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| FUEL CELL INDUSTRY ANALYSIS REPORT |
| 01/01/2015 |

Bambu, the team

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# Introduction

## Intentions

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## History of fuel cells

## Fuel cell as an alternative

## Short industry overview

# 

# Product description

**Oxygen :** It can be found the most in the nature under the form of dioxygen (O2). It is part of the three most plentiful elements in the universe.

**Hydrogen :** The most abundant element in the universe is mostly present in the nature under the form of dihydrogen (H2).

**Water :** The water molecule results of the combination of Oxygen and Hydrogen. Its chemical formula is H2O.

**Electrode :**

**Electrolyte :**

**Reduction :** Chemical reaction during which an element gains electrons.

**Oxydation :** Chemical reaction during which an elements gives electrons away.

In this second part, we will provide the reader with an explanation on the way a fuel cell works. A listing of the different technologies available today will also be made according to their characteristics. These define the application perspectives for the product. Eventually, we will dedicate a whole part to the infrastructure necessary to the production and the distribution of hydrogen.

The aim of the section is to give the reader the keys to understand the results of the market analysis that will be led farther in this report with a product view.

## Introduction

The basic principle underlying in the fuel cell technology is to combine oxygen and hydrogen to produce electricity and water. As well as a battery, it provides electricity out of a chemical reaction. The main difference lies in the fact that a fuel cell uses an external sources of hydrogen and oxygen to keep running. The hydrogen source will later be referred to as the fuel.

The structure of the product is meant to enable such a chemical reaction. It consists of an electrolyte and 2 electrodes. The electrolyte is the element that sets the temperature of operation. The range of temperature then determines what catalyst is to be used in order to accelerate the reaction and what fuel can be used. What with the electrodes, they are of two types: the anode where the fuel is being oxidized, and the cathode where oxygen gets reduced. As a result, the voltage of a fuel cell circuit has an order of magnitude of 1 V. Higher values can be reached by assembling several fuel cells in stacks.

## Technologies

**PEMFC :** Proton Exchange Membrane Fuel Cell.

**AFC :** Alkaline Fuel Cell.

**PAFC :** Phosphoric Acid Fuel Cell.

**SOFC :** Solid Oxide Fuel Cell.

**MCFC :** Molten Carbonate Fuel Cell.

**DMFC :** Direct Methanol Fuel Cell.

**LT :** Low Temperature

**HT :** High Temperature

Polymer :

Research has led today to the development of different fuel cell types. They vary in terms of electrolyte, catalyst, but also in their operating temperature window. Another characteristic that defines them is their tolerance to impurities in the fuel. Indeed, even though hydrogen represents the most abundant chemical element in the universe, it is the most volatile as well. As a consequence, it combines with other elements to form more complex molecules that cannot directly be used as fuels. Eventually, each fuel cell type has its proper power output range, power density, and efficiency, which are determinant in their application perspectives.

In this paragraph, we will give these details about the six most common fuel cell types: PEMFC, AFC, PAFC, SOFC, MCFC, and DMFC[[1]](#footnote-1) [[2]](#footnote-2). They all have already been developed in a commercial context, which testifies of the reliability of their characteristic.

### PEMFC

The Proton Exchange Membrane Fuel Cell is made of with polymer electrolyte. According to the basic component of it, it can operate at low or high temperatures.

Low temperature PEMFC have a water-based electrolyte. They can operate from 40 to 90 °C. This gives them the advantage of handling cold start. However, this temperature range combined with the fact that their electrodes are platinum-based (a noble metal) gives them only little tolerance to impurities in the fuel. Consequently, they have to be run with pure hydrogen. They are appropriate to deliver dynamic supply which gives them all the characteristics for transport uses.

The typical output range for LT PEMFC is between 1 mW and 100 kW and the power density around 0.7 W/cm².



HYGROGEN

EXCESS HYGROGEN

OXYGEN

WATER

HYDROGEN IONS

ELECTRONS

**ELECTROLYTE**

**CATHODE**

**ANODE**

PEMFC can also operate at high temperatures. In such a case, the electrolyte is replaced by a mineral acid-based polymer and the acceptance of impurities in the fuel is improved.

### DMFC

**Alkanline :**

Combined Heat & Power System :

The Direct Methanol Fuel Cell is made of the same kind of membrane polymer electrolyte as the PEMFC. It therefore works at similar temperature. The main difference between the two comes from the catalyst which permits the transformation of methanol into carbon dioxide and hydrogen ions at the anode of the device. Methanol is a cheap fuel and easy to store and transport compared to hydrogen. However, the reaction involved rejects carbon dioxide.



METHANOL

CARBON DIOXIDE

OXYGEN

WATER

HYDROGEN IONS

ELECTRONS

**ELECTROLYTE**

**CATHODE**

**ANODE**

DMFC are usually used for low power applications such as in mobile devices. Its output can indeed only reach 1 kW. The power density of DMFC can go up to 0.25 W/cm².

### AFC

Alkaline Fuel Cell is a name that comes from the fact that the electrolyte consists of an alkaline. The most common one is potassium hydroxide. Thanks to it, the temperature window is large, from 40 to 200°C. In addition to this, the electrodes of the AFC do not have to be made of noble-metals. However, its spread is limited because of the complete intolerance to impurities in hydrogen.



HYGROGEN

WATER

OXYGEN

EXCESS OXYGEN

HYDROXYDE IONS

ELECTRONS

**ELECTROLYTE**

**CATHODE**

**ANODE**

The power output can be expected to be between 1 and 5 kW and the power density between 0.1 and 0.3 W/cm².

### PAFC

The Phosphoric Acid Fuel, as opposed to Alkaline ones, can accept carbon monoxide in their fuel up to 2 %. Their electrolyte is made of phosphoric acid and the electrodes with platinum. The resulting operating temperature is around 200 °C. This type of fuel cell has a low efficiency in itself (55 %), but can be integrated into combined heat and power structures in order to reach an 80 % system ratio.



HYGROGEN

EXCESS HYGROGEN

OXYGEN

WATER

HYDROGEN IONS

ELECTRONS

**ELECTROLYTE**

**CATHODE**

**ANODE**

Its typical output range is higher than the previously mentioned fuel cells with an upper limit of circa 200 kW, which encourages its integration into industrial or commercial heat and power systems. The power density of such cell lies around 0.14 W/cm².

### SOFC

Another HT operating fuel cell is the Solid Oxide Fuel Cell. It can be run between 600 and 950 °C. This is due to the solid ceramic electrolyte of the cell (mostly yttrium stabilized zirconia). It provides a great resistance to impurities, as natural gas or even hydrocarbons can be used as fuels. In addition to this, the heat facilitates chemical reactions, and no catalyst is hence needed. The efficiency of SOFC is higher than the one of PAFC, but it remains interesting to use them as combined heat and power units. This is one of their main applications for domestic use. However, their power output range being very wide, from 1 mW to 5 MW, they can also found an application as small electronic charger. Their power density is between 0.15 and 0.7 W/cm².



HYGROGEN & CARBON MONOXDE

CARBON DIOXIDE & WATER

OXYGEN

EXCESS OXYGEN

OXYGEN IONS

ELECTRONS

**ELECTROLYTE**

**CATHODE**

**ANODE**

### MCFC

CARBON DIOXIDE



HYGROGEN & CARBON MONOXDE

CARBON DIOXIDE & WATER

OXYGEN

EXCESS CARBON DIOXIDE & OXYGEN

CARBONATE IONS

ELECTRONS

**ELECTROLYTE**

**CATHODE**

**ANODE**

Eventually, the Molten Carbonate Fuel Cell can also deliver a high power output (up to 5MW). It consequently is typically used in large heat and power plants. Its temperature window indeed is around 650 °C, which again improves its tolerance in terms of fuel. Its electrolyte consists of a molten carbonate salt, made of components such as lithium, sodium and carbonate potassium. Carbon dioxide has to be injected on the side of the cathode in order to form the carbonate ions that will circulate in it. Once again, its high operating temperature only allows a slow start. It has a low power density, between 0.1 and 0.12 W/cm².

### Conclusion

Among the six types of fuel cells presented above, various output power ranges and operating conditions are available. According to the fuel that is to be used, the output expected (power only or combined power and heat), the profile of the energy demand (stable or not) and the size of the cell, these products already provide a wide range of options, which makes various applications conceivable.

The following table is storing the characteristics mentioned previously in a normalized way.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Type of FC | Electrolyte | Electrodes | Fuel | Operating Temperature (°C) | Output Range | Cell Efficiency (%) | Power Density (W/cm²) | Operating Price ($/W) |
| LT PEMFC | Polymer (Water Based) | Noble Metal | H2 | [40, 90] | 1 mW – 100 kW | [50, 70] | 0.7 | [50, 100] |
| HT PEMFC | Polymer (Mineral Acid Based) | Noble Metal | H2 (/CO) | [125, 220] | 100 W – 10 kW | [50, 70] | 0.7 | [50, 100] |
| DMFC | Polymer | Noble Metal | Methanol | [60, 130] | 1 mW – 1 kW | [20, 30] | 0.25 | 125 |
| AFC | KOH | Noble/ Non-noble Metal | H2 | [40, 200] | 1 kW – 5 kW | [60, 70] | [0.1, 0.3] |  |
| PAFC | Phosphoric Acid | Noble Metal | H2 (/CO) | 200 | 25 kW – 200 kW | 55 | 0.14 | [4, 4,5] |
| SOFC | Solid Oxide | Non-noble Metal | CH4, H2, CO | [600, 950] | 1 mW – 5 MW | [60, 65] | [0.15, 0.7] |  |
| MCFC | Molten Carbonate | Non-noble Metal | CH4, H2, CO | 650 | 50 kW – 5 MW | 55 | [0.1, 0.12] |  |

## Applications

The second paragraph of this part was setting the emphasis on the characteristics of six specific fuel cell products. In doing so, it followed the conventions already used by other informative organisms such as FuelCellToday which defines itself as *the leading authority on fuel cells*. This paragraph being dedicated to the different applications of fuel cells, it will remain consistent with these norms in order to help them become references for the whole fuel cell industry. They differentiate three different range of applications according to the use that is made of the fuel cell corresponding to the following contexts[[3]](#footnote-3) [[4]](#footnote-4):

* **Transport**: Units providing propulsive power to a vehicle.
* **Stationary**: Units providing power (and sometimes heat) but are not meant to be mobile.
* **Portable**: Units integrating systems designed to be moved.

### Transport

“Units providing propulsive power to a vehicle.”

This definition matches with the most advertised fuel cell application: hydrogen cars. However, fuel cell power can also be used for other vehicles. As an example, boats or even submarines can work with hydrogen. In addition to reduce polluting gas emission, it presents the advantage of being silent.

Some light aircrafts are also fuel cell powered, with companies such as Boeing showing their interest for the technology. Other applications in the professional world are light-duty vehicles, forklifts or trucks.

### Stationary

“Units providing power (and sometimes heat) but are not meant to be mobile.”

These applications represent a particularly high ratio in the hydrogen power. The main reason is that they include large power plants. Those can be built in remote places where electricity is hard to “ship” in order to improve the reliability for users by implementing off-line supplies. As an examples, they might be useful for some factories or villages that are hardly reachable. The fact that a fuel cell can work off-line makes it have an advantage towards Uninterruptible Power Systems (UPS).

A stationary application can also be of smaller scale, for simple residential use. It corresponds to the context in which a power and heat combination can be fully exploited and is all the more advantageous for the user. Those units are spreading in Asian countries such as Japan and South Korea thanks to government incentives.

### Portable

“Units integrating systems designed to be moved.”

Portable units are designed to charge or be part of portable devices. Auxiliary power units (APU) that can be used to charge electronic devices are therefore mart of them. They can also integrate portable systems such as a torch, a music player, or even a personal computer. Thereupon they represent a field of investigation for military laboratories. Indeed, a fuel cell powered device discharges more slowly recharges more quickly than one running a conventional battery, which increases reliability. In addition to this, it operates silently weights little, and can work off-grid.

### Conclusion

|  |  |  |  |
| --- | --- | --- | --- |
| Category | Power Range | FC Type | Applications |
| Transport | 1 kW to 100 kW | PEMFC  AFC | Personal Vehicles (cars; motorcycles; scooters)  Transportation (planes; trains; boats or ferries)  Military use (plane; submarine)  Support to other power supplies |
| Stationary | 0.5 kW to 5 MW | PEMFC  SOFC  MCFC  PAFC  AFC | Residential supply (CHP or simply power)  UPS  Primary power units (large or small prime power plants) |
| Portable | 5 W to 500 kW | PEMFC  DMFC | APU  Personal electric devices (small or large)  Military use |

## Infrastructure

As explained previously, a fuel cell is a product able to produce energy out of a chemical reaction that minimizes polluting emissions compared to traditional gas power engines. This reaction nevertheless is not completely natural in the way that it has to be triggered by some specific conditions such as the temperature, the electrolyse structure, and eventually, the supply in a fuel: hydrogen. Depending on the model, hydrogen can be of more or less pure constitution, but the air we breathe does not have a high enough concentration in it to consist of a fuel. As a consequence, the gas used needs to be processed and stored before it is distributed to the operating units.

These steps are preceding the fuel cell exploitation. As a consequence, the fuel cell and the hydrogen industries are profoundly correlated by justifying each other. Indeed they could not survive separately. This paragraph provides a short introduction to the hydrogen distribution infrastructure, which is essential to be thought of for fuel cells to be adopted by the general public. In a second part, it will mention three different hydrogen production modes and their results in terms of expenses.

### Distribution facilities

Hydrogen is the lightest chemical element on earth. In such a normal environment, it has the state of a gas. It therefore is volatile and its volumetric mass is very low. As a consequence, in one given unit of volume, there is less hydrogen than there would be of any other element (8 MJ/L against 32 MJ/L for gasoline). And less hydrogen implies less fuel. Hydrogen therefore is a costly fuel to ship.

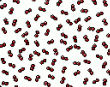
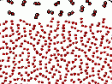
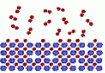
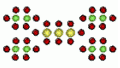
#### Delivery

Today, there are three different ways of transporting hydrogen, in pipelines, or in containers. The first option is particularly expensive in the short term because it requires a complete network and infrastructure to be built in order to adapt to users’ needs. It is the best way to transport large quantities of fuel. The second option is adapted to smaller needs, by storing hydrogen into closed containers that can then be shipped by conventional methods (truck, train or boat carriage). Again, there exist two possibilities to do this. The first one is to compress hydrogen and store it into high pressure tubes. The other one is to liquefy the fuel in order to put it into liquid insulated tankers. However, this option remains costly because it requires to bring the gas at its liquefaction temperature, -253 °C and then to use adapted refrigerating devices. The advantage of it is that is holds more fuel per volume unit.

Eventually, as it is the properties of hydrogen that make it hard to transport, it is also possible to mix it with other elements in order to ship it as ethanol or ammoniac for example. However, the drawback of this method is that a dehydration process has to be carried before use. This last method is referred to as carrier and is still at a development stage.

#### Hydrogen storage

With regards to the previously addressed problems related to hydrogen delivery, storage is also a delicate task, especially when it comes to achieve this in a moving vehicle. Several solutions have been thought of:

* Compressed gas storage: Hydrogen is subject to in 5,000 to 10,000 psi in a tank
* 
* Cryogenic liquid storage: The temperature of the tanks has to be maintained under 253 °C.
* 
* Material-based storage: Hydrogen then infiltrates into the structure of solid or liquid materials and can be stored in conditions of temperature and pressure that are closer to normal.
* 
* Chemical storage: Hydrogen is then stored by the medium of the reaction between hydrogen containing components and water. 

### Hydrogen production

Fuel cell is a promising zero-emission concept. Nevertheless, because hydrogen has to be produced, this statement may not always be true. Indeed, it is in addition to delivery and storage a costly process in terms of energy. Whether hydrogen power is green or not then depends on how it is produced. Today, the sources are natural gas, electricity, solar energy and biomass. The second one is all the more interesting with the fact that it can be collected from natural energy such as wind, solar, or biomass power. Solar and biomass energy however can be involved in direct hydrogen production, which differentiates them from conventional electric sources.

In this paragraph, the emphasis will lie on two specific hydrogen production modes, gas reforming and electrolysis. The first one is already well adopted in the hydrogen industry. As an example, it is responsible for 95% of the hydrogen production in the United States[[5]](#footnote-5). The second works thanks to electricity. It therefore is adaptable to various sources of power and can easily integrate existing electrical grids.

#### Gas Reforming

It is today the main hydrogen production mode because the process is mature and can respond to large needs of the users. It relies on chemical reactions involving methane (CH4):

* Partial Oxidation
* Steam Reforming

Gas reforming is criticized because of its greenhouse gas emissions. It nevertheless remains lower than what results of the use of gasoline power engines.

#### Electrolysis

The idea behind the electrolysis is to reverse the fuel cell process, i.e.: use electricity to split water into oxygen and hydrogen.

The technology required therefore is similar to the one of fuel cells, proton exchange membrane, alkaline and solid oxide electrolysers being preferred in practice.

Electrolysis units can easily integrate power systems. They can be of various size just as well as fuel cell and hence can be used in residential or industrial contexts. This is particularly interesting because it raises the question of centralized or distributed production. Indeed, the previous paragraph about Distribution Facilities mentioned some of the difficulties storage and delivery have to overpass. Decentralizing the production of hydrogen could help reduce delivery-related problems. What with storage, its resort could be minimized with dynamic production units, available thanks to the PEM technology (cf. 2.2.1. PEMFC).

# Future perspectives

## Opportunities

## Limitations and risks

## Forecast

# Conclusion

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