Algerian Journal of Engineering Architecture and Urbanism Vol. 5 Nr. 3 2021
ISSN: 2588-1760

VEHICLE EMBEDDED BY A FUEL CELL SYSTEM: A REVIEW

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Abstract:
Among the various existing fuel cell, proton exchange membrane (PEM) fuel cells now seem to be the best suited to serve as a basis for the motorization of electric vehicles. This is explained in particular by their low operating temperature (about 70 ° C) and the solid nature of the electrolyte involved. In an emerging context of electromechanical system aspect involving the modeling and simulation of a set of components, the present work consists in developing a model of the system for modeling and optimization of an on-board vehicle by fuel cell system. . In this model, we will model the different parts of the system; PEMFC fuel cell, super-capacitor, converters and a permanent magnet synchronous motor. Validation by simulation is essential for its good analysis and comparison with experimental measurements. Finally, this work focuses on solving the problems of optimization to adapt it to the fuel cell system.

Key words: Fuel cell, Batteries, Super-capacitors, Vehicle, Dimension, Control strategy.

1. Introduction:

During the next decades, hydrogen could be brought to take a bigger place in the field of energy. The reasons for this are multiple. For one, the global demand for energy continues to grow and fossil fuel reserves are finite. It is therefore necessary to optimize their use by increasing the overall efficiency of secondary energy production chains such as electricity.
On the other hand, the areas producing and consuming primary energy have significantly different locations. Countries like France want to enjoy a maximum energy independence rate, for financial and political reasons, linked to the risks that sometimes exist in times of international tension.

Energy consumers are also increasingly aware of the impact of energy production on the environment. This awareness has implications for the government's definition of energy policies. The fight against pollution and the resulting climate change has thus become a priority in the environment, energy and state research policies, even though there are debates on the measures to be taken in order to achieve the desired objectives. The use of fossil fuels, coal in particular, causes significant damage to human health and has an impact on global

Algerian Journal of Engineering Architecture and Urbanism Vol. 5 Nr. 3 2021
ISSN: 2588-1760

warming. New, cleaner and more efficient energy technologies, in particular to reduce greenhouse gas emissions, are to be promoted [see Annex to the Introduction]. Actions are being taken in this direction. They concern fuel cells, bioelectricity (biomass and waste for electricity and heat generation), and the integration of renewable energy sources and decentralized generation, cleaner fuels for transport, storage of electricity and energy, photovoltaic and wind energy. Minimizing costs and the ability of these new concepts to penetrate the market are carefully considered.

Problematic:

- ✓ Energy criteria and sizing: An important part of hydrogen saving is obtained by kinetic energy recovery. The sizing of the secondary source must therefore make it possible to recover as much as possible the braking energy. However, the kinetic energy recoverable and the power demand of the motorization depend on the envisaged use of the vehicle (urban, periurban or highway, mixed...).As a result, the sizing of the power source is specific to a particular application.
- ✓ Vehicle mass problem: Hydrogen consumption is influenced by the mass of the vehicle. The mass of the power source (fuel cell system + secondary energy source) is therefore an important factor in the design process. At the limit, the overweight introduced can go as far as canceling the benefits obtained thanks to the secondary source. Due to the additional weight introduced by the secondary source of energy as well as the increase in the complexity of the powertrain, can be considered the use of a single fuel cell which naturally has a high efficiency over a wide range of use.
- ✓ Energy and Power: It is difficult to advocate the use of battery or super-capacitor, the two technologies having very different characteristics. Some authors favor the use of super-capacitors because of their energy efficiency and specific power, but their low capacity can be a handicap. Conversely, batteries are able to store a large amount of energy but are penalized by their specific power. One solution is to couple batteries and super-capacitors to combine their advantages (power and energy), but this inevitably increases the complexity and cost of the secondary energy source.

2. The field of transport

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].This despite the simultaneous increase in mass and power of vehicles, despite the generalization of comfort elements such as air conditioning. Upcoming technological innovations, such as the electrical control of valves on engines, and the appearance of hybrid vehicles [2] [3] should further reduce consumption. All-electric vehicles are also available for sale, but the limited performance of their batteries confines them to niche markets.

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 [4].Transport is the sector that generates the greatest increase in CO2 emissions: a car with a combustion engine releases about one tone of CO2 every 5000 km into the atmosphere. A break in technology seems inevitable.

3. The fuel cell vehicle:

Fueled directly with hydrogen, it generates no local air pollution and is very noisy. It turns out to be a prime candidate in the context.

Fuel cells are still sources of high current and low voltage. Their rational use in vehicle power trains often involves raising the voltage level by means of suitable static converters. In order to optimize these chains globally, it is also necessary to ask the question of the hybridization of the battery by a buffer device allowing intermediate storage of the power. Indeed, the on-board power source must both provide sufficient energy to ensure the autonomy of the vehicle and deliver significant power during transient phases, corresponding to acceleration or a slope crossing. The source must therefore meet these two different needs, while respecting acceptable mass and volume criteria. One solution is to decoupling energy source / power source. Components with appropriate characteristics are then associated with these two sources: fuel cell generator (GE to PAC) and buffers such as super-capacitors. The fuel cell used in transport is most often of the PEM (proton exchange membrane) type; it has the advantage of operating at low temperature and having a solid electrolyte.

The use of super-capacitors is particularly interesting because they are components that have an important ability to accept or restore high energy in very short periods.

PAC GEs can be used in vehicles in different ways. Either they are placed in association with a battery with very limited capacity, comparable to that of the thermal vehicles, and only intended to ensure the startup of the auxiliaries of the group, either they are associated with other elements of energy storage (a stack of more or less large batteries for example) and the two components of the hybrid source together deliver energy to the power train. The architecture chosen and the degree of hybridization largely determine the mode of operation of the EG to PAC. It may be necessary to provide a significant power dynamic or, conversely, to operate as a range extender: it then recharges the batteries by delivering a relatively low power and more or less constant. Hybridization of GE to PAC may also allow for a smaller and therefore less expensive GE. Given the still high price to date of a pile stack, hybridization could allow the launch of the first vehicles to CAP.

- **Hydrogen, an energy vector :**

Certainly, the hydrogen atom is the most abundant element in the universe [5]; it is found in water (lakes, rivers, oceans ...) and in fossil fuels, but hydrogen gas (or Di-hydrogen), in its molecular form, is virtually non-existent in nature. Like electricity, hydrogen must be produced from different sources of primary energy, fossil and non-fossil. The major disadvantage of electricity lies in the difficulty of storing it in large quantities. Assuring an energy storage function, hydrogen could become a second energy vector, complementary to electricity, leading to high yields by limiting the secondary reactions to its transformation into water (oxidation or combustion) and therefore pollutant emissions [6].Fuel cells would convert the chemical energy of hydrogen into electrical energy. Hydrogen production and storage, for example, would allow decoupling over time between consumption and electricity generation from renewable energies, such as wind energy. The choice of production, storage and distribution methods will determine the development of the hydrogen sector.

After a brief history, the main fields of application of the fuel cell (PAC) will be presented. Vehicle-related usage limits favor the use of a particular technology. Its operating principle and its constraints of use are described. Some of these constraints can be removed by the addition of a secondary energy source (ex: super-capacitors).

- **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 [7].

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 1 provides an overview of the annual sales of these vehicles and the total sales of the three vehicle models.

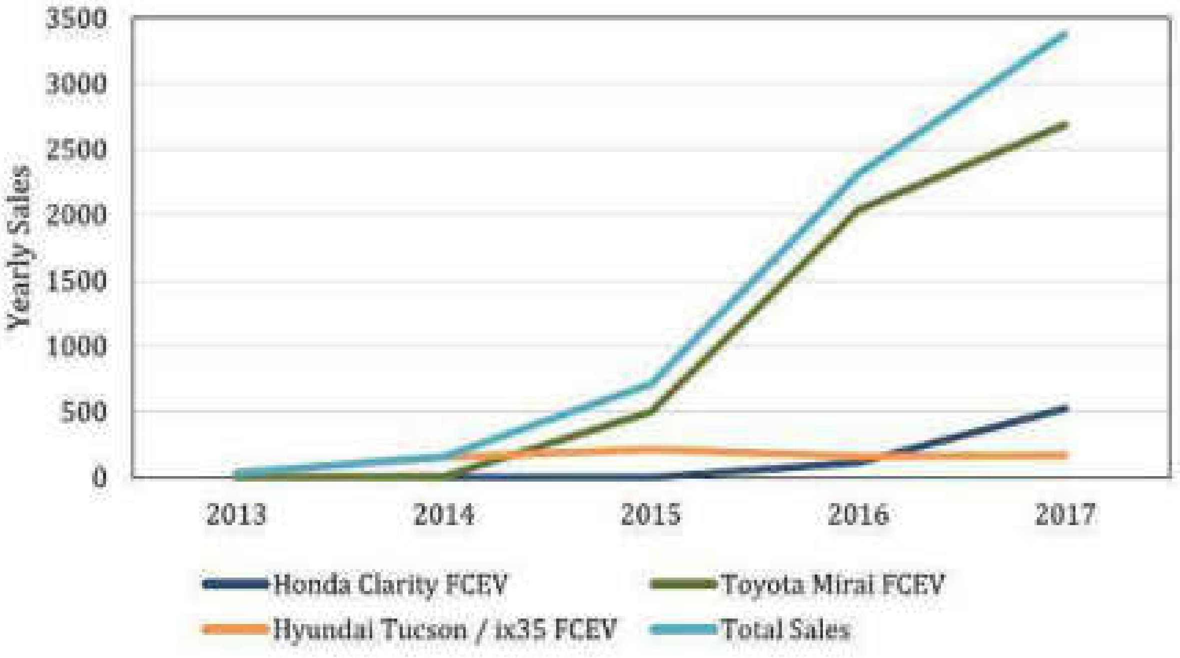

Fig1. Global annual sales of fuel cell vehicles between 2013 and 2017 by vehicle model [8]

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 2.

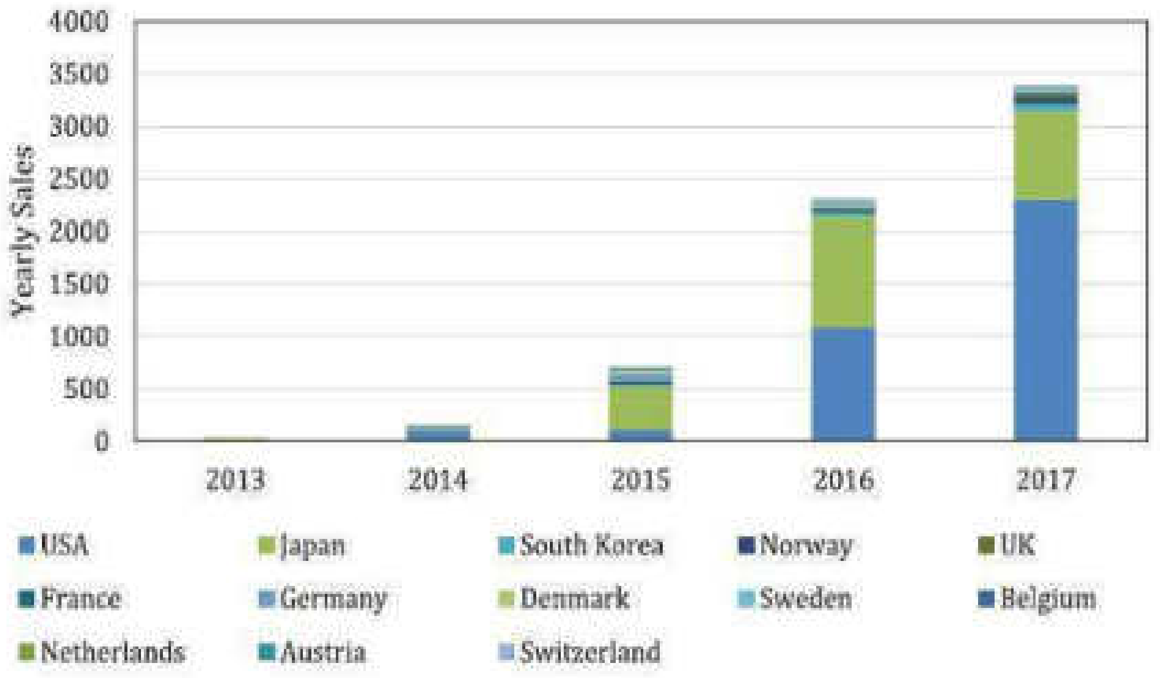

Fig2. Worldwide annual sales of fuel cell vehicles between 2013 and 2017 by country [8]

3.1. The fuel cell, a power full energy converter:

If the hypothesis of the choice of hydrogen as a new energy vector is retained, the fuel cell will become the most efficient converter of hydrogen into usable energy (electricity and heat).

3.1.1. History:

The fuel cell (PAC) converts chemical energy into electrical energy. Its technology has become more and more familiar in recent decades, but has been discovered more than 150 years ago. In 1839, Sir William Grove, an English jurist and amateur chemistry researcher, describes an experiment where water and electricity are produced from oxygen and hydrogen. Grove's experience gives birth to the gas battery (Figure 3), later renamed fuel cell [9] [10].

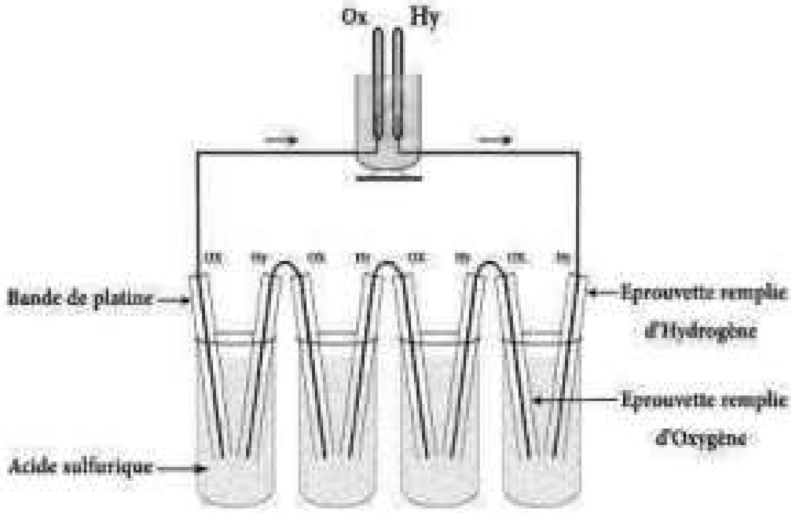

Fig3. The Sir William Grove experience

The discovery of W. Grove, however, was not exploited and was relegated to the rank of scientific curiosity, while the extraction of fossil fuels and the development of the engine were in full swing. In 1932, Dr. Francis Bacon took over the research initiated by W. Grove and managed to build a 5kW fuel cell in 1959.

The fuel cell has emerged with NASA (National Aeronautics and Space Administration, USA) looking for a way to generate electricity on board its spacecraft. The fuel cell appeared as an ideal system because of the presence of oxygen and hydrogen available in the propulsion systems. Fuel cells were successfully used by the Gemini capsule in 1964[11], and the water produced by the reaction between hydrogen and oxygen was consumed by astronauts. This is one of the first concrete uses of fuel cells.

The interest of the use of the fuel cell in the field of transport dates back to 1973.The first oil crisis has led governments, industries and laboratories to seek an alternative to fossil fuels to try to ensure energy independence. Many efforts and means have been provided to reduce the manufacturing costs of fuel cell systems, to increase their reliability and to improve their compactness. In 1993, a fuel cell bus was built by the Ballard company (today one of the world leaders in the field of fuel cells) in partnership with the car manufacturer Daimler-Benz [12]. The fuel cell was of PEM type ("Proton Exchange Membrane").The hydrogen needed to feed the cell was produced by embedded reforming of methanol (Figure 4).

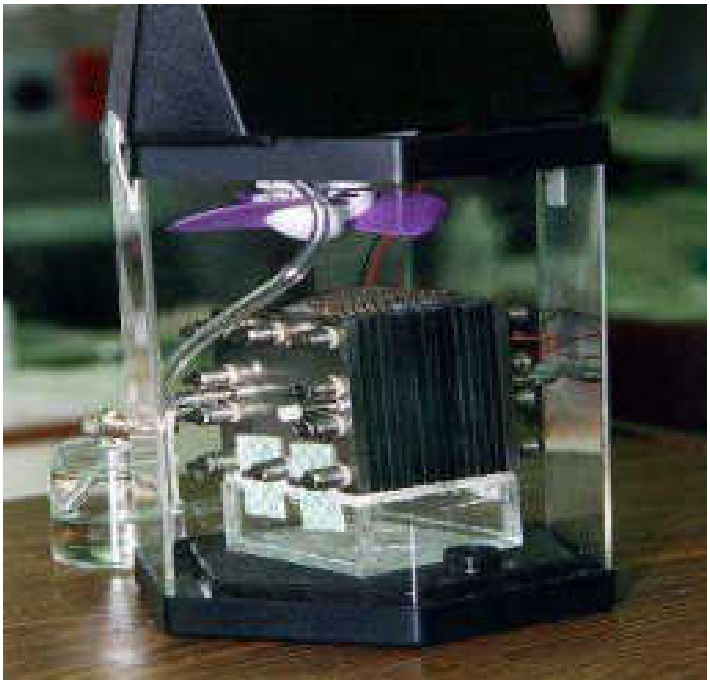

Fig4. Fuel Cell, from NASA to Methanol [13].

Since the 1990s, fuel cells and hydrogen have been considered as possible candidates for the production of sustainable and clean energy, whether for mobile or stationary applications.

Fuel cells are listed based on their operating temperatures, electrolytes, and power ranges. The main fuel cell technologies and their characteristics are given in Table 1 [14] [15]:

Name	Electrolyte	Power range	Operating temperature	Fields of application
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

PAC at low temperatures	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 PAC	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

Tab1. The main types of fuel cells

Each type of fuel cell has a preferred field of application (Table 1).fuel cell called low temperatures are more for mobile applications, while so-called high temperature batteries are generally intended for stationary applications.

The main mobile applications concern portable electronic devices (computer, cell phone ...) and the transport sector (car, bus ...); stationary applications concern the decentralized production of electrical energy (collective or individual housing, etc.).In the latter, the heat produced by the high temperature cells can be recovered by cogeneration a process which increases the overall efficiency of the PAC system [14].

In Figure 5, the different types of fuel cells and the power ranges are linked by their possible fields of application.

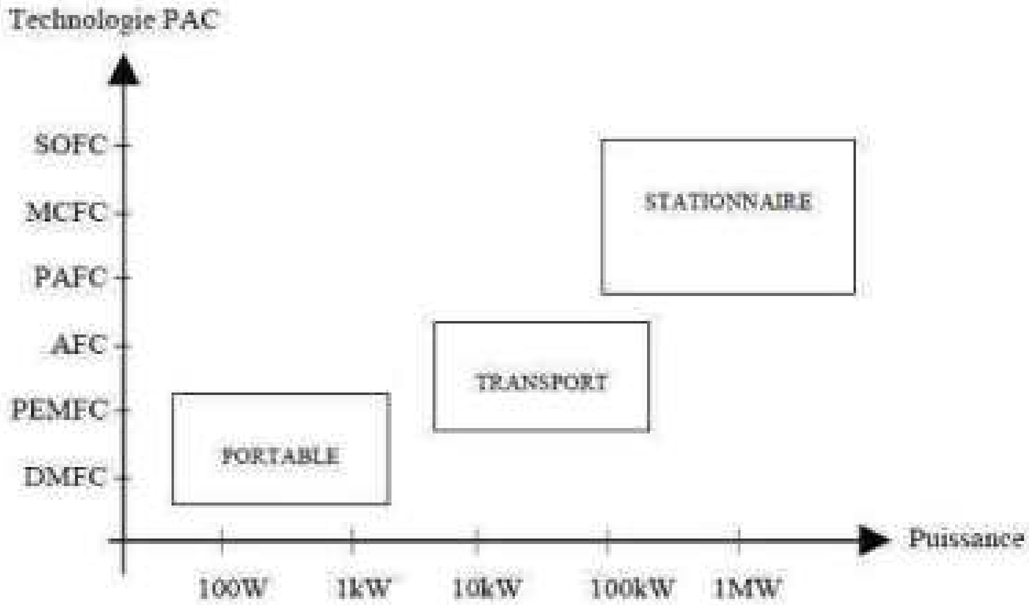

Fig5. Fuel cell technologies and fields of application

Among the different types of fuel cells, the PEM ("Proton Exchange Membrane") type cell, also called PEFC ("Polymer Electrolyte Fuel Cell"), is the technology generally used for automobile use. Several reasons explain this choice [16][17][18]:

- Density of power:

  The propulsion of a vehicle requires a power of a few kilowatts to a hundred kilowatts. In addition, the power train must have an acceptable mass and size.

  The PEM type is best meets these constraints with a power density of between 1 kg / kW and 3 kg / kW.
- Operating temperature:

  The PEM fuel cell has an operating temperature of between 50 ° C and 80 ° C, which is suitable for automotive use.
- Solid structure:

  The PEM fuel cell is composed of solid elements (especially the polymer membrane). This solid structure guarantees a certain mechanical resistance with respect to the constraints related to the automotive environment.

3.1.2. The polymer 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

Algerian Journal of Engineering Architecture and Urbanism Vol. 5 Nr. 3 2021
ISSN: 2588-1760

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.

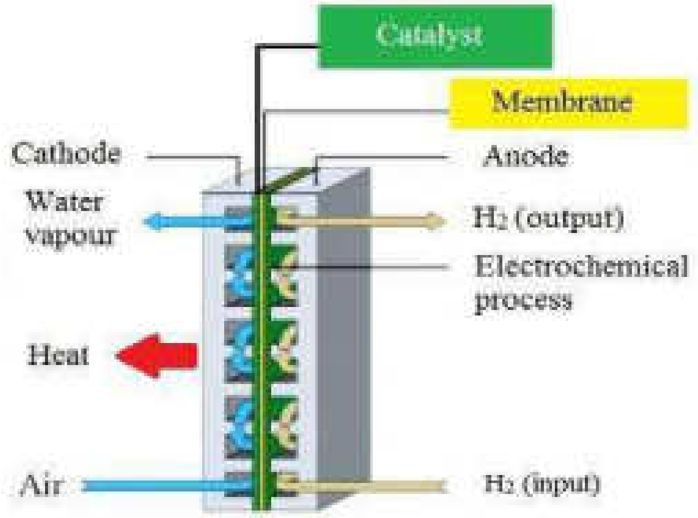

Fig6. Principle of operation of a PEM fuel cell

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**

$\mathbf{H_2 \rightarrow 2H^+ + 2e-}$ (1)

- **Reaction to the cathode:**

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

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

$\mathbf{H_2 + \frac{1}{2} O_2 \rightarrow H_2O + heat}$ (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 6 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.

a. Elementary cell and assembly of the fuel cell:

The electrochemical reaction takes place within an elementary cell. An elementary cell consists of an Electrode-Membrane-Electrode (EME) assembly pressed between 2 bipolar plates (Figure 7).

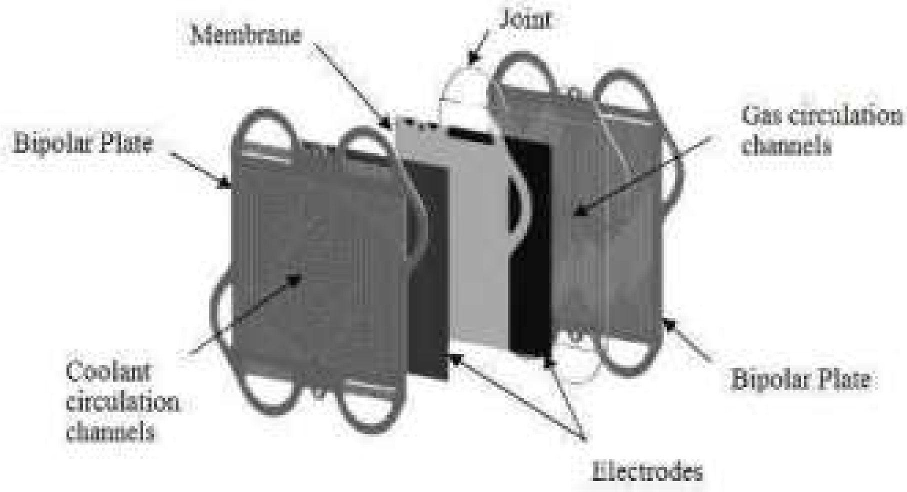

Fig7. Example of assembly of an elementary cell [19]

The membrane is the heart of the elementary cell. The membrane is a polymer electrolyte that is permeable to hydrogen protons H+ and impervious to gases. To guarantee H + proton permeability, the membrane must be permanently moistened. The Nafion® [20] membrane is the most common in PEM fuel cells.

An EME assembly has two electrodes: the anode and the cathode. An electrode is made of two layers of porous material. The Gas Diffusion Layer (GDL) transports and distributes hydrogen and oxygen uniformly over the membrane while discharging the produced water. The catalyst layer (platinum) makes it possible to activate and accelerate the oxidation-reduction reaction.

Bipolar plates fulfill two roles. On the one hand they distribute the gases evenly to the EME assembly through thin channels (Figure 7).On the other hand; they allow the circulation of a cooling fluid to cool the elementary cell.

Bipolar plates must be conductive and withstand a corrosive environment (for example, graphite or stainless steel is used).

The voltage obtained with an elementary cell is less than 1 volt, which is insufficient for most applications. To provide a sufficiently high voltage source, several cells are connected in series to form the fuel cell (Figure 8). To ensure tightness, the cells are pressed against each other by two end plates and tie rods.

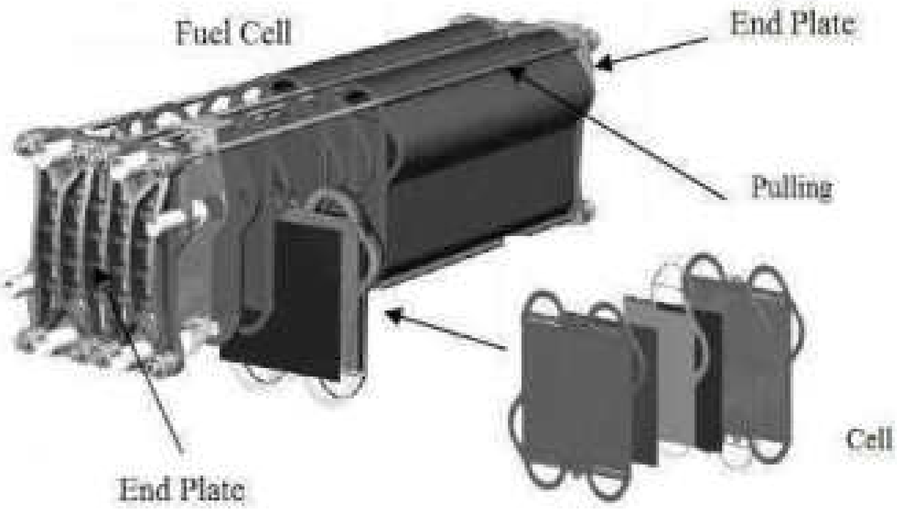

Fig8. Example d'un assemblage de pile à combustible [19]

b. Electrical characteristic of the fuel cell:

The empty voltage of the cell (**Figure 9**) is a function of the electrochemical potential of the oxidation-reduction reaction. Ideally, this electrochemical potential is 1.23 V (standard potential) for standard conditions of temperature and pressure (1 atm, 25 ° C). In practice, the no-load voltage is slightly below **1V** [21].

The polarization curve is the electrical characteristic of a fuel cell. It represents the voltage of the cell as a function of the current density (**Figure 9**) and depends on the operating temperature, the pressure of the reagents and the moisture content of the membrane.

The current density $\boldsymbol{i_{FC}}$ (A / cm²) is defined by:

$$i_{FC} = \frac{I_{FC}}{A_{cell}} \quad (4)$$

With I_{FC} The fuel cell current and A_{cell} The active surface of a membrane.

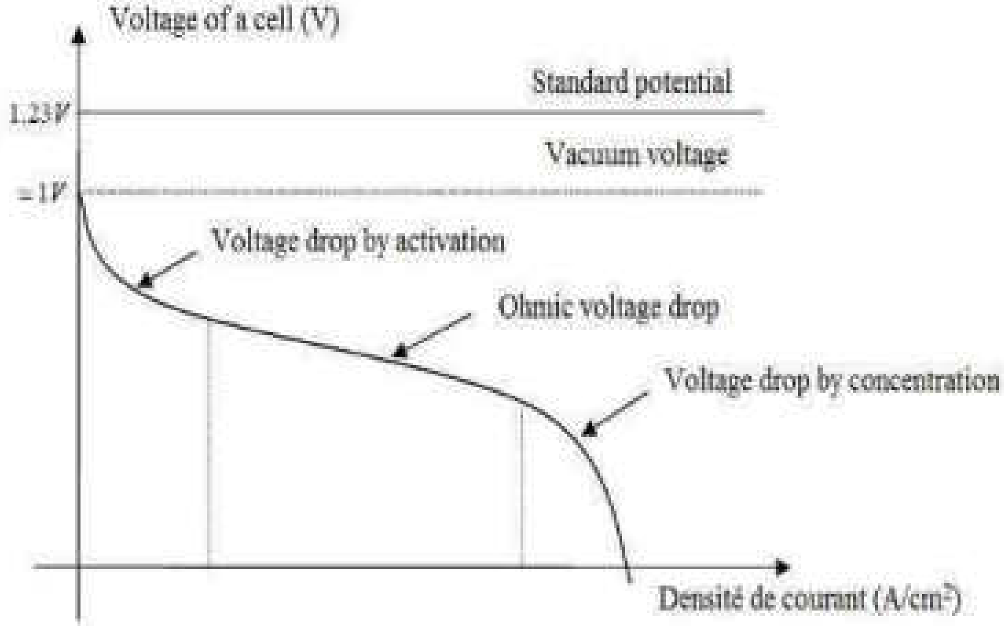

Fig9. Conventional polarization curve of a PEM fuel cell.

The polarization curve (**Figure 9**) can be broken down into three distinct zones, each characterized by preponderant voltage drops **[21]**:

- **Voltage drop by activation:**

The right electrochemical reaction cross a threshold of activation to initiate. This threshold is due to the slowness of the electrochemical reaction at the surface of the electrodes. The catalyst layer present in the electrodes helps to accelerate the reaction.

- **Ohmic voltage drop:**

Ohmic voltage drops are caused by the electrical resistance of the diaphragm and the electrical resistance of the bipolar electrode / plate assembly.

- **Voltage drop by concentration:**

Voltage drops due to concentration result from a lack of reagents. When the current density becomes high the diffusion of the gases in the electrodes is not fast enough to maintain the reaction.

The polarization curve in **Figure 9** is given for an elementary cell. Conventionally, assuming that all cells have the same electrical behavior, the total voltage of the fuel cell V_{FC} is given by:

$$V_{FC}\,(I_{FC}) = N_{Cell}\,.V_{cell}\,(I_{FC}) \qquad (5)$$

With V_{cell} the elementary voltage of a cell and N_{Cell} the number of cells.

The raw power P_{FC} supplied by the fuel cell is:

$$P_{FC}(I_{FC}) = V_{FC}(I_{FC}).\ I_{FC} \qquad (6)$$

A fuel cell is capable of supplying electrical power as long as it is fed with reagents (oxygen and hydrogen).This implies that a fuel cell cannot operate alone and needs a set of peripheral components to function.

c. Fuel cell system:

The fuel cell needs a set of conditions to produce electrical energy **[18]**: it must be supplied with hydrogen and air, the membrane must be permanently humidified, and the heat produced must be evacuated. The auxiliary components have the role of ensuring the proper functioning of the fuel cell. The fuel cell and auxiliary components assembly is called a fuel cell system.

Fuel cell ***systems*** are typically designed specifically for a particular application. There is therefore much possible architecture. A classical architecture is given in **Figure 10**.

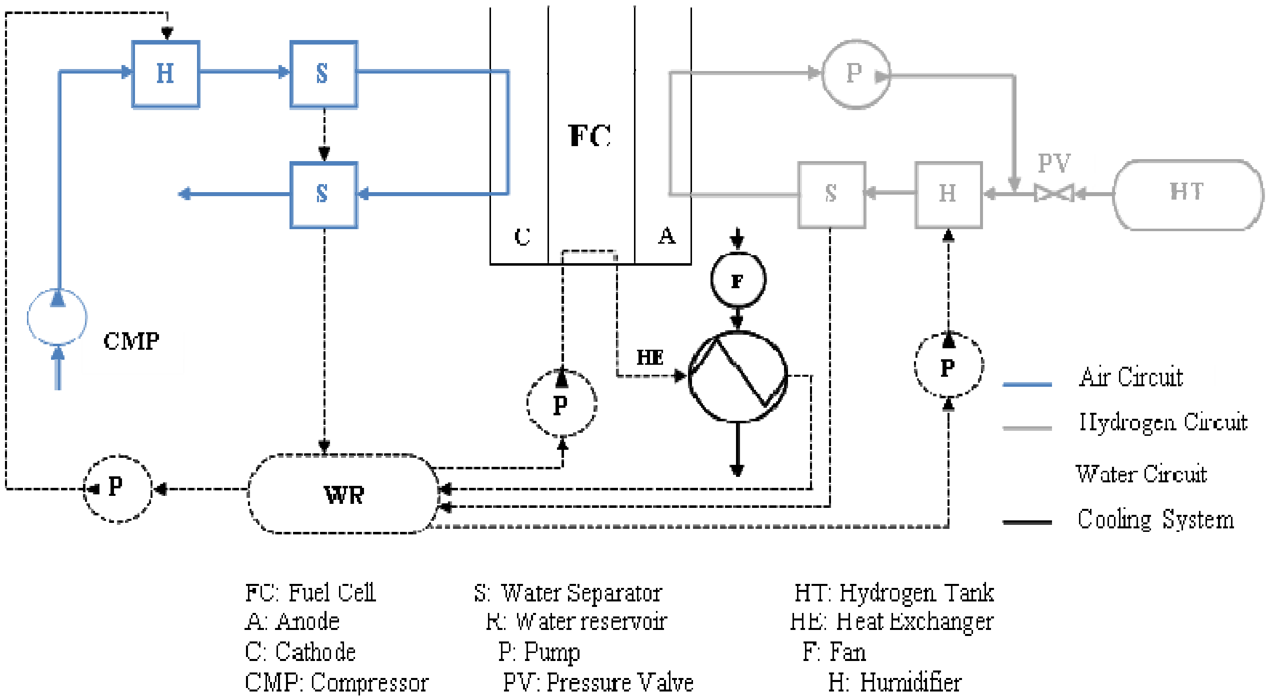

Fig10. Architecture of a fuel cell system [18].

Four main circuits making up a Fuel Cell system **(Figure 10)**:

- **The hydrogen circuit (closed circuit):**

It supplies the anode with gaseous hydrogen. The hydrogen that is not consumed at the outlet of the heat pump can be re-injected at the inlet thereof via a recirculation pump.

- **The air circuit (open circuit):**

Generally, to supply the fuel cell with oxygen, a compressor injects air to the cathode.

- **The cooling circuit:**

The cooling system is an essential part of the fuel cell system **(Figure 10)**.The heat produced by the fuel cell can represent more than **50%** of power losses for high currents. In addition, the limited temperature difference between the fuel cell (about **80 ° C**) and the ambient air does not promote heat exchange and requires the use of large heat exchangers. This represents an important technical constraint in automotive applications.

- **The water circuit:**

Humidification of the membranes is done by the incoming gases (air and hydrogen) via the water circuit **(figure 10)**.The water also contributes to the cooling of the fuel cell as it passes through the heat exchanger.

Auxiliary components are therefore essential for the proper functioning of the fuel cell. They consume some of the energy produced by the fuel cell. The air compressor (Figure 10) is the auxiliary that absorbs the most power **[22]**, and it significantly affects the overall efficiency of the fuel cell system.

The net power available at the output of the fuel cell system (P_{sysFC}) is a function of the gross power (P_{FC}) and the power consumed by the auxiliary components (P_{aux}):

$$P_{sysFC}(I_{FC}) = P_{FC}(I_{FC}) - P_{aux}(I_{FC}) \quad (7)$$

Paces characteristic of the powers are given in **Figure 11**.

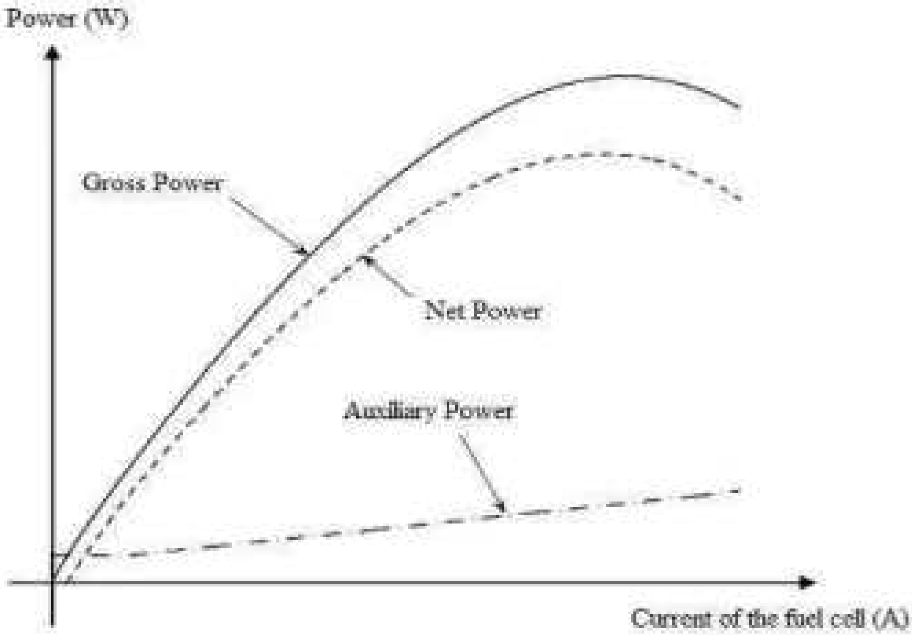

Fig11. Characteristic powers of a fuel cell system
(Gross, net and auxiliary power).

The power losses induced by the power consumption of the auxiliary components affect the overall efficiency of the system **(Figure 12)**.While the fuel cell converts chemical energy into electrical energy with a maximum efficiency of about **70%** for low loads, the fuel cell system achieves a maximum efficiency of about **50%** at around **25%** of the net available power.

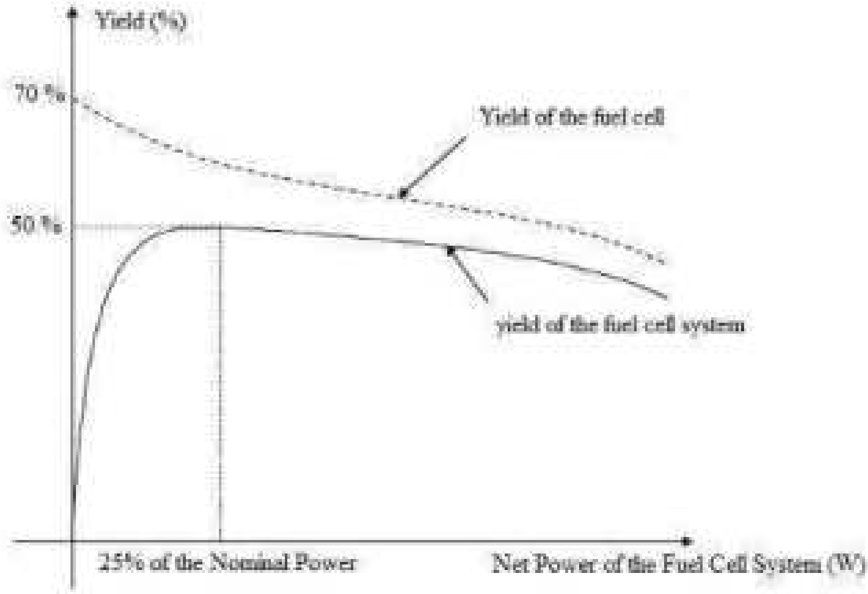

Fig12. Characteristics yield of the fuel cell and fuel cell system.

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ISSN: 2588-1760

3.1.3. Fuel Cell Power train:

a. Constraints in automotive applications:

A fuel cell vehicle is primarily an electric vehicle. The motorization is provided by one or more electrical machines and the power is supplied by the fuel cell system. Since the production of electrical energy is done without greenhouse gas emissions, a fuel cell vehicle is considered non-polluting (***locally***).The fuel cell system has a high efficiency (up to **50%**), so its use in a power train appears as an interesting solution for sustainable mobility.

A classic power-train architecture using a fuel cell is given in **Figure 13**.

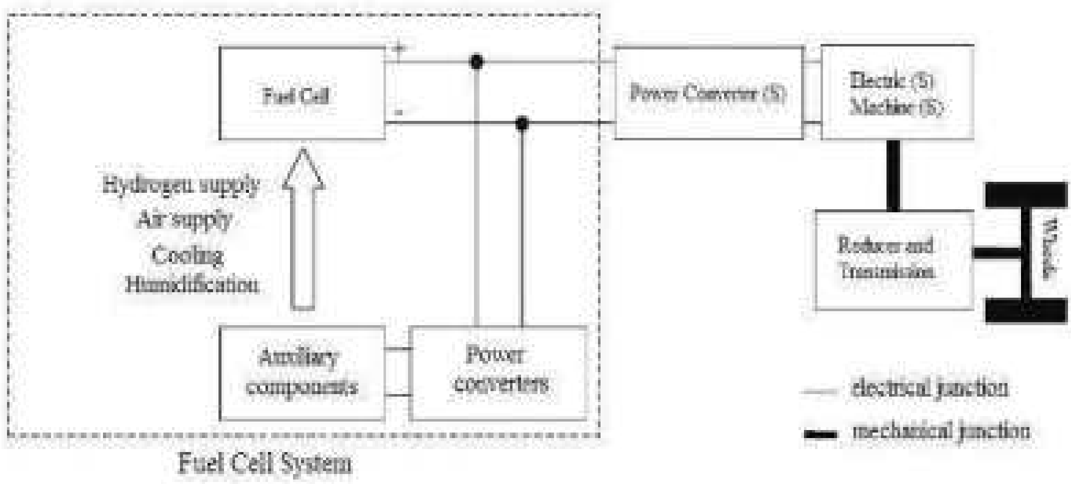


Fig13. Example of Fuel Cell Power train Architecture.

However, certain constraints related to the use of hydrogen and the fuel cell in an automotive environment must be considered:

- **Hydrogen storage:**

Several hydrogen storage technologies have been considered for the automobile **[23] [24] [25]** but do not yet allow storing enough hydrogen to ensure autonomy similar to that of a vehicle conventional:

- ✓ Storage in gaseous form: Hydrogen is stored in metal tanks or composite materials, pressurized between 300 bars and 700 bars. It is the simplest and least expensive solution to store hydrogen.

- ✓ Storage in liquid form: Hydrogen is stored in liquid form at very low temperatures (-253 ° C) in cryogenic tanks.
- ✓ Reforming: Hydrogen is produced in the vehicle by a reformer. A reformer is a "mini-refinery" that extracts hydrogen from hydrogenated liquid fuels (eg methanol).

- ✓ "Solid" storage: Hydrogen can be stored in metal hydride tanks. A metal hydride captures the hydrogen molecules when it is under pressure and releases them when its temperature is increased. The main disadvantage of this solution is the large mass of the tank. The storage of hydrogen in nanostructures and nanotubes is also reported in the literature, but the actual hydrogen absorption capacity is a controversial subject and seems remote from the needs of the automobile **[26]**.

- **Dynamics of the fuel cell system:**

A fuel cell system cannot instantly deliver maximum power. Its dynamics is mainly limited by that of the air compressor **[22]**.Generally the response time of the fuel cell system is of the order of a few seconds and can affect the dynamic performance of the vehicle during strong acceleration.

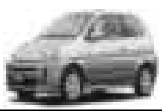
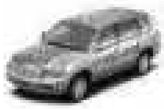
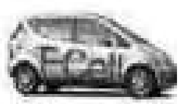
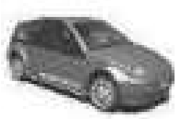
- **Dimensioning of the fuel cell system and cooling circuit:**

In the case of a fuel cell vehicle without other secondary sources of electrical energy, the fuel cell system is sized to meet the power peaks of the electric motor (during high accelerations).For satisfactory dynamic performance of the vehicle, the rated power of the fuel cell system must be high. Cooling of the fuel cell can therefore become tricky **[27]**.

- **Cold start of the fuel cell system:**

During cold starts, the maximum power of the fuel cell system is limited. The fuel cell needs a few minutes to reach its operating temperature **[28]**. Considers that only 50% of the nominal power is available during the first **2** minutes. The power limitation during a cold start is also described by **[18]**.

Fuel cell vehicles without other secondary sources of electrical energy such as General Motors' Hydrogen3 prototype vehicle, **Table 2**, are therefore uncommon because the constraints related to the automotive environment require specific technological developments. In the context of automobile use, the fuel cell is therefore generally assisted by a secondary source of electrical energy. This type of vehicle is then called "***hybrid fuel cell vehicle***".

Builder	Vehicle	Fuel Cell	Secondary source of energy	Hydrogen storage	Auton-omy	Engines
Honda **[29]**	FCX 	86 kW (Honda)	Super-capacitors	High pressure tank (156.6 l, 350 bar)	430 km	80 kW
Toyota **[30]**	Highlander FCHV* 	90 kW (Toyota)	Batteries Ni-MH	Version 3: Metal hydride Version 4: High tank Pressure Version 5: reformer	300 km 250 km	80 kW
Nissan **[31]**	X-Trail FCHV* 	90 kW (Nissan)	Battery Li-ion	High tank Pressure (700 bar)	500 km	90 kW
General Motors **[32]**	Zafira Hydrogen3 	94 kW	sans	Liquid version: Liquidhydrogentank (68 l) Gas version: High pressure tank (77.4 l, 700 bar)	400 km 270 km	60 kW
Daimler-Chrysler **[5]**	Class A F-Cell 	85 kW (Ballard)	Batteries Ni-MH	High pressure tank (350 bar)	150 km	65 kW
PSA **[33]**	Partner Taxi-PAC 	5,5 kW	Batteries Ni-MH	High pressure tank (300 bar)	250 km	22 kW
Michelin-PSI **[34]** **[35]**	Hy-Light 	30 kW (PSI)	Super-capacitors	High pressure hydrogen tank (200 bar) + High pressure oxygen tank (350 bar)	500 km	2 engines 30 kW wheels at the front.

*: Fuel Cell Hybrid Vehicle

Tab2. Examples of fuel cell vehicles

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b. Hybrid fuel cell vehicle:

In a hybrid fuel cell vehicle, it is the power source that is hybrid, the engine remaining fully electric. A hybrid fuel cell vehicle therefore uses a secondary source of electrical power reversible power (charging and discharging).The roles of the secondary source of energy are **[28][36]**:

- **Assist the fuel cell:**

The secondary source provides the additional power when the battery reaches its maximum power (for example during acceleration of the vehicle).

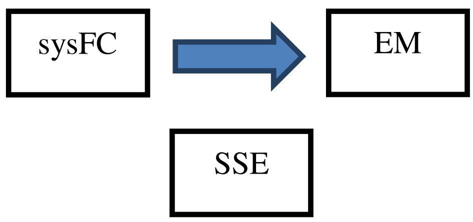
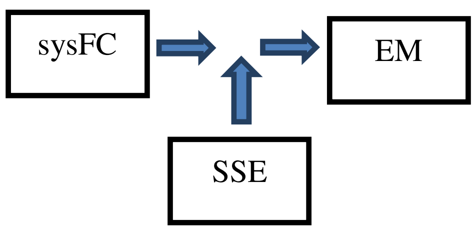
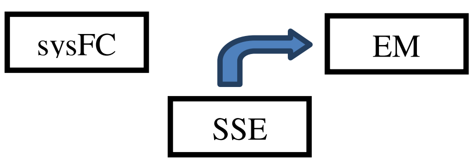
- **Recover kinetic energy during braking:**

The recovery of kinetic energy during braking phases saves hydrogen and increases the range of the vehicle.

- **Introduce a degree of freedom in the distribution of powers:**

Hybridization distributes the power demand between the fuel cell system and the secondary energy source. The operating points of the fuel cell system can thus be shifted to higher yield areas by using appropriate control strategies, thereby reducing hydrogen consumption.

Within the power train of a hybrid fuel cell vehicle (**Figure 14**), several modes of operation can be identified. These modes of operation (traction, braking and stopping) induce different energy flows (**Table 3**).

Mode	Power	Diagram of energy flows	Description
Traction	$P_{EM}> 0$ $P_{sysFC}> 0$ $P_{SSE}= 0$		The fuel cell system supplies only the electric machine.
	$P_{EM}> 0$ $P_{sysFC}> 0$ $P_{SSE}> 0$		The fuel cell system and the secondary source together power the electric machine.
	$P_{EM}> 0$ $P_{sysFC} = 0$ $P_{SSE} > 0$		The secondary source supplies only the electric machine.

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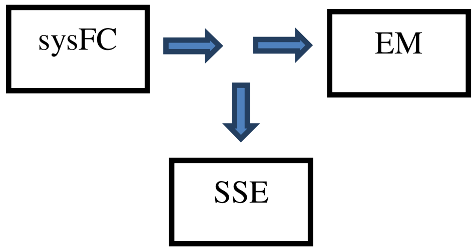
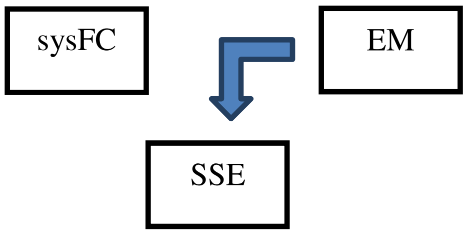
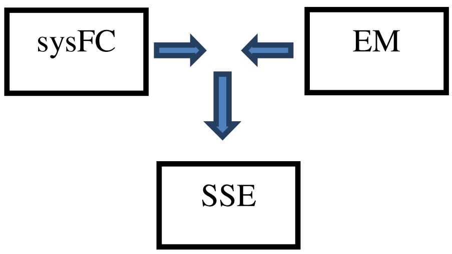
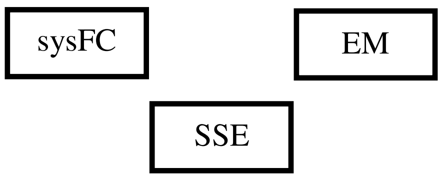
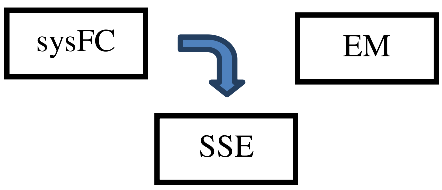
	$P_{EM} > 0$ $P_{sysFC} > 0$ $P_{SSE} < 0$		The fuel cell system powers the electric machine and recharges the secondary source.
Braking	$P_{EM} < 0$ $P_{sysFC} = 0$ $P_{SSE} < 0$		The secondary source recovers the kinetic energy of braking.
	$P_{EM} < 0$ $P_{sysFC} > 0$ $P_{SSE} < 0$		The secondary source recovers the kinetic energy of braking and also receives power from the fuel cell system.
Stop	$P_{EM} = 0$ $P_{sysFC} = 0$ $P_{SSE} = 0$		No energy flow.
	$P_{EM} = 0$ $P_{sysFC} > 0$ $P_{SSE} < 0$		The fuel cell system recharges the secondary source.

sysFC: system FC
SSE: Secondary Source of Energy
EM: Electric Machine

Tab3. Energy flows within the power-train.

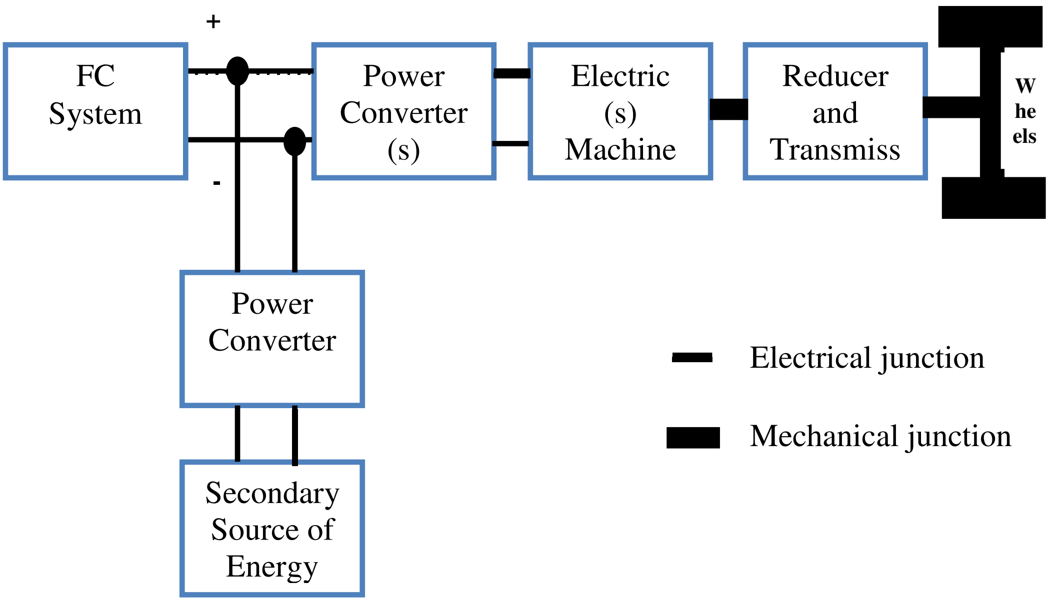


Fig14. Example for Hybrid Fuel Cell Vehicle Architecture

c. The secondary source of energy:

The main characteristic of the secondary source of energy is that it is reversible in power. The secondary source can be recharged by kinetic energy recovery or by the fuel cell system (**Table 3**).

In a hybrid fuel cell vehicle, two technologies are generally retained to form the secondary source of energy: ***batteries and super-capacitors***.

A battery is an electrochemical energy converter that stores energy in a chemical way. In the case of hybrid vehicles, the main technologies used are lead-acid batteries, Nickel Metal Hydride (Ni- MH) batteries and Lithium-ion (Li-ion) batteries **[37]**. Ni-MH technology is the most popular because it offers good performance in terms of capacity, life and cost. Li-ion technology has a higher specific power (W / kg) and a better specific capacity (Wh / kg), but improvements are still necessary concerning the cost, the safety of operation, the service life and performance at low temperatures. Lead technology suffers from a low specific capacity due to the high weight of the batteries; however, it is a robust technology available at low cost and still benefiting from developments **[38]**.

A super-capacitor (or double-layer capacitor) stores the energy electro-statically by polarizing an electrolytic solution. There is no chemical reaction involved, resulting in high lifetimes (a super-capacitor can be charged and discharged hundreds of thousands of times). Les super-capacitors have an extremely low specific capacity but have a significant specific power. In addition, their efficiency in charge and discharge is high. In a hybrid application, super-capacitors are intended to satisfy the strong power peaks **[39]**.

A fuel cell, a battery and a super-capacitor have extremely different electrical characteristics. The Ragone plan (**Figure 15**) illustrates the differences in terms of specific

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powers and specific capacities of different power sources **[40]**.The fuel cell and hydrogen have the highest specific ***capacity***, followed by batteries and then super-capacitors. In contrast, super-capacitors have the highest specific ***power***, followed by batteries and fuel cells.

One of the challenges in the design of a fuel cell hybrid vehicle is to determine an ideal combination of the fuel cell system and the secondary energy source to satisfy the dynamic performance of the vehicle while ensuring sufficient autonomy.

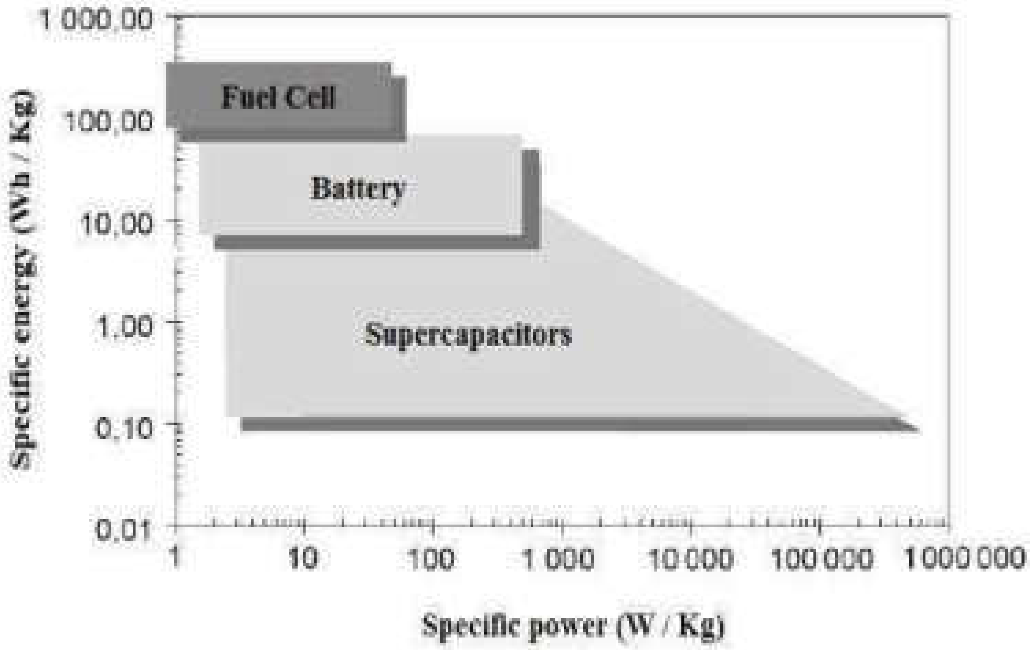

Fig15. Plan of Ragone [40]

3.1.4. Dimensioning and control strategy:

a. Dimensioning of the hybrid power source:

The sizing of the power source (fuel cell system and secondary energy source) has an essential impact on both the dynamic performance of the vehicle (driving pleasure) and the hydrogen consumption (vehicle range).It is obviously a function of a specification related to the application. The solutions obtained for this specification can be many and varied (choice of secondary source for example).In this case, to make a choice, one must be sure to have a control strategy that makes the best use of energy exchanges. The choice of components and the control strategy are therefore intimately linked for sizing. Sizing must take into account several aspects:

- **Driving situations and dimensioning:**

It is not possible to take into account all possible driving situations. The specifications therefore impose minimum performance for "characteristic" driving conditions. For the special cases of constant speed and constant acceleration of the vehicle (**Figure 16**), minimum limits can easily be calculated for the energy and power of the secondary energy source:

- Case of the constant speed of the vehicle:

  The vehicle must be able to drive at a constant speed V_{const} for an extended period of time (typically on the highway for several tens of minutes), which equates to a constant power demand P_{speed_const} of the engine.

  Since the secondary power source has a limited amount of power, it cannot provide extended power assistance to the fuel cell system. The fuel cell system must therefore have a maximum power sufficient $P_{sysFCmax}$ to maintain the speed of the vehicle **[41][42][43][28]**.

- Case of acceleration of the vehicle:

  The acceleration of the vehicle is characterized by power peaks P_{accel} of limited duration of the engine (a few seconds).The fuel cell system is not always able to ensure the acceleration of the vehicle alone either because its dynamics is limited or because it's maximum power $P_{sysFCmax}$ is limited.

  The missing power P_{accel}- $P_{sysFCmax}$ is then supplied by the secondary energy source **[28][42]**.The hybrid configuration is also particularly interesting to overcome the limit dynamics of the fuel cell system **[22][44]**.

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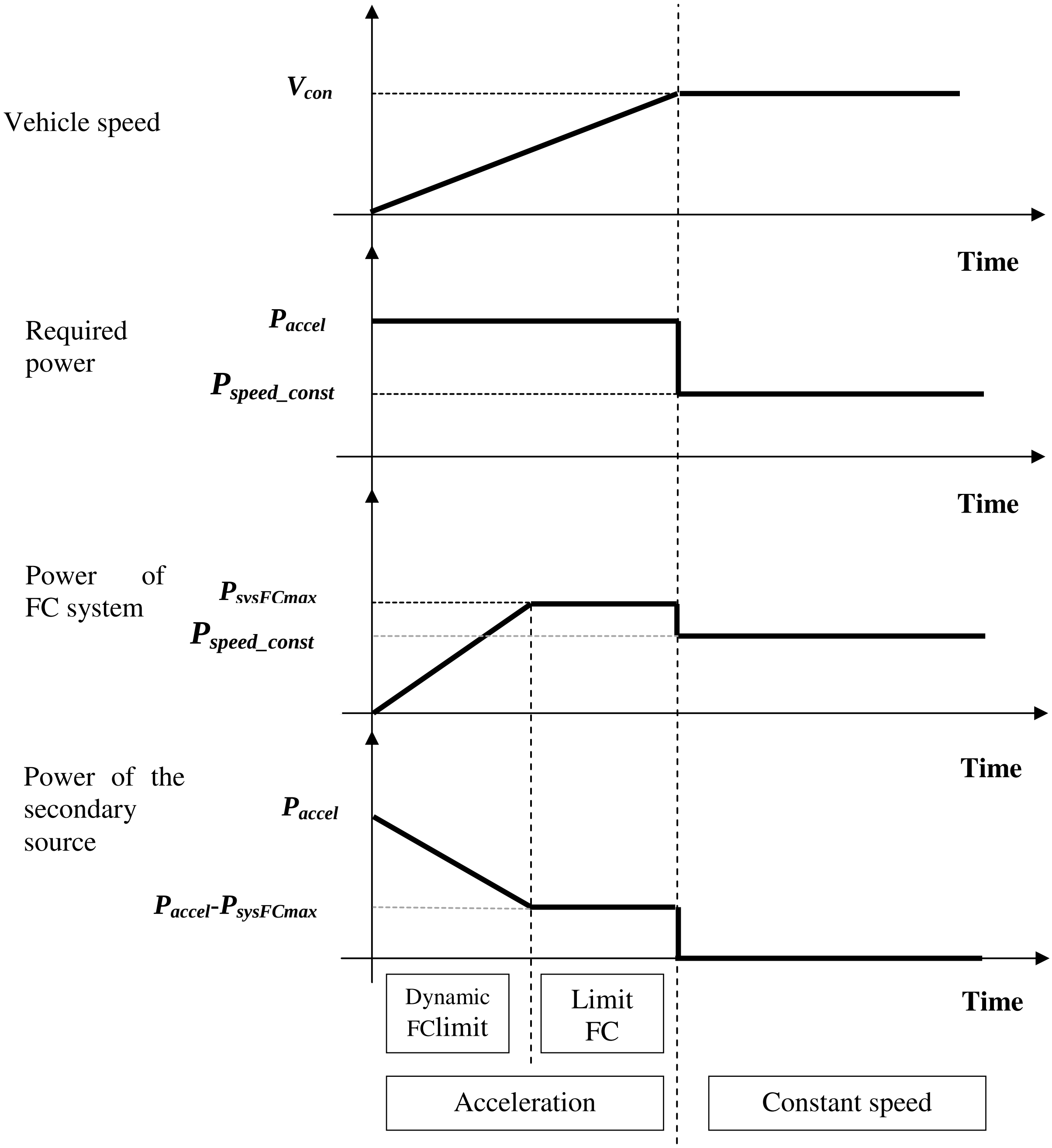

Fig16. Example of the powers involved in accelerating and maintaining the speed of the vehicle.

- **Energy criteria and sizing:**

An important part of hydrogen saving is obtained by kinetic energy recovery **[45][42][46]**. The sizing of the secondary source must therefore make it possible to recover as much as possible the braking energy **[47] [41] [48]**.However, the kinetic energy recoverable and the power demand of the motorization depend on the envisaged use of the vehicle (urban, periurban or highway, mixed...).As a result, the sizing of the power source is specific to a particular application **[49] [50] [42]**.

- **Vehicle mass problem:**

Hydrogen consumption is influenced by the mass of the vehicle. The mass of the power source (fuel cell system + secondary energy source) is therefore an important factor in the design process **[49][51][46]**. At the limit, the overweight introduced can go as far as canceling the benefits obtained thanks to the secondary source.

Due to the additional weight introduced by the secondary source of energy as well as the increase in the complexity of the powertrain, can be considered the use of a single fuel cell which naturally has a high efficiency over a wide range of use **[52]**.

- **Energy vs. Power: Battery or Super-capacitor?**

It is difficult to advocate the use of battery or super-capacitor, the two technologies having very different characteristics. Some authors favor the use of super-capacitors **[41][50]** because of their energy efficiency and specific power, but their low capacity can be a handicap. Conversely, batteries are able to store a large amount of energy but are penalized by their specific power. One solution is to couple batteries and super-capacitors to combine their advantages (power and energy) **[53][41][50]**, but this inevitably increases the complexity and ***cost*** of the secondary energy source.

In summary, in the context of automotive use, if there is consensus on the interest of a hybrid fuel cell system, the choice of secondary source technology remains open. In addition, there does not appear to be a trend among automakers to use super-capacitors or precise battery technology (**Table 2**).

Life-time constraints **[53]** or cost criteria **[54]** are also involved in the sizing process.

Conclusion:

With the growth of environmental problems and the expected shortage of energy sources for the next decades, it is important to find other more efficient and clean forms of energy, the overall oil reserves are only sufficient for about 40 years. However, the global economy is growing rapidly with a subsequent increase in oil consumption, CO2 emission has grown enormously in this period. In addition to contributing to the reduction of the greenhouse effect, vehicles powered by a fuel cell, more commonly called zero emission vehicles (ZEV), allow the improvement of the quality of urban life thanks to their low noise pollution. However, the prospects for commercial development have never been better as a result of the combined efforts of various research institutes worldwide, several large industrial groups and car manufacturers. Performance, reliability, durability, cost, fuel availability, public satisfaction, and performance during transients [19] are essential factors in developing fuel cell electric vehicles that can compete with the ICE vehicles that are monopolizing the streets. Thus, automotive manufacturers started to produce fuel cell vehicles.

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