ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

Especialidad Eléctrica

Estudio del abastecimiento de hidrógeno como combustible de transporte e influencia en el sector eléctrico

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Madrid

Mes y año

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Coordinador: Fernando de Cuadra

Resumen del proyecto

Introducción

El proyecto en cuestión intenta determinar el impacto que tendría una economía del hidrógeno en el sector del transporte español. El hidrógeno es el primer elemento de la tabla periódica y el más ligero de todos. Dicho elemento al entrar en contacto con el oxígeno produce energía y agua. Dicha reacción es en la que se basan los vehículos de pila de combustible. Al ser una reacción libre de emisiones, es de gran interés en un mercado que busca la decarbonización del transporte.

Los vehículos de pila de combustible son muy parecidos a un vehñiculo eléctrico siendo sus únicas diferencias los tanques de hidrógeno y la pila de combustible. La pila de combustible se encarga de mezclar el hidrógeno con exígeno y de transformar esa energía que es desprendida en electricidad para propulsar el vehículo.

Modelo

El modelo de generación de hidrógeno se divide en tres submodelos en los cuales se estima el coste total de una penetración del vehículo de hidrógeno determinada. El primer modelo estima la demanda eléctrica que tendría producir el hidrógeno para cubrir toda la flota de vehículos española. Mediante constantes físicas como el ratio de transformación de la electrólisis o su rendimiento se llega a un valor en GWh que representa esa demanda de hidrógeno. Cabe destacar que el modelo aunque se realizen diferentes escenarios, su último objetivo es simular el PNIEC (Plan de energía integrado español). Por lo tanto también se realizan escenarios con el vehículo eléctrico lo que sirve para ver una comparación y ver si el vehículo de hidrógeno es una opción para el sistema de transporte español.

El segundo modelo se implanta en CEVESA, un modelo de equilibrio de energía y reserva del sistema ibérico, con inversiones centralizadas y generación distribuida. CEVESA utiliza cronología horaria y para reducir el tiempo computacional cada año es analizado por una semana representativa.

El hidrógeno se considera que es producido por eléctrólisis ya que es el método más efectivo para producirlo sin emitir gases de efecto invernadero. Para modelar su producción se tienen en cuenta tanto los costes de instalación de plantas de electrólisis como sus costes variables y la instalación de plantas eléctricas en caso de que fuera

necesario para abastecer la demanda del sector.

Finalmente el tercer modelo se encarga de los costes de transporte y de instalación de hidrolineras. Se toma como hipótesis que las centrales de electrólisis se localizan cerca de los núcleos urbanos para facilitar el transporte. Esta suposición se realiza partiendo del hecho que dichas centrales son libres de emisiones y que en caso contrario los costes del transporte suben exponencialmente. Para los costes de las hidrolineras siempre se considera que son del mayor tamaño posible para reducir el coste de instalación y los variables totales.

Conclusiones

Este estudio tras analizar los resultados ha concluido que el vehículo de hidrógeno no es una solución económicamente viable para el transporte. No solo sus costes son mucho mayores al vehículo eléctrico sino que su pobre eficiencia incrementa el consumo eléctrico provocando que las emisiones incrementen. Sin embargo, este modelo

parte del 2019 cuando todavía no se cuenta con mucha capacidad en renovables. En un escenario en el que las renovables tuvieran mayor peso, el hidrógeno podría servir para almacenar el extra de energía renovable y desbancar a las baterías actuales.

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Project summary

Introduction

The project tries to determine the impact which a hydrogen economy would have on the transportation sector in Spain. Hydrogen is the first element in the periodic table and the lightest of all. This element when it mixes with oxygen produces energy and water. This reaction is the one in which hydrogen fuel cell vehicles are based on. Being a free CO_2 reaction, is of great interest in a market which seeks transport without emissions.

Hydrogen fuel cell vehicles are similar to electric ones being its' only differences the hydrogen tanks and the fuel cell. The fuel cell is the one which mixes hydrogen with oxygen and transforms this energy in electricity to move the vehicle.

Model

The hydrogen generation model is divided into three sub models in which the total costs for a certain H2EV penetration are determined.The first model estimates the electrical demand for hydrogen production with a certain penetration level. Physical constants as the transformation ratio of electrolysis or its' efficiency are used to calculate the GWh necessary. The last objective of the model is to simulate the PNIEC, however , several scenarios are done to asses the impact of hydrogen in the grid. Scenarios where electrical vehicles have a certain penetration are also made to compare H2EV with them and determine if they are a good option.

The second model is made with CEVESA, an equilibrium model of energy and reserve of the Iberian system, with centralised investments and distributed generation. CEVESA uses hourly chronology and to reduce computational time every year is represented by a representative week.

Hydrogen is considered to be produced by electrolysis due to the fact that is the most effective method to produce H2 without GHE. To model its' production ,installation costs and variable costs of hydrogen plants are taken into account. Electrical plants installation are also taken into account in the event of needing more generation to meet the demand.

Finally, the third model is the one in charge of transportation costs and hydrogen station installation. An hypothesis is made about hydrogen plants. Hydrogen plants are nearby big cities so transportation costs are as low as possible. This hypothesis is made taking into account that hydrogen plants don't generate GHE and therefore they wouldn't contribute to the pollution of the cities. For hydrogen station costs we consider that they are of the maximum capacity possible to reduce installation costs.

Conclusions

This study after analysing the results has concluded that the hydrogen vehicle is not economically feasible for transport. Not only its costs are higher that the EV ones, but also its' low efficiency increases electrical consumption leading to greater emissions.

However, this model is done beginning in 2019 when renewable sources are still a minority of the total installed power. In a scenario where renewable power has greater importance hydrogen could be used to store energy removing batteries from the market.

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1 Nomenclature

1.1 Variables & parameters

In the table 1 all the variables, parameters and contractions which are used in the thesis are explained:

Conversion electrolysis [KWh/KgH2]	σ
H2EV average autonomy [KgH2/Km]	α
Electrolysis efficiency [%]	η
Daily H2 demand [KgH2/day]	Q_{ydh}^{H2}
Penetration of H2EV on the Spanish fleet [%]	P_y
Daily H2 electrical demand [GWh/day]	Φ
Conversion factor [KgH2/GWh]	β
H2 plant installation costs [€/KgH2]	Cy
H2 plant variable costs [€/KgH2]	Ce
Electrical demand [KWh]	De_{ydh}
Hydrogen production [KgH2]	q_{ydh}^{H2}
Capacity of H2 plant [KgH2]	cap_y^{H2}
Total demand [KgH2]	de_{ydh}^{H2}
Total H2 transport costs per year [€]	$H2TC_y$
H2 daily demand by transport means [KgH2/day]	Dh_{tr}
H2 transport costs [€/KgH2]	CT_{tr}
Total hydrogen station costs per year [€]	$H2SC_y$
H2 station capacity [KgH2/day]	Cap^{H2}
H2 station capital costs [€]	SC
H2 station variable costs [€/KgH2/day]	SCV

Table 1: Nomenclature

1.2 Glossary

In table 2 all the abbreviations used are explained:

Combined cycle	CC
Nuclear plants	NU
Coal plants	$Coal$
Hydroelectric plants	$hydro$
Eolic plants	$wind$
Hydrogen fuel cell vehicle	$H2$
Electric vehicle	EV
Green house gases	GHG
Steam methane reforming	SMR
Gaseous hydrogen	$GH2$
Liquefied hydrogen	$LH2$
Carbon capture	CC
Operating and maintenance	$O\&M$
Horse power	CV

Table 2: Glossary

2 Introduction

> Yes, but water decomposed into its primitive elements... and decomposed doubtless, by electricity, which will then have become a powerful and manageable force, for all great discoveries, by some inexplicable law, appear to agree and become complete at the same time. Yes, my friends, 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. Some day the coalrooms of steamers and the tenders of locomotives will, instead of coal, be stored with these two condensed gases, which will burn in the furnaces with enormous calorific power. Water will be the coal of the future!
>
> *Jules Verne*
> *"The Mysterious Island" (1874)*

The energy transition most countries are going through nowadays has the main objective of the decarbonization of the energy system, and the way to reach it is by the electrification of heat and transport. Renewable power has taken an important role in our electrical system due to the decrease in their costs which are already competitive with other types of generation. All this with the closure of GHG emitting plants is a challenge.

Electrification of the transport sector has two main alternatives, electric vehicles (EV) which are powered by electric motors and hydrogen fuelled vehicles (H2EV),[ABBO09]. Regarding hydrogen fuelled vehicles there are two main options: H2 combustion engine vehicles or hydrogen fuel cell vehicles (H2EV) [LUO_15].

Currently EV have a greater acceptance due to its time in the market. However, debate over whether EV are the solution for a transition towards an electrification of the transport system, is an open issue. Batteries use rare raw materials, for this reason other alternatives such as H2EV should be studied [NOTT10]. As an example of this, Japan nowadays is supporting H2EV [JAPA19], this country thinks H2EV as an alternative to be taken into account.

Electricity has many advantages, however, mobility issues are always a problem [ADOL17]. Electricity can only be stored in batteries for short periods of time and in small amounts. Nevertheless, hydrogen can be stored for long periods and can be produced using the surplus renewable energies. As a disadvantage hydrogen can't be charged from the grid or inject it directly as energy.

Hydrogen fuel cell vehicles are much more expensive than electrical vehicles due to several factors, the main reason however, the short time in the market and the few companies which deliver this types of vehicles.

3 State of the art

In this section the available information about hydrogen will be put forward, introducing the reader into the theme.

3.1 Hydrogen: Principles and applications

Hydrogen is the lightest element in the periodic table, being only one proton and an electron orbiting around. We can also find the heavy hydrogen, an isotope with a neutron.

This element has been used for many years in the industry for several applications. The most common ones are ammonia production, the fifth material with more production in the world and methanol production. Moreover, it is used for hydrogenation of fats and oils, hydrodesulphurization, hydrocracking and hydroalkylations. In addition, it has been widely used in the spacial industry for its' light weight. The most famous mission in which it was used is likely the Gemini programme. The first spacial flight to ever use fuel cells.

Nowadays the most ambitious project with hydrogen is the ITER project. This project being held in the south of France involves 35 countries and intends to use Deuterium (an isotope of hydrogen) to produce electricity from nuclear fusion.

3.2 Hydrogen as an energy vector

This section will talk about hydrogen as an energy vector and its' importance for the future of clean energy.

Hydrogen is an energy vector since energy can be stored as H2 for later use by the means of fuel cells. Nevertheless, electricity has to fulfil a demand instantly. On the other hand, hydrogen can be stored to be used whenever we choose to. This characteristic is unique to hydrogen and its' the main reason for our interest in it.

Another interesting feature is that no CO_2 emissions are left after its' burn. The after product is just water. Hydrogen particles mix with oxygen in an exothermic reaction producing H_2O.

3.3 Hydrogen production

Nowadays we have a wide variety of methods to produce hydrogen, however, there is not an ideal method and depending on the applications and the hydrogen volume needed ones are chosen before others. In the following list we state some of the most used hydrogen production methods:

- Reformed hydrocarbons.
- Electrolysis.
- Thermochemical decomposition of water.

- Photo conversions.
- Biological.
- From biomass.
- Industrial procedures.
- Biophotolysis of water.

In figure 1 there are several methods for producing hydrogen with all the steps in between. The methods which require electricity produce hydrogen by electrolysis while if fossil energy is used, it is produced by SMR (steam methane reforming). This method has as a byproduct CO_2. This two methods are the most common ones nowadays.

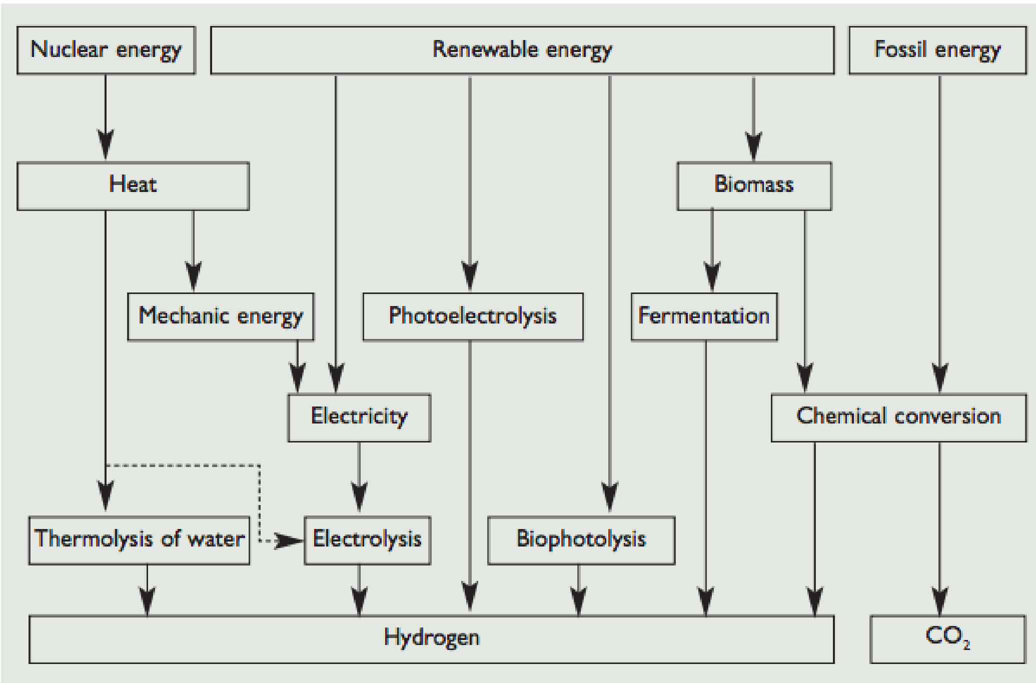

Figure 1: Hydrogen production methods[LINA07]

The most promising hydrogen production methods will be discussed shortly in the following sections.

3.3.1 Reformed hydrocarbons

Even if this is the most polluting method, they are several interesting projects with this which should be mentioned. The Hydrogen Energy California's Integrated Gasification Combined Cycle Project[CEC13] is a project approved by California in 2013. This project uses a mixture between coal and oil to generate energy and hydrogen. Nevertheless, is one of the few plants which uses Carbon capture so its' emissions are a 90% less than a conventional plant of this technology.

In figure 2 a simple diagram of a combined cycle with CO_2 capture is represented. As it is seen, CO_2 is stored and therefore emissions are not a problem with this type of configurations.

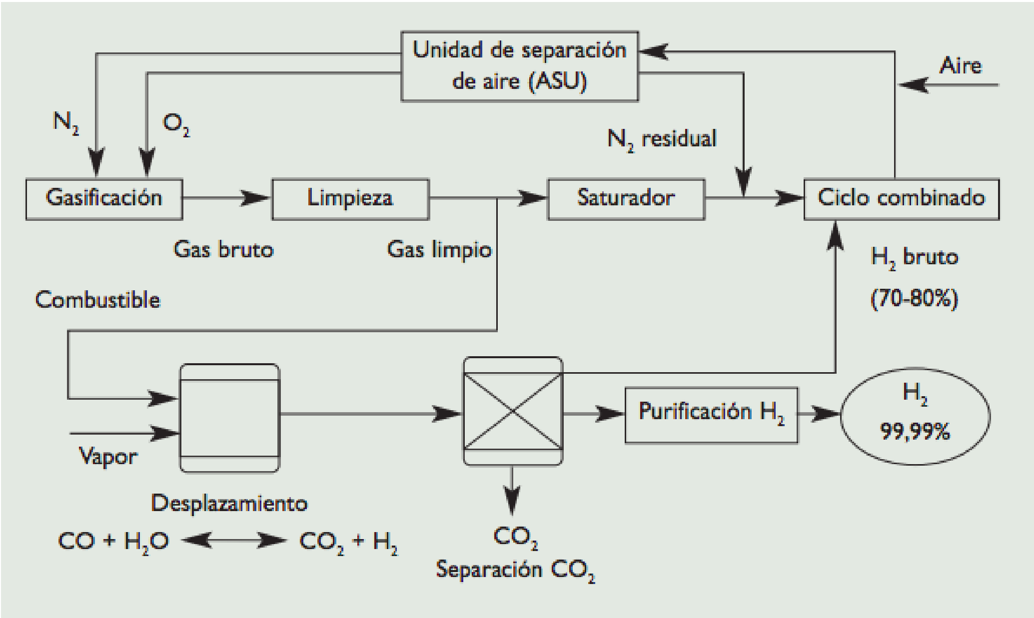

Figure 2: Hydrogen production with carbon capture in a combined cycle of coal.[LINA07]

3.3.2 Electrolysis

Electrolysis is the method with the most potential of all and the oldest one too. Water is divided into oxygen and hydrogen by a catalyse made from Platinum. This technology is called PEM (Proton Exchange Membrane). This process requires energy, however, if it comes from renewable generation it will have no CO_2 emissions. The greatest challenge of this is its' high cost from the catalyse and the hydrogen volume which is able to produce. Hydrogen produced by this method if about 4,9-5,6 KWh per m^3 of hydrogen produced, which means is about two times more expensive than hydrocarbon reforming [FIER11]. Due to this prices, there is a lot of studies on this, developing plants which do electrolysis in vapour phase. Thanks to this technology efficiencies of 75% have been accomplished [PUYA16]. As an example of its' potential Denmark produces all its' hydrogen with this procedure and all comes from renewable energy.

3.3.3 Photo conversions

Photoconversion is a procedure which produces hydrogen directly from solar energy. Solar energy divides water into hydrogen and oxygen. Researchers form Kentacky university have discovered an alloy from Gallium and Antimony nitrite which has the ideal properties for that purpose.[MENO11] [MENO11]

3.3.4 Biophotolysis of water

Certain photosintetic microorganisms are able to break the H_2O links in hydrogen and oxygen. This procedure can be made by exposing this organisms to light and in some other cases in anaerobic conditions. This kind of methos represent a great challenge to biotechnology due to the fact that it is too a clean technology. However, nowadays efficiencies from this method are of only 5% [FIER11].

3.3.5 Production methods comparation

In figure 3 there are the production costs for each technology. As it was expected, production from coal plants without CO_2 capture are the cheapest ones. This is because there are the most common way to produce hydrogen and because coal plants are cheap to install and to operate. Electrolysis from renewable sources is the most expensive due to the still high costs of renewable installation and because of the efficiency of this procedure.

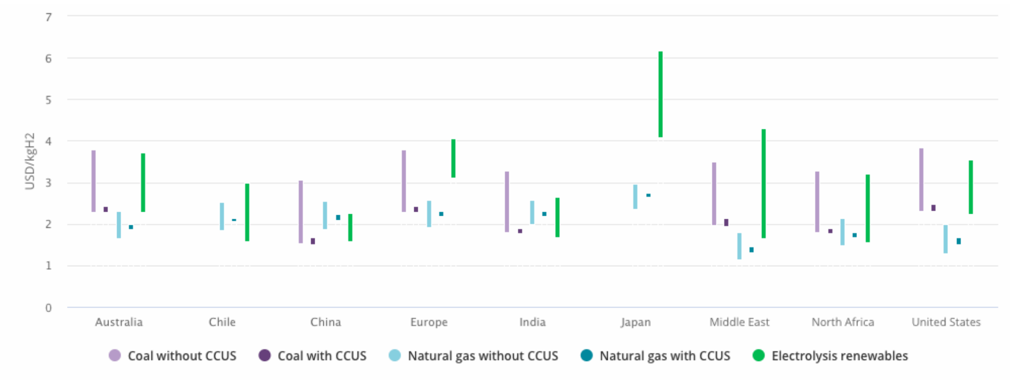

Figure 3: Production cost by method [IEA_19]
CCUS: Carbon capture

3.4 Hydrogen transport

Hydrogen transport is one of the greatest problems. Its' poor volumetric density means it is needed to be compressed it so its' transport can be viable. If we put it into numbers it takes up three more times the volume gasoline does.Therefore, transport is difficult due to this physical properties. In the following sections several methods for transporting H2 are going to be talked about.

In figure 4 different transportation methods are mentioned. As the figure suggests, there are basically only three different ways to transport hydrogen, ship,truck or by pipeline.

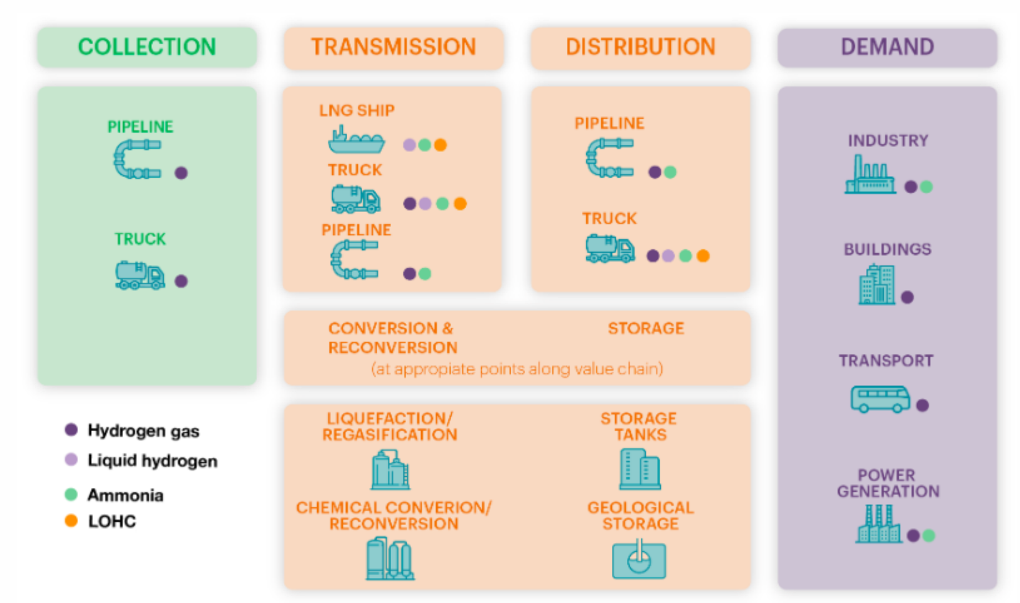

Figure 4: Distrubution chain of hydrogen[IEA_19]

3.4.1 Power to Gas

Probably the most promising way to transport hydrogen. This way consists on using the gas pipelines and merge it with natural gas. The United Kingdom is on the process of doing so [NGN_18]. They will merge a 20% of hydrogen with natural gas which will not affect particular homes since installations will not need to be changed. Moreover, changes in the gas pipelines will be minimum.

Not all gas pipelines can withstand high hydrogen concentrations on it. In figure 5 there are the different limits for hydrogen transportation by pipelines in different countries.´As it can be seen, the % of H2 which can be transported with natural gas it very little. However, in Spain we are one of the best countries in Europe for this type of transport, since our percentage is above average.

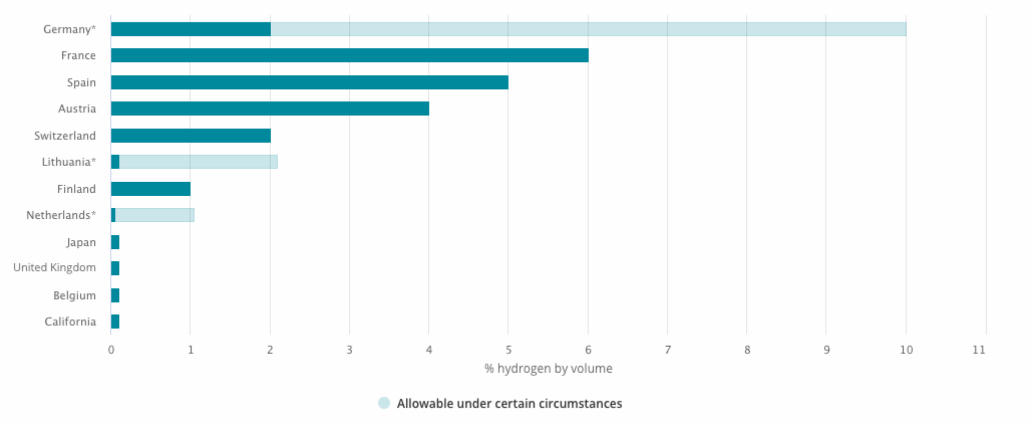

Figure 5: Hydrogen limits in the gas pipelines[IEA_19]

One of the drawbacks from this way of transporting it, is that hydrogen burns with a characteristic blue flame nearly invisible to human eye. This makes it difficult to detect leaks [NGN_18].

3.4.2 GH2

Hydrogen can be transported by special tanks which prevent embrittlement. Embrittlement is a process in which hydrogen can affect the properties of metals.This phenomena is dangerous since it can make the hydrogen container to eventually not withstand the pressures inside it. After compressing the gas this is transported by truck to the hydrogen station. The main drawback is the fossil fuels used by the trucks and the poor volume of hydrogen which can be transported per truck.

3.4.3 LH2

A way to increase the volumetric density of hydrogen is by reducing its temperature to -252,87°C [GUER03] so it becomes liquid. This procedure is also done with natural gas when it is transported by ship. The main problem is the energy needed to reach such temperatures. This extra cost reduces hydrogen efficiency.

3.4.4 Carbon nanotubes

Carbon nanotubes can absorb hydrogen into them.By introducing hydrogen inside a solid material we increase the capacity a tank can take. This procedure increases its volumetric density as its gravimeter. However, its levels are still too low for transport so right now it is still inefficient.

3.4.5 Cost study for different transport methods

In the graph below several methods are being compared. As it is done in the graph a clear differentiation has to be done between long or short distances as it is a critical factor.

Figure 6 shows the different costs for transporting hydrogen by different methods and states of hydrogen. It can be seen the great difference between travelling short distances and large ones. For this reason, it is beneficial to produce hydrogen near the ultimate consumer. The most expensive one is transporting GH2 by truck, this is due to the low density of gaseous hydrogen, leading to many tanks for not so many Kg of H2.

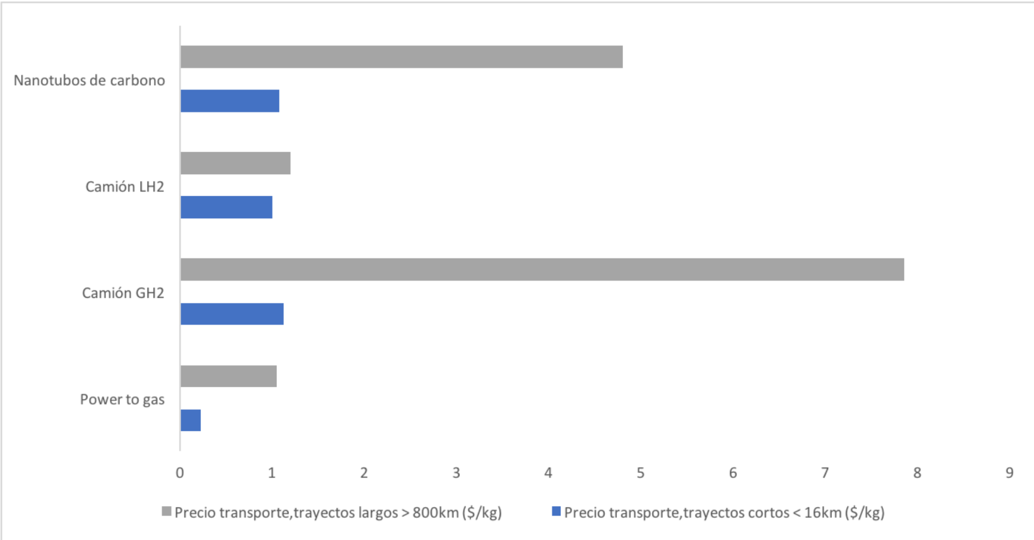

Figure 6: Hydrogen transport costs[PAHW14]

3.5 Hydrogen stations

Hydrogen stations for H2EV refuelling are similar to any other conventional gas station. In Spain there are only 6 hydrogen stations, which is not very encouraging for the H2EV deployment. See figure 7.

Figure 7: Hydrogen stations map of Spain[CNDH19]

3.5.1 Costs

Hydrogen stations costs vary from where hydrogen is produced and how.Depending on where the hydrogen station is, it will have to transport hydrogen from further away increasing variable costs of the station.Compression is also important since for SMR(Steam methane reforming) hydrogen is produced more compressed and therefore this costs are slightly lower.

Table 3 shows the capital costs for different types of hydrogen stations. If hydrogen has to be delivered by truck, capital costs increase greatly since trucks have to be bought. While for onsite hydrogen plants transportation is not needed and therefore costs are lower.

Station	Truck delivery($/kg/day)		Onsite SMR ($/kg/day)		Onsite Electrolysis ($/kg/day)	
Capacity (kg/día)	GH2	LH2	Current	Future	Current	Future
100	13.909	9.025	11.230	7.321	10.601	7.871
400	5.111	4.305	5.182	3.482	5.242	3.811
1000	4.079	3.435	4.031	4.031	4.394	2.950

Table 3: Capital costs from different technologies, 2014 data[MELA15]

Table 4 represents the variable cost of a hydrogen station with the land rental needed for the capacity of the station. Variable costs are higher for GH2 and LH2 since as it was seen before transportation is expensive. Electrolysis is slightly higher than SMR due to compression issues.

Station type	Station Size (kg/day)	Variable O&M Value	Land rental
Mobile refueler	100	\$20/kg GH2	\$130.000
GH2 truck delivery	100	\$20/kg GH2 + 1,25 kWhe/kg	\$130.000
LH2 truck delivery	250-1000	\$10/kg + 0,81 kWhe/kg	\$36.000
Onsite SMR	250-1000	0,156 MMBtu/kg + 3,08 kWhe/kg	\$360.000
Onsisite electrolysis	250-1000	55,2 kWhe/kg	\$360.000

Table 4: Variable costs of a hydrogen station [MELA15]

Taking into account energy prizes $\approx 0,05$ €/kWh, natural gas in Spain and a lifetime of ≈ 15 years, we can make a graph representing the total costs for a station of 1000 Kg/day:

The difference between figure 8 and 9 is the capacity of the station. It can be seen that for higher capacity capital costs increase while variable costs decrease. For this reason for a hydrogen economy is more financially beneficial to install hydrogen stations of high capacity.

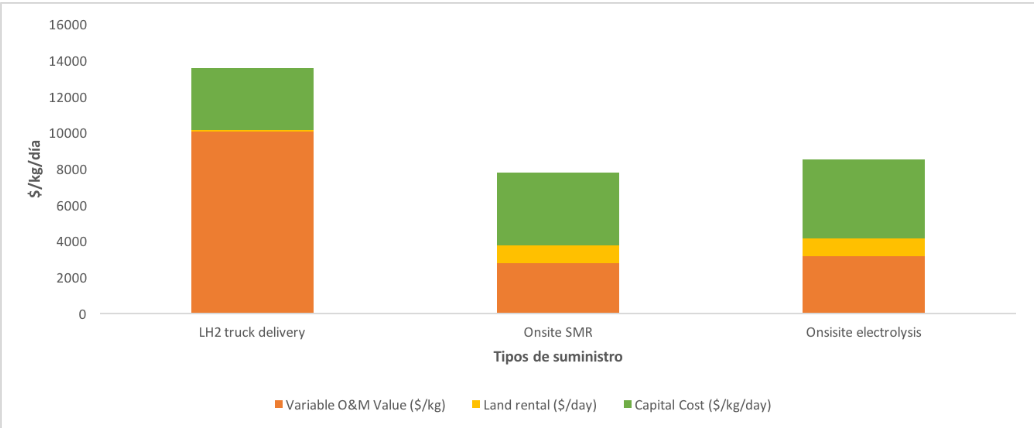

Figure 8: Capital costs and maintenance of a hydrogen station by technology (1000 Kg/day) [MELA15]

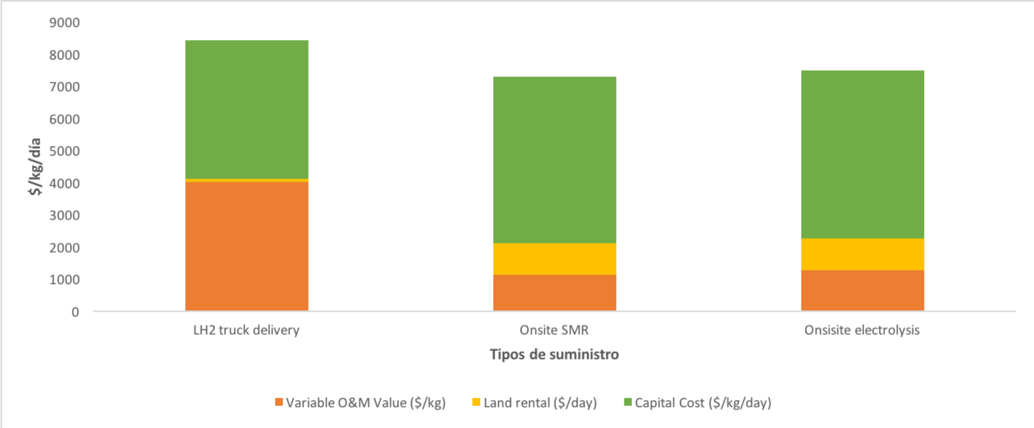

Figure 9: Capital costs and maintenance of a hydrogen station by technology(400 kg/day) [MELA15]

We can also see the possible projection of hydrogen stations with the data from the National Renewable Energy Laboratory. Taking into account the reduction in cost of the catalyses and the progression of this technology:

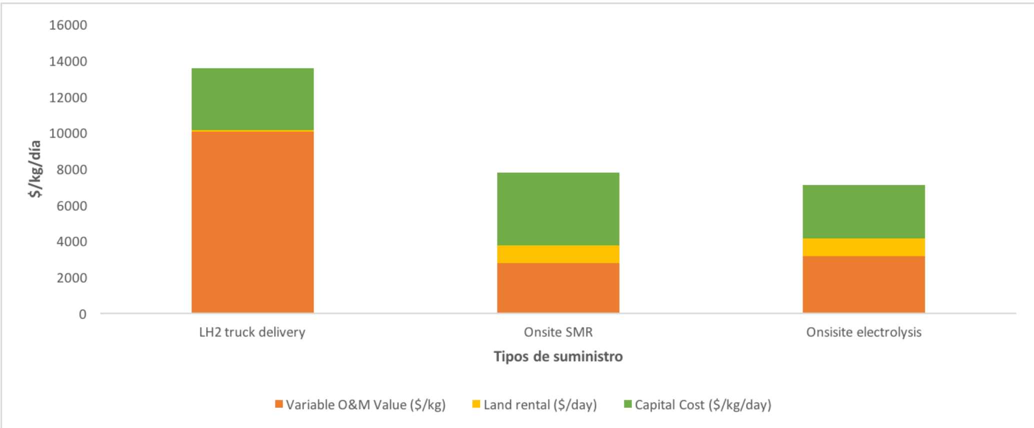

Figure 10: Possible capital costs and maintenance from a hydrogen station by technology in 2025 (1000 Kg/day)[MELA15]

Comparing figure 9 and 10 we observe in a near future the reduction of capital costs of electrolysis plants. Turning them into the most economic ones.

3.6 Hydrogen vehicles

Hydrogen vehicles are becoming more important in our society lately. Highly renown companies such as Hyundai,Toyota or BMW are working in this technology. Both the Hyundai Nexo and the Toyota Mirai are vehicles which can be called full hydrogen. Their price is still out of reach for many, 70.000 € for the Toyota Mirai and 69.000 € for the Hyundai Nexo. However, this vehicles mean a great step in decarbonising our transport system. Hydrogen cars can be put into two categories:

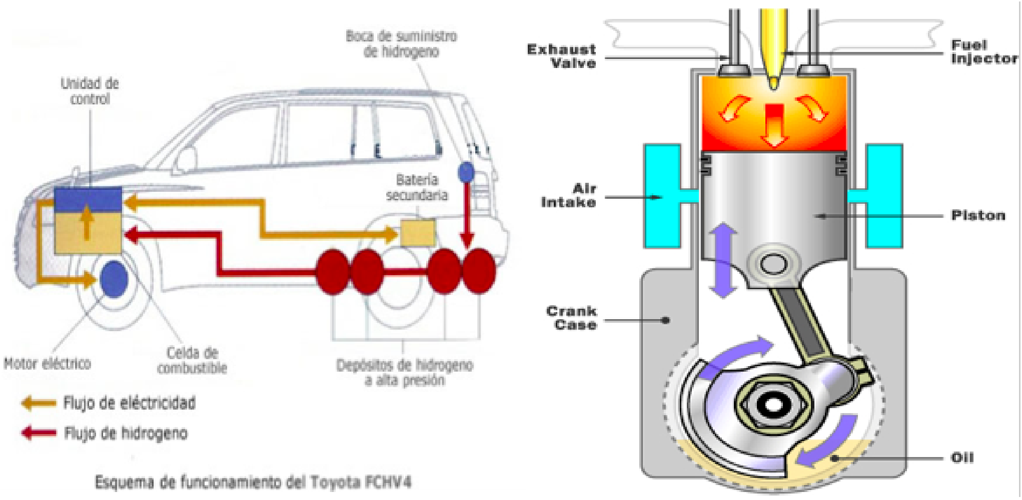

Figure 11: Fuel cell vehicle (left) and combustion engine vehicle (right)[MECA14]

Figure 11 shows the difference between combustion engine vehicles and H2EV. This differences will be explained in more detail in the following sections.

3.6.1 Combustion engine vehicle

This vehicle works as if it was a gas vehicle. Its only difference are the hydrogen tanks which has in the trunk and a slightly different engine. Inside, is really similar to the natural gas vehicles which we can already see in the streets. However, its "green" label is not something which all experts agree on. This is because it uses oil to lubricate the engine and therefore, small particles of oil can end up burning. And this ends up in NO_x emissions [FABR09].

3.6.2 Fuel cell vehicle

This hydrogen vehicle is more complex than the combustion engine version. However, in essence is a electric vehicle which functions with what produces. Hydrogen is turned into electricity by the fuel cell which moves the vehicle. To improve efficiency a battery is installed to recover energy from breaking (regenerative break) . When the vehicle breaks, energy is stored into the battery. However, this vehicles produce its' own electricity,therefore the size of the battery is smaller than the electric one[IRIA14], since it only has to store the energy from breaking and the extra generation from the fuel cell.The fuel cell is a catalyse, hydrogen goes through it mixing up with oxygen which produces ions circulating. The greatest problem are the materials needed, Platinum for the catalyse and Lithium for the battery. Platinum has a high price and even it the membranes of the catalyse are of a few millimetres ,this increases the price.

Figure 12 represents the costs for travelling one km by EV,H2EV and combustion engine vehicles. This costs include fixed costs as the fuel tank needed in the H2EV or the battery. In this figure it can be seen that the costs for a battery in an EV is higher than for a H2EV as it was said before.

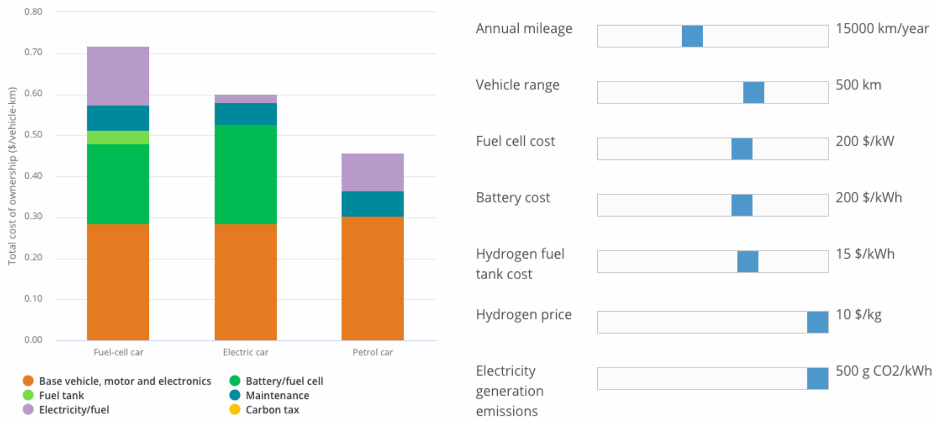

Figure 12: Cost for travelling one Km by different vehicles [IEA_19]

3.6.3 Hydrogen vehicles nowadays

Nowadays the offer of hydrogen vehicles is really poor, but the companies which are making them, have faith in their future. The vehicles in the market are:

Vehicles	Power (CV)	Tank capacity (Kg)	Autonomy (Km)	Pressure (MPa)	Price (€)
Toyota Mirai	155	5	500	70	70000
Hyundai Nexo	163	6.33	666	75	69000
BMW I8 fuel cell	256	7.1	490	35	-
Honda Clarity fuel cell	174	5.46	580	70	57000

Table 5: Hydrogen vehicles [GONZ18]

It can be seen, that the prices are still high compared with conventional or electric vehicles since it is an exclusive type of vehicle. However, the power has nothing to envy a conventional car and the refilling of the tank takes only 3-5 minutes. This table hopefully will increase the number of vehicles since companies like Mercedes or Audi are planning hydrogen vehicles for 2020.

Figure 13 represents the projection H2EV vehicles have in different countries. In Europe this type of vehicles have a low penetration nowadays mostly because of the nearly nonexistent infrastructure for them. Therefore, projections in Europe haven't been studied. However, we can assume that if the US or Japan continue supporting this technology Europe will eventually follow this projections too.

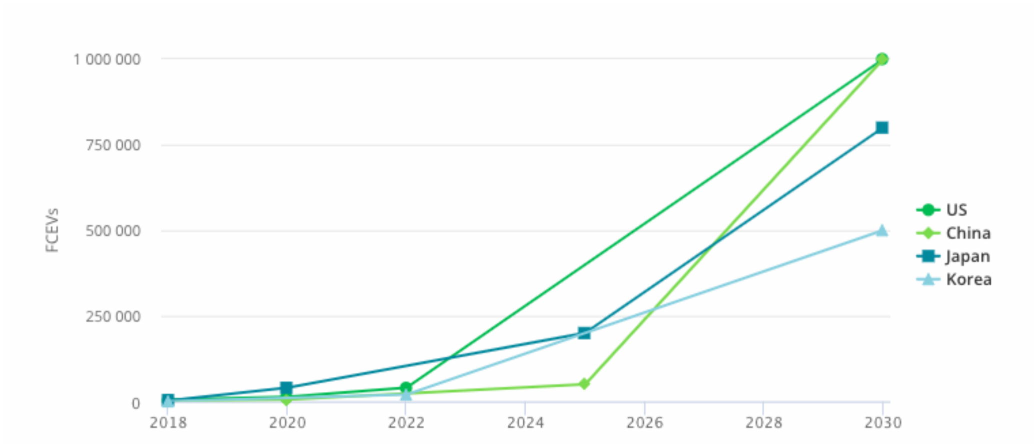

Figure 13: Fuel cell vehicle projection[FUKU19]
FCEVs: hydrogen fuel cell vehicles

3.7 Manufacturing issues

In this section several components of the fuel cell vehicle will be analysed focusing on the materials needed to manufacture them.

3.7.1 Battery

In 1991 the first Ion-Li batteries came into the market and nowadays are the most used. Lithium is the lightest of all metals,has the greatest electrochemical potential and has the greatest energy container. Nevertheless, its' recycling is poor and many countries don't have regulation for its retirement from the streets. This means a great deal of environmental contamination. Both EV and H2EV use batteries so this is a key aspect. H2EV has to use a much smaller battery [IRIA14] and due to this it can be more environmentally convenient.

Another aspect to take into account are the reserves of Lithium we have available. Nowadays we have 14 million tons of Lithium [USG_19] and the battery of an electric car weights around 20 Kg [ABBO09]. Therefore, we can produce 0,7 billion vehicles, enough for the study which has to cover around 20 million vehicles in Spain [DGT18]. However, if the study were worldwide, this numbers wouldn't be so promising. Since H2EV use a smaller battery and they could even function without one this numbers could make H2EV the future transport method.

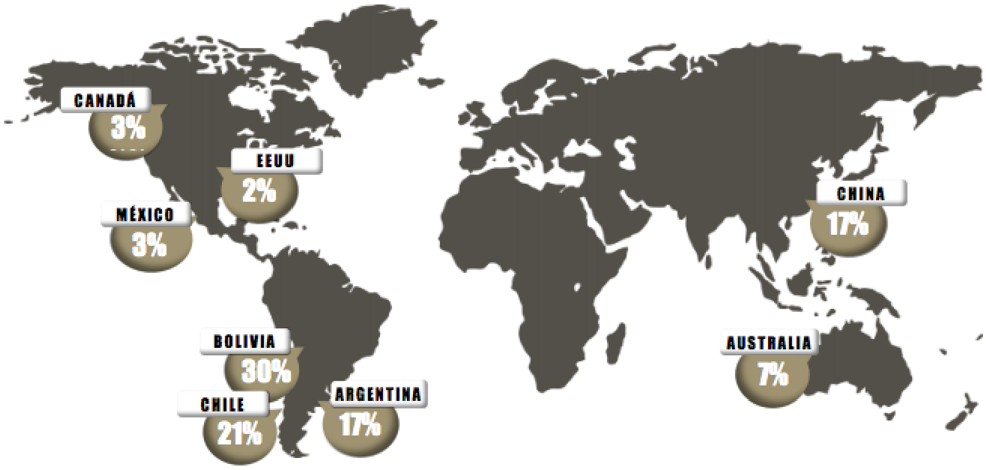

Figure 14: World Lithium reserves[USG_19]

3.7.2 Hydrogen tanks

Hydrogen tanks have to withstand high pressures (between 20 and 69 MPa). As a consequence, materials used are usually expensive. This materials can be light weight metals such as aluminium and its composites. Aluminium is easily found so it is not a problem as Lithium. Regarding its price is expensive but not as Lithium or Platinum. Moreover, hydrogen has a great advantage when it comes to leaks. Since hydrogen is the lightest gas if leaks appear hydrogen dispersion is much higher. In figure 15 we see how combustion engines and H2EV behave under leaks in their fuel/hydrogen tanks. For combustion engines, gasoline concentrate in the tank leading eventually to an explosion. However, for H2EV it can be seen how H_2 escapes to the air, turning this vehicles safer.

Figure 15: Hydrogen and fuel comparison[FERN19]

3.7.3 Fuel cell

As we have mentioned previously, the greatest problem is the Platinum used in it. This is used in the nucleus of the catalyse, which is made by a polymer and in both sides a catalyse from Platinum. Which is used to improve the chemical reaction of hydrogen with oxygen.

Platinum represents 30% [SIGU13] of the cost of the fuel cell, reaching values of even 1500 $. Therefore this part from the vehicle is a critical aspect of it.

In this part it is going to be proven that the reserves of Platinum are enough to cover the Spanish market for this metal. Nowadays they are 196,6 tons of Platinum [STA_18] and its content in the fuel cell is of 30 gr in the most common hydrogen car, the Toyota Mirai. As a result, with its complete depletion, 6553 million vehicles can be made. Enough to cover the needs of this study.

This values are encouraging since they don't compromise the future of the hydrogen vehicle, moreover, they are already studies of fuel cells with different materials. Nowadays the most realistic future are Toyotas' declarations in which they say to have manufactured a fuel cell with only 10 grs of Platinum in it.

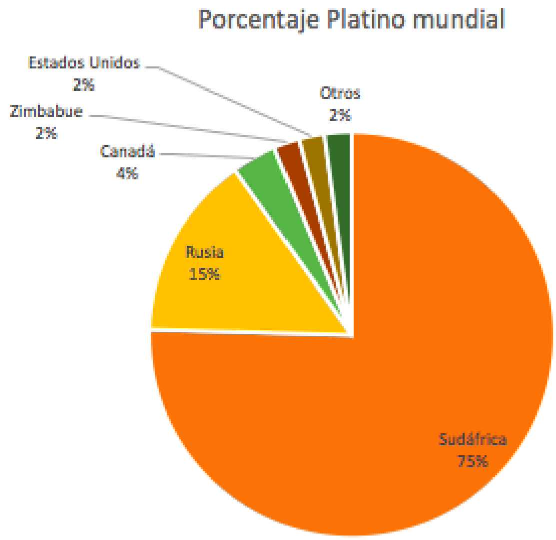

Figure 16: World Platinum reserves[STA_18]

3.8 Renewable energy

The last objective of hydrogen production is to be produced only by renewable means. In addition, taking advantage of storing hydrogen when renewable plants are not needed is a great way to optimise them. This means producing hydrogen when the demand is low and store it for the time when it is needed or for transport. A real case would be a wind plant in Germany which two million KWh of hydrogen are produced per year [SANC14]. This project is still small because it is only a two MW wind plant, however, without any doubt it is a step towards a greener environment.

3.9 The future of hydrogen as an energy vector

Now it is clear hydrogen has a great projection and besides numerous projects are being done. In Spain it is still a new technology without many projects involved. According to the PNIEC(Plan nacional integral de energía y clima) of 2019 projects relating hydrogen are poor and not many inversions will be given to it [PNIE18]. For example, in 2018 121 million dollars where used for fuel cells and hydrogen production [FUKU19].Moreover, since hydrogen tanks can be affected by embrittlement as it was said before and fuel cells have an average life of 60,000 hours , for safety issues the Spanish government limits its' use for 15 years [OTER18]. This means that this vehicle won't be approved by the Spanish ITV (Inspección técnica de vehículos) and be removed from the streets at that age.

3.9.1 Combined cycles

A combined cycle refers to the generation of energy by two thermodynamic cycles in the same system. Natural gas is burned to move the turbine, and the remaining vapours are used to heat water which makes a second turbine spin.

Combined cycles are of great interest due to several reasons:

- Are the cheapest way to generate electricity
- Automatism reduces human resources.
- Construction is really fast, around 3 years.
- High efficiencies.
- They can work with several fuels, between them, hydrogen.
- They are dispatchable and quick contributing to the system flexibility.

On of the greatest advantages of introducing hydrogen into combined cycles is the recycling of the infrastructure already built.Even though the recycling of this infrastructures hasn't been done yet, studies regarding its possible re conversion have been made [GAST18]. In addition, hydrogen combined cycles have been made from scratch.An Italian hydrogen fuelled combined cycle with a capacity of 16 MW was built in 2010 i Fusina[POWE10]. This plant had a cost of 63 M$and it is still five to six times more expensive than conventional means. Nevertheless, it is one of the first steps towards a hydrogen economy.

4 Motivation

This project has been made with the purpose to analyse the feasibility of H2EV as an alternative to EV in the process of electrification of transport. Nowadays, in Spain H2EV are nearly nonexistent, while EV vehicles are becoming popular in the big cities. EV are cheaper and recharging them is easy, which can be done in your own home. Nevertheless, countries as Japan are betting on a H2 economy [JAPA19] and Germany is also working on H2 plants [NGN_18]. For this reason it is of common sense to look for the best option for the electrification of transport.

Moreover, hydrogen has several characteristics which may be beneficial for the grid. It's flexibility, which means that it can be produced when it is more convenient taking advantage of renewable surplus. This will be key in a system where renewable power is oversized to cope with the demand. Also as it was said before it can eventually be used in renewable combined cycles which only work with hydrogen, adding flexibility to the grid.

5 Objectives

The objectives of this study is to do a comparison between EV and H2EV and their impact on the grid. It is of special relevance how much generation capacity is needed to install for this two cases and how investments are made. Both EV and H2EV represent an extra demand to the Spanish grid, therefore, studying the differences in renewable power installation due to this demands is necessary to know their impact in our system. Aside from this, emissions are important, since a vehicle of this characteristics is worth nothing if the emissions of the electric system increase. The ultimate point of transport electrification is to reduce emissions, as a result, EV and H2EV should not imply high emissions. The Spanish government is already working on this, since coal plants are commissioned to close before 2030 together with some nuclear plants. As a result, the only electrical plants which are going to be installed in the following years, will be renewable power plants. This is helping to reduce the GHG emissions associated with EV. However, H2EV represents a larger demand to the grid due to its' lower efficiency.Moreover, interesting conclusions can be drawn from how hydrogen or electricity for EV is produced, at what times of the day and whether it is stored in batteries or not. For this means the production mix will be of use for the comparison between H2EV and EV.

For this purpose, a model simulating a hydrogen economy has been developed and tested. With the results drawn from this, an optimal solution to the electrification of transport will be found. Whether EV are the best solution or instead H2EV. For this study, materials considerations such as how batteries are recycled or Lithium use for this batteries will not be discussed and therefore, this is only a part of the solution. However, since materials used in both this type of vehicles are similar, the most important aspect to study is the impact on out grid.

6 Hydrogen generation model

The following model is used to reach the objectives mentioned and tries to simulate a hydrogen economy, in which hydrogen is produced via electrolysis in a centralised way. This means that hydrogen is produced without GHG emissions, using a catalyse to transform water to H2 by electricity supplied by the grid.

The process for the cost assessment of the deployment of hydrogen vehicles and its impact on the power system is been developed based on three sequential models.

Firstly, the daily hydrogen electrical demand is estimated from a desired penetration of the hydrogen vehicle in the system, considering the selected H2 vehicle and H2 production technologies.

Secondly, the Spanish electrical model called CEVESA is used to solve the electricity market with the new additional electricity demand to produce the H2. This model has also the possibility of computing the investments needed to supply the additional demand.

Lastly, a third model is used to calculate the deployment cost and compare it with the electric vehicle. Since the modelling of the electrical vehicle has already been done by [VILL11] the data from the electrical model will be taken from there. The following picture represents this three stages mentioned

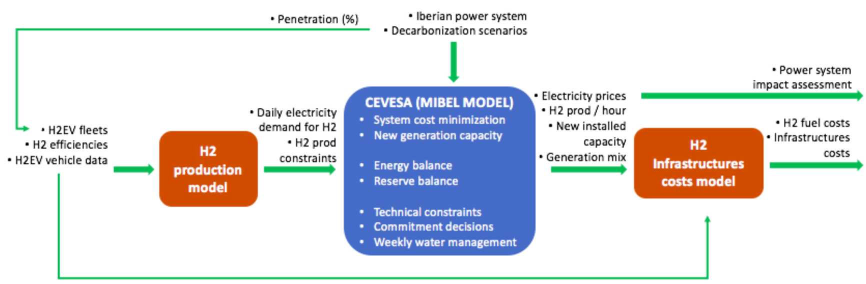

Figure 17: Hydrogen modelling

6.1 H2 production model

The electricity demand to produce the hydrogen is based on the amount of daily H2 demand and on the efficiencies of the process to produce it. The amount of daily H2 demand is computed from the considered amount of H2 vehicles penetration %, using the vehicles fleets (number of vehicles and km per day) proposed in[VILL11].

In[VILL11]there was a fleet of vehicles that travelled ϵ kilometres each day in average. Depending on the number of H2 vehicles replacing the conventional vehicles (since the total amount of electric vehicles can still be neglected) there will be a certain H_2 vehicle penetration. This will lead to several study cases.

6.1.1 Hypothesis

- The autonomy of H_2 vehicles plays an important role since it will be the factor deciding the Kg of H_2 needed for all the Km travelled daily. The less $\frac{Km}{Kg}$ the more hydrogen will be needed to produce.
- The autonomy of the hydrogen vehicle has been estimated taking into account that the only vehicles in the system will be: Hyundai Nexo and the Toyota Mirai (which are the most common nowadays[USDE16]).With both autonomies an average has been made since both are similar, resulting in an autonomy $\alpha \quad \frac{KgH_2}{Km}$.
- We have taken efficiencies η of the hydrogen process from figure 18. This efficiencies account for the AC-DC conversion needed for the conversion from $KWh - KgH_2$, compression of hydrogen needed for distribution and the electrolysis process which is the one producing hydrogen from energy
- The graph also accounts for transport efficiencies, however, this efficiencies are not taken into account due to the fact that it does not involve electric generation.

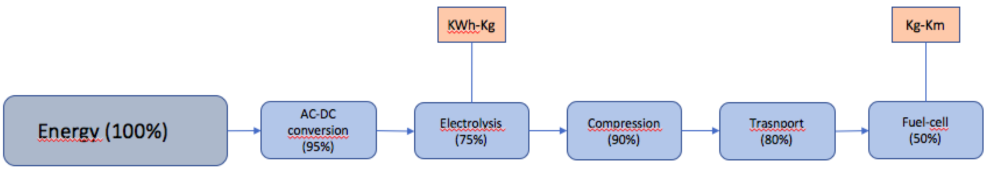

Figure 18: Hydrogen efficiencies from energy to vehicle [PUYA16]

Now we will proceed to calculate this electrical demand.Firstly, we will find the necessary Kg of hydrogen needed to travel the daily average.

$$Q_{ydh}^{H2} = \epsilon \cdot \alpha \cdot P_y = Dh \cdot P_y$$

Afterwards, this Kg will be transformed into electricity needed for their production with the efficiencies mentioned before. To this efficiencies η we have to add a conversion factor for electrolysis σ [ESPA19]

$$\frac{GWh}{day} = \frac{Dh}{\eta} \cdot \sigma \cdot P_y \cdot 10^{-6} = \Phi \cdot P_y$$

With this numbers we can find a conversion fator to change from Kg to MWh which will be helpful later:

$$\frac{KgH_2}{GWh} = \frac{\eta}{\sigma} = \beta$$

6.1.2 H2 production constraints

Sets

$$\begin{aligned} h &= Hours,\ t = [1, 24] \\ y &= Years,\ a = [2019, 2039] \\ d &= Days,\ d = [1, 365] \end{aligned}$$

Parameters

Installation costs $[\frac{€}{KgH_2}]$	Cy
Electrolysis costs $[\frac{€}{KgH_2}]$	Ce
Hydrogen daily demand $[KgH_2]$	Dh
Electrical demand [KWh]	De_{ydh}
Conversion factor $[\frac{kgH_2}{GWh}]$	β
Penetration per year [%]	P_y

Table 6: Parameters

Variables

Hydrogen production (continous) $[KgH_2]$

$$q_{ydh}^{H2}$$

Capacity of plant (integer) $[KgH_2]$

$$cap_y^{H2}$$

Total demand (continous) $[KgH_2]$

$$de_{ydh}^{H2}$$

Total costs (continous) [€]

$$c$$

Constraints

The generation of hydrogen per hour has to be less than the capacity:

$$q_{ydh}^{H2} \leq cap_y^{H2}$$

Production greater or equal demand

$$\sum_{h=1}^{24} q_{ydh}^{H2} \geq Q_{ydh}^{H2} \cdot P_y$$

Relation between electrical and hydrogen demand

$$de_{ydh}^{H2} = De_{ydh} \cdot \beta + q_{ydh}^{H2}$$

6.2 Function

The function below estimates the costs from the installation of hydrogen plants, needed for the production of this gas and the costs from producing it from an electrolysis process.

Other production processes have not been taken into account since the only way to produce hydrogen with a zero emissions scenario and enough volume is by using this kind of technology.

$$c = \sum_{y=2019}^{2030} [cap_y^{H_2} \cdot Cy + \sum_{h=1}^{24} \sum_{d=1}^{365} (Ce \cdot q_{ydh}^{H_2})]$$

6.3 CEVESA

CEVESA is a hydro, thermal and EV equilibrium model for energy and reserve dispatch of the MIBEL (Iberian) power system,[GONZ13], [SALA16],[TRIG13]. CEVESA uses a chronological hourly modelling, and each year of the analysed time period is represented with a synthetic representative week computed as described in [DOME18] to reduce computational time. Hydro generation is performed for each synthetic period using historic data of dispatchable, maximum, and minimum values of energy and reserve and remained constant. CEVESA also includes a partial representation of the transport sector. Since the model has many different options and possibilities, those selected for this study are represented in Figure 19.

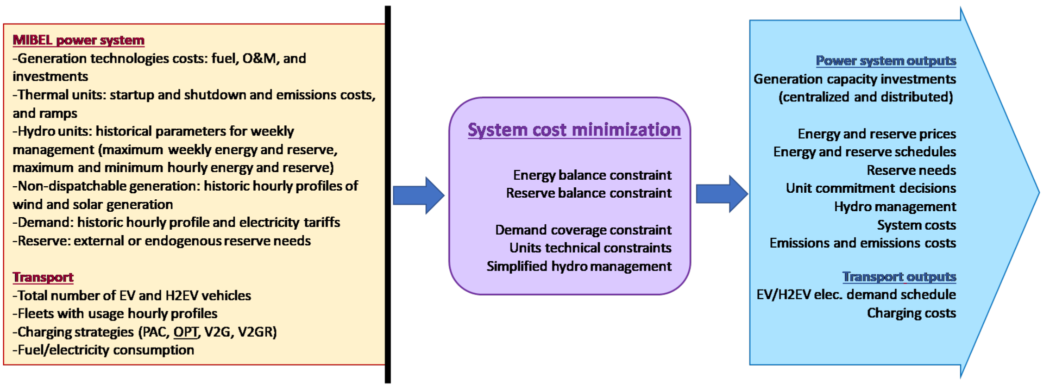

Figure 19: CEVESA diagram [VILL11]

What we are going to introduce in this model is the extra demand we calculated earlier. From this demand and the constraints above written we will be able to compare the costs of the electrical vehicle and the hydrogen vehicle.

Results from this model will be given on the following tables which will be then used to draw conclusions from them.

6.4 H2 Infrastructure cost model

This section will estimate the costs for all the infrastructure needed for the hydrogen vehicle deployment.Is important to notice that no optimisation process is involved in this model. This involves:

- Transportation costs.
- Hydrogen stations investment costs.

As it was said in the state of the art for the hydrogen station costs, transportation is the key aspect for hydrogen stations. Travelling long distances increases the costs greatly. Onsite SMR is the second most common hydrogen station in the US [RUST18], therefore, for our case (emission free), it is reasonable to assume onsite electrolysis as our hydrogen station type .

6.4.1 Transportation costs

In table 7 there are the costs related to three transportation methods which are the most common.

Transportation method	Costs [€/KgH_2]
Tube trailers	2.2
Pipelines	0.15
Tankers	0.14

Table 7: Transportation costs by most common methods [PAHW14]

In order to calculate the transportation costs we have to estimate the quantities which will be delivered by each method. Nowadays, there are no studies about this since there are no countries which produce hydrogen at such scale as to use several methods. Therefore we will assign a 5% of hydrogen transportation through pipelines since they have a limited amount of H_2 they can delivered as it is said in figure 5. For tube trailers and tankers they are assigned a 75% to tube trailers since nowadays is the most common way to transport this gas and a 20% to tankers.

$$H2TC_y = \sum_{tr=1}^{3} \cdot Dh_{tr} \cdot P_y \cdot CT_{tr}$$

Being CT_{tr} the transportation costs by method, Dh_{tr} are the Kg of hydrogen needed to travel the daily average by transportation method. And P_y is the penetration.

6.4.2 H2 station costs

For this costs we have taken data from [MELA15]. In this paper we see that hydrogen station costs differ by the station capacity. Our model considers a large amount of penetration for H2EV therefore for this costs, the largest station capacity will be chosen. This capacity is 1,600 Kg/day with a capital cost of 5 M$and a variable cost of 4,000 $/Kg/day.

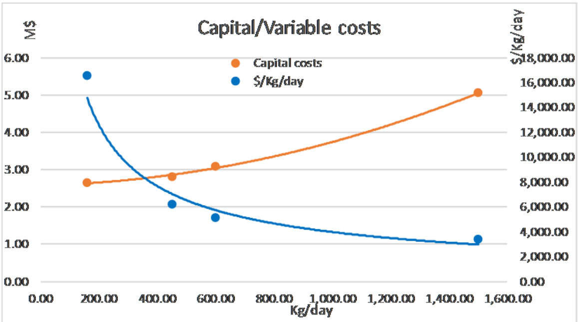

Figure 20: Hydrogen station costs [MELA15]

$$H2SC_y = \frac{Dh \cdot P_y}{Cap^{Hs}} \cdot SC + Dh \cdot P_y \cdot SCV$$

Being Cap^{Hs} the capacity of the hydrogen station, SC the capital hydrogen station costs for that capacity and SCV the variable costs per day for that capacity.

7 PINIEC

Before analysing the results from the hydrogen model it is necessary to explain the PNIEC objectives. The PNIEC is the Spanish energy plan which sets the objectives for 2030 in the Spanish power system. The first scenarios which are going to be taken into account, will try to follow this objectives,however, the optimisation process is not completely PNIEC like since renewable power doesn't reach this objectives due to high renewable investment costs. This model also tries to improve the measures taken by the Spanish government setting slightly different measures.

So we can compare better to this measures, the objectives are presented in figure 21:

Parque de generación del Escenario Objetivo (MW)				
Año	**2015**	**2020***	**2025***	**2030***
Eólica	22.925	27.968	40.258	50.258
Solar fotovoltaica	4.854	8.409	23.404	36.882
Solar termoeléctrica	2.300	2.303	4.803	7.303
Hidráulica	14.104	14.109	14.359	14.609
Bombeo Mixto	2.687	2.687	2.687	2.687
Bombeo Puro	3.337	3.337	4.212	6.837
Biogás	223	235	235	235
Geotérmica	0	0	15	30
Energías del mar	0	0	25	50
Biomasa	677	877	1.077	1.677
Carbón	11.311	10.524	4.532	0-1.300
Ciclo combinado	27.531	27.146	27.146	27.146
Cogeneración carbón	44	44	0	0
Cogeneración gas	4.055	4.001	3.373	3.000
Cogeneración productos petrolíferos	585	570	400	230
Fuel/Gas	2.790	2.790	2.441	2.093
Cogeneración renovable	535	491	491	491
Cogeneración con residuos	30	28	28	24
Residuos sólidos urbanos	234	234	234	234
Nuclear	7.399	7.399	7.399	3.181
Total	105.621	113.151	137.117	156.965

Generación eléctrica bruta del Escenario Objetivo* (GWh)				
Año	**2015**	**2020**	**2025**	**2030**
Eólica	49.325	60.521	92.053	116.110
Solar fotovoltaica	13.860	15.132	42.118	66.373
Solar termoeléctrica		4.968	13.953	22.578
Hidráulica	28.140	28.282	28.663	29.045
Bombeo	3.228	4.690	5.610	8.369
Biogás	982	447	482	897
Geotermia		0	94	188
Energías del mar		0	59	74
Carbón	122.415	47.195	15.094	0
Ciclo combinado		32.800	15.304	34.922
Cogeneración carbón		76	0	0
Cogeneración gas		24.054	20.603	15.566
Cogeneración productos petrolíferos		2.065	1.425	697
Fuel/Gas		5.372	4.700	4.029
Cogeneración renovable	5.766	862	1.192	1.556
Biomasa		3.991	5.605	10.714
Cogeneración con residuos		96	93	84
Residuos sólidos urbanos		605	783	1.447
Nuclear	57.305	57.686	57.686	24.800
Total	281.021	288.843	305.518	337.448

Figure 21: PNIEC strategy [PNIE18]

To add on, electrical vehicle penetration is also contemplated in this plan. In 2030 the electrical vehicle penetration is expected to be of approximately 5 million vehicles [PNIE18] of the total Spanish private vehicles fleet. This values were set on the model being the only difference with the PNIEC the CO_2 price which moves renewable investment. This CO_2 price is difficult to set correctly since prices are volatile and change drastically over time. Since the market seems to be moving towards a decarbonised one, this price has been chosen to increase over time.

Hydrogen vehicles are not taken into account in the PNIEC, so the model developed in this study contemplates a scenario in which electrical vehicles are replaced with this type of vehicle. Replacing electrical vehicles with H2EV ones is not realistic, so an scenario with a mix of this two is also taken into account to asses their impact in our grid.

8 Scenarios

Parameters	**EV**	**H2EV**	**EV_H2EV**	**EV_d_chr**	**EV_d_chr_50%**	**EV_CO_2**	**EV_CO_2_incr**	**H2EV_Inve_decr**	**EV_50%**	**H2EV_50%**	**EV_H2EV_50%**
Demand 2019 [TWh]	243.01	243.01	243.01	243.01	243.01	243.01	243.01	243.01	243.01	243.01	243.01
Demand 2030, excluded EV/H2EV [TWh]	284.40	284.40	284.40	284.40	284.40	284.40	284.40	284.40	284.40	284.40	284.40
CO2 price 2019 [€/tCO_2]	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6	24.6
CO2 price 2030 [€/tCO_2]	51.1	51.1	51.1	51.1	51.1	24.6	inc	51.1	51.1	51.1	51.1
EV 2030 penetration [%]	24.5	0	12.5	24.5	50	24.5	0	24.5	50	0	25
H2EV 2030 penetration [%]	0	24.53	12.5	0	0	0	0	24.53	0	50	25
H2 installation costs 2019 [M€/(Kg/h)]		37,600	37,600					37,600		37,600	37,600
installation costs 2030 [M€/(Kg/h)]		11,800	11,800					11,800		11,800	11,800
H2 variable costs 2019 [€/(kg/h)]		0.064	0.064					0.064		0.064	0.064
H2 variable costs 2030 [€/(Kg/h)]		0.02	0.02					0.02		0.02	0.02
α [Kg/Km]		0.0097	0.0097					0.0097		0.0097	0.0097
ϵ[MKm]	1.178	1.178	1.178	1.178	1.178	1.178	1.178	1.178	1.178	1.178	1.178
η[%]		0.71	0.71					0.71		0.71	0.71
σ [KWh/Kg]		53.4	53.4					53.4		53.4	53.4

Table 8: Scenarios

There are three base scenarios which are EV, H2EV and EV_H2EV.

- EV, the base PNPEC scenario, where decarbonized passengers cars are EV, up to 24.6% of the total fleet,[PNIE18];
- H2EV, as EV scenario, but EV are replaced with H2EV. Current production and variable costs to produce H2 (electricity consumption excluded) decrease at a yearly rate of 10% to account for technological improvements;
- EV_H2EV: as EV, but the 24,6% of decarbonized cars are 50% EV and 50% H2EV.

From this base scenarios there are others which derive from them to determine the impact of EV's and H2EV's would have on the power system under different situations.

- EV_CO_2, for this case we simulate a case were CO_2 emissions remain constant in the following years.
- EV_d_chr, as EV but without optimising the charge of vehicles. This scenario would be a pessimistic EV.
- EV_d_chr_50%, as the last one but with a larger EV penetration.
- EV_CO_2_incr, this scenario involves several ones in it and tries to asses the impact of CO_2 price changes in the following years. For this scenario CO_2 is made to increase annually at certain rate.
- H2EV_inve_decr, as the one before it it involves several cases. By changing the decrease rate of investment costs in H_2 plants we see its' impact.
- EV_50%, as EV with a larger penetration up tp 50%.
- H2EV_50%, as H2EV with a larger penetration, up to 50%.
- EV_H2EV_50%, as EV_H2EV with a larger penetration, up to 50%.

In the following table this scenarios are put into numbers:

8.1 Base scenarios results

Figure 22 represents the evolution of electricity generation capacity for the analysed period for the base scenarios and for the main technologies (NU standing for nuclear, CC for combined cycle, and batt for batteries). H2 is produced during low electricity price hours. This is because hydrogen can be produced in any hour while the total daily demand is covered. Therefore, it concentrates in only a few hours bringing up the installed capacity to cover the demand at those hours. This is the reason behind the large solar power investment in H2EV. In addition, batteries become of greater importance for the EV in contrast with the H2EV. EV demand is given through the whole day not as the H2EV. Due to this, batteries have to charge energy during day time from solar power to supply the EV demand during night time. From this point of view, hydrogen has more advantages, since batteries are not needed to store it.

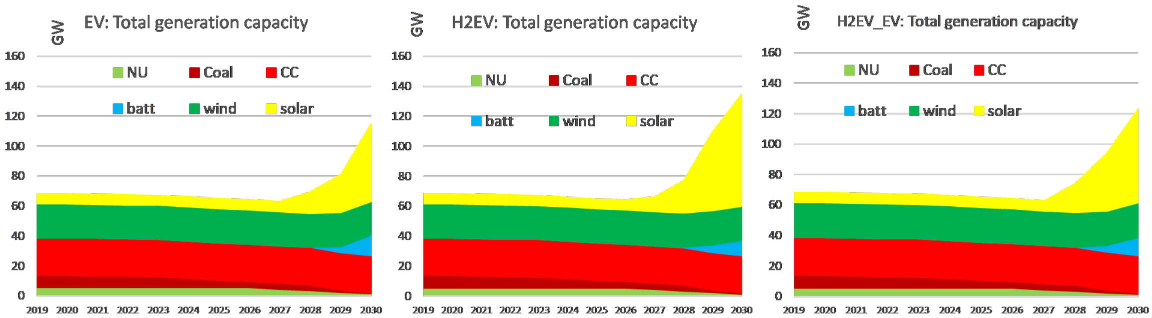

Figure 22: Base capacity

Figure 23 shows the long-term electricity prices from 2019 and 2030 for each scenario, reflecting an increase in the total electricity production costs. Higher electricity costs in 2030 are driven by the increasing demand and not so much from EV or H2EV penetration. As it was said before hydrogen production is concentrated in low electricity prices. As a result, prices increase at those hours significantly, on the other hand, the hours where H2 production is zero makes prices to drop below the EV average. For this reason, H2EV electricity price curves have more zero electricity price hours in comparison with EV or EV_H2EV.

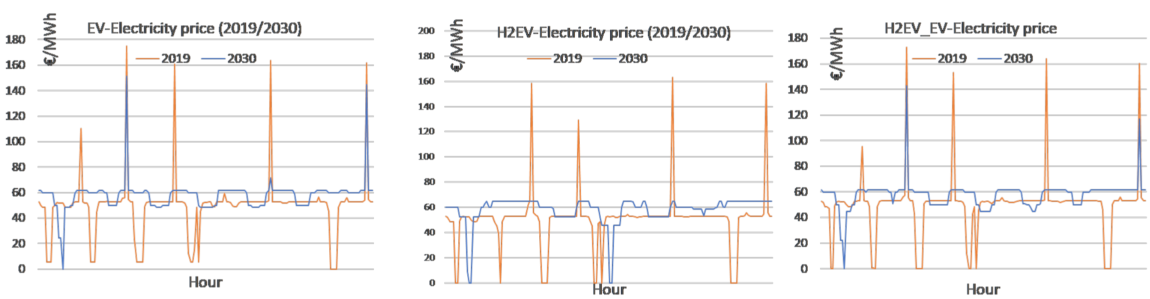

Figure 23: Base electricity price

Figure 24 shows the energy production mix. It is interesting to note how batteries profit from the solar surplus to produce when solar is missing, something more necessary in EV scenarios, where demand is needed through the whole day. Since hydrogen generation is mainly given during day time, batteries are not that necessary.

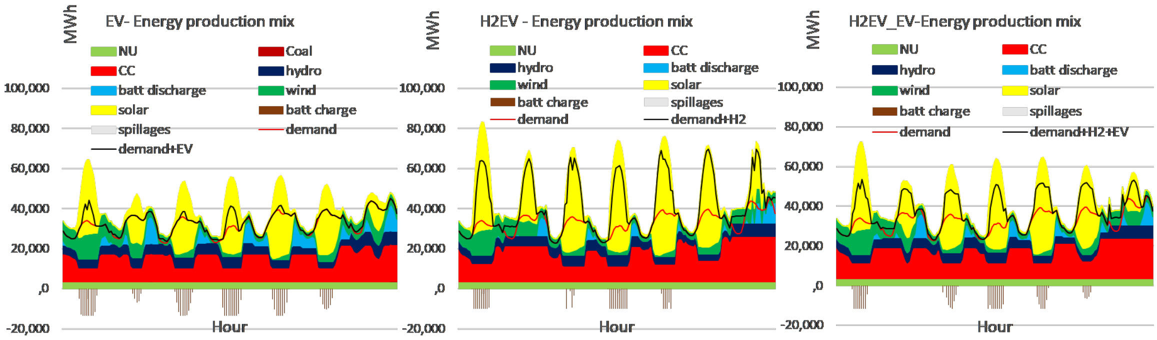

Figure 24: Base energy production mix

Figure 25 shows the evolution of CO2 emissions and emissions costs. It is relevant to note how H2 production, increases emissions.This is because of its' larger demand, which needs combined cycles and nuclear power to produce more energy. However, when solar power increases at the end of the period, emissions decrease for all scenarios. Nevertheless, H2EV can't decrease at enough rate to be comparable to the EV.

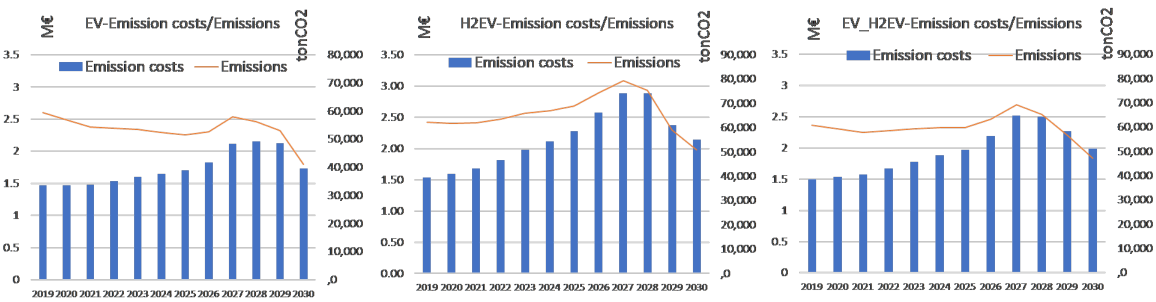

Figure 25: Base Emissions

In order to understand better the results in the figures, a table has been made will key results of the different base scenarios:

Results	EV	H2EV	EV_H2EV
H_2 investment costs[M€]	0	3,123	1,351
Power system investment costs[M€]	26,078	38,896	31,397
Total emissions[tonCO_2]	643,277	790,855	717,352
Average electricity price 2030[€/MWh]	57.95	58.02	58.00
Total demand 2030[TWh]	291.4	361.35	326.34
H2EV power demand [TWh]	0	76.95	38.45
EV power demand [TWh]	7.00	0	3.49

Table 9: Base scenario results

In table 9 it can be observed that investment costs for the H2EV scenario are higher due to hydrogen plant installation. Even for only the power system investment costs it is higher. This is due to poor electrolysis efficiency with the re conversion of this hydrogen into electricity later in the H2EV. This re conversion with the efficiency mentioned, makes a huge difference in the power demand from EV and H2EV.In this table the total demand represents the whole electrical demand plus the vehicle demand. Regarding the total demand (sum of electrical demand plus vehicle demand), it is clearly seen how H2EV demand for the same penetration as EV is totally different. As it was said before, this is due to low efficiencies in its' process and re conversion processes.

8.2 EV_dumb_charge scenarios results

The dumb charge strategy is different from the one used for the EV in this study. This strategy doesn't optimise the charges of electrical vehicles, therefore it is more pessimistic. If we would like to simulate reality, it would lie between this two strategies, more pessimistic than EV but more optimistic than dumb charge.

However, as it can be seen, this differences are hard to appreciate. In figure 26, where the total generation capacity is represented, the capacity from equal penetrations,(EV,EV_dumb_charge and EV_50%,EV_dumb_charge_50%) are nearly the same.Nevertheless, from common sense it can be said that the capacity from the dumb charge are higher. This can be confirmed with the inversion costs presented in table 10. If the charge is not optimised, the result is not being able to maximise the solar power and recurring to extra power instalment.

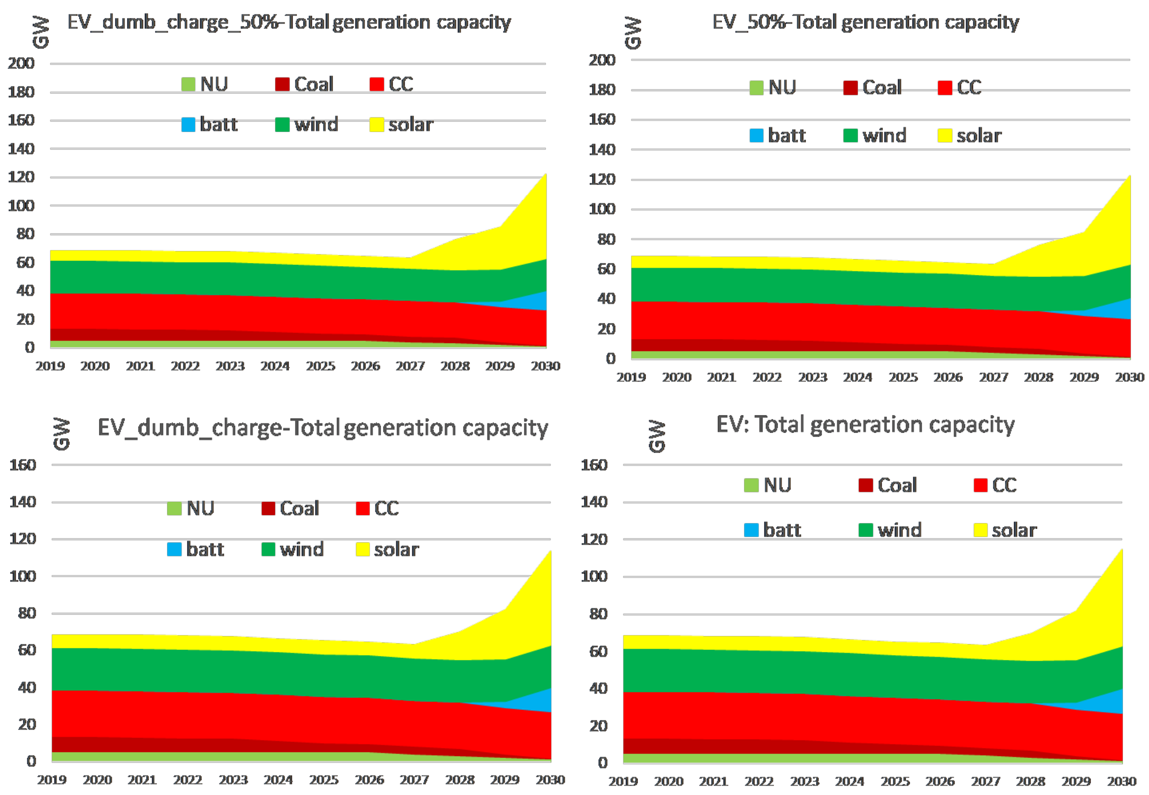

Figure 26: Dumb_charge scenario,capacity

Figure 27 are the emissions for each scenario. This ones as expected from what the capacity looked like, are similar between them. Since this model minimises the total cost of the system, emissions from EV and EV_50% compared to dumb charge scenarios, may be higher since power instalment will be minimised. This leads to less solar power investment and therefore the production from combined cycles and nuclear power will be higher.

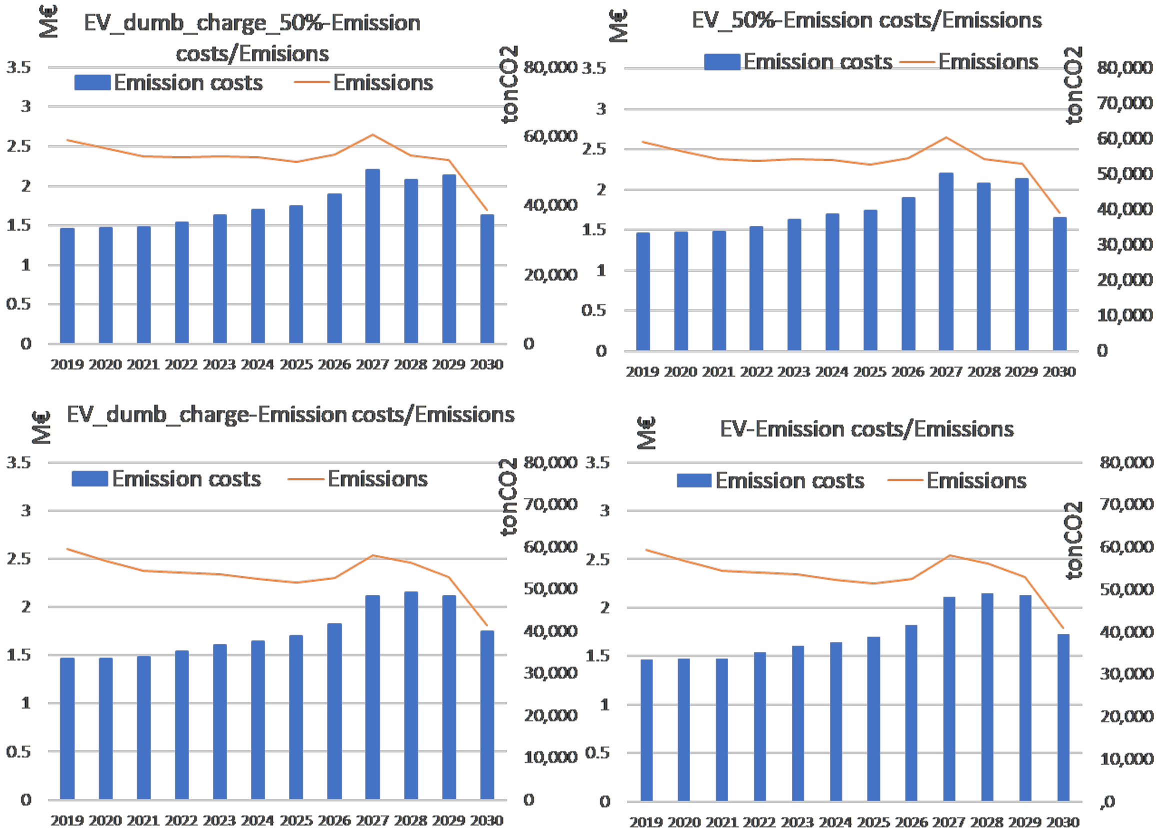

Figure 27: Dumb_charge scenario,emissions

Figure 28 represents the production mix. This production mix is nearly the same, however, as it was said before with the emissions, combined cycles and nuclear power should have a slightly higher production for EV and EV_50% compared with dumb charge scenarios. This types of production are cheaper for low CO_2 increases as it is the case.

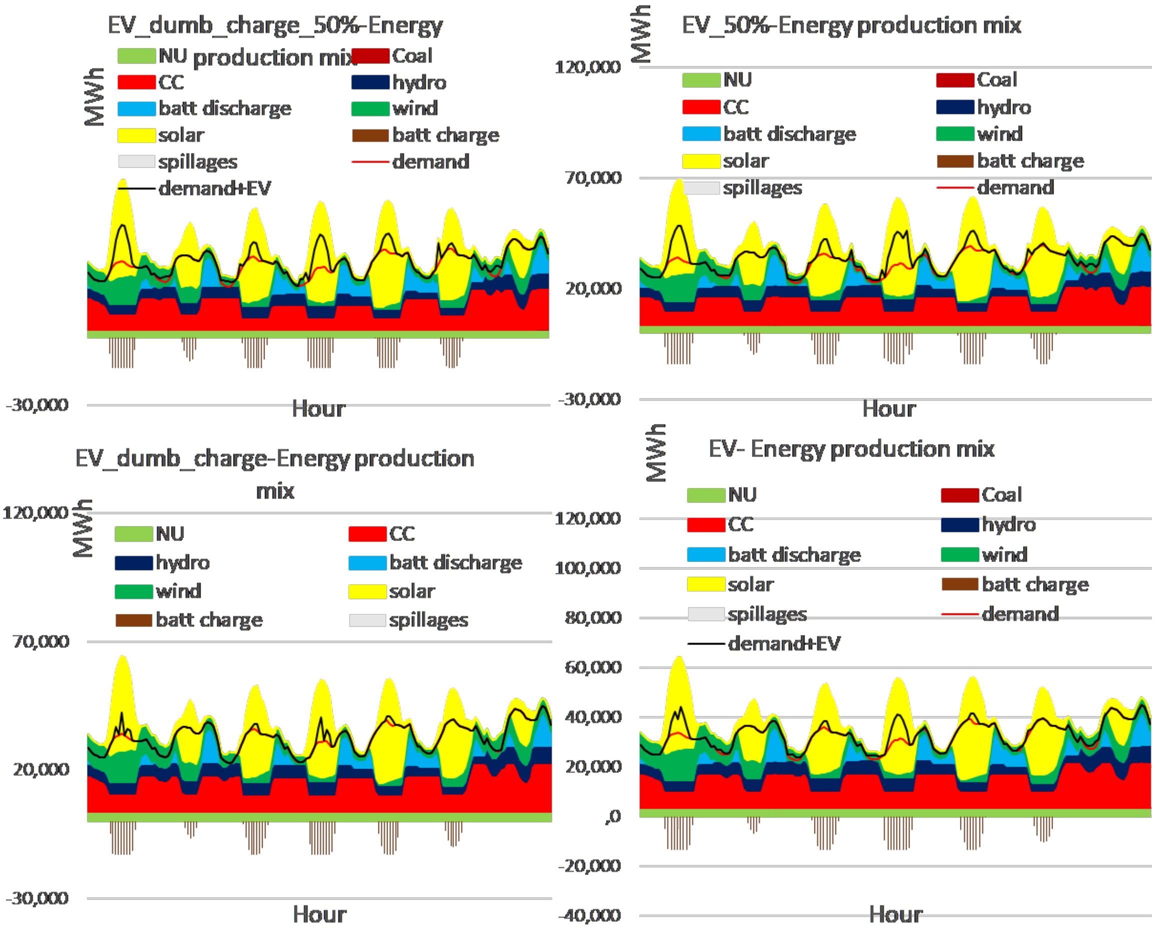

Figure 28: Dumb_charge scenario, energy production mix

Table 10 shows what we already expected. Investments from dumb charge scenarios are higher. The optimised charge in both EV and EV_50% makes this scenarios less dependant on new power instalment and therefore their costs are lower. Regarding emissions we also confirm what is was said before. Since the model optimises cost and not emissions, dumb charge scenarios, which have greater solar power have less emissions. Electricity price is nearly the same and the reasons behind it can be many.

Results	**EV_dumb_charge**	**EV_dumb_charge_50%**	**EV**	**EV_50%**
Power system investment costs[M€]	25,602	30,287	25,078	30,182
Total emissions[tonCO_2]	642,928	646,383	643,277	646,566
Average electricity price 2030[€/MWh]	57.97	57.87	57.95	57.88

Table 10: Dumb charge/optimised charge scenarios

8.3 EV_CO2,EV_CO2_increase scenarios results

This scenarios pretend to asses the impact of CO_2 price in the grid.For this scenarios, CO_2 price has been increased every year with the rate indicated in the figures .Our power system is still dependant of coal and combined cycles. Even if coal plants are commissioned to close by 2030 and combined cycles by 2050, a sharp increase in CO_2 price could mean a faster response to change the whole system.

Regarding the total generation capacity shown in figure 29 we can see plainly that solar power increases drastically with increasing CO_2 prices. Combined cycles are forced to stop producing due to this price and therefore the power system is forced to produce everything with renewable sources. This has a positive effect on emissions but the total costs increase. It is also interesting to note how solar capacity has to be installed earlier due to this CO_2 prices. Even if the total capacity is the same.

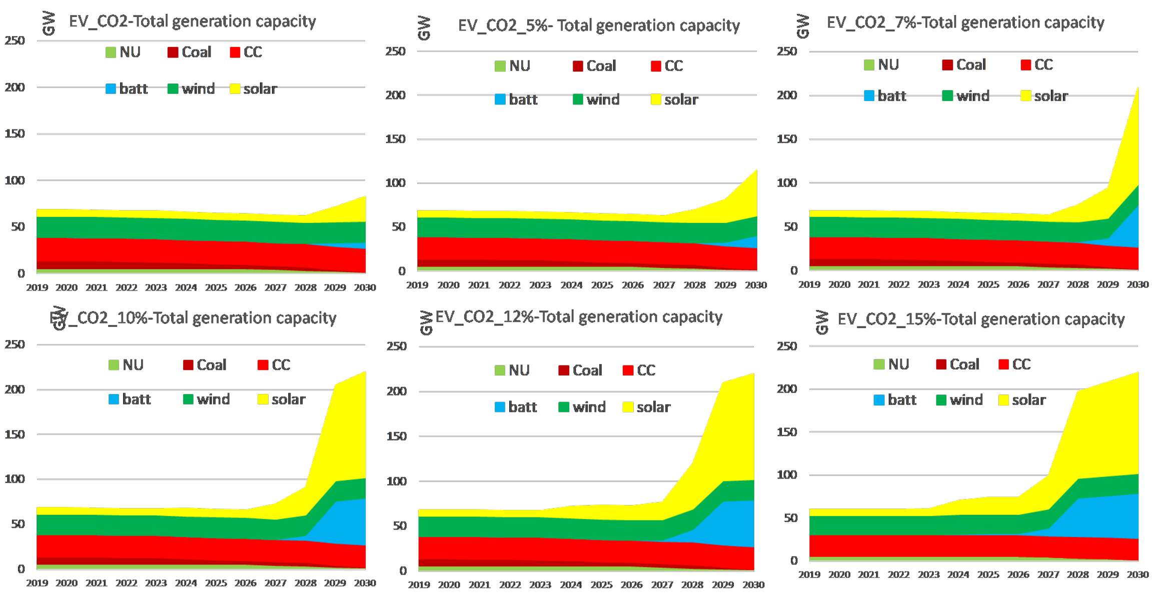

Figure 29: CO_2 increase scenarios,capacity

In order to see the electricity price changes, (figure 30) we requires a table with the average price since prices are similar. What can be said is that prices are higher during night time. This is because batteries supply demand during night time, therefore, the price is driven by not only solar power investments (as during day time) but also by battery investments .However, it should be said that for this cases when CO_2 increases noticing the reasons behind its' results can be difficult.

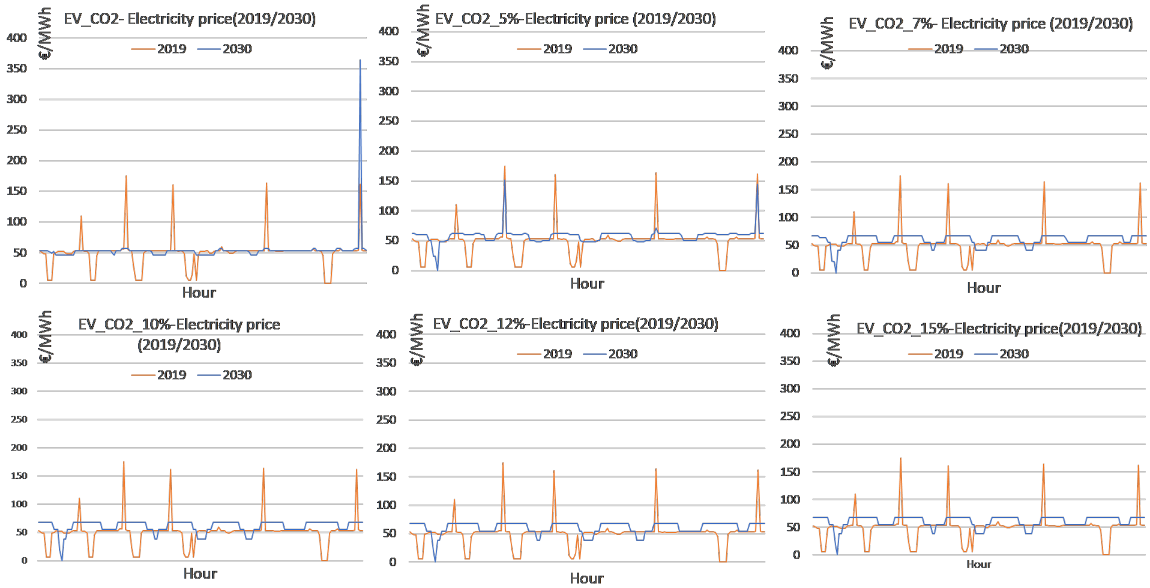

Figure 30: CO_2 increase scenarios,electricity price

Emissions (figure 31) decline as it was expected, reaching zero at the end of the period for high CO_2 prices. There is a noticeable difference between an annually CO_2 increase of a 5% and a 7%. This is because between this two costs, CO_2 prices are high enough to make combined cycles not profitable. This CO_2 price is approximately of 70€/tonCO_2. If CO_2 prices increase even further that a 7% annually, emissions decrease earlier due to earlier solar power instalment.

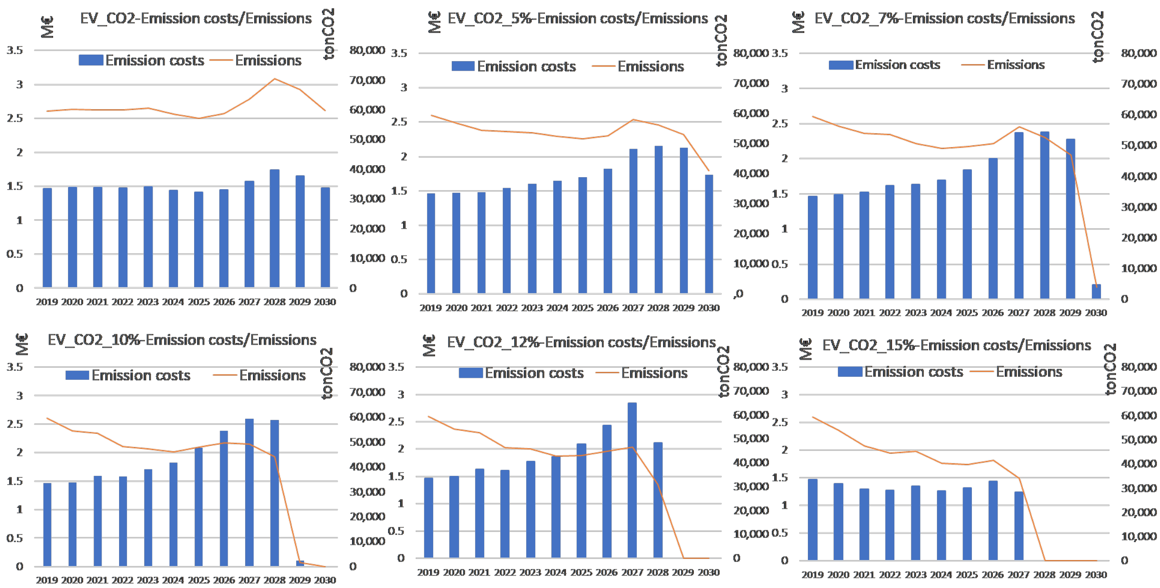

Figure 31: CO_2 increase scenarios,emissions

Production of energy (figure 32) is entirely renewable for high CO_2 prices. This means that batteries have a great importance. During night time batteries have to deliver the extra solar energy which has been produced during daytime. As a result from this battery investment costs increase.

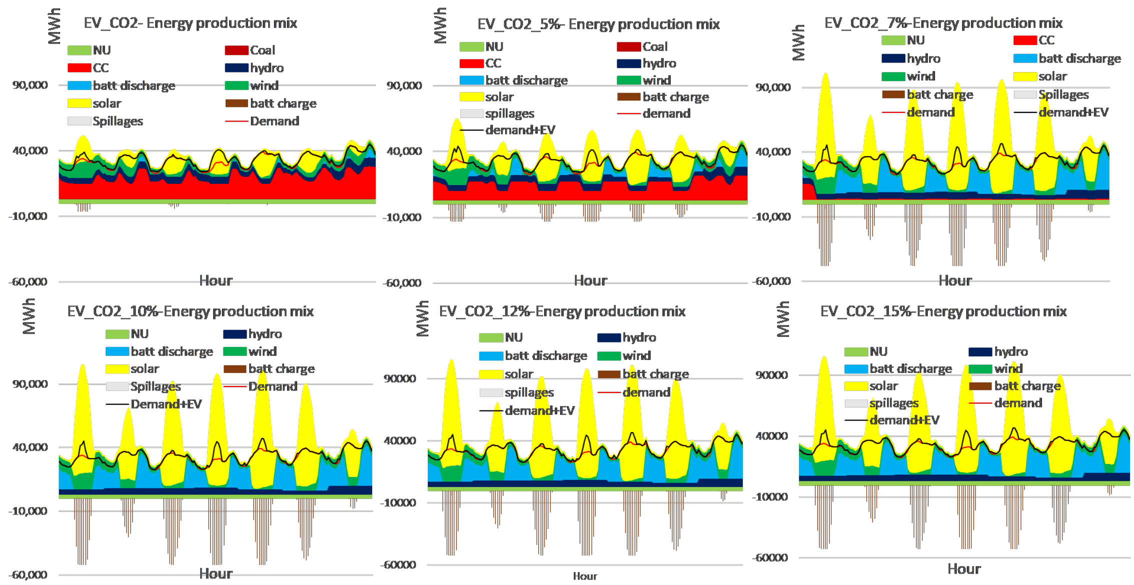

Figure 32: CO_2 increase scenarios,energy production mix

In figure 33 we see the sensitivity of solar power instalment to CO_2 price. It is seen that solar power is really sensitive for low CO_2 price increases. However, it reaches a point the total solar power installed won't change. This is due to the fact that it has reached its' limit. This limit corresponds to being able to meet the whole demand with the renewable power and nuclear already installed, the difference is when to invest in solar power, this time is earlier for high CO_2 increases.

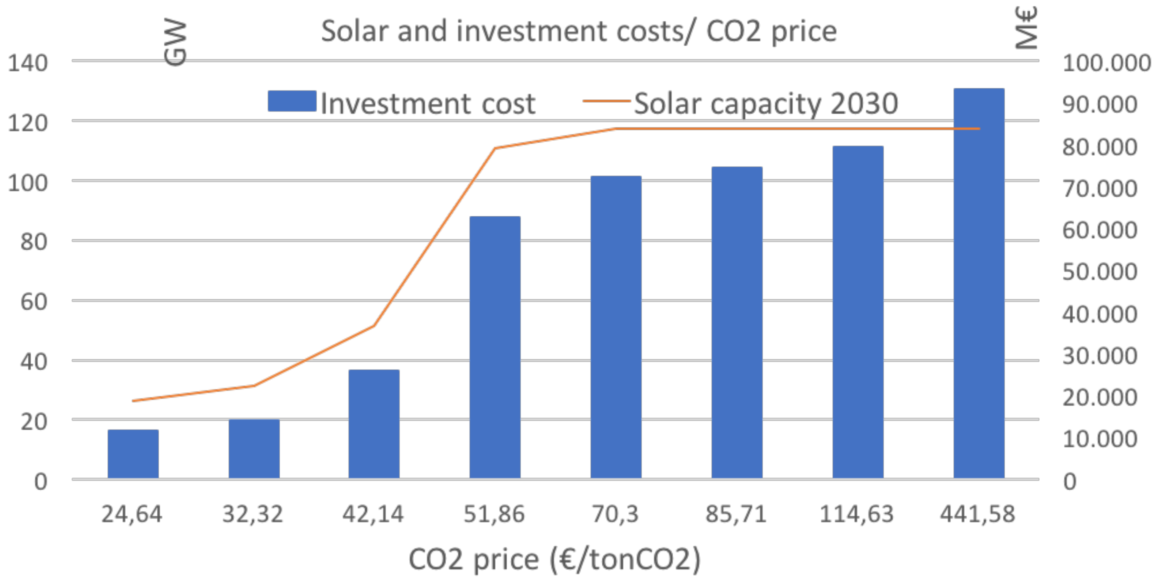

Figure 33: Solar power instalment sensitivity towards CO_2 price

With table 11 the results can be seen in a better way. The investment costs increase for every scenario with a higher CO_2 price. This increase is mainly due to combined cycles not producing, however, nuclear power also has an impact. Regarding electricity prices, they increase due to the extra CO_2 prices until emissions can't decrease further, point were prices stay the same.

Results	**EV_CO$_2$**	**EV_CO$_2$_5%**	**EV_CO$_2$_7%**	**EV_CO$_2$_10%**	**EV_CO$_2$_12%**	**EV_CO$_2$_15%**
Power system investment costs[M€]	11,521	26,078	62,653	72,182	74,441	79,378
Total emissions[tonCO$_2$]	735,601	643,277	583,016	501,402	466,609	406,313
Average electricity price 2030[€/MWh]	54.00	57.95	60.53	60.80	60.80	60.80

Table 11: CO_2 price variation scenarios

8.4 H2EV_Investment_decrease scenarios results

This scenarios are used to analyse the sensitivity of the investment costs of hydrogen plants in the system. Investment costs are decreased annually with different percentages to see its' impact.

Figure 34 represents the capacity installed in the power system for different investment costs decrease of a hydrogen plant. The final capacity is nearly the same in all the cases, the difference is when it is necessary to invest in solar power. Producing hydrogen has to be via a hydrogen plant so when the costs are low, more capacity can be installed in a year. This leads to a hydrogen production which takes advantage of low electricity prices to produce the maximum possible at this hours. As a result, instalment of new capacity takes place earlier with the decrease of hydrogen plant investment costs.

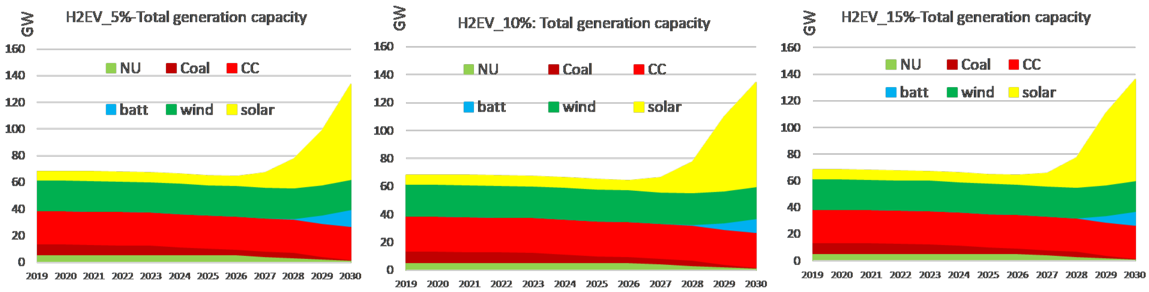

Figure 34: H2EV_Investment_decrease,capacity

Production mix (figure 35) is affected since hydrogen demand is higher at certain hours and lower for other.The reason behind this is explained in the previous paragraph. If H2EV investment costs are lower, higher investments will be done earlier leading to an increasing H2 production at low electricity hours.

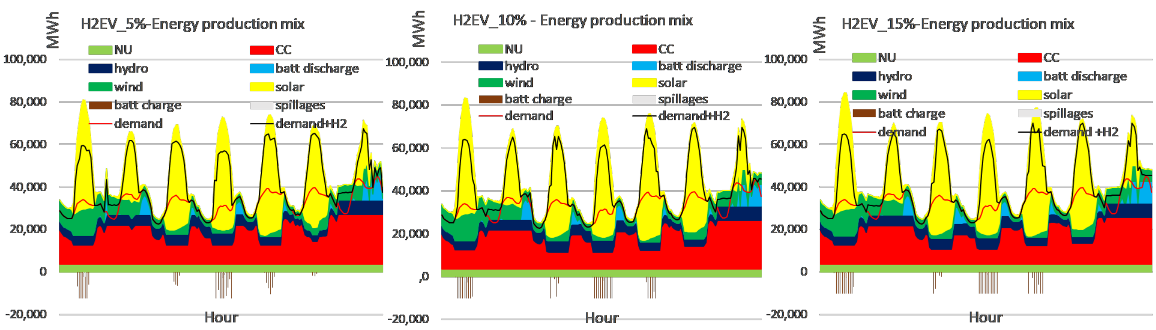

Figure 35: H2EV_Investment_decrease,energy production mix

The emissions decrease with the investment costs. The fact that hydrogen is more intensively produced when low prices occur, has an impact in the emissions. Electricity prices become lower when renewable sources are used. This is because of CO_2 prices and because of their already low electricity prices. This effect can be seen more easily on figure 37.

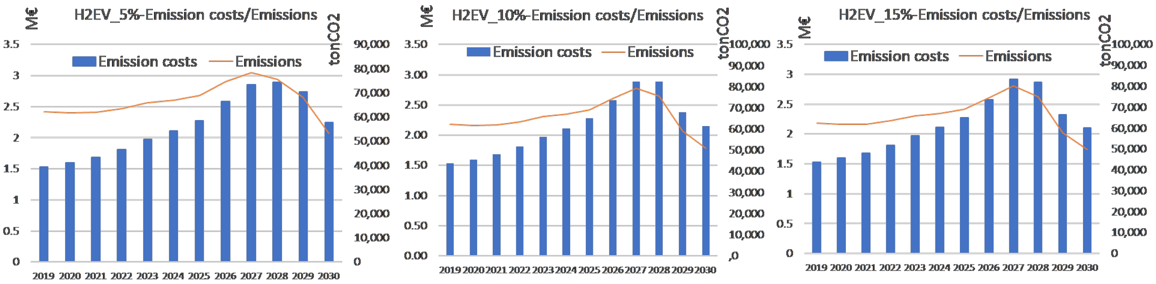

Figure 36: H2EV_Investment_decrease,emissions

As it was said before, in figure 37 we can see how hydrogen production increases in certain hours of the day. This hours are the ones with lower electricity price. Hydrogen plant investments are done earlier and therefore H2 production increases. As a result, hydrogen production is higher for the hours with low electricity prices taking more advantage of this ones.

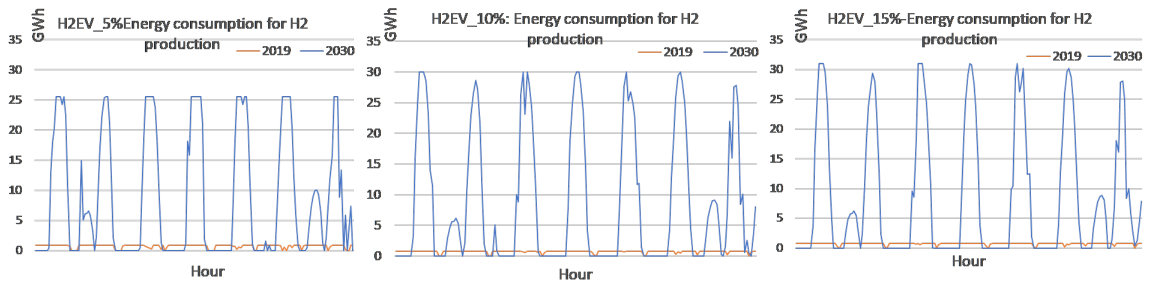

Figure 37: H2EV_Investment_decrease,hydrogen production

For the electricity price (figure38) differences are difficult to see in a graph. However, hydrogen production is given in low electricity prices as was explained earlier. This hours are mainly the ones in which combined cycles are not producing as much electricity as in other hours (figure 35), due to the costs involved in combined cycles. Since solar power generation has lower operating costs, hydrogen generation is located at hours where solar power generation is high and CC low. This is the reason why hydrogen generation is mainly done when solar power is present and as a consequence, the whole generation of hydrogen is cheaper bringing down electricity prices.

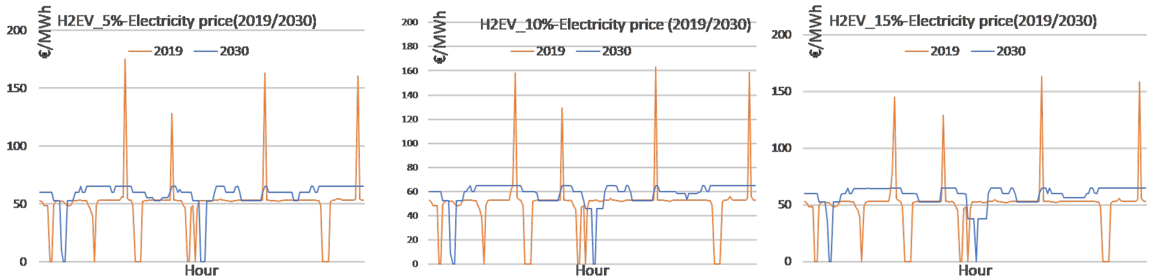

Figure 38: H2EV_Investment_decrease,Electricity price

In table 12 the results confirm what was said above. The power system costs increase due to the extra demand in certain hours. The emissions decrease due to producing with more solar power instead of combined cycles and the average electricity price decreases.

Results	**H2EV_Investment_5%**	**H2EV_Investment_10%**	**H2EV_Investment_15%**
H_2 investment costs[M€]	3,955	3,123	2,242
Power system investment costs[M€]	37,123	38,896	39,680
Total emissions[tonCO_2]	801,599	790,855	789,187
Average electricity price 2030[€/MWh]	58.17	58.02	57.96

Table 12: Investment variation scenarios

8.5 EV_50%,H2EV_50%,EV_H2EV_25%

For this scenario we observe a greater penetration which involves the same conclusions as in the base case, however, here we can see them more clearly and the table of results may not be needed. Basically, the results are the same but the effect of the vehicles is multiplied by two.

Regarding the total generating capacity (figure 39) it can be seen an obvious difference between the H2EV scenario and the EV. Hydrogen demand is much higher than the EV for the same penetration as was said in previous scenarios. In addition, H2 generation is only done when prices are low which means that at those hours the grid has to cover a great part of the total H2EV demand. Due to this two reasons capacity for H2EV scenario is extremely higher than for the EV one.

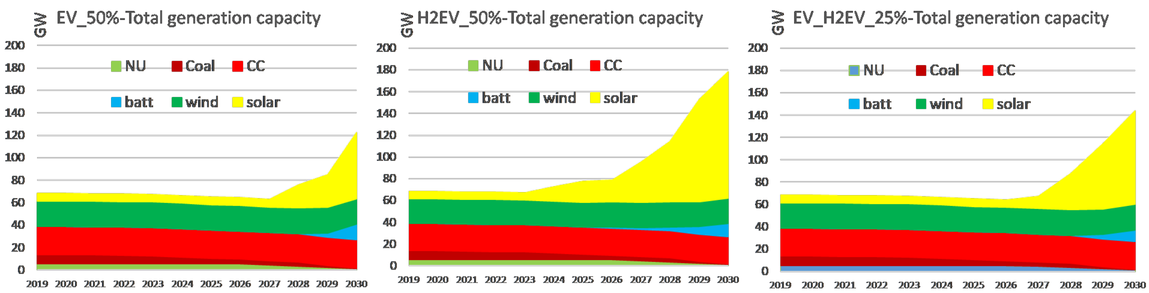

Figure 39: 50% scenario,capacity

Electricity price change is more obvious here (figure 40). For H2EV it is higher most of the time but it has more zero price hours. This is because hydrogen is only produced at certain hours and not during the whole day. This leads to hours in which the demand is lower than the EV case causing it to drop to zero.

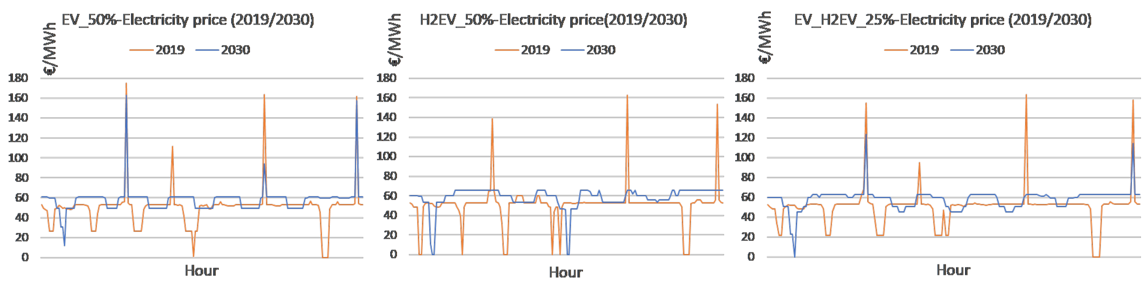

Figure 40: 50% scenario,electricity price

Figure 41 are the emissions produced by the system for this three scenarios. As it was seen in the base scenario it is confirmed that H2EV generates much more emissions than EV. This is because its' high power demand, requires of combined cycles and nuclear to supply it and therefore emissions increase. If this case would have been with a higher CO_2 price probably H2EV power system costs would have been extremely high. Comparing this figure with figure 25 (base scenario) we see that emissions are similar. This is because there are no investments in combined cycles or nuclear, therefore there is a limit to what they can produce. As a result, emissions don't increase as much as the penetration of EV or H2EV.

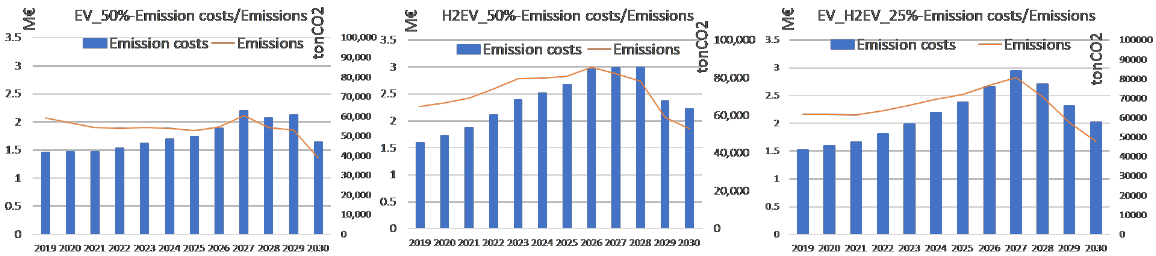

Figure 41: 50% scenario,emissions

In figure 42 we see the production mix in which H2EV has the highest demand and the highest combined cycle production. Hydrogen production is much higher than its' hourly demand since it stores energy when solar power is active to compensate for night time. We can see also that H2EV demand for this case is more than half the demand from the rest of the system. For this reason, H2EV aren't suited for large penetration rates. They require too much production generating a strain in the grid.

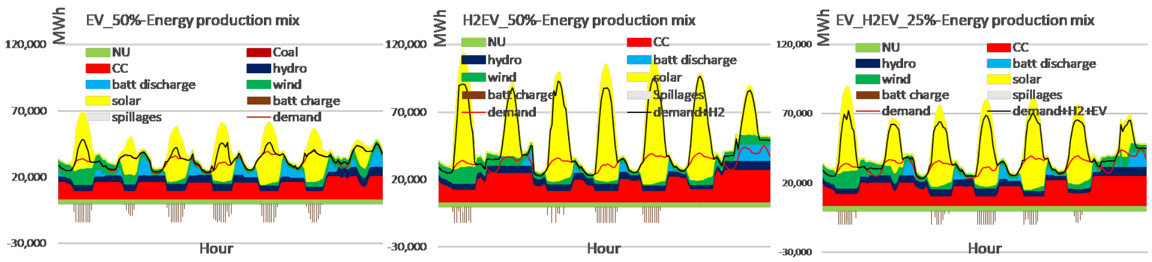

Figure 42: 50% scenario, energy production mix

In table 13 we see all the aggregated results from the scenario. Power system costs increase greatly due to extra demand. Emissions also increase, however, not so heavily. This is due to the fact that only renewable power and batteries are allowed investments. The extra H2EV or EV demand is covered mainly by solar power. Combined cycles produce more intensively, nevertheless, their capacity is fixed and therefore, emissions can't grow exponentially. Regarding electricity price, the highest price corresponds to H2EV since it has the highest power demand.

Results	**EV_50%**	**H2EV_50%**	**H2EV_50%**
H_2 investment costs[M€]	6,312	0	2,835
Power system investment costs[M€]	30,182	66,454	44,368
Total emissions[tonCO_2]	646,566	873,394	791,155
Average electricity price 2030[€/MWh]	57.88	58.10	58.02
Total demand 2030 [TWh]	298.66	441.25	369.95
H2EV power demand [TWh]	0	156.85	78.42
EV demand 2030 [TWh]	14.26	0	7.13

Table 13: 50% penetration scenarios

9 Conclusions

Hydrogen fuel cell vehicles are high energy consuming as it has been discussed, however, it has also be seen that hydrogen is flexible and can be produced when the grid has a surplus of renewable power instead of relying in batteries. Electric vehicles demand on the other side is rigid and has to be produced at the same time as charging occurs. Its' demand is less energy consuming, however, batteries are needed to supply EV demand during night time, which is when most consumers charge their EV.

The scenarios analysed reveal the poor efficiency of H2EV which energy demand is much higher than the EV. This has a negative effect on investments which have to be higher for the same penetration. In addition, H2EV has the disadvantage of not having an infrastructure build nowadays. The costs associated with this infrastructure is around a 10% of the power system investment costs. Moreover, in an scenario in which high technology advances occur, as the H2EV_Investment_15% which reduces the investment costs a 15% every year, this investment costs don't decrease excessively. This massive reduction in investment costs only reduces its' total cost in a 0.23%. As a result, from the economic point of view, H2EV are not as promising as the EV.

Emissions are not in its' favour either. H2EV has a 22.9 % more emissions than the EV scenario for the base case. This is due to the high energy demand from H2EV . Since H2EV objective is the decarbonization of the energy power system this results are of great importance.

Electricity prices are higher for the H2EV than for the EV. As it has been discussed, high energy demand leads to higher prices, this consequence from H2EV poor efficiency has a negative effect on the energy market and on the final consumer.

H2EV have advantages regarding its' flexible production and its' ability to take full advantage of solar power. However, investment costs, electricity prices and mainly emissions make it a secondary option regarding the electrification of the transport system.

10 Bibliography

[STA_18] Statista. Ranking de los principales países productores de platino a nivel mundial en 2018 (en toneladas métricas), Accesible in: https://es.statista.com/, 2018.

[USG_19] USGS.Lithium Statistics and Information, Accesible in: https://www.usgs.gov/, 2019.

[ABBO09] Derek Abbott.Keeping the Energy Debate Clean: How Do We Supply the World's Energy Needs?, Accesible in: https://www.phoenixprojectfoundation.us, 2009.

[DGT18] DGT.Parque de vehículos 2018, Accesible en: http://www.dgt.es, 2018.

[SIGU13] Gustavo Sigueiro.Platino en las pilas de combustible, Accesible in: https://forococheselectricos.com, 2013.

[GUER03] María Esther Guervós Sánchez.PRINCIPALES TÉCNICAS DE ALMACENAMIENTO DE HIDRÓGENO, Accesible in: http://estherguervos.galeon.com, 2003.

[REE_18] Red Eléctrica de España.Series estadísticas nacionales, Accesible in: https://www.ree.es, 2018.

[LAZA17] Lazard's Analysis.Lazard's Levelized Cost of Energy Analysis, Accesible in: https://www.lazard.com, 2017.

[EOI_18] Escuela de organización industrial.Coste y precio de las diferentes fuentes de energía,Accesible in: https://www.eoi.es, 2018.

[MENO11] Madhu Menon, R. Michael Sheetz y Mahendra Sunakara.Visible-light absorption and large band-gap bowing of GaN_{1-x} Sb_x from first principles,Accesible in: https://pdfs.semanticscholar.org, 2011.

[CEC13] California Energy Commission.2013 Building Energy Efficiency Standards, Accesible in: https://www.energy.ca.gov, 2013.

[FIER11] José Luis G. Fierro.El hidrógeno: metodologías de producción, Accesible in: http://www.fgcsic.es, 2011.

[SANC14] Carlos Sánchez.A pilot project by E.ON succeeds in feeding over 2 million KWh of hydrogen into the gas network in Germany, Accesible en: https://www.energynews.es, 2011.

[NGN_18] Northern gas network.NGN and ITM Power hail compelling power-to-gas energy storage study results, Accesible in: https://www.northerngasnetworks.co.uk, 2018.

[PNIE18] Plan Nacional Integral de energía y clima.BORRADOR DEL PLAN NACIONAL INTEGRADO DE ENERGÍA Y CLIMA 2021-2030 , Accesible in: https://www.idae.es, 2019.

[OTER18] Alejandra Otero.Coches de hidrógeno: así funciona esta tecnología de cero emisiones contaminantes, Accesible en: https://www.motorpasion.com, 2018.

[GONZ18] Pablo David González.Toyota Mirai (2015), Accesible in: https://www.km77.com, 2015.

[LINA07] José Ignacio Linares Hurtado y Beatriz Yolanda Moratilla Soria.El hidrógeno como vector energético (I/II), Accesible en: https://www.icai.es, 2007.

[FUKU19] Hiroyuki Fukui.Hydrogen Tracking Clean Energy Progress, Accesible in: https://www.iea.org, 2019.

[IEA_19] IEA Stadistics.IEA stadistics, Accesible in: https://www.iea.org, 2019.

[MELA15] M. Melaina and M. Penev.Hydrogen Station Cost Estimates , Accesible in: https://www.nrel.gov, 2015.

[PAHW14] P K Pahwa, G K Pahwa.Hydrogen Economy. , Accesible in: https://books.google.es, 2014.

[PINE09] Daniel Alejandro Pienda Erice.Evaluación técnico económica de una planta de producción de hidrógeno mediante electrólisis de agua utilizando energía eléctrica producida con caldas fotovoltaicas de alta eficiencia , Accesible in: http://repositorio.uchile.cl, 2009.

[SEND19] SendeCO2. SendeCO2, Accesible in: https://www.sendeco2.com, 2019.

[TEMPL18] James Temple.Así comienza la era de la captura y almacenamiento de carbono , Accesible in: https://www.technologyreview.es, 2018.

[ENER18] Energía16.Planta de hidrógeno en España generará 135.000 kg/año , Accesible in: https://www.energia16.com, 2018.

[ENAG19] Enagás .Flujo de Caudales Instantáneos , Accesible in: https://www.enagas.es, 2019.

[CNDH19] Centro Nacional de Hidrógeno .Mapa Hidrogeneras , Accesible in: http://auto.cnh2.es, 2019.

[PUYA16] Oscar Puyal .El modelo de energía y el hidrógeno , Accesible in: https://blog.somenergia.coop, 2016.

[ESPA19] Asociación Española del Hidrógeno . Los números del hidrógeno , Accesible in: http://www.aeh2.org, 2019.

[RENE18] National Energy renewable laboratory . Next Generation Hydrogen Station Composite Data Products: All Stations , Accesible in: https://www.nrel.gov, 2018.

[VILL11] Jose Villar, Ignacio Trigo, Cristian A.Diaz, Pablo Gonzalez. Cost-benefit analysis of plug-in electric vehicles penetration,2011.

[CAUS06] Andrés Causapé Rodríguez. Las tecnologías de almacenamiento de hidrógeno en vehículos y su proyección de futuro,2006.

[REE_17] Red Eléctrica de España. EL SISTEMA ELÉCTRICO ESPAÑOL, Accesible in: https://www.ree.es,2017.

[CNDH13] Centro Nacional del Hidrógeno. Hidrógeno almacenamiento y vector energético, Accesible in: https://www.fenercom.com,2013.

[MECA14] Aficionados de la mecánica. Vehículos de Hidrógeno, Accesible en: http://www.aficionadosalamecanica.net,2014.

[FABR09] MARC FÀBREGA RAMOS. Hidrógeno, aplicaciones en motores de combustión interna, Accesible in: https://upcommons.upc.edu,2009.

[USDE16] US Department of Energy. Fuel Cell Technologies Market Report 2016, Accesible in: https://www.energy.gov,2016.

[NREL11] National renewable energy laboratory. Hydrogen Production Cost Analysis Map (Text Version), Accesible in: https://www.nrel.gov,2011.

[EICH17] Josh Eichman, Bri-Mathias Hodge, and Jennifer Kurtz.Cost-Competitive Electrolysis-Based Hydrogen Under Current U.S. Electric Utility Rates, Accesible in: https://www.nrel.gov,2011.

[SCHM17] O.Schmidtab A.Gambhira I.Staffellb A.Hawkesc J.Nelsona S.Fewa. Future cost and performance of water electrolysis: An expert elicitation study, Accesible in: https://www.sciencedirect.com,2017.

[DANI16] Brian D. James Daniel A. DeSantis Genevieve Saur.Final Report: Hydrogen Production Pathways Cost Analysis (2013 – 2016),Accesible in: https://www.osti.gov,2016.

[FERN19] Patxi Fernández.Desmontando mitos sobre el coche de hidrógeno,Accesible in: https://www.abc.es,2019.

[GVR_19] Grand view research.Fuel Cell Vehicle Market Size, Share & Trends Analysis Report By Region (Europe, North America, Asia Pacific), Competitive Landscape, And Segment Forecasts, 2018 - 2025,Accesible in: https://www.abc.es,2019.

[OERE14] Office of Energy Efficiency and Renewable Energy.DOE Technical Targets for Hydrogen Production from Electrolysis ,Accesible in: https://www.energy.gov,2014.

[GONZ13] P. González, J. Villar, F. A. Campos, and C. A. Díaz, 'Hourly energy and reserve joint dispatch with a hydro-thermal technological based representation', in European Energy Market (EEM), 2013 10th International Conference on the, 2013.

[TRIG13] J. Villar, I. Trigo, C. A. Diaz, and P. Gonzalez, 'Cost-benefit analysis of plug-in electric vehicles penetration', in European Energy Market (EEM), 2013 10th International Conference on the, Stockholm, Sweden, 2013.

[SALA16] J. Villar, E. Salas, and Fco. A. Campos, 'Combined Penetration of Wind and Solar Generation with Plug-in Electric Vehicles', Energy Procedia, vol. 106, pp. 59–72, Dec. 2016.

[DOME18] S. Doménech and J. Villar, 'Synthetizing Representative Periods for Chronological Hourly Electricity Generation Expansion Models', in 2018 15th International Conference on the European Energy Market (EEM), 2018, pp. 1–5

[EUCO18] 'EU Coal Phase Out Detailed Information'. [Online]. Available: /briefings/eu-coal-phase-out/eu-coal-phase-out-detailed-information/. [Accessed: 11-Oct-2018].

[RENE18] 'As renewables replace coal, planned gas plants destined to become expensive white elephants', WWF. [Online]. Available: https://www.wwf.org.uk/updates/renewables-replace-coal-planned-gas-plants-destined-become-expensive-white-elephants. [Accessed: 11-Oct-2018].

[LUO_15] X. Luo, J. Wang, M. Dooner, and J. Clarke, 'Overview of current development in electrical energy storage technologies and the application potential in power system operation', Applied Energy, vol. 137, pp. 511–536, Jan. 2015.

[NOTT10] D. A. Notter et al., 'Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles', Environ. Sci. Technol., vol. 44, no. 17, pp. 6550–6556, Sep. 2010

[JAPA19] 'Power of choice: The future of hydrogen-powered cars in Japan', Japan Today. [Online]. Available: https://japantoday.com/category/tech/power-of-choice-the-future-of-hydrogen-powered-cars-in-japan. [Accessed: 20-Aug-2019].

[ADOL17] J. Adolf (project leader), 'Shell Hydrogen Study: Energy of the future? Sustainable Mobility through Fuel Cells and H2', Shell, 2017.

[POWE10] Power engineering, Hydrogen fuelled combined-cycle gas turbine power plant inaugurated by Enel, 2010.

[RUST18] Neha Rustagi , Overview of Status of Hydrogen Fueling Infrastructure in U.S., 2019.

[IRIA14] David Iriarte.¿A pila de hidrógeno o a baterías?, Accesible in: `https://forococheselectricos.com`, 2014.

[GAST18] Borja Gastón.Estudio de viabilidad de conversión de una central de ciclo combinado a una Power -to-Gas, Accesible in: `https://addi.ehu.es/`, 2018.