Bachelor thesis

Hydrogen Fuel Cell Vehicles

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under the guidance of

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and under the responsible participation of

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Abstract

Hydrogen fuel cell vehicles are meant to be the alternative for all these cars on the road - more than one billion. Why now? Mankind are realizing the importance of the environment and this new technology avoid the noise and the emissions of pollutants. How it works? A reaction between hydrogen and oxygen in the fuel cell generate the power for the vehicle with water as the only residue. Thus, no fossil fuel dependence? These vehicles use hydrogen as an energy source, and it is possible to produce hydrogen without fossil fuel. What about the infrastructure? Automakers, governments, and oil and energy companies are working together on it. Although it requires a lot of investment, nowadays, more than 180 hydrogen refuelling stations are underway and hundreds more are planned. Automakers are pushing to increase the amount of it, because they intend the launching of these vehicles in a short-term. Hydrogen fuel cell vehicles are the present with a great future.

Contents

1. List of abbreviations and symbols

AFCC – Automotive Fuel Cell Corporation

CaFCP – California Fuel Cell Partnership

CARB – California with Air Resources Board

CCGT - Combined Cycle Gas Turbine

CGH_2 – Compressed hydrogen

CNG – Compressed natural gas

DOE’s – United States Department of Energy’s

EC – European Commission

EU – European Union

FCEV – Fuel Cell Electric Vehicle

FCV – Fuel Cell Vehicle

GHG – Greenhouse Gas

GM – General Motors

HHV - Higher Heating Value

HIT - Hydrogen Infrastructure Transport

HRS – Hydrogen Refuelling Stations

HySUT - Hydrogen Supply-Utilization Technology

IC - Internal Combustion

ICE - Internal Combustion Engine

LBST - Ludwig-Bölkow-Systemtechnik

LH_2 – Liquid (cryogenic) hydrogen

MoU – Memorandum of Understanding

NASA – (U.S.) National Aeronautics and Space Administration

NO_x – Nitrous Oxides

NOW - Nationale Organisation Wasserstoff

PEM – Proton Exchange Membrane

PEMFC – Proton Exchange Membrane Fuel Cell

PM – Particulate Matter

RD&D – Research, Development and Demonstration

SAE – Society of Automotive Engineers

SO_x – Sulphurs Oxides

SUV – Sports Utility Vehicle

USA – United States of America

V_c – Fuel cell voltage

ZEV – Zero Emission Vehicle

2. Introduction

2.1. Aim and scope of the project

Nowadays more than one billion cars are on the road. These noisy and polluting vehicles are the main contributors of the greenhouse gas emissions (GHG). Mankind knows the its severe consequences for the environment. The climate change is the order of the day, it is a present in our lives. However, the comfort of the car is not something easy to give up. In this scenario is where alternative drive systems enter in the game. The awareness of governments and population was decisive for developing eco-friendly cars.

The main aim of this project is to reflect the actual state of alternative drive system. Getting to know all the problems of launching hydrogen fuel cell vehicles and understand how these work. It is deeply explained the principle of fuel cell as to realize the importance of hydrogen as an energy source and all that entails. The goal of using hydrogen is to avoid carbon dioxide, thus, some pathways to achieve this environmental target are going to be described.

The picture of hydrogen fuel cell vehicles future lies on the implication of government, oil and energy companies, and automakers. The scope of this project is to visualize how far are their efforts going to be as to get the balance infrastructure-car equilibrated. The comparison between different vehicles in the market will be useful to understand the necessity of big investments in this field.

3. Alternative drive systems

The aim of developing alternative drive systems is having clean and quite vehicles. Silence and zero-emission are the main characteristics for the future car, and that is what automakers are trying to achieve.

3.1. History

First electrical vehicles were developed to avoid the noise and contamination of the gasoline ones. Since the commercialization of the first electric car at the end of 19th century, the major motor companies have invest lots of money for the development of friendly environmental vehicles.

Unlike internal combustion engine vehicles (IC) of the time, these first electrical vehicles were relatively reliable, non-smelly and with an instantly start. The electric vehicle was promising, however the development of a new self starter for IC engine and the low price of the oil changed this picture. In addition, the low specific energy of a lead acid battery and the time it takes to recharge the electric cars make the IC vehicles more attractive.

The deciding factor for the development of electric vehicles was environmental issue. A regulation of the state of California, with the introduction of Low Emission Vehicle Program, encouraged the production of electric vehicles. It was with the Zero Emission Vehicle (ZEV) program when started the development of fuel cell, battery and hybrid electric vehicles. All these Californian legislative programmes have a main goal and it is having a healthier air and reducing heat-trapping emissions 80 percent by 2050.

Nowadays, there are different types of electric vehicles: battery electric vehicles; hybrid electric vehicles; fuelled electric vehicles; electric vehicles using supply lines; solar powered vehicles - see Figure 3.1- and electric vehicles which use flywheels or super capacitors [1]

Figure 3.1 Solar powered car from the University of Central Florida [2].

3.1.1. History of hydrogen fuel-cell vehicles

The first fuel cell, called 'Grove Gas Battery', was created by Sir William Rober Grove in Wales, by 1843. In 1959, Francis Bacon developed a fuel cell with an output power of 5 kW. But it was in the 1960s when General Electric had big development with Proton Exchange Membrane fuel cell (PEM). NASA became the first to use them, they used fuel cells with *Project Gemini* and *Apollo Program*. After that, automakers began working with fuel cells in vehicles. *Chevrolet Electrovan* was the first fuel cell road vehicle, it was developed in 1966 by General Motors. George W. Bush declaration of a Hydrogen Fuel Initiative and Arnold Schwarzenegger announcement of an Hydrogen Highway had a good impact for the sector.

Hydrogen fuel-cell vehicles have evolved a lot, nowadays they can drive around 500 to 800 km on a full tank. The development of these vehicles is increasing, but they still have a huge way to improve.

It has to be said that actually fuel cell electrical vehicles (FCEV) are more promising in city bus applications –Figure 3.2- for two reasons: the supply of hydrogen is not a problem because the buses refuel in one place, thus only one refilling point is necessary and the second reason is the price of fuel cells. Fuel cells are still expensive so it makes more sense buying them for vehicles which are in use for many hours each day [1][3].

Figure 3.2 Hydrogen fuel cell bus [4].

3.1.2. Future plans of hydrogen fuel-cell vehicles

This technology shows a great promise but need to get over the main problems like: cost of the equipment need to make work the system; rival technology with low pollutant emission; water management ; cooling; hydrogen fuel price and its supply is not easy for the difficulties in storing and transporting; fuel cell durability and reliability, the actual durability is 120.000 km, but it is expected to be 240.000 km as to compete with gasoline vehicles [1][3][5][6]

Automakers plan to commercialize thousands fuel cell electric vehicles in the 2015-2017. On Californian roads is estimated to have 53.000 of these by 2017 [7]. According to that prediction, California is planning to make available hydrogen fuelling stations [8]. Exgovernor Arnold Schwarzenegger vision of an Hydrogen Highway with at least 200 hydrogen stations, with an estimated cost of $90 million - 70 million euro [9].

In Europe, *France's Air Liquide* and *Germany's Linde AG* work together to increase Germany's stations from 15 to 100 by 2017 and 400 by 2023. About 1,000 Hydrogen Refuelling Stations (HRS) would be needed to provide full coverage in countries like France or Germany with a cost of 1,5-2 billion euro [10][11].

The main automakers working on these vehicles are: *Ford* (USA), *General Motors* (USA), *Honda* (Japan), *Hyundai* (Korea), *Daimler* (Germany) , *Nissan* (Japan) and *Toyota* (Japan). In September 2009, these parties co-signed a letter with the aim to commercialise a significant number of fuel cell vehicles from 2015. They also agreed to progress hydrogen refuelling infrastructure. In the chapter 6 some cooperation between automakers and their plans are going to be explained.

3.2. Environment

Nowadays, mankind is starting to concern more about the environment, and electric vehicles can have a good play in that issue (see Table 3.1). The environmental impact of vehicles is analysed ‘well to wheels’, so it is considered the pollution of all the parts of energy cycle, not just the vehicle by itself. First, it must be remembered that the energy comes from somewhere, it does not just appear. At this point, there is a question: ‘could be possible to move people towards more environmentally modes of transport?’ Of course. However, the power of law and regulation is needed in favour of less pollution. The best example took place in California with *California Air Resources Board* (CARB). The goal of this organisation is to maintain healthy air quality. CARB had a huge impact on the development of electric vehicles. In the 1980s CARB enacted a directive that required that any motor manufacturer selling vehicles in Califronia would have to ensure a minimum of zero-emission vehicles sold. As a consequence there were taken place the major developments in fuel cells, hybrid vehicles...

Vehicle type	NO_x $g.km^{-1}$	SO_x $g.km^{-1}$	CO $g.km^{-1}$	PM $g.km^{-1}$	CO_2 $g.km^{-1}$	Energy $MJ.km^{-1}$
Gasoline ICE car	0.26	0.20	2.3	0.01	209	3.16
Diesel ICE car	0.57	0.13	0.65	0.05	154	2.36
CNG ICE car	0.10	0.01	0.05	<0.0001	158	2.74
Hydrogen ICE car	0.11	0.03	0.04	0.0001	220	4.44
Gasoline fuelled hybrid	0.18	0.14	1.61	0.007	146.3	2.212
MeOH fuel cell car	0.04	0.006	0.014	0.0015	130	2.63
Hydrogen fuel cell car	0.04	0.01	0.02	<0.0001	87.6	1.77
Battery car, British electricity	0.54	0.74	0.09	0.05	104	1.98
Battery car, CCGT electricity	0.17	0.06	0.08	0.0001	88.1	1.71

Table 3.1 Emissions and energy for different types of vehicles [1].

Hydrogen for fuel cells can be obtained by reforming conventional fuels or by electrolysing water. If the production of hydrogen is matched to alternative energy, like solar energy, renewable biological methods,...the emissions can be zero, however it depends on the nature of the energy, more information in chapter 4 [1][7].

3.3. Hydrogen Fuel Cell Vehicles

3.3.1. Basic Principle

The principle to produce electricity is based in a chemical reaction (3.1) between hydrogen and oxygen as to get water and energy. This energy is released as an electric current (Figure 3.3 and Figure 3.4)

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (3.1)$$

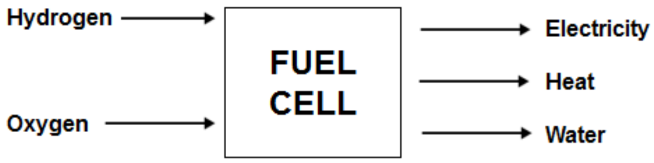

Figure 3.3 Fuel cell inputs and outputs

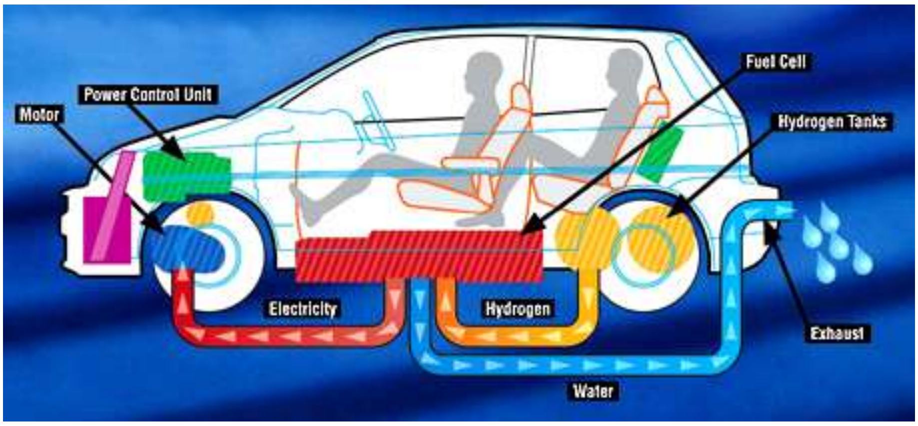

Figure 3.4 How works an hydrogen fuel cell vehicle [12].

3.3.2. Reactions

The electrode reaction that takes place vary depending on the different types of fuel cell, here it is going to be explained the most common types, the cell based on an acid electrolyte and polymer electrolyte. Each fuel cell contains two electrodes, cathode and anode, with a substance between them that conducts electricity, electrolyte.

At the anode the hydrogen gas ionizes releasing energy(3.2) and at the cathode, oxygen reacts with these H^+ ions and electrons to form water (3.3). All the process is described in the Figure 3.5.

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (3.2)$$

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O \qquad (3.3)$$

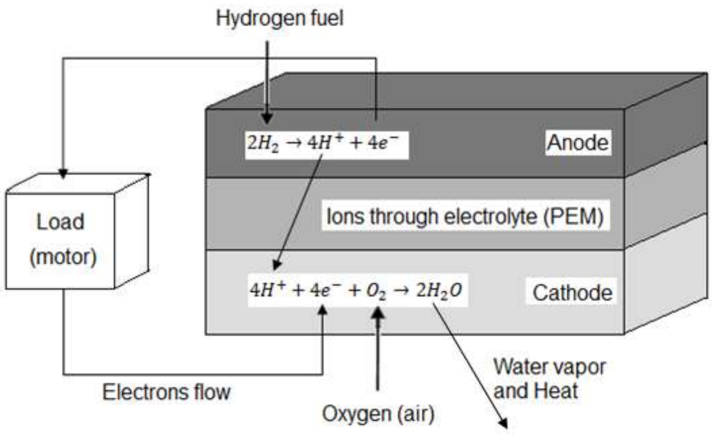

Figure 3.5 Reaction at the electrode in a fuel cell

Proton Exchange Membrane fuel cell (PEM) let the pass of H^+ ions through. PEM uses a solid polymer as an electrolyte. The main applications are for vehicles and mobile. It can operate in the rate of 30ºC and 100ºC. The running of these at low temperatures causes a slow reaction, so it is needed catalysts on the electrode like platinum. Raising the temperature and increasing the electrode area help dealing with the slow reaction rates. It is possible to rise the area of the electrode making it more porous.

The voltage of a working fuel cell is about 0,7V, thus, it is necessary to connect them in series, also known as 'stack'. As to connect them is used a system of 'internal manifolding', a complex bipolar plate [1][13].

3.3.3. Vehicle System

Although the main component of the system is the fuel cell stack. Some other important parts need to be explained, and the basic – more used- characteristics are the ones reflected in Figure 3.6 [13][14].

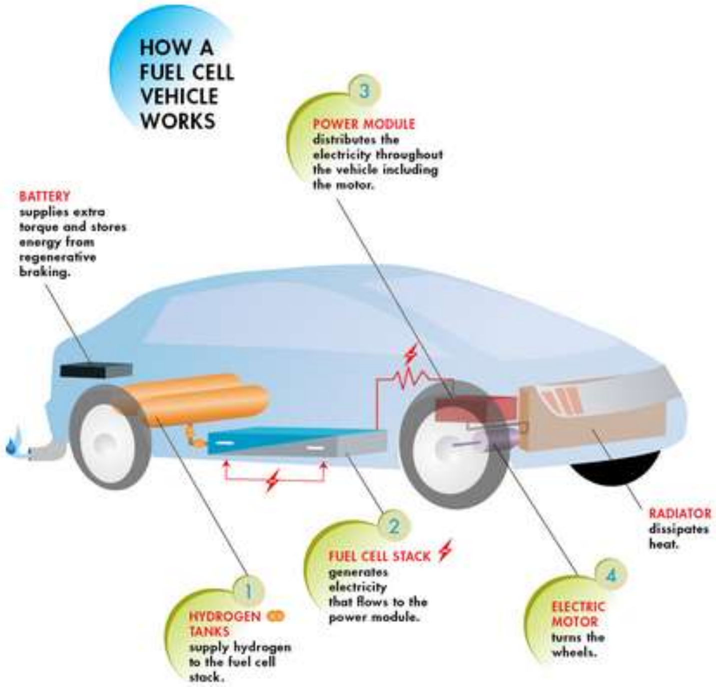

Figure 3.6 Hydrogen fuel-cell car system and its components [14].

- Fuel tank system: special cylinders containing compressed hydrogen at 300 or 700 bar as to increase the driving range.
- Battery: llithium-ion battery stores electrical energy and support the vehicle when it accelerates. Their power come from recovering kinetic energy - energy recuperation.
- E-engine: the high-torque electric motor drives the vehicle and it is located on the front axle. It obtains its energy from the fuel cell stack and the battery. These motors boost the vehicle quietly, smoothly, and efficiently. It requires less maintenance than combustion ones.
- Power control unit or power module: governs the flow of electricity.

In the case of fuel cell buses, see Figure 3.7, these can store the hydrogen tanks, batteries and air conditioning system in the roof. The large roof area of these buses allowed them to store as many tanks as to run for 16-18 hours. Their batteries capture the energy from braking as to power the cooling/heating system [15].

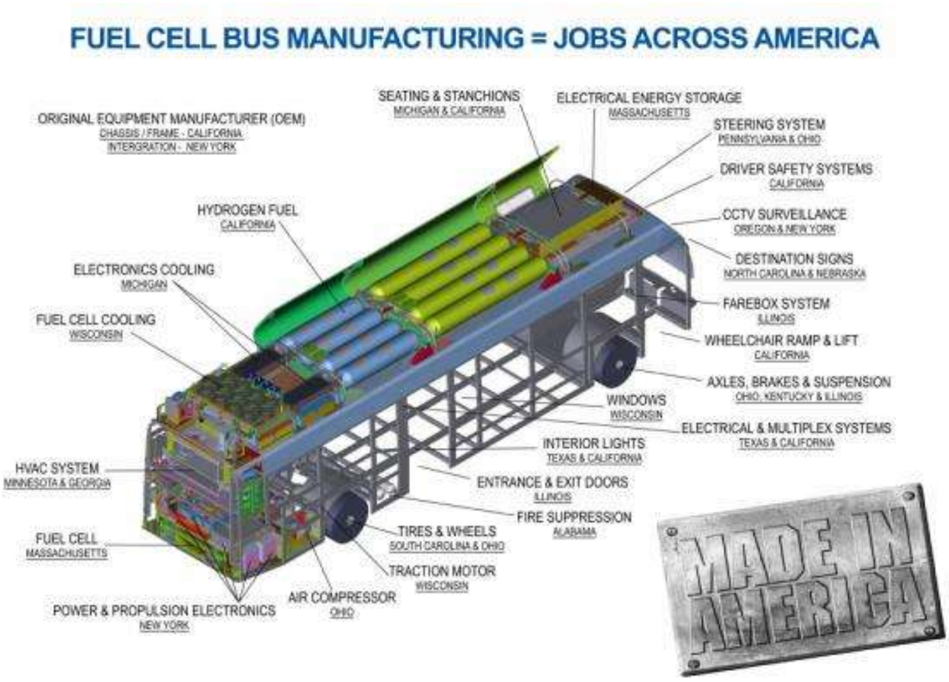

Figure 3.7 Hydrogen fuel-cell bus system and its components [15].

4. Hydrogen as an energy source

4.1.1. Why Hydrogen?

Hydrogen is the most abundant element in the universe. It is considered the forever fuel and it can be produced by any primary energy fuel: oil, coal, nuclear, natural gas, renewable energies, and grid electricity. Hydrogen is sustainable economically, climatically and environmentally, as well as societally [16].

4.1.2. Where does Hydrogen come from?

The hydrogen chain, like any other energy conversion chain, consists of five links: production, storage, transport, dissemination, and use.

Hydrogen comes basically from: fossil fuel or renewable, and it is also possible by nuclear fission.

- Fossil fuels, like coal and natural gas, via reformation or partial oxidation or gasification. Fossil fuels contain hydrocarbons, and with a reformer it is possible to split the hydrogen off the carbon. However, the reformers discard this carbon leftover to the atmosphere as carbon dioxide.

- Renewable electricity from solar irradiance, wind,… which is used to split de-mineralized water into hydrogen and oxygen- electrolysis.

- Renewable fuels, like biomass, converted to biogas in the anaerobic digester and then in a fuel cell is separated into hydrogen and CO_2, or via Pyrolysis.

Nowadays, most hydrogen is produced from natural gas. It is a safe, efficient and cost effective way.

For the storage and transport of the hydrogen the main issue to be considered is safety. Hydrogen is a gas with high thermal conductivity, molecular velocity and low viscosity and density. It is highly volatile and flammable gas. Hydrogen needs to be handled with care and the systems must be designed with the lowest chance of any leaks.

The choice of a hydrogen production affects the cost and method of its delivery. The technologies for providing hydrogen might try to reduce delivery cost, increase energy efficiency, maintain hydrogen purity, and minimize hydrogen leakage. As to achieve these challenges it is necessary to think about the production and delivery options as a system, both together.

Today, the transportation of hydrogen from the production point to the use point can be via pipeline, by rail, by barges, or by trailers.

If it is transported via pipelines, it is possible to adapt part of the natural gas delivery infrastructure. This is the lowest-cost option to deliver large volumes of gaseous hydrogen. In the other hand, other options are possible: trucks, railcars, barges, and ships deliver cryogenic liquid hydrogen, compressed hydrogen gas, or novel hydrogen liquid or solid carriers.

Two distinct methods groups to store the hydrogen are identified: storing hydrogen compressed, liquefied or held; and hydrogen stored as man-made fuel - methanol, ammonia, sodium borohydride - hydrogen carriers.

The main advantages for hydrogen stored as a compressed gas, at high pressure, are: simplicity, indefinite storage time and no purity limits on the hydrogen. This is the most used way. Otherwise, when it is storage as a liquid at about 22K, it is possible to store large quantities of hydrogen. More systems are compared in Table 4.1 [1][16][17].

Method	Gravimetric storage efficiency, % mass H_2	Volumetric mass (in kg) of H_2 per litre	Comments
High pressure in cylinders	0.7-3	0.025	Cheap, widely used
Metal hydride	0.65	0.028	Suitable for small systems
Cryogenic liquid	14.2	0.040	Bulk storage, widely used
Methanol	6.9	0.055	Low chemical cost
Sodium hydride pellets	2.2	0.02	Problem of disposing of spent solution
$NaBH_4$ solution in water	3.35	0.036	Expensive to run

Table 4.1 Comparing currently methods of storing hydrogen fuel [1]

There are many compounds that can be used to hold large quantities of hydrogen, these are cold hydrogen carriers. These compounds must have three characteristics: these must give up easily their hydrogen; the energy and financial costs of placing hydrogen into the compound must be low; these must be safe to handle [16][18].

For the question: how is actually hydrogen stored? The two options more used are: high pressure gaseous hydrogen tanks (CGH_2) or liquefied hydrogen containers (LH_2) [16].

CGH_2 key challenges are the volumetric capacity, weight, high pressure, and cost. The volumetric capacity is really important, thus it has a direct impact on the number of times to refuel. When the pressure and the amount of hydrogen is increased, it is greater the driving range achieved. However the cost and the vehicle space are negatively affected. High-pressure compressed gas tanks are made of carbon fiber as to give a light-weight structural reinforcement. The cost of carbon fiber tanks dictates the cost of CGH_2. Thus, it is important to get a low cost without compromising the weight and the volume of these tanks.

On the other hand, LH_2 tanks issues are hydrogen boil-off, weight, volume, energy required for hydrogen liquefaction, and tank cost. The 30% of the heating value of hydrogen is the energy required for hydrogen liquefaction. The good point about this method is that LH_2 tanks can store more hydrogen than CGH_2 in the same volume, 0,07 kg/l against 0,03 kg/l at 70MPa [1][18][19].

In the **Figure 4.1** is summarized the different ways to get hydrogen.

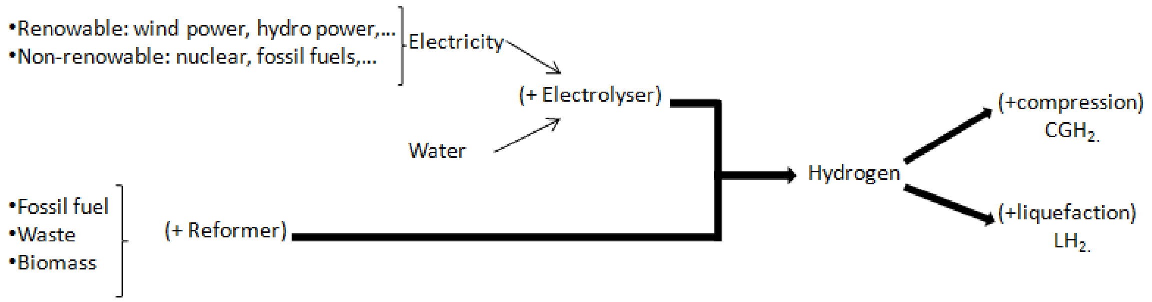

Figure 4.1 Different ways of achieving hydrogen

In Figure 4.2, there is a good representation of how hydrogen chain is and shows some pathways of the process.

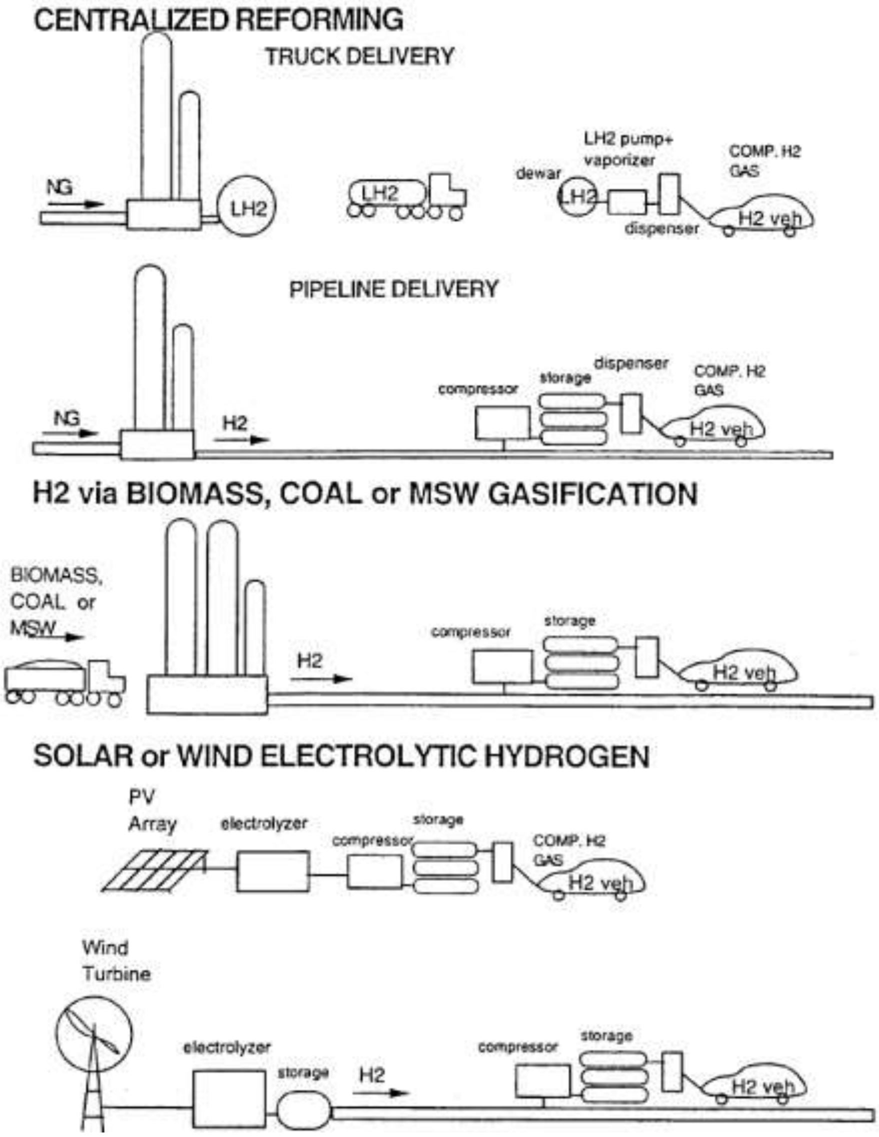

Figure 4.2 Different pathways to produce, transport and store hydrogen [20].

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5. Current international progress of fuel cell propulsion technology and infrastructure

5.1. Comparing actual cars

The three vehicles that are going to be compared in this section are: internal combustion vehicles, battery electric, and hydrogen fuel cell electric. The different vehicle types have different power technology. Internal combustion vehicles burn fuel, battery electric cars are powered by rechargeable batteries, and fuel cell electric vehicles power relies on hydrogen and fuel cells.

5.1.1. Rechargeable Batteries Versus Fuel Cell

Fuel cell and rechargeable battery operate in a similar way, both transform chemical energy into electricity. These electrochemical reactions are controlled and do not produce pollutants. However, the storage of the fuel is different. A battery stores internally the chemical compound and converts it into electricity. On the other hand, the chemical compound of the fuel cell, hydrogen, is stored externally in a tank onboard.

5.1.2. Combustion Engines Versus Fuel Cell

Combustion engines and fuel cell store the fuel in a tank onboard. In that case they differ in the control of the chemical reactions that take place. The gasoline combustion has some uncontrolled chemical reactions with the result of many undesired compounds as NO_x, SO_x,..These compounds are not environmentally friendly. Another difference is the efficiency of each one, a fuel cell is three times more efficient than a traditional combustion one. A conventional combustion engine has an efficiency of 20%, on the other hand, a fuel cell converts 68% of the chemical energy[1]. The hydrogen used in fuel cell cars reduces greenhouse gases by 55%-65% compared to the gasoline one, even when it is produced from natural gas.

[1] Using HHV: fuel cell efficiency=$\frac{V_C}{V_{100\%}}=\frac{V_C}{1.48}$

All the similarities and differences are summarized the Table 5.1. and Table 5.2 [7][21].

Characteristic	**Vehicle**		
	Conventional Gasoline Vehicle	**Battery Electric Vehicle**	**Fuel Cell Electric Vehicle**
Power Source	Internal combustion engine	Rechargeable battery	Hydrogen fuel cell
Existing Infrastructure	✓✓	✓	✗
Long range	✓	✗	✓✓
Short refuelling time	✓	✗	✓
Availability for purchase	✓✓	✓	✗
Environmentally friendly	✗	✓	✓
Quiet operation	✗	✓	✓
Quick-smooth acceleration	✗	✓	✓
High fuel efficiency	✗	✓	✓✓
Purchase incentives	✗	✓	✓

Table 5.1 Similarities and differences between conventional, battery electric, and fuel cell electric vehicles [7].

Fuel cost	2010	2030 optimistic	2030 pessimistic	2030 average	Miles·GJ^{-1}	Typical units
Gasoline	\$12,7 GJ^{-1}	\$19 GJ^{-1}	\$38 GJ^{-1}	\$28,5 GJ^{-1}	253	40 mpg
Hydrogen	\$42 GJ^{-1}	\$14 GJ^{-1}	\$56 GJ^{-1}	\$35 GJ^{-1}	506	72 miles·kg^{-1}
Electric	\$36 GJ^{-1}	\$27 GJ^{-1}	\$45 GJ^{-1}	\$36 GJ^{-1}	1013	3,6kW·h^{-1}

Table 5.2 Summary of the running cost input data, normalized to \$ GJ^{-1} for comparison [22].

5.2. Evolution

The costumers of hydrogen fuel cell cars need to know that they are able to refuel wherever they go. The fact is that as much cars on the road, the number of stations will increase. Currently most of the Europe countries has HRS- Spain, France, Germany, Austria, England, Italy, Switzerland,...- also in Japan, South Korea, United States,...

In Germany, three hundred million euro are planned to be invest for the construction of 400 HRS by 2030. This initiative of *H_2 Mobility* was made by six partners - Air Liquide, Daimler, Linde, OMV, Shell and Total. It is expected that the cost of HRS will be five times lower than the network required for hybrid vehicles. About the costs of fuel cell systems for vehicles, they are hoped to decrease 90% by 2020.

The capacity to produce enough hydrogen will not be a problem. Actually, the hydrogen industry produces the amount of hydrogen equivalent as to provide for 130 million vehicles.

As to incentivizing the population to buy these vehicles, some countries have started campaigns supporting it. For example, Denmark. They support the introduction of hydrogen fuel freeing hydrogen cars of all taxes. Danish Government has doubled their public support for energy RD&D as well [23][24].

5.2.1. Progress and accomplishments

Fuel cell improvements:

- The cost of automotive fuel cells has been reduced more than 80% since 2002
- Durability proved. Fuel cell vehicles can operate more than 2.500 hours with less than 10% degration. Double time than 2006. The driving range is more than 120.000 km.
- 25% increase in system power density
- 30% reduction of stack volume and 15% of stack weight

Developments in hydrogen field:

- The cost of hydrogen production from natural gas has been reduced, making it competitive with gasoline.

- The cost of hydrogen production from renewable resources has been reduced, by more than 80% since 2002 with water electrolysis as pathway.
- The cost of hydrogen delivery has been reduced by 40% for tube-trailer, 20% for pipeline, and 15% for tanker truck.
- The capacity to storage hydrogen has been increased by 50% since 2007 with the development of cry-compressed tanks [25]

5.3. Infrastructure

For the introduction to the market of fuel cell vehicles two things are necessary: the cars and the HRS to support them. A minimum number of each is needed to support the demand of the other. All development is worthless without a good infrastructure in highways, roads,... It is necessary to build HRS.

HRS may receive trucked-in hydrogen or generate it on-site. These stations have compressing, storing and dispensing, equipment for the hydrogen. The compressing equipment -350bar or 700bar- reduces the volume of the hydrogen. These compressed hydrogen is stored onsite in cryogenics tanks, high pressure, or, in a few sites, in liquid form.

The fuelling process must be quickly, easily, and securely. The production, transport and storage of hydrogen are the previous steps, more information in chapter 4. For the full market introduction of fuel cell-powered vehicles, there must exist comprehensive infrastructure. Thus, automobile manufacturers, companies in oil and energy industries as well as the world's policy, need to work hand to hand.

As a consequence of not enough network, by 2009, the seven world's largest automakers – Ford, Daimler, General Motors, Hyundai, Honda, Toyota and Nissan - joined to sign a letter of understanding, it was a calling for infrastructure – see *Appendix A*. The aim of this letter, addressed to oil and energy industries and government organizations, was to inform their intention of commercialize fuel cell vehicles from 2015. Thereby, it was urged to develop HRS in Europe, and specially in Germany. They agreed that all HRS must meet the requirements of SAEJ2601 – Fueling Protocols for

Light Duty Gaseous Hydrogen Surface Vehicles, where it is established the safety limits, performance and requirements for hydrogen dispensers, as well as temperature and pressure limits. The actual status quo is summarized in Table 5.3.

Pre-cooling	<-40ºC
Pressure	350-700bar
Standardized refuelling process	Infrared data interface vehicle-filling station
Refuelling time	3 min (4kg hydrogen)
Hydrogen filling connector	Standardized: SAE J2600, ISO/FDIS 17268
Hydrogen fuel quality	SAE J2719, ISO/FDIS 14687

Table 5.3 Characteristics of hydrogen refuelling stations [26]

5.3.1. Actual hydrogen network

Hydrogen fuel-cell vehicles are not a future project, are a present fact. Governments of powerful countries are investing lots of money in these infrastructures. Actually, on March 2014, there are 186 HRS – see Figure 5.1.

Figure 5.1 Map of Hydrogen refuelling stations around the world [8].

- Europe:

Some programs in Europe countries:

- United Kingdom: UK H_2Mobility project has the aim to analyse and identify their opportunities in the refuelling infrastructure. This project identifies three phases: by 2015, 65 HRS will be deployed to cover major cities; before 2025, the number of HRS will increase to 330, providing refuelling for 50% of UK; the full coverage will be achieved by 2030, with 1.500 HRS.

-France: *Mobilité Hydrogène France* is their hydrogen infrastructure program. It is a partnership of twenty members – gas production, storage, energy utilities and government departments. Their propose is to formulate an economically competitive plan for public and private HRS in France between 2015 and 2030.

- Scandinavia: Nordic countries, who are really concerned about the environment, are pro renewable energies and, of course, in favor of fuel cell technologies. Scandinavian Hydrogen Highway Partnership was formed in 2006 as to do a common effort to build HRS. *H_2 moves Scandinavia* organized an European Hydrogen Road Tour and ended with Hyundai, Honda, Toyota and Nissan signing a Memorandum of Understanding (MoU) with the aim to develop a refuelling network in these countries. Norway want to use their gas reserves and hydropower for the hydrogen production, on the other hand, Denmark plan to use their wind energy as to produce hydrogen..

- Germany: After the major automakers call for infrastructures, a MoU was signed with the aim to evaluate German hydrogen infrastructure. The introduction of the program *H_2 Mobility* make possible to bring together the automaker Daimler and energy companies Linde, Shell, Total, Vattenfall, OMV, EnBW and NOW GmbH – National Organization for Hydrogen of Fuel Cell Technology. Some agreements have been done as to build HRS: Daimler and Linde will build 20 new HRS by 2014; German Government's Federal Transport Minister and Daimler, Linde, Air Liquid, Air Products and Total with an investment of 20 million euro will increase the number of HRS to 50, by 2015.

Actually in Europe there are more than 72 HRS in operation – 26 of them in Germany-, but tens more are planned, as seen in Figure 5.2. [8][24][26][27][28].

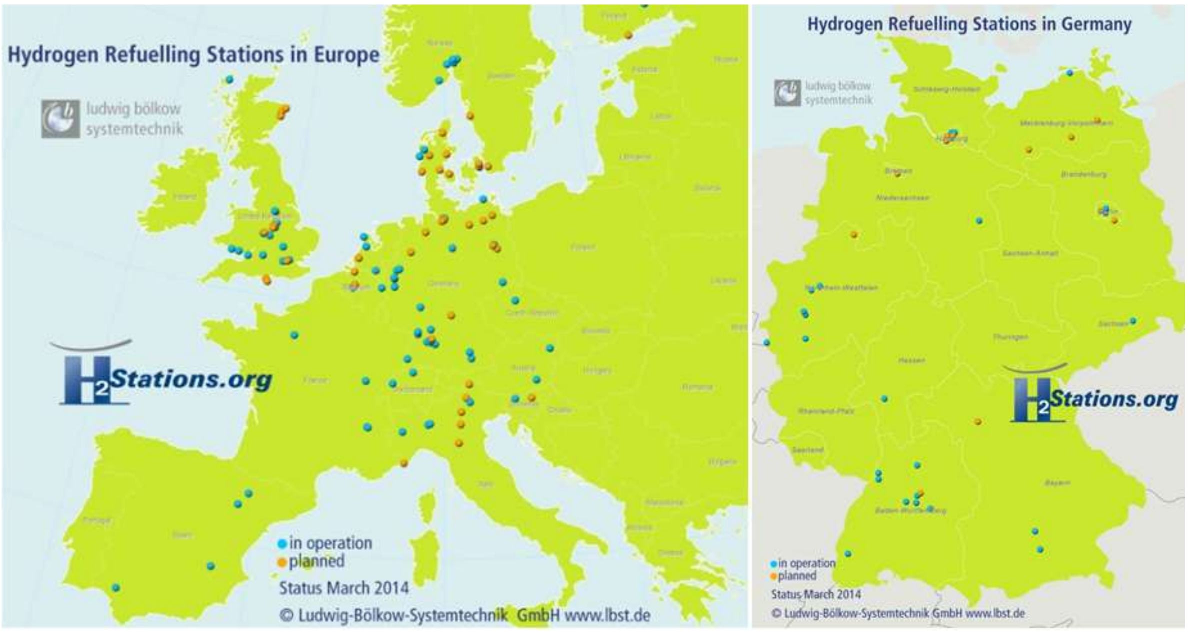

Figure 5.2 Map of Hydrogen refuelling stations in Europe and Germany [8].

In Austria, the first public HRS in operation was on October 2012, in Vienna, by oil and gas company OMV in partnership with Linde AG. It opened as a demonstration of future commercial launch of fuel cell vehicles. This station provides fast fill CGH_2 700 bar according to SAE J2601. In Figure 5.3 is illustrated this station.

Figure 5.3 Hydrogen refuelling station of Vienna- front side and back side-, connections map, and the actual price of Hydrogen and fuels. May 2014

- North America:

Actually in North America there are 67 HRS – see Figure 5.4.

USA launched their hydrogen infrastructure project, *H_2USA*. However, it has always been California the one who lead USA to develop in the field, with their automotive legislation.

California, as one of the main promoters of the technology, have some infrastructure already built as seen in Figure 5.5. [8][24][26][27][28].

Figure 5.4 Map of Hydrogen refuelling stations in North America [8].

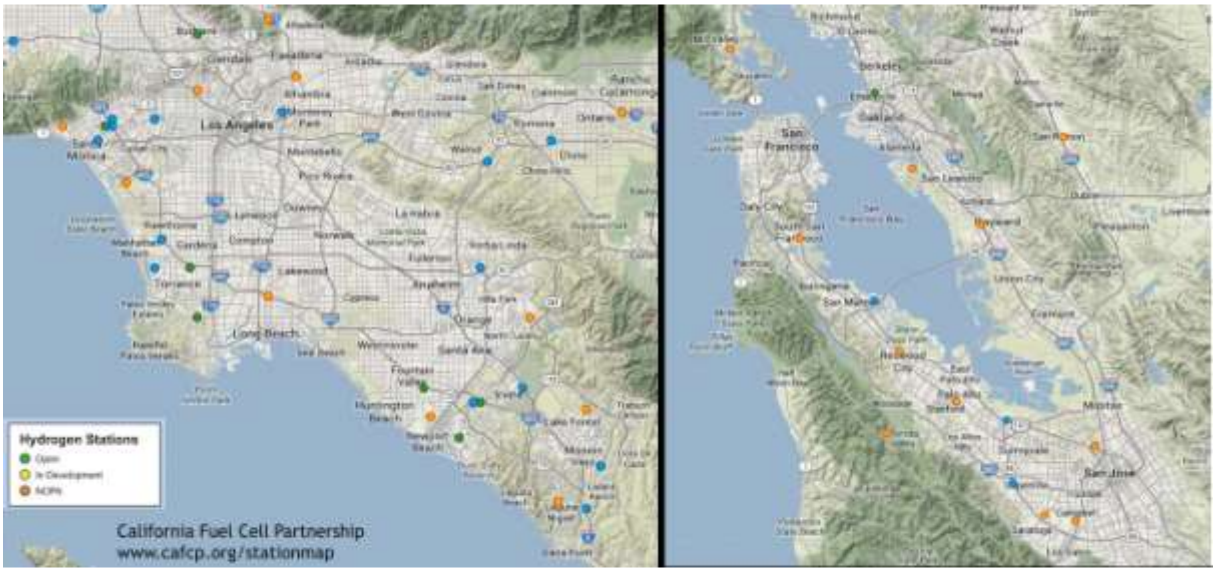

Figure 5.5 Map of Hydrogen refuelling stations in California – North and South [29].

- Asia-Japan.

Japan government subsides with $50million – 37 million euro- as to support the construction of new HRS, the equivalent of 20 stations.

The commitments of JX Nippon Oil & Energy Cup and Iwatani to build HRS – 40 and 20 each – puts Japan close to the target of 100 HRS by the end of 2015.

Research Association of Hydrogen Supply-Utilization Technology (HySUT) is coordinating their infrastructure efforts.

Nissan, Toyota and Honda together with Japanese oil and energy companies agreed in three main point by signing a MoU:

- Automakers' aim to reduce manufacturing costs and popularize FCEV.
- Fuel suppliers and automakers will work together for the introduction of FCEV network.
- Plan to build 100 HRS by 2015 – in Tokyo, Nagoya, Osaka and Fukuoka.

Actually in Asia there are 46 HRS, mainly in Japan – see Figure 5.6-[8][24][26][27][28].

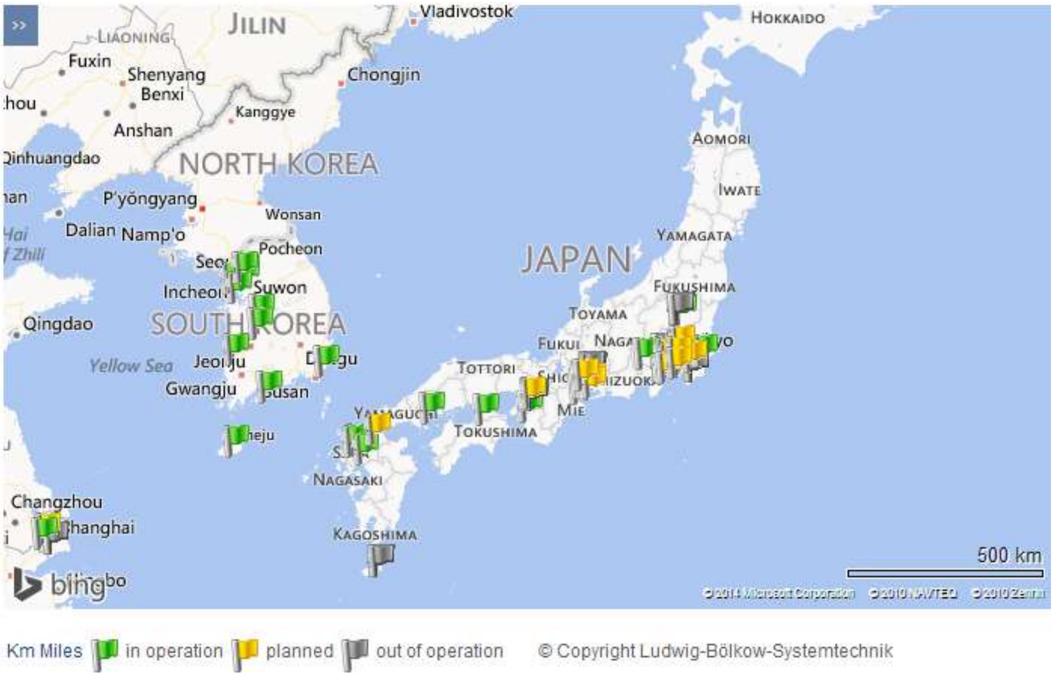

Figure 5.6 Map of Hydrogen refuelling stations in Japan and South Korea [8].

6. Automakers, European, and Californian activities

6.1. Automakers

- Daimler (Germany):

Since the first car using Proton Exchange Membrane Fuel Cell (PEMFC) in 1994, Necar, Daimler has remained active producing variants of it. It evolve to its first generation fuel cell vehicle in 2002, A-Class F-CELL. The second generation arrived at 2010, the B-Class F-CELL. Actually they have 200 vehicles in operation around the world. The next step is to commercialize the third-generation, from 2014, its target is for markets with supporting infrastructure. By 2017, they plan to have the fourth-generation.

Besides the development of fuel cell technology, Daimler is also involved with the initiatives to build German infrastructure.

- Honda (Japan):

Honda had their first fuel cell prototype by 1999, and by 2008 they had in the market the world's first commercial FCEV. The limited launch was in California because of the available infrastructure. The costumers paid $600 per month for three years. By 2015 they plan to launch a new FCEV – FCX Clarity - in Japan and in USA.

In development of Japan hydrogen network, Honda has been proactive. Even they had their own solar hydrogen station since 2012.

- General Motors (USA):

GM is the automaker with the longest history in fuel cell technologies. Since the ElectroVan from 50 years ago – see Figure 6.1- they have succeed in the field. In 2007 they launch their 4th generation vehicle HydroGen4. The project Driveway, put these vehicles in costumer's hands, and these accumulated more than 2 million miles on the road. The fifth generation is expected to be in 2015, with half size and more reliability.

Figure 6.1 GM Electrovan using Union Carbide fuel cell [30].

- Hyundai (Korea):

Hyundai unveiled its first fuel cell vehicle in 2000. They have special interest in Scandinavian countries, where they have done some demonstration programs. Hyundai sees in Scandinavia a perfect market for FCEV, however they do not forget the important market of Germany, UK and USA.

- Nissan (Japan):

Nissan is one of the most recent automakers entering in FCEV game. Their first demonstration took place in 2003, X-Trail SUV. The company is focusing in the development of fuel cell stack, and they are making great evolutions with its size. They plan to integrate this stack version for their commercial launch in 2016.

- Toyota (Japan):

The first prototype of Toyota was in 1996, RAV4. And they closest future plan is the commercialization of the newest version from 2014 in Japan, US and Europe.

- Ford (USA):

Ford first models were in 2000 and 2001, and they developed 30 fuel cell cars by 2007 to be tested in USA, Canada and Germany. Their narrowly bankruptcy in 2009 was the main fact to decide to wait until 2020 to commercialize their cars, when the technology will have a better price-competitive [24].

6.1.1. Automakers partnerships

Some agreements have taken place between the main automakers of the world as to develop fuel cell vehicles for the next years. These accords make the automakers coordinate their activities between their different countries. In this section is going to be explained some of the partnerships.

Daimler and *Ford* started their joint venture of developing fuel cell technology by 2007- Automotive Fuel Cell Corporation (AFCC). It was on January 2013 when Nissan joined them. The cooperation *Nissan-Ford-Daimler* (Japan-US-Germany) wants to accelerate the commercialization of FCEV by reducing investment costs associated. They are also looking for the compliance with global standards and specifications. In the field of H_2 infrastructure, they want to send a message to policymakers and supplier industry as to work on further development. The aim is the production of more than 100.000 fuel cell vehicles in 2017, when infrastructure will be more developed and with a better economy of scale.

General Motors and *Honda* are working together since 2013 in the develop of fuel cell technologies. They plan to share expertise and economies of scale in the production phase.

Volkswagen has signed a four-year agreement with *Ballar Power Systems* to proceed the development of fuel cells

Hyundai (Korea) has decided to go alone on the run of fuel-cell development. Their intention is to run in production 1.000 vehicles by 2015, as to encourage infrastructure builders to construct HRS. And one year after, the full commercial production of 10.000 vehicles.

Toyota and *BMW* will share their technologies and develop fundamental fuel cell vehicle platform by 2020. These partnership will include the develop of hydrogen tank, supporting battery system and electric motor. *BMW* had avoided fuel cells for many years. *Toyota* will lend to *BMW* years of experience in the development of fuel cell, because they know that Germany is an important market for fuel cell vehicles. Even so, Toyota will not wait until 2020 to release a fuel cell car, their plans is to enter Japan market in 2014, and Europe and USA from 2015 [24][28]

Worldwide fleet operation has been done with the aim of market preparation. The fleet demonstrations of fuel cell vehicles were basically in Germany and California, these have been done since 2005. The 100 fuel cell vehicles fleet of the Clean Energy Partnership completed 5 million km with the participation of vehicles from the main automakers. It was dispensed more than 152.000 kg of hydrogen with more than 33.000 refuellings[25][27].

Several markets are pushing for the commercialization of H2-infrastructure. Germany will build-up 85, other EU countries are starting activities as well. California is planning gas suppliers for 2015. Japan has a big importance in this issue too, they have sufficient H2-infrastructure covering in the four important metropolian areas, and they are planning more – complete information about HRS is explained in chapter 5.

6.2. Europe

The European Comission (EC) published a proposal with the aim to support the development of alternative fuels. This includes targets as hydrogen infrastructure, light duty regulations, new definitions for fuel cell vehicles,...

The main investments in Europe are in German. German market for FCEV is expected to be the largest in Europe. However, it needs to be remind that Scandinavian countries are also in a good position for their awareness of environment and for their recent activities and programs with some important automakers.

Horizon 2020 is the eighth iteration of EU Framework Programme for Research and Innovation, its proposal is to reincarnate the public-private partnership focused on sustainable transport and energy security. The total investment between 2014 and 2020 is estimated 1,4 billion €.

In 2013 Hydrogen Infrastructure Transport project(HIT) was founded and cost 3,5 million euro. Money that EU decided to allocate from TEN-T transport infrastructure program. The aim of HIT is to form an interconnected hydrogen network between several European countries – Netherlands, Denmark, Sweden, and France [24]

6.3. California

In United States, the U.S. Department of Energy's (DOE's) invested 31 million euro as to accelerate the fuel cell commercialization. This investment has been the key as to deploy 1.200 fuel cells [25].

The strong support for fuel cells and hydrogen technologies by US Government and the activities of DOE's and Renewable Energy has been the mainstay for the development of this technology.

California Fuel Cell Partnership (CaFCP) promote the FCEV commercialization and coordinate the development of its infrastructure. CaFCP published the document "A California Road Map: The Commercialization of Hydrogen Fuel Cell Vehicles" where it is explained the strategy of building HRS for the next years –see Figure 6.2

Figure 6.2 A California Road Map Infographic [31].

It is hoped that by 2050 87% of the cars on-road will be ZEV, more than 50% of these will be hydrogen fuel cell vehicles.

6.3.1. Fuel Cell Buses

Two Centres of Excellence are going to be created in California – AC Transit and SunLine Transit. These will incorporate:

- Introduction fuel cell buses in 2015-2016
- Production of 80 fuel cell Buses - $1milion/bus
- 40 of these at each location
- 12 years of operating period
- Training and education for the transit staff
- One HRS in each place that provides sufficient hydrogen

Each centre will cost $50,2milion - including 40 buses, refuelling infrastructure, maintenance and operations. The HRS will also be available for passenger fuel cell vehicles. All these investment is summarized in Figure 6.3

Figure 6.3 Fuel cell buses investment in California [32].

Every fuel cell bus in service can reduce the amount of carbon by 100 tons per year and eliminate the necessity of 9.000 gallons of fuel annually [33].

6.3.2. Trucks and Heavy-duty vehicles

In California, the 600.000 diesel trucks doubles the amount of Particulate Matter (PM) and NO_x from all the 20 million passenger cars - which causes more cancer risk. Thus, replacing these trucks has became one of the main priorities for California. The first actions have started, TTSI, a nationwide transportation company, is already testing fuel cell trucks [33].

Some specific regulation have been written as to optimize the reduction of the emissions, it is the case of heavy-duty vehicles.

"Box-type trailers that are at least 53 feet long and the heavy-duty tractors that pull these trailers must be equipped with fuel-efficient tires and aerodynamic trailer devices that improve fuel economy and lower greenhouse gas emissions. Tractors and trailers subject to the regulation must either use U.S. Environmental Protection Agency SmartWay certified tractors and trailers or retrofit existing equipment with SmartWay verified technologies. Vehicle owners must comply with these regulations when operating on California highways regardless of where the vehicles are registered. Exemptions apply for some local- and short-haul tractors and trailers. The compliance schedule depends on the type and age of the tractor or trailer. (Reference California Code of Regulations Title 17, Section 95300-95311)"[2]

6.3.3. California Regulations

The big development of fuel cell systems mainly started with Califronia regulations by CARB.

- Regulations and market mechanisms as to reduce by 2020 California's greenhouse gas emissions by 29%
- ZEV program requiring automakers to commercialize zero emission vehicles
- Implementation of greenhouse gas limits for vehicles of personal-use

[2] U.S. Department of Energy: Energy Efficiency & Renewable Energy. Alternative Fuels Data Center. 2013. *Alternative Fuels Data Center: California Laws and Incentives for Air Quality / Emissions*. [ONLINE] Available at:http://www.afdc.energy.gov/laws/laws/CA/reg/3843 [Accessed 26 May 2014]

- Plan to increase the use of alternative fuels
- Encourage the operation of zero emission buses
- Reduction of carbon intensity by 10% of passenger vehicle fuels, by 2020
- Creation of incentive programs for air quality mitigation and clean technology [7]

6.3.4. Goals for state government

- Complete needed infrastructure and planning: ensure a minimum network of 68 HRS to support the commercial launch of fuel cell vehicles between 2015-2017 and expand to 100. By 2020 be able to support up to 1million vehicles.
- Expand consumer awareness and demand: support and promote funding programs; participate and planned consumer campaigns as to raise awareness and report the benefits of fuel-cell vehicles.
- Transform fleets: ensure that by 2015 a minimum of 10% of light-duty vehicles are ZEVs and 25% by 2020; expand forums to support the efforts of companies to integrate ZEVs. Develop a strategy to accelerate medium and heavy-duty ZEVs commercialization.
- Grow jobs and investment in the private sector: provide workforce training funds to trade associations, employers, Chambers of Commerce,...[34]

Conclusion

The main objective of this thesis is to show the scenario of the hydrogen fuel cell vehicles as one of the alternative drive systems. The awareness for the environment has induced the develop of different types of electric vehicles. Hydrogen fuel cell cars have great characteristics as to become the future in the automation world. These vehicles are quite and eco-friendly without losing the power or range of the actual ones. Some attractive points of fuel cell car compared with conventional is its efficiency, 68% against 20% and all of that reducing by 60% of Greenhouse gas emissions (GHG).

Its power relies in a basic and simple reaction between oxygen and hydrogen. Thus, it has became indispensable the use of hydrogen as an energy source. Hydrogen is sustainable economically, climatically, environmentally and societally. Hydrogen is the most abundant element in the universe but really inflammable. The hydrogen chain and the treatment of hydrogen needs special attention. Different pathways are possible as to get hydrogen, some of them do not need fossil fuels, thereby, the dependence of fossil fuels could end. Its storage and supply is another main issue. High gaseous hydrogen tanks (CGH_2) or liquefied hydrogen containers (LH_2) are the two options, with LH_2 the storage of hydrogen is bigger although you require more energy for hydrogen liquefaction but CGH_2 is cheaper.

The weakest point of hydrogen fuel cell vehicles is the existent infrastructure. The introduction of these vehicles need the support of a good network of hydrogen refuelling stations (HRS). The cost of one HRS is about 1,5 million euro each. Without this network, there is no possibility of commercial launching for these vehicles. Automakers, government, and oil and energy companies are investing a lot of capital to throw it forward. Thus, actually, there are 186 HRS in operation – 72 in Europe, 67 in North America, 46 in Asia and 1 in South America – but hundreds more are planned . Governments of main countries are introducing programs for H_2Mobility as to build the necessary infrastructure. Countries like Germany, France,…would need 1000 HRS as to provide full coverage.

Automation companies are driving the introduction of hydrogen fuel cell vehicles, they see in them a great future as to invest lots of money. Now, some of them see the commercial launch really close, 2014-2015, like GM, Daimler, Hyundai,…Partnerships between automakers have taken place with the aim to develop fuel cell technology together.

California and Germany are the most involved ones, with their policy, investments and introduction of new laws. California fuel cell development mainly started because of CARB regulations – ZEV program. In California are introducing fuel cell buses in 2015 and fleet demonstrations have been taken place in many countries as to start gaining the trust of citizens for these vehicles. All the activities, investments and policies make California hope that by 2050 50% of the cars on-road will be hydrogen fuel cell vehicles.

Governments, automakers and oil and energy companies are making huge efforts to pull forward hydrogen fuel cell vehicles and in a short-term it will be possible to see them on-road. If they have seen in hydrogen fuel cell vehicles a great future, the time to show it is coming, so they hope to have the network ready.

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Appendix A. Automobile Manufacturers Stick up for Electric Vehicles with Fuel Cell

**Letter of Understanding on electric vehicles with fuel cell development and market introduction signed*

September 2009, 9th – *Stuttgart – Today, Daimler AG announced that the leading vehicle manufacturers in fuel cell technology - Daimler AG, Ford Motor Company, General Motors Corporation/Opel, Honda Motor Co., Ltd., Hyundai Motor Company, Kia Motors Corporation, the alliance Renault SA and Nissan Motor Corporation and Toyota Motor Corporation - gave a joint statement to the development and market introduction of electric vehicles with fuel cells with a Letter of Understanding (LoU). These companies have built up remarkable know-how in fuel cell technology and thus, the signing marks a major step towards the serial production of such locally emission-free vehicles.*

The signing automobile manufacturers strongly anticipate that from 2015 onwards a quite significant number of electric vehicles with fuel cell could be commercialised. This number is aimed at a few hundred thousand units over life cycle on a worldwide basis. As every vehicle manufacturer will implement its own specific production and commercial strategies as well as timelines, commercialisation of electric vehicles with fuel cells may occur earlier than in the above-mentioned expected year.

Road traffic has been steadily increasing in recent years and vehicle ownership is expected to grow. As a result, there will be increased priority on low and zero emission vehicles and an increase in overall CO2 reduction goals. Over the last decade, governments, car manufacturers and the energy sector have given special attention to the introduction of hydrogen as a fuel for road transport as a priority option to reach several goals associated with emission management and CO2 reduction. Current demonstration projects involving fuel retail companies, utility providers and engineering companies have shown that the production, storage, transportation and deployment of efficient equipment for hydrogen as a fuel are technically feasible.

In order to ensure a successful market introduction of electric vehicles with fuel cells, a hydrogen infrastructure has to be built up with sufficient density. The network is required by 2015 and should be built-up from metropolitan areas via corridors into area-wide coverage. The signing manufacturers strongly support the idea of building-up a hydrogen infrastructure in Europe, with Germany as regional starting point and at the same time developing similar concepts for the market penetration of hydrogen infrastructure in other regions of the world, including the USA, Japan and Korea as further starting points.