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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

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# 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.

***The basic principle is to combine oxygen and hydrogen to produce electricity.***

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.

### 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

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

**Alkanline :**

Combined Heat & Power System :

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.

### Summary

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 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

### Categorisation choices

### Transport

### Portable

### Stationary

## Infrastructure

### Distribution facilities

#### Delivery

#### Hydrogen storage

### Hydrogen production

#### Introduction

#### Electrolysis

#### Steam reforming

#### Summary

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