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Fuel Cells and Hydrogen Storage: Challenges Facing Vehicle Manufacturers

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Abstract **— The main challenge of our time is to find renewable energy sources that meet the needs of society. Nevertheless, energy must meet several criteria such as abundance, ease and speed of use, but also the cost of production which must be low. In addition, the aspect of "clean and renewable energy" is also to be taken seriously.**

Today, fuel cells are a magnet for researchers because they have many advantages. First of all, these batteries have the capacity to produce a significant amount of electricity, water and heat. In addition, the reagents of the battery are the oxygen naturally present in the atmosphere and the di-hydrogen that needs to be produced. Its production is therefore a major stake for the installation of the fuel cell.

Many hopes rest on the fuel cell. As we have seen, it is one of the energy sources that have the most to become and application areas. With a relatively high efficiency, zero pollutant emissions, this fuel cell has many other advantages such as the variety of batteries that can be adapted to all current needs such as transportation, global electricity generation or digital.

Because of the benefits that flow from its use as an automobile fuel, hydrogen is expected to take precedence over other synthetic fuels in the not-too-distant future.

Keywords ***— Fuel cell; Hydrogen storage; vehicle***

I. INTRODUCTION

All nations across the globe face a severe energy crisis. Our current energy systems are based on fossil fuels, which not only have adverse effects on the environment, but are also depleted and running out. With the growing demand for energy predicted to increase by more than 50% by 2025 due to the rising world population, pressure is mounting to fi nd alternative, renewable sources of energy.

Oil covers 95% of the needs in this sector, energy consumption related to transport in France represents a quarter of total consumption and this share is one that increases faster. Automakers are making thermal vehicles cleaner by adding new, cleaner engines, catalytic converters and particulate filters. The introduction of these new technologies has led to a significant decrease in emissions of pollutants such as SO2, CO, total hydrocarbons (HC), NOx, particulates and has made it possible to comply with Euro1, Euro2 and Euro3 standards issued by the European Union [1]. Today, fuel cells are a magnet for researchers because they have many advantages. First of all, these batteries have the capacity to produce a significant amount of electricity, water and heat. In addition, the reagents of the battery are the oxygen naturally present in the atmosphere and the di-hydrogen that needs to be produced. Its production is therefore a major stake for the installation of the fuel cell.

The evolution of air quality, in terms of pollutant concentration, shows that CO2 emissions are now the main transport challenge in the face of air pollution [2]. Transport is the sector that generates the greatest increase in CO2 emissions: a car with a combustion engine releases about one tonne of CO2 every 5000 km into the atmosphere. A break in technology seems inevitable.

The fuel cells' environmental qualities and their excellent efficiency contribute, where they are used to replace traditional systems, to the improvement of air quality and the reduction of greenhouse gas emissions.

II. FUEL CONSUMPTION AND EMISSIONS

Figure 1 shows the distribution of petroleum consumption by industry sector in the world in 2005

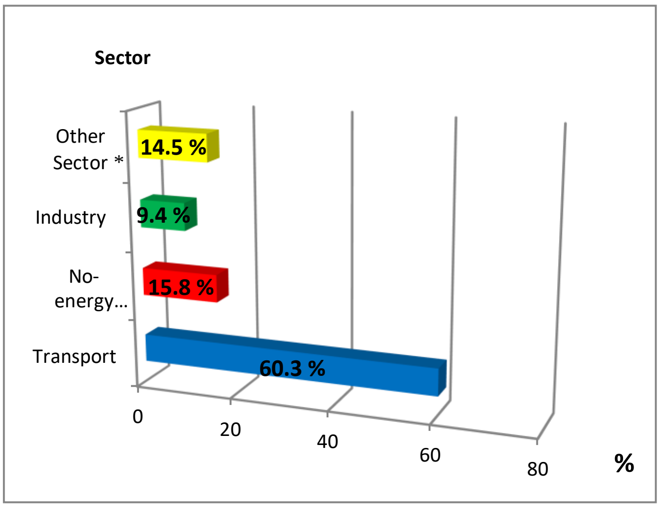

Fig.1: Distribution of global oil consumption by industry sector in the world in 2005
**including agriculture, public and commercial service, residential and unspecified [3]*

The transport sector accounts for a large share of global oil requirements (60.3%), but other sectors are not to be neglected.

Oil is irreplaceable today in transport; it covers 97% of needs. The globalization of the economy and trade implies an important development of the transport sector. It is estimated that transport currently accounts for 60.3% (1860 Mtoe) of oil consumption; this proportion should rise to 65% (3194 Mtoe

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by 2031 [4]. In other words, oil consumption for the transport sector alone is expected to increase by about 71% by 2031.

Although it represents the largest share of global oil consumption, the transport sector is not the main contributor to the increase in global greenhouse gas emissions (mainly CO2) as shown in Figure 2.

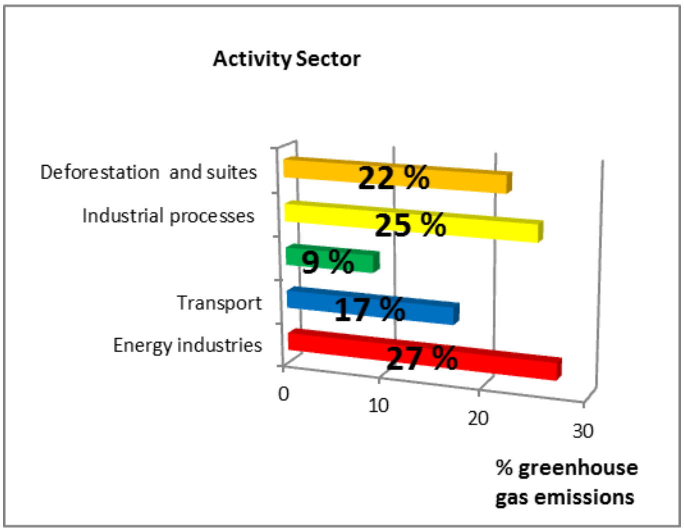

Fig.2: Distribution of greenhouse gas emissions by activity sector in the world in 2004 (%) [3]

It should be noted that the bulk of CO2 emissions (74%) come from different sectors of the industry, namely the energy industries, industrial processes and deforestation. This is explained by the fact that the electricity producers, the refineries and a part of the means of transport, correspond to these sectors. On the other hand, if these numbers are attributed to electricity in the sectors that consume it, another trend is observed as shown in Figure 3.

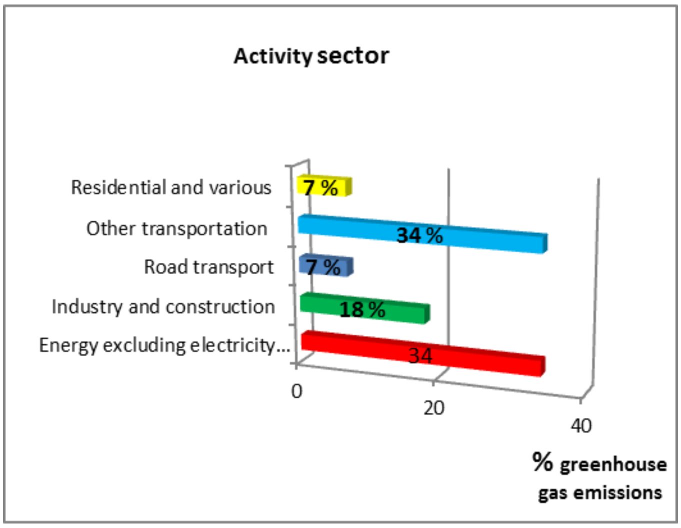

Fig.3: Distribution of greenhouse gas emissions by activity sector in 2004 (%) in the world, by attributing electricity to the consumption sector [5]

Although it represents the largest share of global oil consumption, the transWe can see that the industry sector is still very strong (34%), but it is now joined by the residential sector (heating) (34%). The transport sector contributes 25% of emissions.

In the transport, industrial and residential sectors, the current technology will not be able to last very long because of its contribution to the greenhouse effect, the scarcity and the increase of the fossil fuels (for the transport and the industry).

For the automobile, a probable evolution is the hybrid vehicle equipped with both a heat engine and an electric motor coupled to a battery or super-capacitor.

In the longer term, fuel cell technology seems to be very promising for the future. Indeed, it theoretically offers the advantage of electric propulsion and heat generation (zero local emission and silence) without its major drawbacks (limited autonomy and problems related to the massive production of electricity).

III. Fuel Cells and Their Applications

The principle of the fuel cell was stated in 1839 by Sir William GROVE [6] [7] [8].

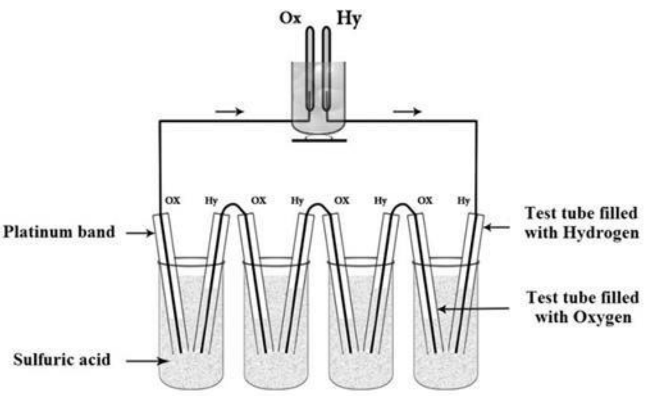

Figure 4: The Sir William Grove experience 1839

A fuel cell makes it possible to directly convert chemical energy into electrical energy. Typically, a stack is composed of the assembly of elementary cells, the number of which depends on the desired voltage and current.

Each cell comprises an anode compartment supplied with fuel and a cathode compartment supplied with oxidizer separated by two electrodes loaded with the catalyst and an intermediate electrolyte providing ionic bond. Since their discovery, enormous scientific and technological progress has been made.

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There are currently 6 types of fuel cells:

- AFC (Alkaline Fuel Cell),
- PEMFC (Polymer Exchange Membrane Fuel Cell),
- DMFC (Direct Methanol Fuel Cell),
- PAFC (Phosphoric Acid Fuel Cell),
- MCFC (Molten Carbonate Fuel Cell),
- SOFC (Solid Oxid Fuel Cell).

These fuels cell differ according to:

- ✓ The nature of their electrolyte;
- ✓ Their operating temperature;
- ✓ Their architecture;
- ✓ Their field of application.

In addition, each cell has different requirements in terms of fuels. Their characteristics are summarized in Table 1.

	Name	Electrolyte	Power range	Operating temperature	Fields of application
FC at low temperatures	DMFC(« Direct methanol fuel cell »)	Polymer membrane	1mW to 100 kW	60-90 ° C	Portable
	PEMFC(« Proton exchange Membrane fuel cell »)	Polymer membrane	100W to 500kW	60-90 ° C	Transport Portable Stationary
	AFC («Alkaline fuel cell »)	Aqueous alkaline solution	10kW to 100kW	50-250 ° C	Transport Spatial
	PAFC (« Phosphoric acid fuel cell »)	Phosphoric acid	Up to 10 MW	160-220 ° C	Stationary
High temperature FC	MCFC (« Molten carbonate fuel cell »)	Molten carbonate	Up to 100 MW	650 ° C	Stationary
	SOFC (« Solid oxide fuel cell »)	Solid Oxide	Up to 100 MW	750-1050 ° C	Stationary

Table 1: The different types of fuel cells and their characteristics

Low temperature fuel cell (PAFC, PEMFC, AFC and DMFC) operate at temperatures below 250 ° C. Their fast start, compact size and low weight are particularly relevant to the transport sector.

The PEMFC fuel cell seems for the moment the most appropriate for the on-board application because it best meets the criteria of temperature and speed of operation.

The major problem with implementing this type of energy source in a vehicle is its supply of hydrogen. Although hydrogen has high qualities, storing this gas in a vehicle remains a delicate operation for users.

Hydrogen powered vehicles emit only water; they are "Zero Emission" vehicles. Nevertheless as with electric vehicles, the real environmental impact of the fuel cell vehicle is dependent on the origin of the hydrogen.

The hydrogen fuel cell can be used for various applications other than automotive. Indeed, the transport sector, as shown in Figure 3, shares the responsibility for increasing greenhouse gas emissions with the agriculture, residential-service sector, industry, etc.

A. The polymer exchange membrane fuel cell (PEM type):

- *Operating principle:*

The fuel cell allows the direct conversion into electrical energy of the free energy of a chemical oxidation-reduction reaction. Like a battery or accumulator, a fuel cell has two electrodes. The negative electrode is the seat of the oxidation drafting of the fuel, usually hydrogen. On the side of the positive electrode is the reduction reaction of the oxidant, usually the oxygen of the air. The two electrodes are separated by an electrolyte. In the case of a PEM cell, a solid membrane performs the function of electrolyte; the faces of the electrodes are covered by a catalyst, platinum. The negative electrode - electrolyte - positive electrode assembly constitutes the heart of the cell. The supply of the latter in reagents is via distributing plates. The fuel and oxidant are provided to the cell in conditions of pressure, temperature, humidity and purity defined continuously to ensure the production of the current.

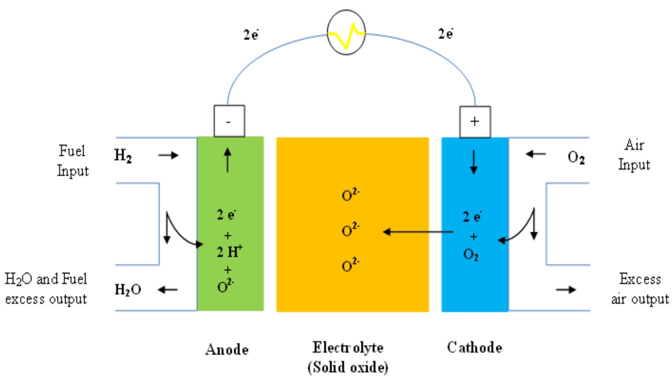

Figure 5: Principle of operation of a PEM fuel cell

Depending on the type of cell, the intermediate chemical reactions involved vary but the general principle remains unchanged. The overall reaction of a PEM type fuel cell can be written as follows:

➢ Reaction to the anode

$$H2 \rightarrow 2H+ + 2e- \qquad (1)$$

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- Reaction to the cathode:

$$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

- By combining (1) and (2) the overall reaction is:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O + heat \quad (3)$$

Electricity is produced by the 2 electrons released by the hydrogen molecule (1). The H+ hydrogen protons pass through the membrane separating the anode from the cathode and recombine at the cathode with the electrons and the oxygen atoms. Ideally, the only side products.

The reaction is water and heat. Figure 5 summarizes the principle of the PEM fuel cell. The potential difference across each cell is small; in operation, it is less than volt. For most applications, it is therefore necessary to build a stack of cells, commonly called stack, to have a sufficient level of voltage.

But before hydrogen entering our daily lives and exploitation in feeding fuel cells, progress must be made at every stage of the industry stages: production, transport, storage and use.

IV. Hydrogen storage for fuel cell vehicles

A. *History and characteristics of hydrogen*

The few important dates in the history of hydrogen are:

- 1766: The British chemist Henry Cavendish manages to isolate a strange gaseous substance, which by burning in the air gives water.
- 1781: Until now called "flammable gas", hydrogen owes its name to the French chemist Antoine-Laurent de Lavoisier, who performs the synthesis of water.
- 1804: Frenchman Louis-Joseph Gay-Lussac and German Alexander Von Humboldt jointly demonstrate that water is composed of a volume of oxygen for two volumes of hydrogen.

Some figures concerning the physicochemical properties of hydrogen are reported in Table 2.

Property	Gasoline	Methane	Hydrogen
Density (kg/m^3)	4.40 (*)	0.65 (**)	0.84 (***)
Diffusion coefficient in air (cm^2/s)	0.05 (*)	0.16 (**)	0.610 (***)
Specific heat at constant pressure (J/kg K)	1.20 (*)	2.22 (**)	14.89 (***)
Flammable limit in air (vol%) + (LEL-UEL)	1.0 – 7.6 (***)	5.3 – 15.0 (**)	4.0 – 75.0 (*)
Flammable energy in air (MJ)	0.24 (**)	0.29 (***)	0.02 (*)
Flammable temperature (K)	501–744 (*)	813 (**)	858 (***)
Flame temperature in air (K)	2470 (*)	2148 (***)	2318 (**)
Explosion limit in air (vol%)	1.1 – 3.3 (*)	6.3 – 14.0 (**)	13.0 – 59.0 (***)
Fuel toxicity	(*)	(**)	(***)
Combustion products toxicity	(*)	(**)	(***)
Flame emissivity	(*)	(**)	(***)

Safety level: (***) More safety; (**) Intermediate safety; (*) Less safety
+ (LEL: Volume concentration of a gas, from which it can be ignited;
UEL: Maximum concentration in volume of a gas, above which it cannot be ignited)

Table 2: H_2 compared with traditional fuel

Hydrogen has many advantages. Indeed, this molecule has the advantage of being particularly energetic: 1 kg of hydrogen releases about 3 times more energy than a kilo of gasoline (120 MJ / kg against 45 MJ / kg for gasoline). It is an abundant element, but it does not exist in pure form on Earth. It is a component of water or organic compounds (biomass ...).

Hydrogen is colorless, odorless, non-toxic and has no environmental impact (its combustion produces water and heat) and is lighter than air (it dissipates 4 times faster than natural gas).

Despite all these advantages, it has many disadvantages. For example, it has a low density. Thus, to produce as much energy as with 1 liter of gasoline, 4.6 liters of compressed hydrogen are required at 700 bars. It is highly flammable (0.02 mJ), has a wide flammability range (5 times that of CH_4) and has a very fast flame spread rate. Moreover, his flame is invisible.

Hydrogen has a negative image with the public since it is considered a dangerous gas and its acceptability is not acquired.

However, hydrogen has long been used as a raw material in the chemical and petrochemical industry as shown in Table 3 and table 4.

- ***In Europe:***

Industrial Sector	Europe	
	Consumption (Million tons / year)	%
Ammonia Production	3,2	39
Other Chemicals	1,15	14
Refining	3.9	47
Total	**8.25**	**100**

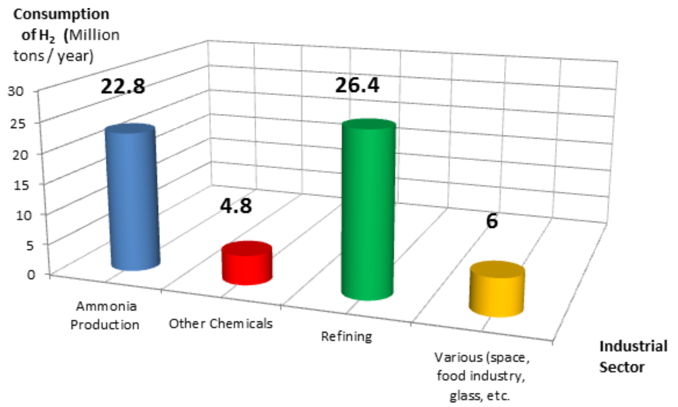
Table 3: European distribution of hydrogen consumption in industry (2014) **[9]**

- ***In the World*:**

Industrial Sector	World	
	Consumption (Million tons / year)	%
Ammonia Production	22.8	38
Other Chemicals	4.8	8
Refining	26.4	44
Various (space, food industry, glass, etc.	6	10
Total	**60**	**100**

Table 4: Global distribution of hydrogen consumption in industry (2014) **[9]**

The sector where hydrogen consumption is the most important is oil refining since it requires 26.4 million tons per year (44%). In the manufacture of ammonia the consumption of hydrogen is 22.8 million tons per year (38%). Hydrogen is also used to manufacture other chemicals (8%) such as amines, methanol, and hydrogen peroxide.



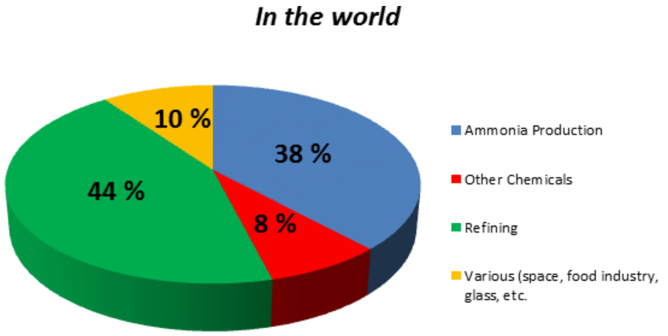


Fig.6: Graphic representation of global distribution of hydrogen consumption in industry

Today, hydrogen is little used in the field of energy, with the exception of space propulsion.

It should be noted that from the late 19th to the beginning of the 20th century, hydrogen was used (mixed) for lighting lamps and as city gas for heating.

B. Fuel Cell vehicle

A fuel cell vehicle (FCV) or fuel cell electric vehicle (FCEV) is a type of electric vehicle which uses a fuel cell, instead of a battery, or in combination with a battery or super-capacitor (secondary source of energy) to power its on-board electric motor.

Fuel cells in vehicles generate electricity to power the motor, generally using oxygen from the air and compressed hydrogen. Most fuel cell vehicles are classified as zero-emissions vehicles (ZEV) that emit only water and heat. As compared with internal combustion vehicles, hydrogen vehicles centralize pollutants at the site of the hydrogen production, where hydrogen is typically derived from reformed natural gas. Transporting and storing hydrogen may also create pollutants [10].

The engine schematic for a fuel cell vehicle is represented in the following figure (Figure 7):

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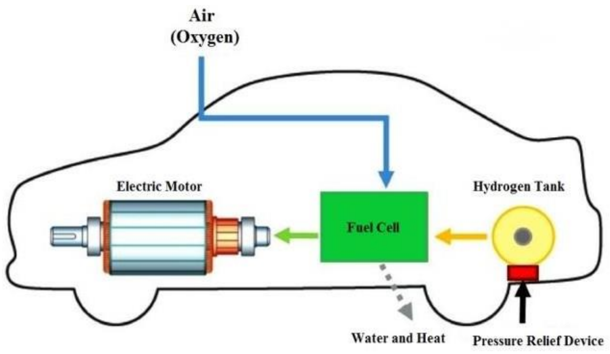

Fig.7: Engine schematics for a fuel cell vehicle

C. The early adopters of fuel cell vehicles

Several car manufacturers promote FCVs to consumers. Vehicles are often compared to battery electric vehicles (BEVs). Both types of vehicles emit no exhaust, can be powered by renewable energies and are powered by electric motors. The main difference between these vehicles is their range and style of refueling. FCVs have a range of over 300 miles and can be refueled in less than 10 minutes at a hydrogen refueling station [11].

Three FCVs are currently available to consumers. These include the Hyundai Tucson / ix35 FCEV, the Toyota Mirai FCEV and the Honda Clarity FCEV. These vehicles are currently on sale in North America, Europe and Asia. In 2014 sales of these vehicles began. The Toyota Mirai was sold in record numbers with 5233 units delivered to consumers from 2013 to 2017, including 2944 in North America. By the end of 2017, 637 Honda Clarity FCEVs had been delivered to consumers, including 440 in North America. Finally, 727 Hyundai Tuscon / ix35 FCEVs were delivered, the most important market for these vehicles being Europe with 373 units delivered. Figure 8 provides an overview of the annual sales of these vehicles and the total sales of the three vehicle models.

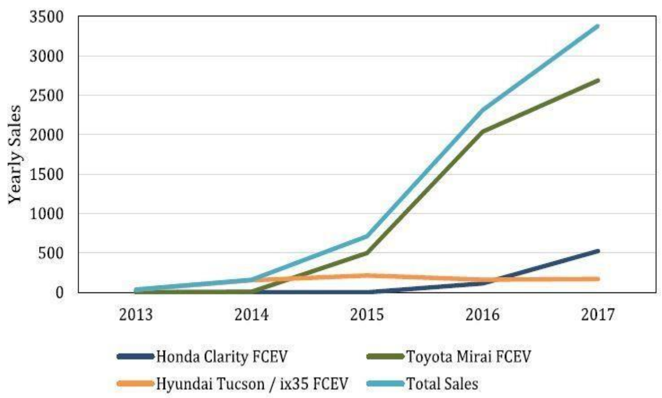

Fig.8: Global annual sales of fuel cell vehicles between 2013 and 2017 by vehicle model **[12]**

The main producers of FCVs are the United States and Japan. In 2017, **2298** vehicles were sold in the United States and **849** in Japan. South Korea is the third largest market with **61** vehicles sold in 2017. Annual sales of these vehicles by country of sale are shown in Figure 9.

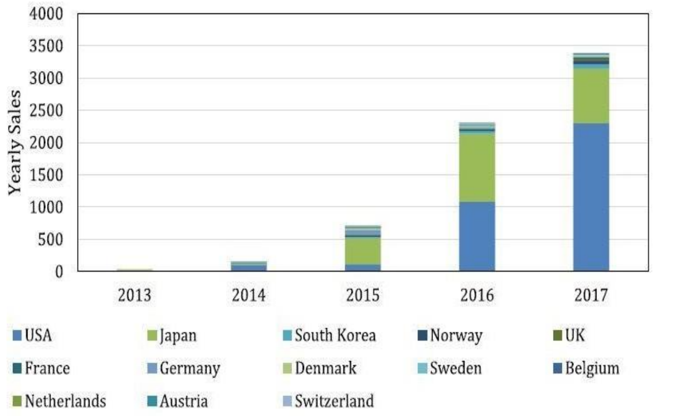

Fig.9: Worldwide annual sales of fuel cell vehicles between 2013 and 2017 by country **[12]**

V. THE MAIN PRODUCTION METHOD OF DIHYDROGEN:

Hydrogen is one of the fuels needed to operate a fuel cell. However, dihydrogen is not an energy source strictly speaking but rather an energetic vector. Compared to oxygen, it is necessary to produce it using energy. Until now, hydrogen production has been carried out using fossil fuels such as vapo-forming, which consists of reforming natural gas. The gaseous fuel (methane) is subjected to water vapor to achieve different chemical reactions. It is necessary to carry out this experiment at very high temperature, at atmospheric pressure and in the presence of a catalyst. Figure 10 shows hydrogen production and applications [13].

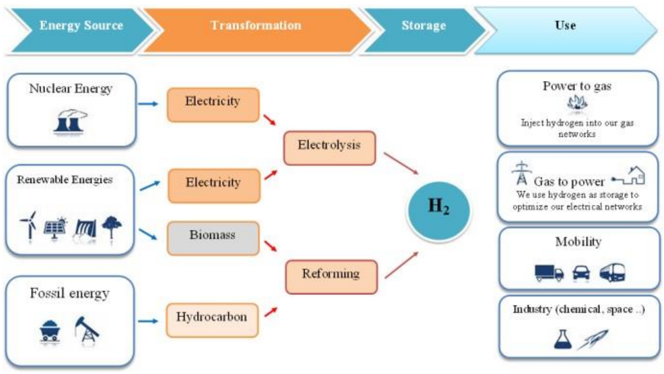

Fig.10: The "hydrogen" chain **[13]**

Hydrogen production today represents 630 billion cubic meters, used mainly to produce ammonia, methanol, HNO_3; this production will have to increase significantly to meet the

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new energy needs. World demand for primary energy was 443 EJ (1 Exajoule (EJ) = 10^{18} joules**)** in 2003, dominated by oil and coal followed by natural gas, meaning that current hydrogen production would cover only 1.5% of demand **[14]**. There is therefore a lot of work to be done in the field of mass hydrogen production to achieve a significant share (especially considering a growing global energy demand). According to the reference scenario of the IEA (International Energy Agency), global demand for primary energy is expected to grow by 53% between 2004 and 2030 **[14]**, an average annual rate of 1.6% **[14]**. Developing countries will be responsible for more than half of this global increase **[14]**.

Hydrogen can be produced from many different sources. Currently, however, most hydrogen (97%) is produced from hydrocarbon reforming **[14]**. The choice of hydrogen manufacturing process is based on many parameters (type of available primary energy, purity, flow rates,).

To produce hydrogen, several possibilities are studied, some have already reached technological maturity and others are still at the stage of development:

- ❖ from fossil fuels:
  - thermal decomposition
  - catalytic reforming
  - steam cracking
  - partial oxidation
  - auto-thermal reforming
- ❖ from the electrolysis of water or by thermodynamic decomposition
- ❖ from biomass (gasification, biological transformation)
- ❖ from green algae or bacteria
- ❖ from the nuclear

The vapor-forming and partial oxidation techniques correspond to about **95%** of the total production, only **2%** of hydrogen being produced by electrolysis.

The use of fossil fuels leads to the formation of a gas rich in H2 and CO. But a fuel cell such as PEMFC is very sensitive to CO. It is therefore necessary later to eliminate the maximum CO (<10 ppm) to obtain a fairly pure H_2.

To be used in fuel cells, existing technologies for purifying hydrogen are:

- the oxidation of CO by water (Water Gas Shift);
- molecular sieve purification with PSA (Pressure Swing Adsorbed)
- purification by methanation
- Purification by metal membranes (Pd, Pd-Ag).
- the preferential oxidation of CO (CO-PROX)

VI. STORAGE MODES

The major obstacle to the implementation of fuel cell technology in the various fields is the supply of hydrogen and its storage. A lot of research then looked into the problem in order to fix it and develop reliable storage systems. The evaluation of these performances is done mainly by volumetric and gravimetric densities (of hydrogen and of the whole with the means of storage) and the general conditions of storage and destocking of the hydrogen (efficiency, speed, apparatus necessary annexes). This is in addition to the determining criteria of safety and cost.

The introduction of hydrogen as fuel in the automotive sector requires that a suitable means of storage on board the vehicle be developed. Currently, the three storage possibilities, namely:

- ✓ Compressed gas under high pressure, **[15]**
- ✓ liquefied hydrogen
- ✓ Solid: **-** in metal hydrides in which the hydrogen is absorbed (chemisorption), or in carbon compounds (activated carbon, nano fibers and carbon nanotubes) in which hydrogen is adsorbed (physisorption).**[15]**

It is interesting to examine the three possibilities of hydrogen storage and to analyze to what extent they are able to meet the requirements of this application and which include:

- High mass and volume storage capacity
- Storage pressure and temperature are as close as possible to the ambient.
- Handling conditions that do not impose too stringent safety standards.
- Almost unlimited storage time
- Investment fees and acceptable operating costs

A. Storage in liquid form:

This process can store hydrogen in liquid form at -253 C ° at pressures between 1 and 10 bar (cryogenic tank). Its advantages are the low pressures, its weight reduction potential and moreover this process has been demonstrated on a vehicle (BMW year 1988) [16].

But this process requires high liquefaction energy (30-40% lost energy), moreover it requires a constant thermal insulation and there is loss of hydrogen by evaporation (1 to 2% per day)

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B. *Storage in compressed form*

This process makes it possible to store hydrogen in gaseous form (in composite tanks) at high pressures (up to 700 bars). This process has various advantages such as the lightness of the tanks (when they are in polymer liner), the speed of filling and it does not need thermal management.

C. *Hydrogen storage in hydrides (Indirect storage)*

Several processes involve embedding hydrogen in the form of molecules or atoms bound to other materials or more easily transportable molecules. In this area, several avenues are being explored:

- metal hydrides (main disadvantages: mass capacity, cost, autonomy ...),
- Organic hydrides, the Hydrogen on Demand ™ process and embedded production from a fuel.

We can also note the carbon nanotubes (principle of gas adsorption on the surface of a solid).

The on-board production of hydrogen by a fuel seems to be a promising way. On the other hand, it will be necessary to find a mode of production and an adequate raw material.

VII. Comparison of different storage modes

The characteristics of the possible hydrogen storage methods are summarized in Table 5:

Storage mode / Characteristics	H_2 compressed	H_2 liquefied	Condensed in a hydride
Mass capacity (kg H_2 / 100 kg system)	1.6 (steel) 2.2 (aluminum)	18	4 to 5
Volume capacity (kg H_2 / 100 dm^3 system)	1.4	5.5	~ 5
Storage pressure (atm) at ambient temperature	200	1 to 8	1 to 10
Storage temperature (° C)	Ambient	-253	Ambient
Storage losses (% per day)	null	0.5 to 1	null
Energetic cost	high	very high	low

Table 5: Comparative characteristics of different modes of hydrogen storage

The storage of gaseous hydrogen under high pressure is essentially penalized by the low value of the mass capacity and volume relative to this system. Added to this are the risks that accompany the use of high pressures, this solution is not indicated on board a vehicle.

The cryogenic storage of hydrogen is also not advisable in this case, because of the dangers it presents (constant losses) and the cost of its liquefaction. The permanent surveillance of which it must be the object, limits its use to very particular uses (aeronautical and space applications). Add to the risks associated with high pressures

VIII. Discussion:

It is finally metal hydrides that seem to be able to best meet the requirements that this type of storage requires.

A decisive advantage of this storage method lies in greater safety of use, because, in case of rupture of the reservoir, the endothermic of desorption reaction causes a rapid cooling of the hydride mass, which reduces both the equilibrium pressure and the rate of the decomposition reaction.

Given that none of the hydrides already known meets all the necessary qualities, it is therefore essential to modify the characteristics by adapting them to the specifications imposed on them, in particular as regards:

- Their mass storage capacity
- Their desorption temperature
- Their enthalpy of decomposition
- The exchange kinetics

IX. Conclusion

The theme of the hydrogen economy has become in the last five years one of the most debated issues in specialized energy backgrounds.

The production and transport of hydrogen is not without problems. The bulk of current production is done by reforming fossil sources and releases as much CO2 or more than the direct use of these sources. Hydrogen can also be produced by electrolysis, with renewable energies such as sun and wind, which allows the energy produced to be stored according to natural cycles to be used when needed.

Because of the benefits that flow from its use as an automobile fuel, hydrogen is expected to take precedence over other synthetic fuels in the not-too-distant future.

In order to make better use of the energy content of stored hydrogen, it seems more advantageous to move towards the use of fuel cells, which make it possible, from the same quantity of hydrogen to produce a quantity of hydrogen energy 4 to 5 times more than internal combustion engines.

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Among the possibilities to store it in a motor vehicle, it seems that it is the metal hydrides that will be the best compromise solution.

However, this attractive solution which is the combination of the storage of hydrogen in a hydride with its combustion in a stack cannot be put into practice immediately.
Significant research and development efforts are still needed, both with regard to hydrides and their implementation as well as with regard to fuel cells.
The hydrogen is widely used in automotive applications, along with materials discovery; efforts are needed to optimize the overall performance of the fuel cell system to overcome the relevant technical barriers for all hydrogen storage approaches.

Finally, to see if current and future hydrogen technologies have the opportunity to replace fossil fuels, it is not only necessary to consider the entire production-storage-transport-use chain, but also to assess the time and capital needed to install the necessary infrastructure.

In the future:

In the field of hydrides, research programs should be oriented in particular towards an improvement:

- Their mass storage capacity;
- Their adsorption-desorption conditions (temperature, pressure, amount of heat put into play, exchange kinetics);
- Their chemical insensitivity to the different impurities that can contain hydrogen.

Although currently in a much more advanced stage of development, fuel cells can only be generalized in their use if:

- Their power density
- Their lifespan and reliability
- Their low temperature operating characteristics (fast start-up capability).

Significant improvements can be made, provided that their cost of production can reach a reasonable value.

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