study on zero-emission trucks sets the average current storage price in $37/kWh and excepts it to decrease to $21/kWh by 2030 (Sharpe & Basma, 2022).

Taking that hydrogen has an energy density of 33,6kWh/kg (Cenex, 2021), battery cost can be calculated using the following expression:

$$Storage\ cost\ = Capacity\ (kg) * \ 33{,}6\left(\frac{kWh}{kg}\right) * Cost\ (\frac{\$}{kWh})$$

In order to reach a driving range of at least 500miles driving range, a long-haul fuel cell truck would need at least a storage capacity of 70kg of hydrogen (Zhao, Wang, Fulton, Jaller, & Burke, 2018).

Vehicle type	Specific cost ($/kg H2)				Capacity (kg H2)
	Real	2020	2030	2050	
LDV	33	14,19	11,24	8,29	5,6
MDV	37,5	19,595	11,24	8,65	20
HDV	42	25	11,24	9	72

Table 7 Storage assumptions

4.1.3 BATTERY

During battery design, there is a tradeoff between the power density, which refers to the maximum energy discharged, and energy density, which is the amount of energy stored. According to that, there are two main types of batteries regarding vehicle use: power batteries, which can provide high instant power, and capacity batteries, which store large amounts of energy. For FCEVs, the use of the battery is different than BEVs, as it only stores small amounts of energy generated from the regenerative braking, while providing supplementary energy to the motor. Therefore, FCEVs batteries are power dense, with low capacity and high voltage.

According to BloombergNEF battery prices have dropped to US$132/kWh in 2021 and will reach prices below $100/kWh by 2024 (Frith, 2021). Similarly, according to CNBC, current 2022 prices are $128/kWh and will go as low as $90/kWh by 2031 (LeBeau, 2022).

However, FCV batteries have low capacity while providing high peak power, and therefore it's cost can't me modelled using conventional battery costs. Instead, Hybrid Electric Vehicles (HEV) are a better reference for battery costs since they also have power dense batteries that provide additional support for the car. According to Brooker et al. (2021), Plug-in Hybrid Electric Vehicle (PHEV) battery costs are expected to be $365/kWh in 2020, droping to $160/kWh by 2025 and $120/kWh by 2045. For Heavy Duty vehicles, Sharpe & Basma (2022) report estimates current power battery prices at almost $500/kWh, dropping to less than $300/kWh by 2030. In a study by Ruf et al. on hydrogen vehicles (2020) costs of small batteries for trucks are considered to be $364/kWh in 2023 dropping down to $173/kWh in 2040 if mass production were to be reached.

For the LDV battery cost estimation, peak battery power is significantly higher than battery capacity and therefore represents a major cost element. To account for that the following formula will be used obtained form an NREL study by O'Keefe et al. (2010) substituting the original battery cost per kWh with values estimated from more recent studies:

$$\frac{\$22}{kW} * Peak_{power} + Battery_{cost}\left(\frac{\$}{kWh}\right) * Battery\_capacity + \$680$$

MDV and HDV have higher battery capacities and therefore will be calculated as a function of capacity.

Vehicle type	Specific cost ($/kWh)				Capacity (kWh)
	Real	2020	2030	2050	
LDV	410	365	160	120	1,6
MDV	450	365	220	146,5	36
HDV	490	365	280	173	50

Table 8 Battery assumptions

4.1.4 ELECTRIC DRIVE

The IEA report annex estimates the cost for the electric motor to be $14/kW for cars and $39/kW for trucks. Sharpe & Basma (2022) study reports average e-drive cost of $60/kW for trucks in 2020 and expected cost of $25/kW by 2030. In another study by Zhao et al. e-drive cost is divided in motor and controller costs adding up to $25/kW (2018).

Vehicle type	Specific cost ($/kWgross)				Capacity (kWgross)
	Real	2020	2030	2050	
LDV	14	14	11,5	9	134
MDV	26,5	26,5	18,25	14,5	190
HDV	39	39	25	20	350

Table 9 Electric Motor assumptions

*Prices for MDV estimated as the average between LDV and HDV

4.1.5 GLIDER

The glider includes the vehicle parts that don’t involve the powertrain. For LDV, in James et al. (2018) the Toyota Mirai glider cost is estimated to be $11.000. For medium and heavy duty vehicles, costs can vary enormously depending on the selected vehicle. Ruf et al. (2020) study considers glider costs of cost of $54.600 and $63.000, respectively. Another study by Zhao et al. (2018) estimates long-haul trucks glider to cost $95.539 per unit. Therefore, and intermediate value of 80.000$ has been assumed for HDVs.

Vehicle type	Cost/unit
LDV	$11.000
MDV	$54.000
HDV	$80.000

Table 10 Glider cost assumptions

4.1.6 OTHER COMPONENTS

Some of the components include the regenerative breaking system and the gear box for the LDV, which are estimated to be $800 and $400, respectively (James, Huya-Kouadio, Houchins, & DeSantis, 2018). For the HDV, Zhao et al. (2018) considers a transmission cost of $2.000.

4.1.7 OPERATIONS AND MAINTENANCE

Finally, regarding the O&M costs for these vehicles, the IEA report annex estimates $0,0776/km for cars and $0,106/km for trucks. In a study by Ruf et al. on hydrogen vehicles (2020) similar values of $0,11/km are considered for fuel cell trucks. In a more recent study, Wang et al. (2020) estimates fuel cell heavy trucks maintenance and repairment (M&R) costs to be $0,124/km and expects it to drop down to $0,093/km in the future. For MDVs, a study by the NREL showed maintenance cost of FC buses to be $0,26/km, similar to the compressed gas bus results (Eudy & Post, 2020).

The average distance travelled per vehicle varies depending on the country and vehicle type. According to the US DOE the average annual travelled distances for each vehicle type are ~100.000 km for trucks, ~70.000km for transit buses, ~20.000km for delivery trucks and ~18.500km for cars (US. DOE, 2020). In Norway the average is lower, being ~36.000 km for heavy trucks, ~31.000 km for buses and ~11.000 for cars (Statistics Norway., 2022). For this study the assumptions will be 16.000km for LDV, 50.000km for MDV and 96.000 for HDV. Therefore, O&M costs are:

Vehicle type	Cost/km	Km/year	Cost/year
LDV	0,0776	16000	**$1.242**
MDV	0,26	50000	**$13.000**
HDV	0,11	96000	**$10.560**

Table 11 O&M assumptions

Regarding expected lifetime for each vehicle, the target for FC Buses is 12 years/500.000 miles (Eudy & Post, 2020). Heavy trucks have a lifetime of 12 years and 800.000 miles (CARF, 2021). For LDVs, a lifetime of 8.000 hours is expected for the fuel cell and 25.000hrs for HDV before replacement (James, 2021 DOE Hydrogen and Fuel Cells Program Review Presentation. Fuel Cell Systems Analysis, 2021).

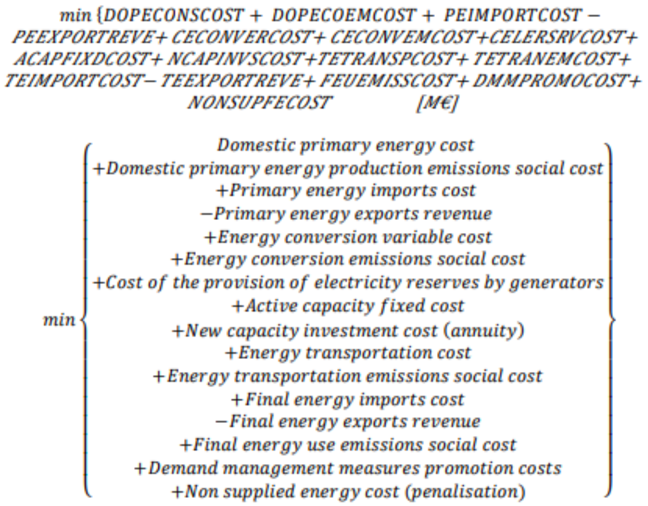
5. DESCRIPTION OF THE MODEL

Hydrogen is expected to play and increasingly larger role in the future mobility sector. The objective of this thesis is to analyze the impact which these vehicles will have in the future Spanish energy system for the year 2050. To perform this analysis, data for current and future hydrogen vehicle technologies will be incorporated into a MASTER model of the Spanish energy system for the year 2050. Master.SO, created by Álvaro López Peña at the Institute for Research in Technology (IIT) in Comillas ICAI, is a GAMS mathematical model which optimizes the Spanish energy mix given a set energy demand by maximizing social welfare (López-Peña, Linares, & Pérez-Arriaga, 2011). The scope of the model has been expanded with the addition of green hydrogen's value chain by Marta Galdos Ispizua as part of another project (Ispizua, 2021). The data incorporated in this thesis will further expand the scope of this model allowing to incorporate FCEVs into the energy demand. The results obtained with the model allow for the analysis of the impact of different FCEV costs into the energy mix in Spain.

5.1. OBJECTIVES AND SPECIFICATION

"Model for the Analysis of Sustainable Energy Roadmaps. Static Optimisation version" or MASTER.SO maximizes the energy supply sustainability of the Spanish energy mix by using linear programing (LP). The minimization function is the following.

Figure 7 MASTER.SO minimizing function



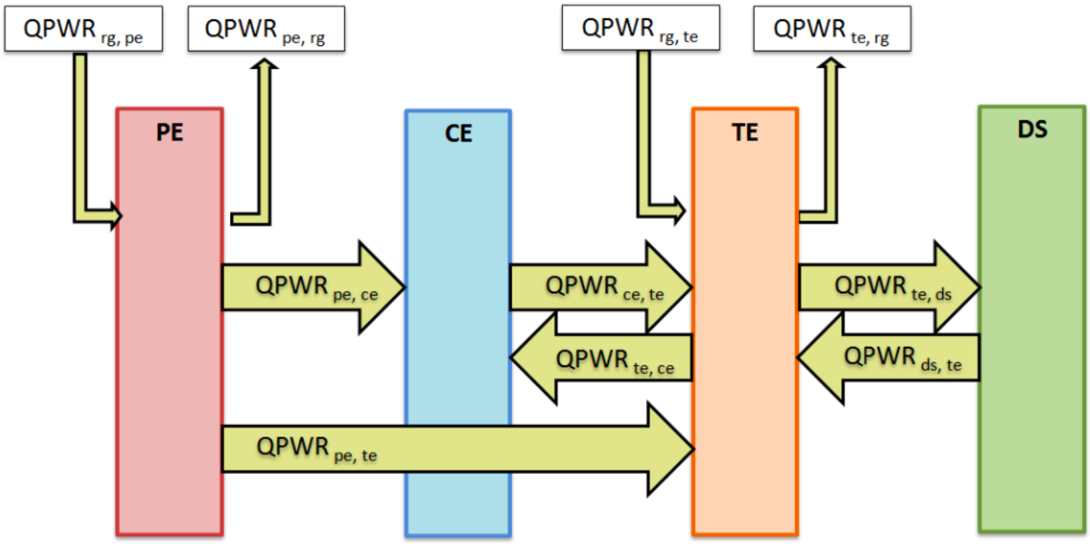
$$\min\{DOPECONSCOST + DOPECOEMCOST + PEIMPORTCOST - PEEXPORTREVE + CECONVERCOST + CECONVEMCOST + CELERSRVCOST + ACAPFIXDCOST + NCAPINVSCOST + TETRANSPCOST + TETRANEMCOST + TEIMPORTCOST - TEEXPORTREVE + FEUEMISSCOST + DMMPROMOCOST + NONSUPFECOST \quad [M€]$$

$$\min\left\{\begin{array}{c} \text{Domestic primary energy cost} \\ +\text{Domestic primary energy production emissions social cost} \\ +\text{Primary energy imports cost} \\ -\text{Primary energy exports revenue} \\ +\text{Energy conversion variable cost} \\ +\text{Energy conversion emissions social cost} \\ +\text{Cost of the provision of electricity reserves by generators} \\ +\text{Active capacity fixed cost} \\ +\text{New capacity investment cost (annuity)} \\ +\text{Energy transportation cost} \\ +\text{Energy transportation emissions social cost} \\ +\text{Final energy imports cost} \\ -\text{Final energy exports revenue} \\ +\text{Final energy use emissions social cost} \\ +\text{Demand management measures promotion costs} \\ +\text{Non supplied energy cost (penalisation)} \end{array}\right\}$$

Source: (López-Peña, Linares, & Pérez-Arriaga, 2011)

While sustainability is a broad concept, in this model its weight is incorporated by encompassing the costs associated with environmental impact, represented through economic indicators such as CO2 prices or the externalities of energy imports. These considered, the model looks for the energy system of minimum cost to society. The minimizing function operates with a series of constrains which include general power balance, capacity, reserve and adequacy limitations. From that, the output of the model is the amount of power flowing between each of the processes in the system. The following Sankey Diagram shows a general representation of the different processes and relations between them encompassed in the model.

Figure 8 Generalized Sankey Diagram of the model



Source: (López-Peña, Linares, & Pérez-Arriaga, 2011)

To simplify, the Sankey Diagram groups the energy flow in boxes each of which represents a process. These boxes are:

- Primary Energy (PE): Which includes the primary energies used in the country energy system such as nuclear, gas, or renewables.
- Conversion of Energy (CE): Involves the energy conversion processes such as electricity generation or oil processing.
- Transportation Energy (TE): Represents the transportation and distribution networks.
- Demand Sectors (DS): The economic sectors which demand energy. These are grouped into industry, transportation and other uses.

5.2. SCOPE OF STUDY

While the MASTER model was designed to analyze the Spanish energy system until 2050, the parameters of the model are only updated for the time horizon of 2030, and therefore that will be the set time of the study. With respect to the selected vehicle, a relevant aspect of the model analysis is to compare the data between electric and hydrogen vehicles. Currently, the model only contains data regarding passenger electric vehicles. For this reason, only the impact of FC LDV will be studied in this analysis due, while Medium and Heavy duty vehicle data will be left for future studies when electric data of these vehicles is implemented into the model.

As previously presented, the MASTER model includes data regarding the hydrogen green hydrogen's value chain, which include the cost of infrastructure regarding hydrogen production and transportation. However, infrastructure costs directly associated with hydrogen vehicles such as refueling stations are not included in that version of the model.

In this project, given the sustainability scope of the model, H2 production is only considered from electrolysis through renewable sources.

Finally, the minimizing function of the model only contemplates economic factors into the equation such as CO2 costs, CAPEX and OPEX. Therefore, personal preferences regarding vehicles are not taken into account. These are factors such as refueling availability and speed or vehicle driving range which could have an impact in the buying decisions of consumers leading to higher demand of one sector.

5.2.1 FUEL CELL VEHICLES

Considering the cost estimation data presented, the cost model assumptions for the three different vehicles are summarized in the tables bellow:

LDV COSTS											
Component		Specific cost				Capacity		Total cost			
		Real	2020	2030	2050			Real	2020	2030	2050
FC system	$/kWnet	159	76	40	30	108	kWnet	$17.172	$8.208	$4.320	$3.240
H2 Tank	$/kWh	33	14,19	11,24	8,29	5,6	kg	$6.209	$2.670	$2.115	$1.560
Battery	$/kW	410	365	160	120	1,6	kWh	$2.656	$2.584	$2.256	$2.192
Electric motor	$/kWgross	14	14	11,5	9	134	kWh	$2.301	$2.301	$1.966	$1.631
Gear box	$	400				-		$400	$400	$400	$400
Reg. Braking	$	800				-		$800	$800	$800	$800
Glider	$	11000				-		$11.000	$11.000	$11.000	$11.000
Total Cost								**$40.538**	**$27.963**	**$22.857**	**$20.823**
Markup (%)	%	**50%**						$20.269	$13.981	$11.428	$10.411
Total Price	**$**							**$60.807**	**$41.944**	**$34.285**	**$31.234**

Table 12 LDV cost estimates

MDV COSTS											
Component		Specific cost				Capacity		Total cost			
		Real	2020	2030	2050			Real	2020	2030	2050
FC system	$/kWnet	246	170	125	60	160	kWnet	$39.360	$27.200	$20.000	$9.600
H2 Tank	$/kWh	37,5	19,595	11,24	8,645	20	kg	$25.200	$13.168	$7.553	$5.809
Battery	$/kW	450	365	220	146,5	36	kWh	$16.200	$13.140	$7.920	$5.274
Electric motor	$/kWgross	26,5	26,5	18,25	14,5	190	kWh	$5.035	$5.035	$3.468	$2.755
Transmision	$	2000				-		$2.000	$2.000	$2.000	$2.000
Glider	$	54600				-		$54.600	$54.600	$54.600	$54.600
Total Cost								**$142.395**	**$115.143**	**$95.541**	**$80.038**
Markup (%)	%	**50%**						$71.198	$57.571	$47.770	$40.019
Total Price	**$**							**$213.593**	**$172.714**	**$143.311**	**$120.058**

Table 13 MDV cost estimates

HDV COSTS											
Component		Specific cost				Capacity		Total cost			
		Real	2020	2030	2050			Real	2020	2030	2050
FC system	$/kWnet	246	185	129	80	300	kWnet	$73.800	$55.500	$38.700	$24.000
H2 Tank	$/kWh	42	25	11,24	9	72	kg	$101.606	$60.480	$27.192	$21.773
Battery	$/kW	490	365	280	173	50	kWh	$24.500	$18.250	$14.000	$8.650
Electric motor	$/kWgross	39	39	25	20	350	kWh	$14.075	$14.075	$9.175	$7.425
Transmision	$	2000				-		$2.000	$2.000	$2.000	$2.000
Glider	$	80000					-	$80.000	$80.000	$80.000	$80.000
Total Cost								**$295.981**	**$230.305**	**$171.067**	**$143.848**
Markup (%)	%	**50%**						$147.991	$115.153	$85.533	$71.924
Total Price	**$**							**$443.972**	**$345.458**	**$256.600**	**$215.772**

Table 14 HDV cost estimates

5.2.2 Electric Vehicles

In order to compare with the hydrogen LDV, the costs of passenger BEV are also included into model. These costs obtained from Islam et al. study for 300miles range LDV with low technological progress considering 5-year delay between lab and manufacturing. (Islam, Moawad, Kim, & Rousseau, 2020)

BEV			
	2020	2030	2050
Coste Total	**$37.400**	**$28.200**	**$24.000**
Markup (50%)	$18.700	$14.100	$12.000
Precio total	**$56.100**	**$42.300**	**$36.000**

Table 15 Passenger BEV cost assumptions

O&M BEV			
Vehicle type	Cost/km	Km/year	Cost/year
LDV	0,065	16000	**$1.040**

Table 16 O&M costs for passenger BEV

5.3. ALGORITHMS

As inputs for the model, two main inputs need to be calculated:

1. Cost Per Act Lvl: Total cost of the vehicle per activity level measured in (M€/Mvkm). The cost of the fuel is not included in this calculation.

$$Annual\ cost\ \left(\frac{€}{year}\right) * Yearly\ Activity\ \left(\frac{vkm}{year}\right)$$

The annual cost is determined with the following equation:

$$Annual\ Investment\ Cost + Annual \text{O\&M}$$

The annual investment cost is calculated as the annual payment for loan whose value is equivalent to the cost of the vehicle given a specified life expectancy and interest rate.
The annual O&M is calculated using the average annual driving distance and the O&M costs per kilometer value previously presented

2. TE2ACT: Is the activity level which can be achieved with one unit of transport energy measured in (Mvkm/GWh). This depends on the energy density of the fuel and the vehicle consumption.

$$\frac{100}{H2\ Energy\ density\left(\frac{kWh}{l}\right) * Vehicle\ Consumption\ (\frac{l}{100km})}$$

This input is calculated for urban (up to 50km), mixed (50-100km) and highway (>100km) consumptions.
It is important to mention that for ranges higher than 500km electric vehicles are not considered in the model due to the limitations in driving ranges. Therefore, for this type of vehicle, only activities up to 500km are calculated.

5.4. NUMERICAL IMPLEMENTATION

The following parameters are introduced into the equations:

DESCRIPTION	FC LDV 2030
Urban Cons. L/100km	1
Mixed Cons. L/100km	0,8
Highway Cons. L/100km	0,55
Investment Cost (€)	22857
Life	12
Interest rate	9%
Yearly Activity (Total) (Vkm/Year)	16000
Energy Density H2 (Kwh/L)	33,60

Table 17 FC LDV parameters

From these parameters annual O&M and investment costs are calculated:

YearlyO&Mcosts (€/year)	1015
Annual InvCost (€/year)	3192
Total Cost_NO ENERGY (€/year)	4207

Table 18 FC LDV annual costs

Using these calculations and the rest of parameters in the table the input parameters for the base case are obtained:

INPUT	VALUE
Cost Per Act Lvl (M€/Mvkm)	0,26
TE2ACT Urban (M Vkm/Gwh)	2,98
TE2ACT Mixed (M Vkm/Gwh)	3,72
TE2ACT Highway (M Vkm/Gwh)	5,41

Table 19 FC LDV model inputs

6. ANALYSIS OF RESULTS

Two main results are drawn from this thesis:

1. Estimation of the future cost of Fuel Cell Vehicles up until 2050.
2. Analysis of the impact that hydrogen LDV can have on the Spanish energy system for the year 2030.

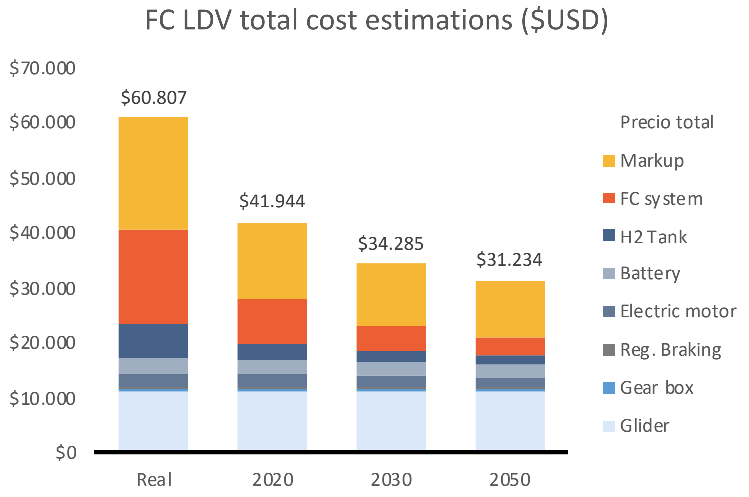
6.1. COST ESTIMATIONS

Through a deep analysis of the current literature, an estimation for the future costs for three different fuel cell vehicles categories is performed. The magnitude of these costs will have a relevant impact on the economic feasibility of hydrogen mobility for the future. Not only that, but the relative price and features with respect to electric vehicles, its main competitor, will affect the buying decisions of consumers. In this section, not only the estimated costs are analyzed, but also its similarities with the existing data in the literature in order to validate the results.

6.1.1 LDV

The following graph summarizes the cost predictions for a Fuel Cell Light Duty Vehicle comparable to the Toyota Mirai 2nd Generation.

Figure 9 FC LDV cost estimations graph



The results show that the final price for the consumer is expected to drop to almost a half of the current price. The main cost components, not considering the glider, are the FC system and the storage tank, both of which are expected to experience a considerable fall in manufacturing cost in the following decades. The manufacturing cost of the FC system is expected to drop by an 80% and the storage system cost could go down by almost 75%, a reduction mainly caused by the economies of scale and the expected advances on the research of these two relatively new technologies. Other components such as the battery or the electric motor are already fairly advanced technologies currently being used in electric cars, so the expected cost reduction is lower.

The estimations obtained are comparable to those resulting from other studies. The Toyota Mirai MSRP in 2017 was $57.000, which is similar to our estimated current price of $60.807. This figure is also close to the price estimations presented in James et al. (James, Huya-Kouadio, Houchins, & DeSantis, 2018) for a FCV at 1k and 3k sys/yr were $65.681 and $56.199, respectively. Regarding future cost predictions, estimation results for 2020, 2030, and 2050 were $27.963, $22.857 and $20.823, which align to those presented in the Islam et al. study of which range from $26.713 to $18.960 depending on the year, the technology progress and the category of the vehicle (Islam, Moawad, Kim, & Rousseau, 2020).

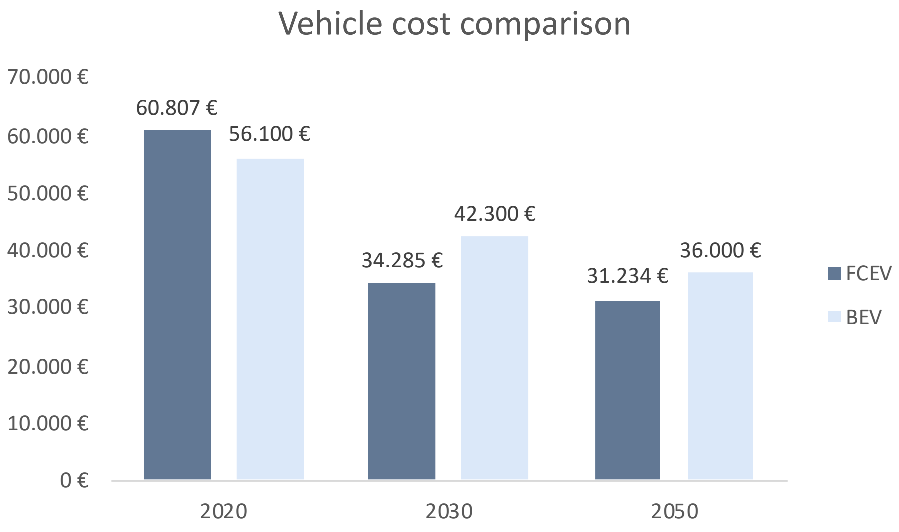


Figure 10 FC and BEV cost estimates for 2050

When compared to electric vehicles,

Figure 10 FC and BEV cost estimates for 2050 above shows that, currently electric vehicles are cheaper. However, that is expected to change for the end of this decade and continue to be so by 2050. However, in order for that to happen, manufacturing rates of 100k to 500k units per year need to be achieved. This result match those stated by the Hydrogen Council study which found that 400km range FCEV vehicles will break even with BEV by 2030. According to that study, taxi fleets with required range of 650 km will reach price parity with BEVs as soon as 2025 (Hydrogen Council, 2020). This is because centralized vehicle fleets, such as taxis or coaches, usually count with a centralized refueling infrastructure that, given the low refueling time per vehicle, allows for optimal utilization and cost reduction. In contrast, BEV will likely remain as a better alternative for small vehicles and short ranges, where batteries are smaller (Hydrogen Council, 2020).

6.1.2 MDV AND HDV

The following graphs summarizes the cost estimations for medium and heavy duty fuel cell vehicles. The graphs show that for Medium and Heavy duty vehicles the cost reduction is similar to that of LDVs, reaching a final price of around 50% the original by 2050. It can be observed that, due to the need of long driving ranges, the cost contribution of the H2 tank is higher in these vehicles, being more expensive than the FC system in the case of HDVs current cost.

Figure 11 FC MDV cost estimations graph

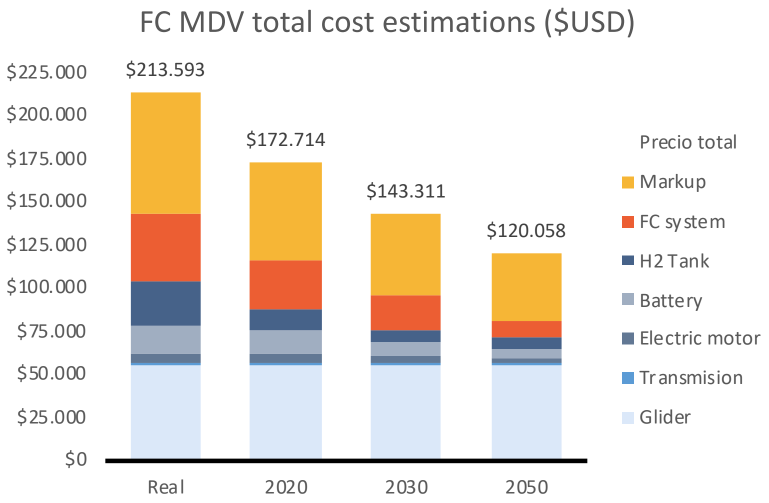
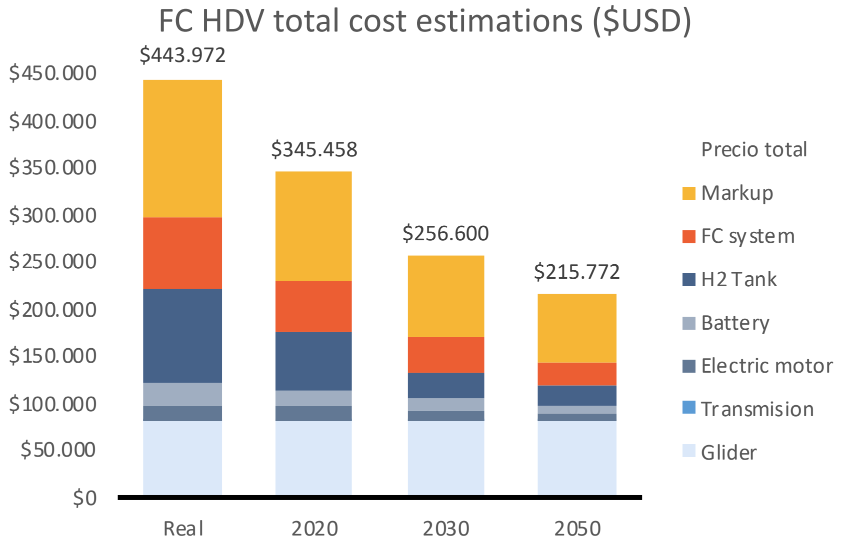


Figure 12 HDV cost estimations graph



Zhao et al. (Zhao, Wang, Fulton, Jaller, & Burke, 2018) truck analysis showed an estimated cost for FC trucks of $176.000 by 2030, which is very similar to the cost estimated in this project of $171.067. Hunter et al. study (Hunter, y otros, 2021) estimates class 8 truck manufacturer's suggested retail prices (MSRPs) to be $386.000 and $258.000 for 2018 and 2025, respectively, and an ultimate price of $180,000. These figures are comparable to our results of $345.458, $256.600 and $215.772 for 2020, 2030 and 2050. In Sharpe and Basma study (Sharpe & Basma, 2022) a cost reduction of 23% is predicted for FC Trucks between 2025 and 2030, with a 30% cost reduction of fuel cell system. These results are also analogous to the ones obtained in our study which are a 25,7% cost reduction between the 2020 and 2030 scenario with a decrease in the cost of FC systems of 30,3%.

With regards to electric vehicles, although this study doesn’t contain data about costs for medium and heavy electric vehicles, it’s worth mentioning that cost parity is also likely to be achieved in the present decade (Hydrogen Council, 2020).

6.2. BASE SCENARIO

With regards to the Spanish energy system, an analysis of the impact of LDVs in the year 2030 is performed. By introducing the parameters previously presented regarding hydrogen passenger vehicles, the model incorporates them into the minimization and calculates the optimal energy mix.

Regarding the minimization function, after passenger vehicles are included the resulting total cost of the energy system is 298,8G€. This cost includes both investment and operating expenditures, on top of CO2 costs, which are highly underestimated in this model. Regarding sustainability, the total CO2 emissions resulting from this system 164,12MtCO2. From those, 59,02 MtCO2 come from conversion of energy (CE) and 105,1 MtCO2 from the demand sector (DS).

PARAMETER	VALUE
Total Cost (G€)	298,80
CO2 Emissions CE (MTCO2)	59,02
CO2 Emissions DS (MTCO2)	105,10
CO2 Emissions Total (MTCO2)	164,12

Table 20 MASTER cost and emissions results for 2030 base scenario

Regarding vehicle distribution, the results of the model are divided in 5 different groups:

- Urban: Land transportation of passengers in urban (less than 10km)
- L50: Land transportation of passengers metropolitan not urban (between 10 and 50km)
- G50: Land transportation of passengers interurban (between 50 and 100km)
- G100: Land transportation of passengers interurban (between 100 and 500km)
- G500: Land transportation of passengers interurban (longer than 500km)

For this scenario, the activity level assigned for hydrogen passenger vehicles was:

PARAMETER	H2 ACTIVITY LVL (VKM)	% OF H2 OF TOTAL
URBAN	19155,15	11%
L50	30512,79	12%
G50	4910,51	13%
G100	15537,17	13%
G500	33384,63	42%

Table 21 MASTER transportation demand distribution for 2030 base scenario

As can be observed in the table, for driving ranges up to 500km FCEVs meet 11-13% of the total activity level in Spain. For distances longer than 500km, this number rises to 42% of the activity.

For urban and metropolitan distances, 60% and 64% of the demand is met through standard gasoline vehicles, respectively. At the estimated cost of FCEVs, the model doesn't consider optimal to assign electric vehicles any transportation demand. This is a result of the model tendency to experience the "penny switching effect", which leads to the complete switch to the technology with the lowest cost.

6.3. SENSITIVITY ANALYSIS

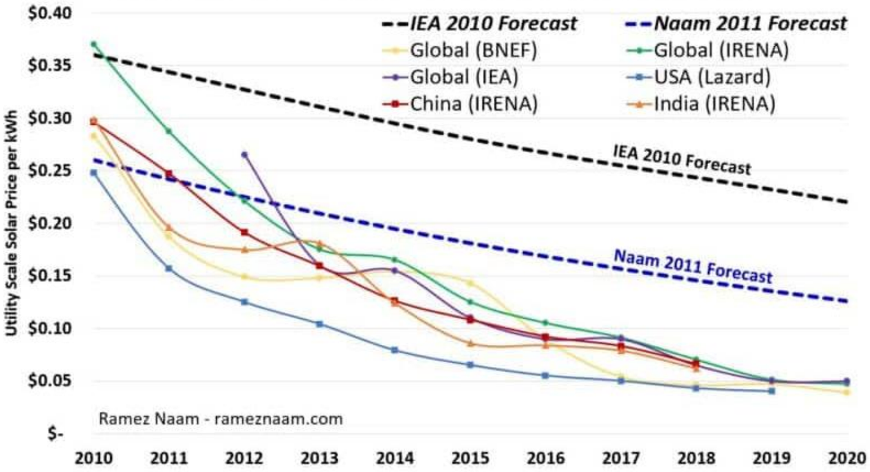
The MASTER model is a simplified representation of the Spanish energy system. On top of that, some of the parameters in the model are outdated and some others need to be included in future versions of the model. Therefore, gross results obtained from the model are not conclusive. Instead, a sensibility analysis can be conducted to analyze the impact which changes in the input parameters have in the outcome of the model.

In this analysis, the impact that the price of hydrogen vehicles has on the energy mix is compared with two scenarios, an optimistic and a pessimistic one.

6.3.1 OPTIMISTIC SCENARIO

Since 2010 the price of solar energy has dropped by a factor of 5 (Naam, 2020). If the current price is compared to the price that which most relevant agencies predicted in 2010 it can be observed that the difference is considerable. The figure below shows that the IEA 2010 price forecast for 2020 was 4 times higher than what it ended up being (Naam, 2020). What is more, the price reached by solar in 2020 was 30 to 40 years ahead of what the IEA forecasted in a new report in 2014 (Naam, 2020).

Figure 13: Solar real prices and 2010-2011 forecasts from 2010 to 2020



Source: (Naam, 2020)

Although this is an exceptional example, it shows that price forecasts for new technologies can strongly differ from reality. Hydrogen is a relatively new technology, and so was solar in 2010. As previously presented, hydrogen is currently stuck in a loop where its high costs and lack of infrastructure lead to low demand, which leads to low manufacturing rates and investment, which ultimately translates back into high costs. However, the current global scenario might force hydrogen out of this cycle, causing a rapid development of the technology following the learning curve. On top of that, many research fronts are open, such as hydrogen transportation through solid materials.

In this optimistic scenario, a 20% decrease in the predicted cost of FC passenger vehicles is assumed. Therefore, the manufacturing cost for 2030 is 20.571€. It is also considered that O&M cost, since they don't include fuel price, are highly correlated with the price of the vehicle since replacement part costs increase as the vehicle cost increases. Therefore, a 20% decrease is also considered for the O&M costs.

Hydrogen and electric are very similar technologies with regards to sustainable transportation and therefore, they will likely compete in the future for the role of clean solution for passenger transportation. Currently, battery electric vehicles are cheaper, but according to the cost estimations made in this study that could change in the following decade. For that reason, one of the main utilities of this analysis is to compare how different relative prices between these two technologies can impact their role in the Spanish energy mix. Therefore, another reason to consider

FC vehicles to be cheaper in this scenario is that, by comparison, consumers give value to some of the intrinsic advantages of hydrogen vehicles over electric vehicles such as the faster refueling or the longer driving range and therefore are willing to pay a higher price. Moreover, as it was presented previously in this paper, many users are willing to pay a higher price for a zero emissions vehicle. Therefore, reducing H2 vehicles cost can reflect this consumer preference against other less sustainable options.

Finally, by comparison, instead of considering that hydrogen vehicles end up being a 20% cheaper by 2030 it could be considered that electric vehicles cost is a 20% higher. This could happen for a number of reasons such as lack of materials which can cause an increase in manufacturing costs.

The results of this scenario are presented in the following table:

PARAMETER	BASE SCENARIO	OPTIMISTIC	%CHANGE
Total Cost (G€)	298,80	296,91	-0,63%
CO2 Emissions Total (MTCO2)	164,12	162,91	-0,74%

Table 22 MASTER cost and emissions results for base and optimistic scenario comparison

The results of the model show that, due to the reduction in FCEVs cost, the total cost of the model is reduced by 0,63%. The total CO2 emissions are also reduced by 0,74% in the optimistic scenario.

Regarding the transportation demand, there are no major changes with respect to the base scenario.

PARAMETER	H2 ACTIVITY LVL (VKM)	% OF H2 OF TOTAL
URBAN	175588,84	11%
L50	264979,52	12%
G50	36918,32	13%
G100	116811,87	13%
G500	78983,15	94%

Table 23 MASTER transportation demand distribution for 2030 optimistic scenario

For driving ranges up to 500km the demand distribution is the same. The main variation occurs within the G500 group, where hydrogen vehicles activity grows from 42% in the base scenario to 94% in the optimistic scenario, meaning that 94% of the land transportation is met by H2 vehicles, which shows the potential of hydrogen to compete even with fossil fuel alternatives. Since electric vehicle price hasn't changed and H2 costs are reduced, demand met by electric vehicles in this scenario is still nonexistent.

6.3.2 PESSIMISTIC SCENARIO

Both the base and optimistic scenario assume that certain technological progresses, on top of high manufacturing rates, are going to be achieved with respect to hydrogen vehicles. However, these scenarios are still far away. In the last few years, some studies have analyzed the decrease of fuel cells performance over time, leading to the correction of price forecasts to include this factor. Currently, the majority of the research in vehicle technologies is placed on electric vehicles, mainly driven by the search for more durable and faster rechargeable batteries. A scenario where hydrogen vehicles cost ends up being higher than predicted is possible.

In this pessimistic scenario, a 20% increase in the predicted cost of FC passenger vehicles is assumed. Therefore, the manufacturing cost for year 2030 is 27.428,4€. Following previous scenario reasoning, O&M are also increased by 20% in this scenario.

The results of this scenario are presented in the following table:

PARAMETER	BASE SCENARIO	PESIMISTIC	%CHANGE
Total Cost (G€)	298,80	301,48	0,9%
CO2 Emissions Total (MTCO2)	164,12	162,91	1,31%

Table 24 MASTER cost and emissions results for base and pessimistic scenario comparison

As a result of the higher cost of FCEVs, the total cost of the energy system is 0,9% higher and CO2 emissions are up 1,31%. With regards to transportation, in this scenario changes are notable.

PARAMETER	H2 ACTIVITY LVL (VKM)	% OF H2 OF TOTAL	%BEV
URBAN	0	0%	11%
L50	0	0%	12%
G50	0	0%	13%
G100	0	0%	13%
G500	33384,63	42%	0%

Table 25 MASTER transportation demand distribution for 2030 pessimistic scenario

It can be observed that, with the 20% increase in FCEV costs, electric vehicles are now a preferred choice for transport mobility for ranges up to 500km, meeting 11-13% of the demand. This percentage of activity is the same covered by FCEVs in previous scenarios. Again, this is a result of the model tendency to suffer the "penny switching effect", and therefore completely switching to electric as soon as it becomes slightly cheaper. The model only considers economic factors, and therefore it'll choose the option which provides the lowest total cost of the system. Being electric and hydrogen vehicles so equivalent, the variations in the relative prices between them lead to the model to choose either one or the other.

For ranges higher than 500km, electric vehicles where not considered in this model due to the limitations in driving ranges, therefore, it is expected that none of the demand for this sector is met by these vehicles.

7. CONCLUSIONS

Hydrogen offers a bridge for the complete decarbonization of transportation sector, something that, for the moment, cannot be achieved with the rest of the existing technologies.

Currently, the technology is not economically viable, but the price of hydrogen is expected to fall considerably in the coming years, but for this to happen it is necessary to increase production and demand. With proper planning, hydrogen could become a competitive alternative in the next decade. The advantages that hydrogen vehicles provide are clear, including completely emission-free driving, greater driving range, faster recharging and greater power. In addition, its use combines very well with the increasing presence of renewable energies in the electrical system, providing stability and flexibility to the network.

The cost estimates obtained in this thesis show that, by 2050, the price of hydrogen vehicles will be approximately half of the current price, reaching cost competitiveness with electric vehicles by 2030. The most relevant factor is the economies of scale, so for prices to become competitive if manufacturing rates of 100.000 to 500.000 units per year need to be reached. The fuel cell system and the hydrogen storage tank are two components that have a high impact on the final cost of the vehicle, but they are also very new technologies, so important advances can be expected in the coming years. Cost estimates are summarized in the following table:

VEHICLE	REAL	2020	2030	2050
LDV	\$60.807	\$41.944	\$34.285	\$31.234
MDV	\$213.593	\$172.714	\$143.311	\$120.058
HDV	\$443.972	\$345.458	\$256.600	\$215.772

Table 26 FCEVs cost estimates summary

Although hydrogen cars will be competitive with electric cars by 2030, the greatest potential for hydrogen vehicles is for heavy-duty, long-distance vehicles such as buses and trucks where the advantages of hydrogen are larger. Specifically, those with a centralized organization such as bus fleets will be the first ones to become economically viable due to the optimal use of infrastructure.

In this project, the data for the light duty vehicles is implemented into the model of the Spanish electrical system. The results show that, if the estimated costs for 2030 are reached, hydrogen cars would become a preferable solution to electric cars in terms of system cost efficiency and sustainability. However, the model is a simplified representation, so there are great limitations in the results. Relevant data such as the investment cost needed for the hydrogen vehicle refueling infrastructure is not included in the model, which could impact the result. Despite everything, the results are positive and show that the hydrogen economy has potential within in the Spanish energy system.

The sensitivity analysis carried out in this work shows the impact that variations in the price of hydrogen vehicles have on the results of the model. The findings revealed that decreases in the estimated prices result in a lower total cost of the system and a reduction in CO2 emissions, by increasing the level of transport demand covered by hydrogen vehicles for long-distance journeys. For the pessimistic scenario, in which prices by 2030 are higher than predicted, the model chooses electric vehicles as the preferred solution, showing that both vehicles will probably share the demand for clean transport in the future. In both scenarios, the model contemplates that approximately 12% of the transport demand is made up of electric or hydrogen vehicles. Although these vehicles can be seen as enemies, the truth is that the future will probably include a mixture of both. For short trips, electric cars are a preferrable option due to their higher energy efficiency and lower cost, while for heavy load and long-distance trips the incremental cost of batteries make hydrogen vehicles a better solution.

In future studies, the costs of medium and heavy hydrogen vehicles obtained in this work can be added to the model in addition to electric vehicles cost estimations, adding further depth to the demand of the model. Moreover, additional work is needed to calibrate the model to avoid the so called “penny switching effect”. In addition, if the rest of the parameters of the model are updated, an analysis of the Spanish energy system can be carried out for the year 2050.

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9. APPENDIX

9.1. ABBREVIATIONS

ABBREVIATION	DESCRIPTION
AE	Alkaline Electrolysis
AFC	Alkaline Fuel Cells
ATR	Autothermal Reforming
BEV	Battery Electric Vehicle
CAPEX	Capital expenditure
CHP	Combined Heat and Power
CO2	Carbon Dioxide
DOE	United States Department of Energy
EV	Electric vehicle
FC	Fuel Cell
FCEB	Fuel Cell Electric Buse
FCEV	Fuel Cell Electric Vehicle
FCT	Fuel Cell Train
H2	Hydrogen
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric Vehicles
HFCV	Hydrogen Fuel Cell Vehicle
HICEVS	Hydrogen-fueled Internal Combustion Engine Vehicles
HPP	Hydrogen Production Pathway
HRS	Hydrogen Refuelling Station
HV	Hidrogen Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
LDV	Light Duty Vehicle
LOHC	Liquid organic hydrogen carriers
MASTER	Model for the Analysis of Sustainable Energy Roadmaps
MDV	Medium Duty Vehicle
MSRP	Manufacturer's Suggested Retail Price
MVKM	Million vehicle-kilometres
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OPEX	Operational expenditure
PEM	Proton Exchange Membrane
PEM	Polymer electrolyte membrane

PEMFCS	Proton Exchange Membrane Fuel Cells
PHEV	Plug-in Hybrid Electric Vehicle
PNS	Purple non-sulfur
RES	Renewable Energy System
SMR	Steam Methane Reforming
SOEC	Solide Oxide Electrolyser Cells
SOFCS	Solid Oxide Fuel Cells
SYS/YR	Systems per year
TPRD	Thermal Pressure Relief Device

9.2. SUSTAINABLE DEVELOPMENT GOALS (SDG)

Hydrogen economy provides a potential opportunity for the reaching of a clean and sustainable energy supply and the decarbonization of the global industry sector. In special, green hydrogen, which is produced from renewable sources, represents a breaking point in the integration of RES by providing a long-term solution for the intermittency and lack of predictability. The hydrogen economy still faces multiple challenges, but it could significantly reduce the carbon emissions and pollution across multiple sectors, especially those hard-to-abate.

This project aims to further advance the research on hydrogen vehicles and its integration in the energy mix. Therefore, its relationship with the United Nations Sustainable Development Goals is implicit. Its main point of alignment is with the SDG7, which is to “Ensure access to affordable, reliable, sustainable and modern energy for all”. Although hydrogen is still a costly alternative, it is expected that improvements in technology and economies of scale, in addition to sufficient government policies, will make it an affordable and clean alternative. On top of that, green hydrogen is likely to replace a relevant portion of fossil fuel energy and provide support for further implementation of renewable systems. Therefore, hydrogen development is also aligned with SDG13 of “Take urgent action to combat climate change and its impacts”.

As a collateral, hydrogen can have further positive impacts in other SDGs such as SDG9 (Industry innovation and infrastructure), by contributing to sustainable industrialization, or SDG11 (Sustainable cities and communities), by reducing carbon emissions and air pollution in cities through the use of hydrogen-powered heat and fuel cell vehicles.