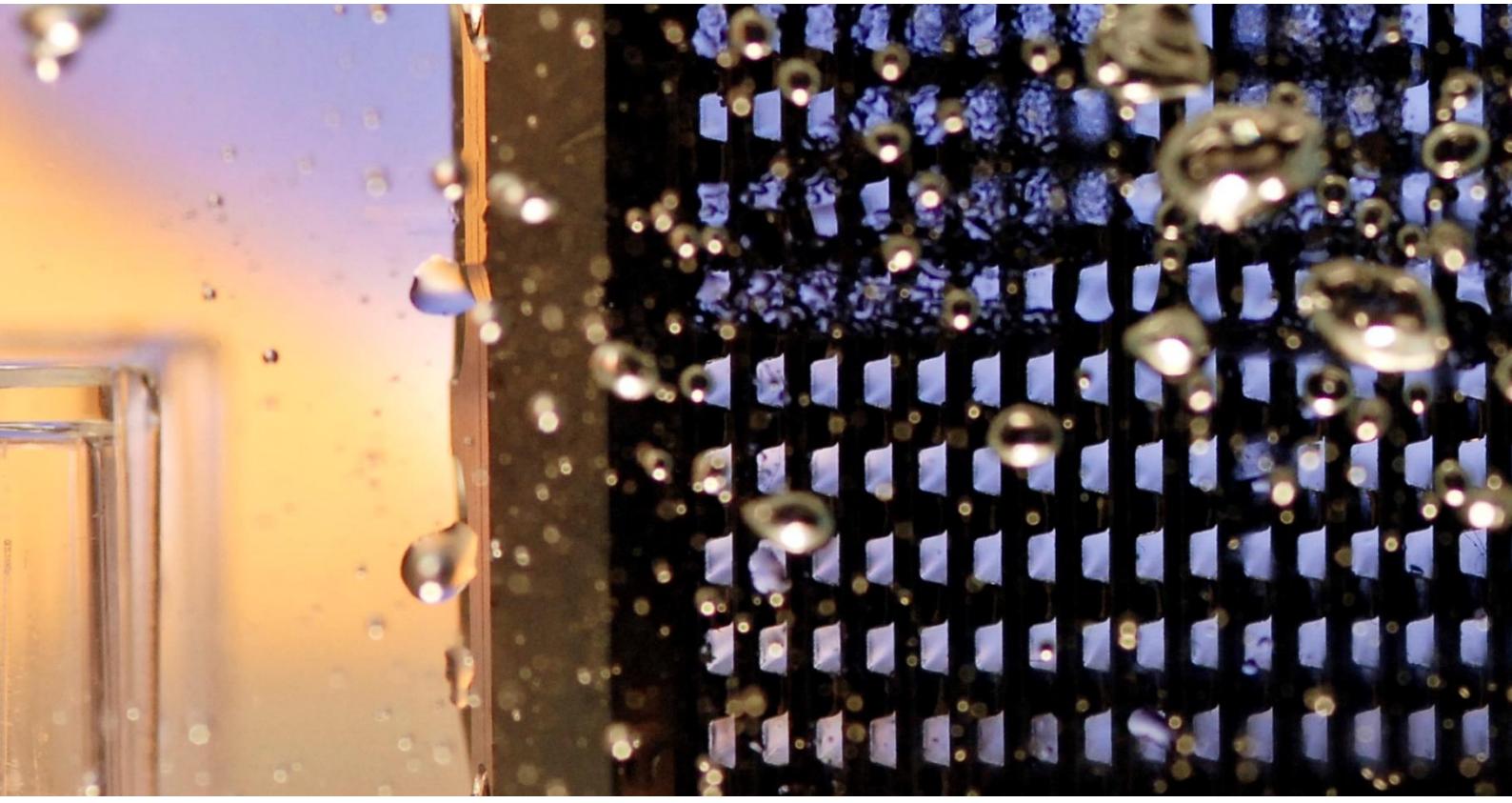


# FUEL CELL INDUSTRY ANALYSIS REPORT

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2015











## BAMBU, THE TEAM



**Benoit Serot**

**Product Description**

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**Market Perspective**

Hailing from Thailand, Pongsathorn Tiranun is an enthusiastic candidate of the 2 years MSE program of Industrial Engineering Department, Tsinghua University starting from the year 2014. He already took a keen interest in 'Fuel Cell' since the time he was doing his Electrical Engineering Degree earlier, he takes this IAR as a good opportunity to research more on fuel cells.



**Konstantin Neumann**

**Introduction, Policy Framework**

At the moment Konstantin Neumann is taking part in a two semester exchange program at Tsinghua University. After finishing his B. Eng. he started his M. Sc. in Industrial Engineering at TU Darmstadt in Germany.

### Acknowledgement

This Report is the result of a project during the class Global Manufacturing Strategy at Tsinghua University, Beijing China in spring term 2015. Therefore we want to thank Professor Benjamin Koo for his guidance in this project. Furthermore we want to thank all collaborators who gave advices either directly in the classroom or through the collaboration tool GitHub.





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## Part 1

### 1. INTRODUCTION

Visit the webpage to read, download or participate via GitHub



<http://bambugms.github.io/Industry-Analysis-Report/>

#### 1.1 Intentions

As shown in the logic model the report aims at informing about the state of the fuel cell industry. The report is targeting readers who want to learn more about the technology, but especially it is targeting global policy institutions. This is a large group of people, and can include those who are in contact with fuel cells for the first time as well as those who already have a profound expertise in this field. Therefore the report gives a short introduction of history and also explains the different types and working mechanisms of fuel cells but also shows threads and chances by linking the gathered knowledge with new topics like block chain.

The underlying information for this report was gathered by a broad literature and internet research. Knowledge from previous Industry Reports as well as research papers, newspapers, press releases and governmental authorities were used to collect and show a broad spectrum of facts.



# Introduction

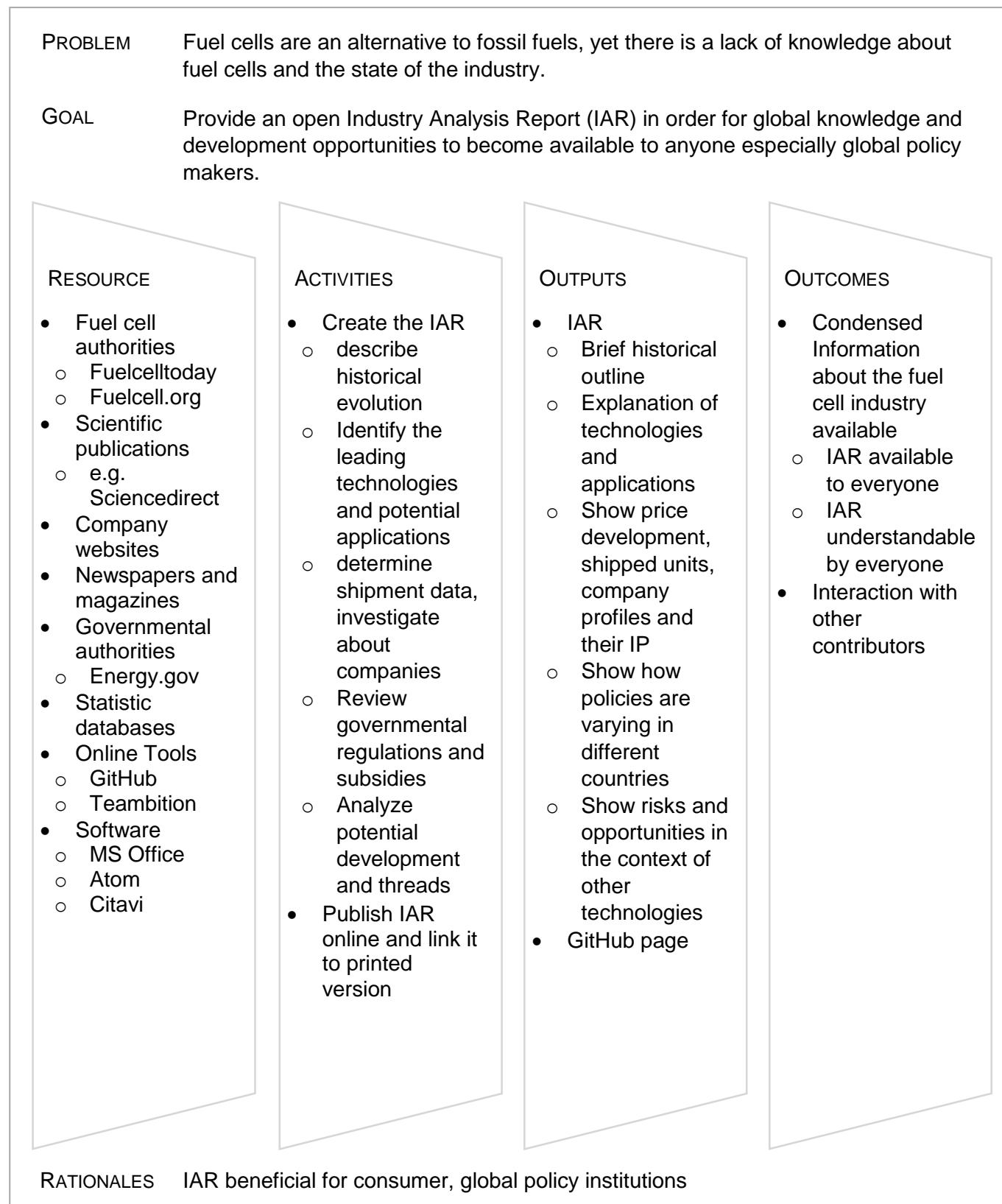


Figure 1: Logic Model





## 1.2 History of Fuel Cells

The beginnings of fuel cells reach back to 1838. At this time William Robert Grove worked on what was later called a fuel cell. Grove, who is credited with the invention of the fuel cell, used platinum together with hydrogen and oxygen to create a constant current. Several scientists including Christian Schönbein tried to show how exactly fuel cells are working. Although great discussions and large efforts, it took several years to explain the complete system. In the early years no practical device emerged. In the early 20<sup>th</sup> century the first molten carbonate fuel cell was built by Emil Baur. Further investigations were made by Francis Thomas Bacon who developed first fuel cells with a practical use. His work was promising enough to be licensed by Pratt & Whitney for the Apollo missions. From the 1960s the history is becoming more branched as the different technologies, developed independently.<sup>1</sup>

**PEMFC:** Proton Exchange Membrane Fuel Cell

**FCEV:** Fuel Cell Electric Vehicle

**PAFC:** Phosphoric Acid Fuel Cells

At General Electric Willard Thomas Grubb and Leonard Niedrach invented the first PEMFC which was later refined and used by NASA for the Gemini Mission in the 1960s. International fuel cells developed other systems for the Apollo missions. Also in the Soviet Union there was research in this field of technology, mainly for military purposes, later also for space missions. Driven by the oil crisis in the 1970s nearly all major car manufacturer had developed a FCEV. Another effect of the oil shortage was progress in the development of PAFC which are allowing to reach higher power outputs. Although high growth rates were predicted in the 1980s, there was just a slow adaption of the new technology. In the 1990s the focus was laid on small stationary applications.<sup>2</sup> Also the first battery of methanol was developed as a portable device. Another promising field is the public transport, especially buses, where first models where available around 2000. First applications for end users included auxiliary power units, e.g. for caravans. In the 2007 the first hydrogen car was presented, the Honda FCX Clarity, which was available for customers since 2008 for leasing. Since then many other models from different manufacturers are available. Residential fuel cells as well as micro devices, like phone chargers became more popular and available during the last years. Therefore the industry is changing from mainly R&D focused to commercializing of products.<sup>3 4</sup> The strongest development on the market is

<sup>1</sup> "Fuel Cells: Discovering the Science," accessed May 6, 2015, <http://americanhistory.si.edu/fuelcells/origins/origins.htm>

<sup>2</sup> "Fuel Cell History - Fuel Cell Today," accessed May 6, 2015, <http://www.fuelcelltoday.com/history>

<sup>3</sup> ibid.

<sup>4</sup> J. M. Andújar and F. Segura, "Fuel cells: History and updating. A walk along two centuries," *Renewable and Sustainable Energy Reviews* 13, no. 9 (2009), doi:10.1016/j.rser.2009.03.015, <http://www.sciencedirect.com/science/article/pii/S1364032109001336>



happening since the 1990s. The market now includes large companies from energy equipment, chemicals and materials sectors and new start-up firms.<sup>5</sup>

## 1.3 Fuel Cell as an Alternative?

Fuel cells can be used as a substitute as well as a complementing technology. The applications can be divided into the three categories stationary, transport and portable (cf. **2.3 APPLICATIONS**). The area of stationary fuel cells includes systems like plants or one household systems. In this area it is possible to complement for example regenerative energies with fuel cells to store the energy during the time it is not needed and by doing so building a smart network. As it is a clean and very fast reacting technology it can be also used in cities, for example instead of gas plants. Portable systems in different scales can be used for example as a supplement for diesel generator to support of grid systems with energy. Micro systems compete with traditional batteries. The transport sector is probably the most competitive area as fuel cells are in direct competition with traditional fuel as well as electrical energy powered cars. Further discussion about the possible future discussion will be hold in **PART 5**.

## 1.4 Quick Industry Overview

As pointed out in the history section above the fuel cell market for customers is quite young and therefore still shaping itself rapidly. On the market there are several big players as well as niche producers. In general big stationary systems (e.g. plants) are built by bigger companies whereas the portable systems are mostly distributed by smaller companies. The fuel cell market is strongly varying according to regional factors, which was the reason to divide the analysis of the market in **PART 3** in three main regions.

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<sup>5</sup> James E. Brown, Chris N. Hendry, and Paul Harborne, "An emerging market in fuel cells? Residential combined heat and power in four countries," *Energy Policy* 35, no. 4 (2007), doi:10.1016/j.enpol.2006.07.002, <http://www.sciencedirect.com/science/article/pii/S0301421506002813>





## Part 2

**Chemical representations:**

- Oxygen (O)
- Hydrogen (H)
- Water ( $H_2O$ )

**Electrode:** An electrical conductor used to make contact with a non-metallic part of a circuit. (Wikipedia contributors 2015a)

**Electrolyte:** A substance that ionizes when dissolved in suitable solvents such as water. (Wikipedia contributors 2015b)

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

## 2. PRODUCT DESCRIPTION

In this second part, the reader will be provided 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. In the end, one paragraph will be dedicated 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.

### 2.1 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

**A fuel cell combines oxygen and hydrogen to produce electricity and water.**





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.

**Oxidation:**  
Chemical reaction during which an element gives electrons away.

## 2.2 Technologies

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.<sup>6</sup> <sup>7</sup> They all have already been developed in a commercial context, which testifies of the reliability of their characteristic.

### 2.2.1 PEMFC

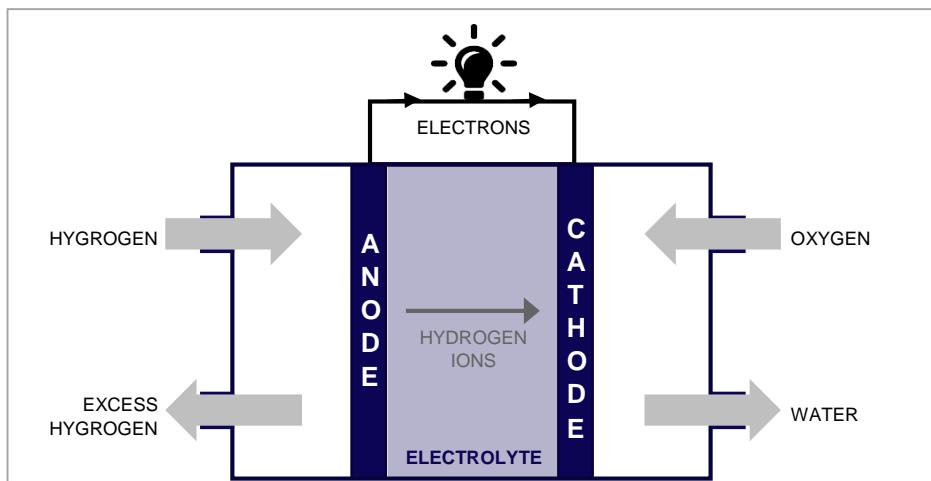


Figure 2: Schematic representation of the structure of a PEMFC

### Fuel Cell Abbreviations:

- 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:** A polymer is a kind of chemical molecule. It is a large molecule in which subgroups of elements are repeated sequentially. The basic subgroup defines the type of polymer.

<sup>6</sup> nedstack, "Fuel Cell Types," nedstack, accessed April 14, 2015, <http://www.nedstack.com/technology/fuel-cell-types>

<sup>7</sup> FuelCellToday, "Technologies," FuelCellToday, accessed April 14, 2015, <http://www.fuelcelltoday.com/technologies>





The proton exchange membrane fuel cell is made of 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.cm<sup>-2</sup>.

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.

### 2.2.2 DMFC

The direct methanol fuel cell is made of the same kind of membrane polymer electrolyte as the PEMFC (for the schematic representation cf. [2.2.1 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.

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.cm<sup>-2</sup>.



### 2.2.3 AFC

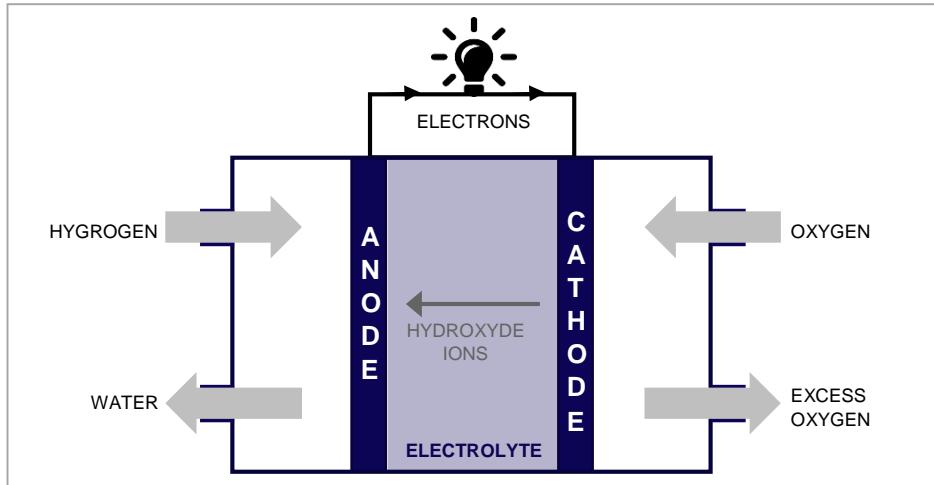


Figure 3: Schematic representation of the structure of an AFC

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.

The power output can be expected to be between 1 and 5 kW and the power density between 0.1 and 0.3 W.cm<sup>-2</sup>.

**Alkali:** A basic, ionic salt of an alkali metal or alkaline earth metal chemical element. (Wikipedia 2015a)

**Alkaline elements:** Elements part of the second of the periodic table of elements.

### 2.2.4 PAFC

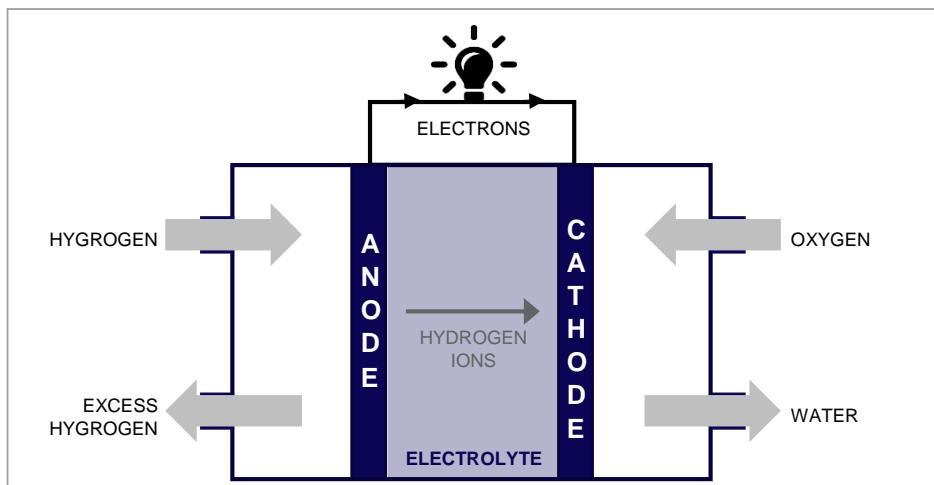


Figure 4: Schematic representation of the structure of a PAFC

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

**Combined Heat & Power System (CPH):** System that uses a heat engine or power station to generate electricity and useful heat at the same time. (Wikipedia 2015b)





can be integrated into combined heat and power structures in order to reach an 80 % system ratio.

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  $0.14 \text{ W.cm}^{-2}$ .

### 2.2.5 SOFC

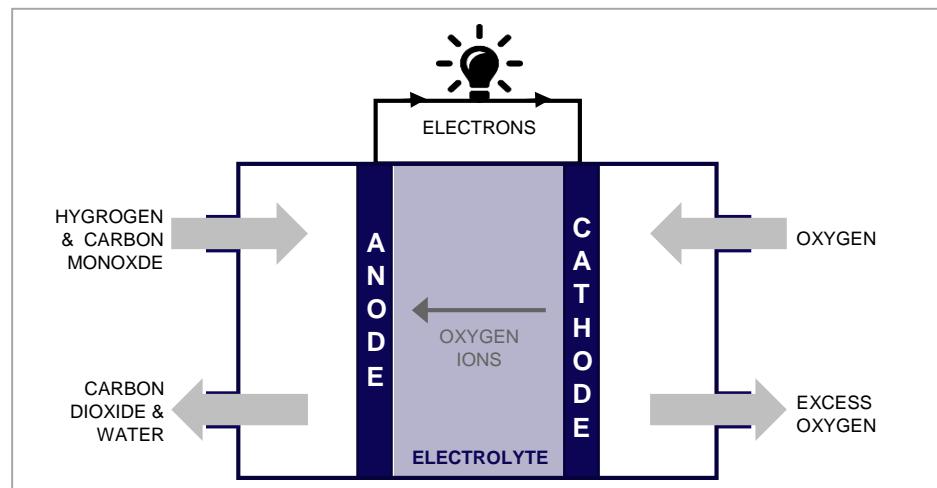


Figure 5: Schematic representation of the structure of a SOFC

**Yttrium-stabilized zirconia:** YSZ is a ceramic combining oxides to stabilize its structure.

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  $0.7 \text{ W.cm}^{-2}$ .



### 2.2.6 MCFC

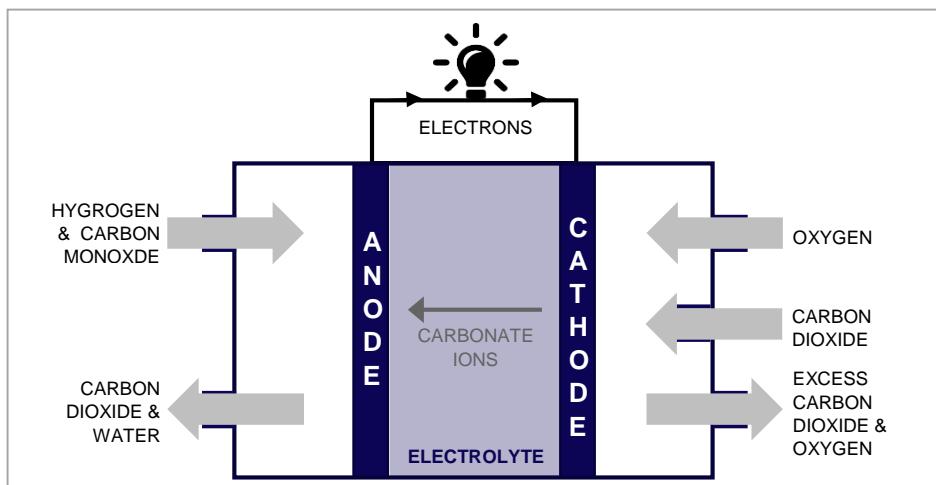


Figure 6: Schematic representation of the structure of an MCFC

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.cm<sup>-2</sup>.

In order to understand what fuel cell technology is through an explanatory video and to have an introduction about the following parts, you can visit the U.S. Department of Energy's YouTube account and watch:

**Energy 101: Fuel Cell Technology**



<https://www.youtube.com/watch?v=QGXei47c0>

### 2.2.7 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.

Table 1 on the next page is storing the characteristics mentioned previously in a normalized way.





## Product Description

Table 1: Summary of the different fuel cells and their operating conditions

Type of FC	Electrolyte	Fuel	Operating Temp. (°C)	Output Range	Cell Efficiency (%)	Power Density (W.cm <sup>-2</sup> )
LT PEMFC	Polymer (Water Base)	H <sub>2</sub>	[40, 90]	1 mW – 100 kW	[50, 70]	0.7
HT PEMFC	Polymer (Mineral Acid Base)	H <sub>2</sub> (/CO)	[125, 220]	100 W – 10 kW	[50, 70]	0.7
DMFC	Polymer	Methanol	[60, 130]	1 mW – 1 kW	[20, 30]	0.25
AFC	KOH	H <sub>2</sub>	[40, 200]	1 kW – 5 kW	[60, 70]	[0.1, 0.3]
PAFC	Phosphoric Acid	H <sub>2</sub> (/CO)	200	25 kW – 200 kW	55	0.14
SOFC	Solid Oxide	CH <sub>4</sub> , H <sub>2</sub> , CO	[600, 950]	1 mW – 5 MW	[60, 65]	[0.15, 0.7]
MCFC	Molten Carbonate	CH <sub>4</sub> , H <sub>2</sub> , CO	650	50 kW – 5 MW	55	[0.1, 0.12]

Electrodes:  Noble metal     Noble or non-noble metal     Non-noble metal

## 2.3 Applications

The second paragraph of this part is setting the emphasis on the characteristics of six specific fuel cell products. In doing so, it followed the conventions already used by other informative organs 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:<sup>8 9</sup>

- **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.

### 2.3.1 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

<sup>8</sup> FuelCellToday, “Applications,” FuelCellToday, accessed April 14, 2015, <http://www.fuelcelltoday.com/applications>

<sup>9</sup> David Hart et al., “The Fuel Cell Industry Review 2014” The Fuel Cell Industry Review 1 (E4tech, 2014) (unpublished manuscript, April 1, 2015), <http://www.fuelcells.org/pdfs/TheFuelCellIndustryReview2014.pdf>

## Product Description



addition to reduce polluting gas emission, it presents the advantage of being silent.



Figure 7: A hydrogen powered bus in London

Boeing's project to build a completely hydrogen powered unmanned aircraft is advertised on YouTube:

**Boeing's fuel cell technology is making sustainable flight closer to reality**



<https://www.youtube.com/watch?v=SrTKT7Opcpl>

### 2.3.2 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



Figure 8: SOFC installation by Bloom Energy at a NASA centre



### UPS Uninterruptible Power System

In UPS, fuel cells are often installed as backup supply units that would be able to keep running and provide electricity even in case of a failure from the grid. As an example, it can be used for servers or other IT products.

If you are curious about how to charge your phone with hydrogen, you can visit this YouTube page:

Fuel-cell phone charger makes its own electricity



<https://www.youtube.com/watch?v=EvruUjMa-AEo>

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.

### 2.3.3 Portable

“Units integrating systems designed to be moved.”



Figure 9: A fuel cell charger designed by Brunton, using small hydrogen reservoirs to refuel.

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 part 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 and recharges more quickly than one running a conventional battery, which increases reliability. In addition to this, it operates silently, weighs little, and can work off-grid.



## 2.3.4 Conclusion

Table 2: Summary of the different applications for fuel cells

Category	Power Range	FC Type	Applications
Transport	1 kW to 100 kW	<ul style="list-style-type: none"> <li>• PEMFC</li> <li>• AFC</li> </ul>	<ul style="list-style-type: none"> <li>• Personal Vehicles (cars; motorcycles; scooters)</li> <li>• Transportation (planes; trains; boats or ferries)</li> <li>• Military use (plane; submarine)</li> <li>• Support to other power supplies</li> </ul>
Stationary	0.5 kW to 5 MW	<ul style="list-style-type: none"> <li>• PEMFC</li> <li>• SOFC</li> <li>• MCFC</li> <li>• PAFC</li> <li>• AFC</li> </ul>	<ul style="list-style-type: none"> <li>• Residential supply (CHP or simply power)</li> <li>• UPS</li> <li>• Primary power units (large or small prime power plants)</li> </ul>
Portable	5 W to 500 kW	<ul style="list-style-type: none"> <li>• PEMFC</li> <li>• DMFC</li> </ul>	<ul style="list-style-type: none"> <li>• APU</li> <li>• Personal electric devices (small or large)</li> <li>• Military use</li> </ul>

## 2.4 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 electrolysis 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 address two different hydrogen production modes and their implementation conditions.

### 2.4.1 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 ( $8 \text{ MJ.L}^{-1}$  against  $32 \text{ MJ.L}^{-1}$  for oxygen).

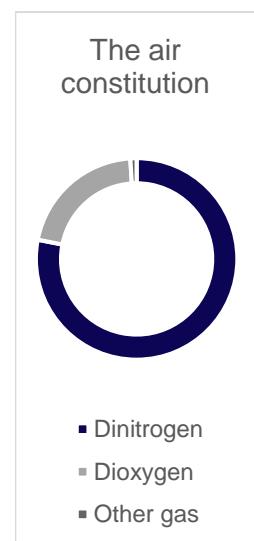


Figure 10 : The Air constitution

The air present on the surface of Earth is made of 78,08 % of dinitrogen, 20,95 % of dioxygen, and 1 % of other gas. Hydrogen represents only a 0,000072 % fraction of it.





MJ.L<sup>-1</sup> for gasoline). And less hydrogen implies less fuel. Hydrogen therefore is a costly fuel to ship.



Figure 11: A hydrogen "plug" on a car

### Hydrogen Transportation:

- Pipeline



- Conventional transportation modes



#### 2.4.2 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 tanks. 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 it 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.



Figure 12: Hydrogen high pressure tubes designed by Shijiazhuang Enric Gas Equipment Co.

### 2.4.2.1 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 implemented:



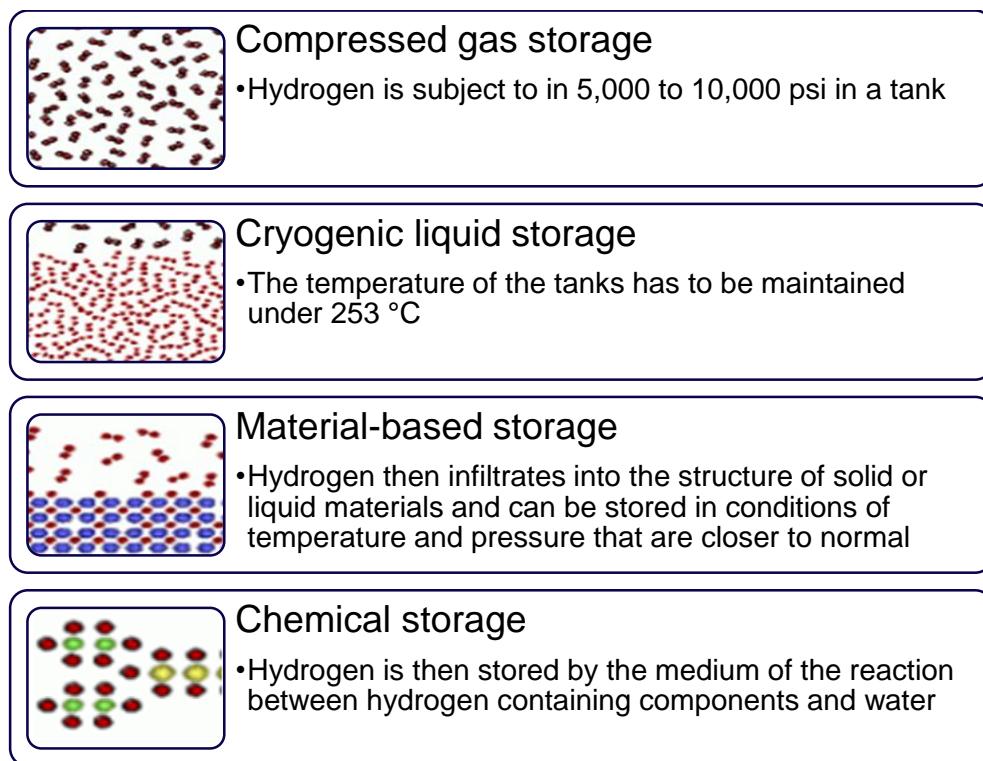


Figure 13 : Illustration of the different storage modes for Hydrogen

#### 2.4.3 Hydrogen Production

Fuel cell is a promising zero-emission concept. Nevertheless, because 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.<sup>10</sup> The second works thanks to electricity. It therefore is adaptable to various sources of power and can easily integrate existing electrical grids.

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<sup>10</sup> EERE, "HYDROGEN PRODUCTION: NATURAL GAS REFORMING," EERE, <http://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming>



### 2.4.3.1 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 ( $\text{CH}_4$ ):

- 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.

### 2.4.3.2 Electrolysis

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

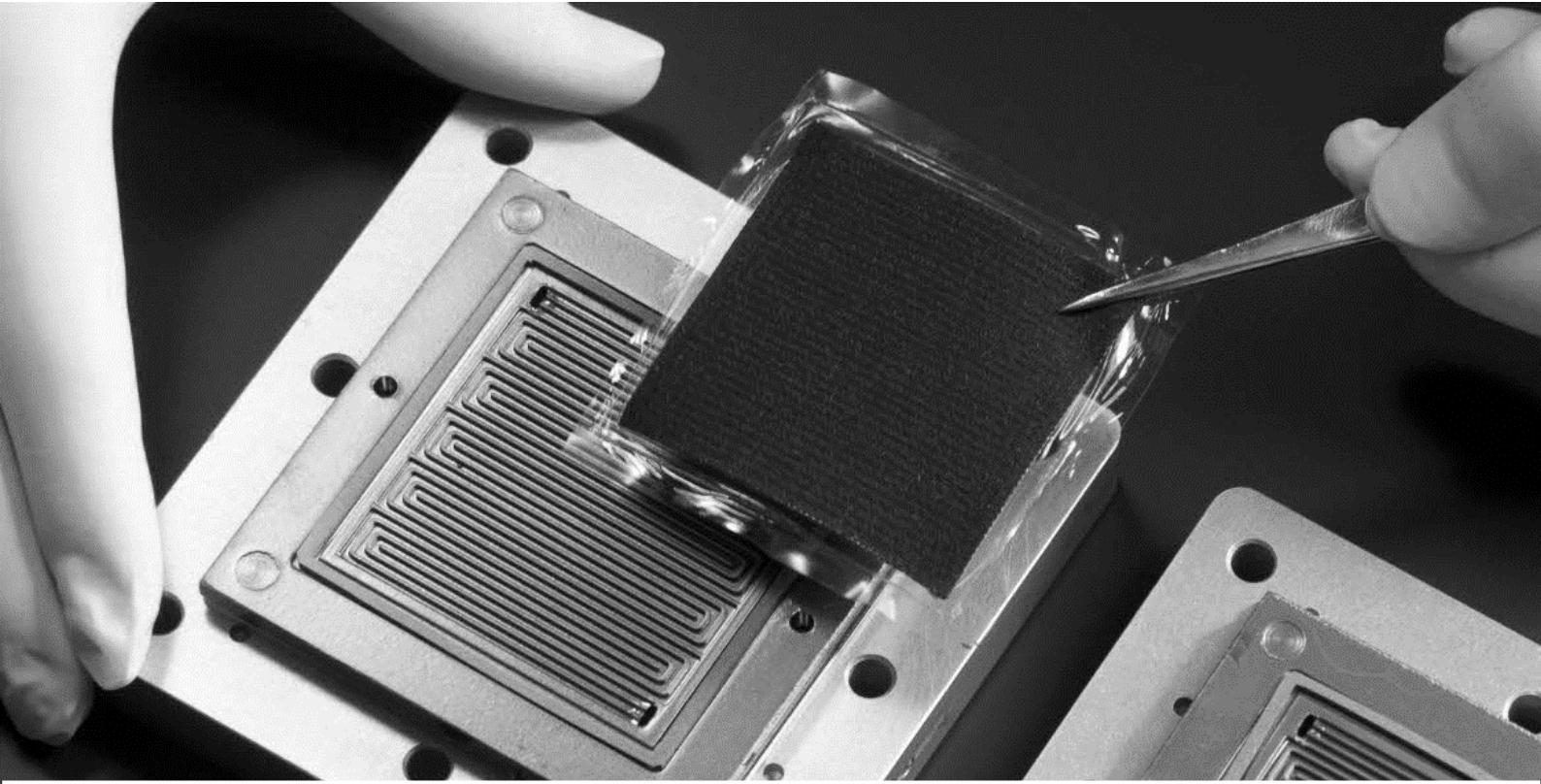
The technology required therefore is similar to the one of fuel cells, proton exchange membrane, alkaline and solid oxide electrolysers being preferred in practice.

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](#)).



Hydrogen production plant in Rotterdam





## Part 3

### 3. MARKET PERSPECTIVE

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#### 3.1 Introduction

In general, the trends for the fuel cell industry have been positively increasing for a few years, manufacturing costs continued to decline especially for the transportation applications while at the same time hydrogen infrastructures are continually being deployed in many countries to support the new FCEVs which be launched into to market in the near future.

Like its applications, the markets for fuel cells can be broadly divided into 3 subcategories as previously mentioned in **PART 2**:

1. **Stationary power:** applications where the fuel cells are working at a stationary or fixed location mostly for primary power, CHP or backup power sources;
2. **Transportation power:** applications where fuel cells are used in transportation vehicles like passenger cars, buses and other FCEVs ;
3. **Portable power:** applications where fuel cells are in portable electronic devices like MP3 players, laptops, and mobile phones.

**FCEV:** Fuel Cell Electric Vehicle.

**CHP:** Combined Heat and Power





### 3.2 Intellectual Property

The data in this section is referring to the Clean Energy Patent Growth Index report which keeps tracks of clean energy patents and covers many sectors involved, including fuel cells.<sup>11</sup>

In brief, automakers took most control. Toyota Corporation has once again been receiving most fuel cell patents since it did so in 2012, now with 101 in total. While General Motors Corporation with 89 patents comes as the second highest. Samsung and Honda are in the third and fourth places respectively. The approximate number of patent entities granted is 300. The figures below show the distribution between the top ten assignees and how the patents are distributed geographically.

#### Did You Know?

Most of the patents awarded to the top three assignees in the recent years cover the innovations of fuel cells existing in the automotive industry. Also the R&D department of General Motors Corps invested less in FC technology as a result form the American Recovery and Reinvestment Act.

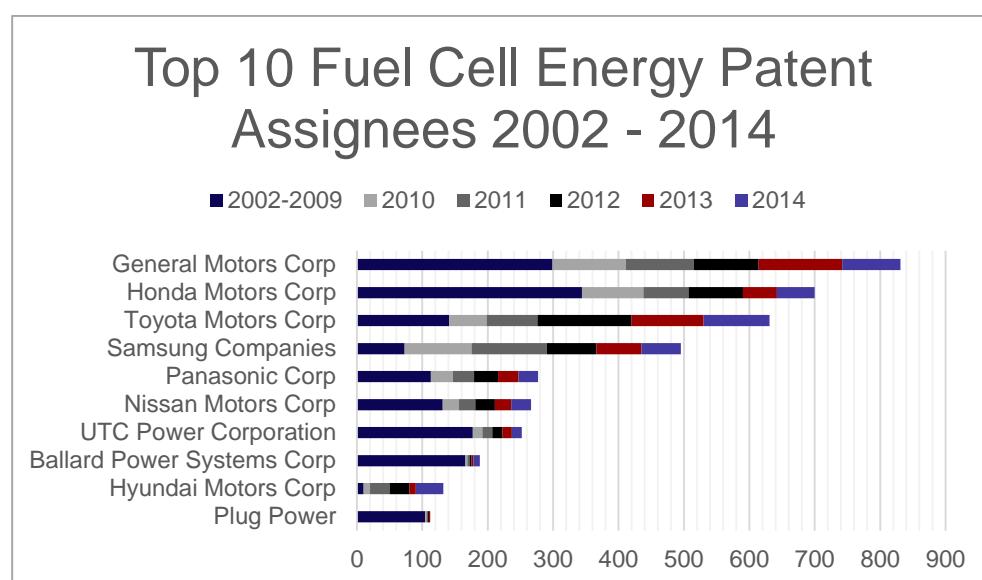


Figure 14 : Top 10 Fuel Cell Energy Patent Assignees 2002 - 2014<sup>12</sup>

<sup>11</sup> "Clean Energy Patent Growth Index: CLEAN ENERGY PATENT GROWTH INDEX 2014 Year in Review," accessed May 14, 2015, <http://www.cepii.com/2015/04/2014-year-end.html>

<sup>12</sup> Ibid.





### What makes Japan the biggest market in terms of megawatt shipped?

Most stationary cells are shipped to Japanese market where the government encourages the usage of CHP, Japan is also the biggest customer of stationary fuel cells. Read more about the policy in Japan in **PART 4.**

### Why are portable applications invisible in the Graph?

For fuel cell products belonging to the portable category, the power usage by the application is dramatically lower than the other two categories. Hence, the portable application power is seemingly invisible in the graph.

Fuel Cell Patents Geographic Distribution

- Japan
- Korea
- Germany
- Canada
- Taiwan
- France
- Great Britain
- Others
- United States

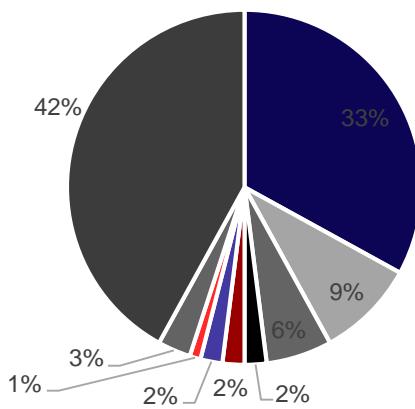


Figure 15 : Fuel Cell Patents Geographic Distribution<sup>13</sup>

### 3.3 Quantity of Fuel Cells Shipped

A way to categorize the fuel cell shipments is to divide them according to their corresponding applications: stationary power, transportation power and portable power. Transportation power used to be the majority of the shipped system in 2008. However, with the introduction of the CHP units in the market, residential units of CHP were continuously deployed in Japan. And in the year 2013 alone, more than 26,000 units have been shipped to Japan. The shipments of transportation and portable FC have been quite stable and experts forecast that it will remain so at least for a couple of years.

Fuel Cell Megawatts shipped by Applications between 2008 and 2013

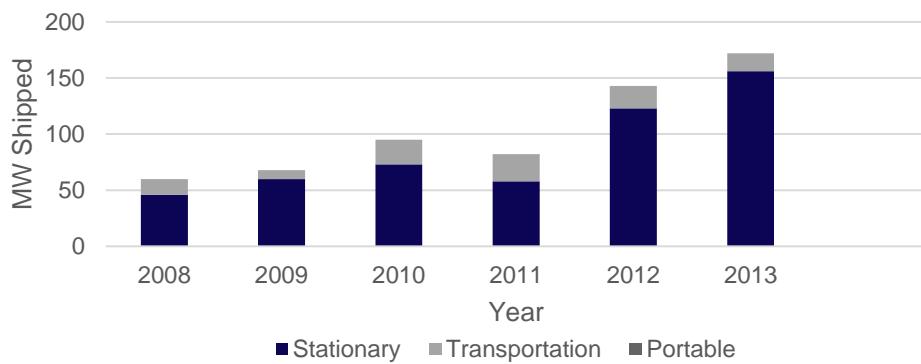


Figure 16 : Fuel Cell MWs shipped by Applications (2008-2013)<sup>14</sup>

<sup>13</sup> Ibid.

<sup>14</sup> Sandra Curtin and Jennifer Gangi, "2013 Fuel Cell Technologies Market Report," news release, Nov. 2014, accessed May 20, 2015, [http://energy.gov/sites/prod/files/2014/11/f19/fcto\\_2013\\_market\\_report.pdf](http://energy.gov/sites/prod/files/2014/11/f19/fcto_2013_market_report.pdf)





From the figure above, we may notice that portable shipments are not visible. This is mainly because the power consumed by portable type fuel cell is normally negligible when compared to that of the other two categories. Majority of stationary FC displayed in this graph is contributed from CHP units, telecommunication backup power generation, off-grid power supplier for CCTVs and energy sources for other stationary military devices.

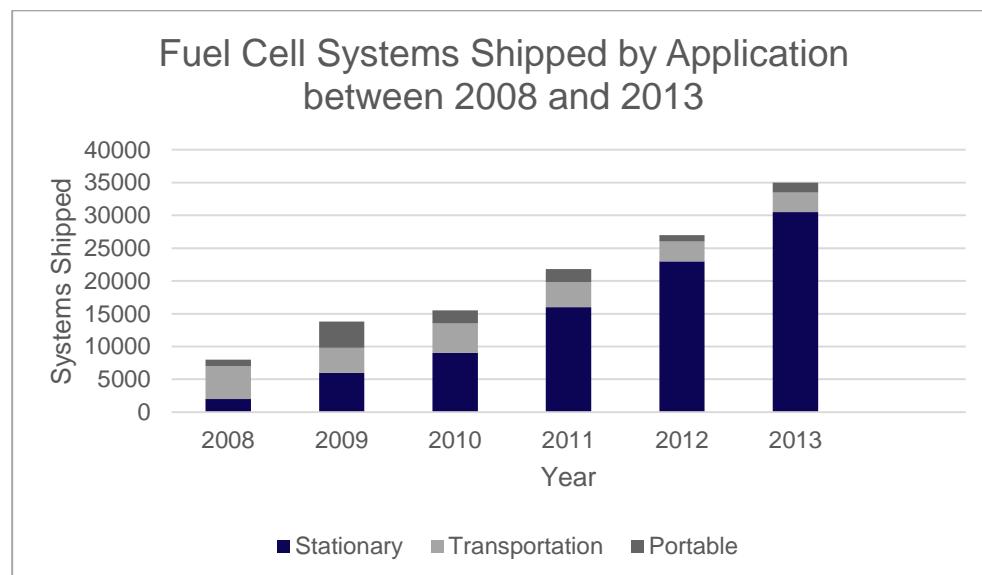


Figure 17 : Fuel Cell System Shipped by Application (2008-2013)<sup>15</sup>

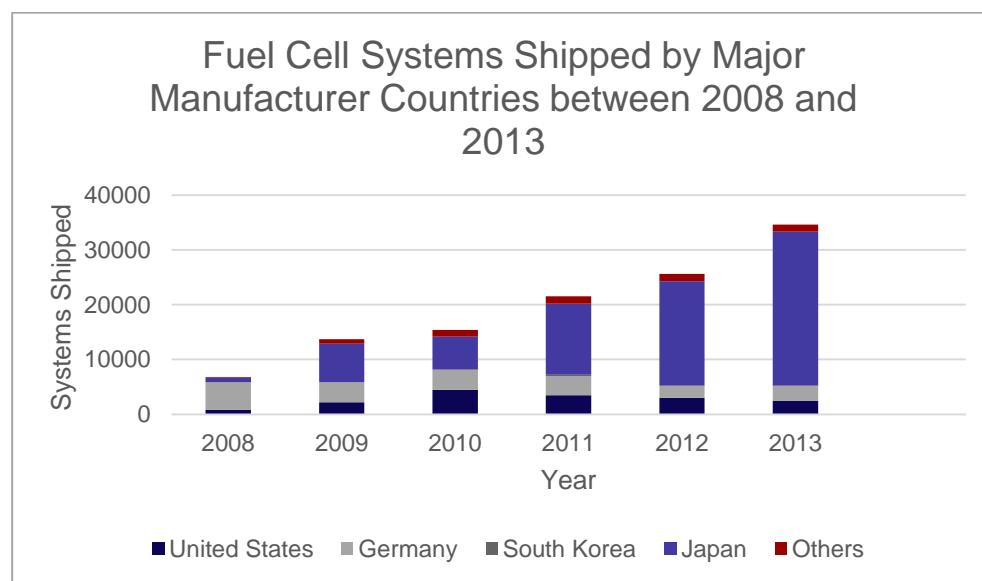


Figure 18 : Fuel Cell Systems Shipped by Major Manufacturer Countries (2008-2013)<sup>16</sup>

<sup>15</sup> Ibid.

<sup>16</sup> Ibid.



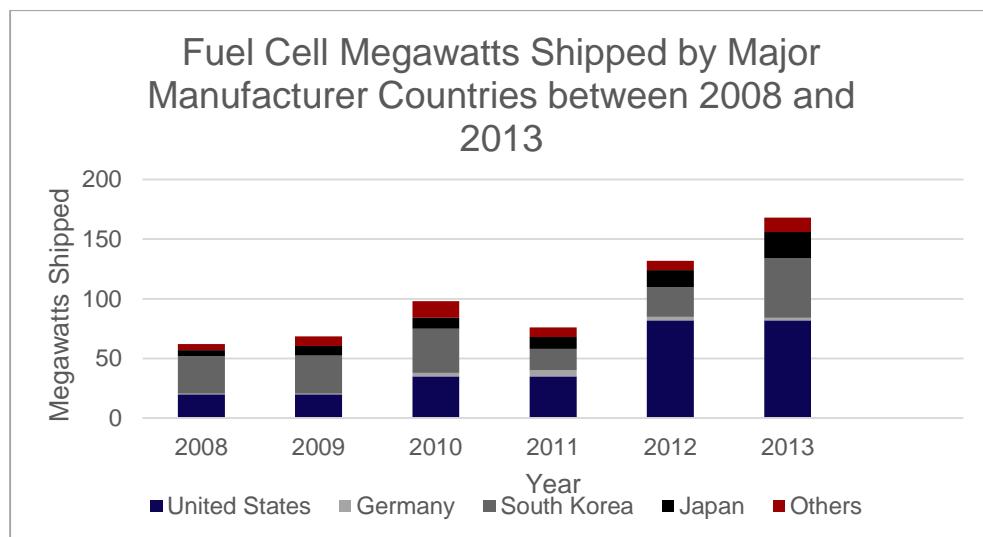


Figure 19 : Fuel Cell MWs Shipped by Major Manufacturer Countries (2008-2013)<sup>17</sup>

In terms of countries, the US FC shipments remain quite stationary and the growth is stagnant mainly due to the end of federal American Recovery and Reinvestment Act or (ARRA) which leads to the decline in fuel cell shipments but the decline is expected to be reversed in the few years. When the policy will be re-enacted, it will encourage a number of companies to deploy fuel cells at their warehouses.<sup>18</sup> For fuel cell electric vehicles, the global shipments remain quite low. This is because the major auto manufacturers planned to release their commercial fuel cell electric vehicles starting in the year 2017. The significant company that took initiative in shipping commercial fuel cell vehicles is Hyundai who started the shipment to European Region in the year 2013.<sup>19</sup>

### 3.4 Company Profiles

Currently the fuel cell market has flourished with many companies developing a variety of different products ranging from small hand held fuel cell mp3 players to big fuel cell substations used as backup power for vital communications. In order to enable the reader to understand the estate of the fuel cell market more concretely, an introduction of fuel cell companies from all corners of the world is given in this part. Notice that this is not an exhaustive list of the manufacturers, since there are many public and private companies in existence. However, the company profiles mentioned in this chapter should prove significant to give insight to the entire fuel cell industry.

<sup>17</sup> Ibid.

<sup>18</sup> “Tracking the money,” accessed April 20, 2015, <http://www.recovery.gov/arra/Pages/default.aspx>

<sup>19</sup> “Hydrogen Fuel Cell powered Cars,” accessed April 22, 2015, <http://www.hyundai.co.uk/about-us/environment/hydrogen-fuel-cell>



Here is the list of companies included in this IAR in alphabetical order:

- Bloom Energy
- Horizon Fuel Cell Technologies
- Intelligent Energy
- Nedstack
- Panasonic
- Plug Power
- SFC Energy
- Toshiba

## 3.4.1 Bloomenergy

The company was founded in the year 2001 and is headquartered in Sunnyvale, California. Its first customer was the University of Tennessee, which ordered the company a SOFC product for educational purposes in 2006. Many other universities across the United States similarly ordered the same product to conduct field trials. But it wasn't until July 2008 that the first commercial version of Bloom Energy's products were shipped to Google. The company proved to be one of the most well-known SOFC producers since its establishment some notable customers of this firm includes: Adobe, Bank of America, Coca-Cola, eBay, Google, Kaiser Permanente, and Walmart. The Company claimed that their products have already generated more than 100 million kilowatt-hours of clean energy for its customers.<sup>20</sup>

Table 3 : Brief market information of Bloomenergy

Headquarters	California, USA
Fuel Cell Type	SOFC
Market	Stationary (Large-Scale)
Application	Buildings(commercial, universities, arenas) data centers

**Bloomenergy®**

Bloom Energy Website:



<http://www.bloomenergy.com/>

Bloom Box (picture on the lower side of this page), a bloom energy product is designed to operate under extreme conditions of temperature, it can withstand up to 1800 Fahrenheit

<sup>20</sup> "Clean, Renewable Energy | Bloom Energy Solid Oxide Fuel Cells," accessed May 14, 2015, <http://www.bloomenergy.com/>





Figure 20 : Bloom box, a stationary fuel cell manufactured by Bloomenergy



### 3.4.2 Horizon Fuel Cell Technologies

**PEM:** proton exchange membrane

Horizon is currently the largest micro fuel cell producer and the largest producer of PEM fuel cell stacks below 1,000 W. Today, the firm produces compact, lightweight PEM fuel cells at various performance levels, and also delivers hydrogen storage and on-site hydrogen generation solutions for multiple applications. The company was founded in 2003 and it currently owns five subsidiaries around the globe.<sup>21</sup>

Table 4 : Brief market information of Horizon Fuel Cell Technology

Headquarters	Singapore
Fuel Cell Type	PEM
Market	Portable, Stationary(backup)
Application	Educational, consumer electronics, military, aerospace

<sup>21</sup> "Horizon Fuel Cell Technologies," accessed May 14, 2015, <http://www.horizonfuelcell.com/>



Figure 21 : Horizon MiniPak, FC product made from recycled plastics

### 3.4.3 Intelligent Energy

Intelligent Energy was founded in Loughborough, United Kingdom 2001. Its main focus is Proton Exchange Membrane type fuel cells. The firm partners with global companies that research on automotive, stationary power, and consumer electronics markets. Very notable accomplishments include collaborating with Suzuki Motor Corporation and built "Burgman" the first fuel cell scooter to achieve European Whole Vehicle Type Approval, and supplying fuel cells to Boeing who used it for the first fuel cell aircraft.<sup>22</sup>

Table 5: Brief market information of Intelligent Energy

Headquarters	Loughborough, United Kingdoms
Fuel Cell Type	PEM
Market	Portable, Stationary(backup)
Application	Aerospace, defense, generation portable power, automotive



Intelligent Energy also manufactures backup power in telecom sectors as an alternative to the commonly used diesel gases.

**Intelligent Energy Home Page:**



<http://www.intelligent-energy.com/>

<sup>22</sup> "Intelligent Energy," accessed May 14, 2015, <http://www.intelligent-energy.com/>





Figure 22 : A fuel cell taxi developed by Intelligent Energy



**Nedstack**  
PEM FUEL CELLS

NedStack obtains hydrogen partly from Chlorine industry by-product and uses the same hydrogen to generate power for chlorine plants resulting in a saving of upto 20% on energy consumption of the plants.

Here's the link to  
more info  
regarding  
Nedstack:



<http://www.nedstack.com/>

### 3.4.4 Nedstack

Nedstack is a PEM fuel cell stack provider for system integrators which deliver energy systems to the telecom, rail, and utilities industries. The company was founded in 1998 when seven engineers took over AkzoNobel's PEM activities. Right now, over 1,000 Nedstack fuel cells are in operation world-wide mostly as backup power sources.<sup>23</sup>

Table 6: Brief market information of Nedstack

Headquarters	Amhem, The Netherlands
Fuel Cell Type	PEM
Market	Transportation, Stationary(backup)
Application	Stationary power, telecommunication backup, buses



Figure 23 : PEM Fuel Cells by Nedstack

<sup>23</sup> "Nedstack," accessed May 14, 2015, <http://www.nedstack.com/>



### 3.4.5 Panasonic

The firm was founded in the year 1918, at the moment it was known as Matsushita Electronics, the company now comprises more than 500 sub-groups. The company was the first to manufacture a DMFC laptop which was capable of operating continually on battery for 20 hours and displayed it publicly at the International Consumer Electronics Show, 2006<sup>24 25</sup>. The firm is also one of the largest global manufacturers for residential CHP, and in recent years, the company managed to miniature and simplify fuel cell's structures.<sup>24 25</sup>

*Table 7: Brief market information of Panasonic*

Headquarters	Osaka, Japan
Fuel Cell Type	DMFC, PEM
Market	Stationary, Portable
Application	CHP units, Electronics, DMFC Consumer

**Panasonic**  
ideas for life

Panasonic's  
Homepage:



<http://panasonic.net>

DMFC: Direct  
Methanol Fuel Cell



*Figure 24 : A Panasonic laptop operating on fuel cell*

<sup>24</sup> "Panasonic Global," accessed May 14, 2015, <http://www.panasonic.com/global/home.html>

<sup>25</sup> "Panasonic to demo 20-hour laptop-friendly fuel cell," accessed May 14, 2015, [http://www.theregister.co.uk/2008/10/20/panasonic\\_dmfc\\_demo/](http://www.theregister.co.uk/2008/10/20/panasonic_dmfc_demo/)





#### Do you know?

Walmart uses multiple units of GenDrive® fuel cell, a Plug Power's product, to provide power for its distribution centres all around USA and Canada.

#### More about Plug Power and its products:



<http://www.plugpower.com/>

#### 3.4.6 Plug Power

Plug Power is a major player in the PEM fuel cell material handling equipment market. The company was incorporated the year 1997 as a joint venture between Edison Development Corporation and Mechanical Technology Inc. Right now, the company mainly focuses on GenDrive®, a PEMFC designed for industrial vehicles especially material handling equipment and distribution facilities. The company has deployed over 3,000 GenDrive® units with run times exceeding 8.5 million hours.<sup>26</sup>

Table 8: Brief market information of Plug Power

Headquarters	Latham, New York
Fuel Cell Type	PEM
Market	Stationary, Transportation
Application	Material Handling Equipment



Figure 25 : GenDrive, a forklift fuel cell manufactured by Plugpower

<sup>26</sup> "Plugpower," accessed May 14, 2015, <http://www.plugpower.com/>



### 3.4.7 SFC Energy

The firm produces power generator for mobile homes, yachts and vacation cabins. SFC Energy ally itself with other big companies in different industries and had already shipped more than 30,000 commercial products. The company's facilities are located mainly in the Netherlands and Romania, its fuel cartridges are manufactured in Germany near Munich where its R&D department is located. SFC Energy also manufactures DMFC for mobile and off-grid power serving leisure, industrial and defense market.<sup>27</sup>

*Table 9: Brief market information of SFC Energy*

Headquarters	Brunnthal, Germany
Fuel Cell Type	DMFC
Market	Stationary
Application	Leisure, industrial and defense



*Figure 26: Jenny, a portable fuel cell used in military operations*



#### SFC Energy:

SFC currently partners up with Volkswagen Corp. to develop "Volkswagen T5" a light commercial vehicle powered by fuel cell.

T5 article on science-direct:



<http://www.sciencedirect.com/science/article/pii/S146428591501085>

More about SFC Energy:



<http://www.sfc.com/>

<sup>27</sup> "Welcome to SFC," accessed May 14, 2015, <http://www.sfc.com/en>



**CEATEC:** Combined Exhibition of Advanced Technologies, an annual tradeshow in Japan.

Learn more about Toshiba:



<http://www.toshiba.co.jp>

### 3.4.8 Toshiba

In the year 1984, Toshiba operated an experimental 50 kW fuel cell power plant, the first power plant in Japan. The company actively researches on DMFC and PEM technologies for the Japanese market. Among the main products are residential PEM fuel cells and PAFC developed since 1990s. The company also demonstrates its DMFC-powered cell phones and MP3 players at the CEATEC conference which can operate for 320 hours using fuel cell and methanol fuel.<sup>28</sup>

Table 10: Brief market information of Toshiba

Headquarters	Tokyo, Japan
Fuel Cell Type	DMFC, PEM
Market	Stationary, Portable
Application	Consumer Electronics, Residential



Figure 27: MP3 player powered by a methanol-based fuel cell

<sup>28</sup> “Toshiba Global Top Page,” accessed May 14, 2015, <http://www.toshiba.co.jp/worldwide/index.html>



## Part 4

### 4. POLICY FRAMEWORK

It has been proven that innovations in their early stages need technology specific support, to prevent lock-in effects of earlier technologies from only incentivizing incremental innovations.<sup>29</sup> When developing such innovations new products or entering markets, firms are acting in a network of governmental influence, universities and customer. The actors, which are engaging in this network, can be classified as the role of the government and the interaction between firms and non-firm. This chapter will discuss the different influences of the institutional framework, which influence the development of technologies, by framing policies, opportunities and capabilities.<sup>30</sup>

Support of new technologies may happen through R&D funding, support for demonstration trials, testing etc. Another form of influence can be planning

<sup>29</sup> Raimund Bleischwitz and Nikolas Bader, "Policies for the transition towards a hydrogen economy: the EU case," *The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers* 38, no. 10 (2010), doi:10.1016/j.enpol.2009.03.041, <http://www.sciencedirect.com/science/article/pii/S0301421509002006>

<sup>30</sup> Gurneeta Vasudeva, "How national institutions influence technology policies and firms' knowledge-building strategies: A study of fuel cell innovation across industrialized countries," *Research Policy* 38, no. 8 (2009), doi:10.1016/j.respol.2009.05.006, <http://www.sciencedirect.com/science/article/pii/S004873309001152>





incentives on a regional level, for example incentives for the use of fuel cells in new buildings.<sup>31</sup>

For further discussions the countries with the highest support for fuel cells were chosen. Table 11 shows the average R&D budget in 2003 to 2005.

Table 11: R&D budgets average 2003-2005, rounded values in US\$<sup>32</sup>

	PEM	MCFC	SOFC	H2 & FC	FC	Mobile FC	Stationary FC
Germany	x	x	x	71	65	40	25
Japan	x	x	x	311	249	173	76
USA	x	x	x	249	151	105	46

The targets of stimulation in the fuel cell industry vary from region to region. In the US they are mainly driven by national security issues, in Europe by environmental targets and in Japan economic (high value manufacturing) as well as environmental targets and energy security. As shown in PART ERROR! EFERENCE SOURCE NOT FOUND. there are several technologies, policies may vary from technology to technology depending on which focus is set and therefore create competition between those. Also other technologies compete or complement fuel cell. Incentives can have a high influence on creating the wanted effects.<sup>33 34</sup> One of the main indicators of political influence are the expenditures for R&D in this area. In the following part, the situation in the three countries which are ranked highest with regard to expenditures are analyzed.<sup>35</sup>

Although often seen together hydrogen and renewable energies have some distinctions, which influence the policies, as it is unlikely that the same policies for both technologies will work. Hydrogen is an energy carrier and therefore needs infrastructure for production and distribution. Hydrogen has to be made compatible for the existing infrastructure and cannot be blended. The future development is heavily relying on critical issues like storage where technological progress is necessary. Therefore a successful policy has to connect market requirements, climate requirements and the hydrogen technology development.<sup>36</sup>

<sup>31</sup> Paul E. Dodds et al., "Hydrogen and fuel cell technologies for heating: A review," *International Journal of Hydrogen Energy* 40, no. 5 (2015), doi:10.1016/j.ijhydene.2014.11.059, <http://www.sciencedirect.com/science/article/pii/S0360319914031383>

<sup>32</sup> Lako P. and Ros M.E.

<sup>33</sup> Vasudeva

<sup>34</sup> Lako P. and Ros M.E.

<sup>35</sup> ibid.

<sup>36</sup> Bleischwitz and Bader



A study in Germany has shown that the political conditions influence the adoption of FC. There is a difference in the adoption through commercial and private users. For commercial user the investment decision is influenced by feed in laws for CHP systems and the oil and energy price. Private consumers are positively affected by a future oriented energy policy and clear law statements. Whereas commercial users deny subventions, because they are unreliable, private users endorse subventions to cover expenses which arouse by the use of FC.<sup>37</sup>

Most of the policies are facing the same problem. On the one hand they have to be broad enough to create new markets and encourage firms to enter, but on the other hand they are focused on specific technologies where there is the greatest chance to success. A proposed solution includes to keep regulatory measures flexible while focusing R&D on special technologies.<sup>38</sup>

## 4.1 Situation in Japan

Due to the lack of fossil fuel sources Japan's government is heavily investing in fuel cells and their research during the last years through R&D funding.<sup>39</sup>

<sup>40 41</sup> Already in 1974 the sunshine project was launched to examine hydrogen power among other renewable energy sources. Around 1980 the development was pushed by the moonlight project which aimed at developing fuel cells. With the new sunshine project of 1993 the effort on PEMFC was increased. All the efforts culminate in the millennium project from 2000. This is including R&D for PEMFC for use in automobile and residential application. This project is flanked by another program to develop tests and evaluation for safety and reliability standards which is stated to be a critical factor for the adoption of a new technology.<sup>42</sup> As a result of the announcement of Daimler-Benz of their failed plan to commercialize fuel cells, the government developed a strategic plan. According to this a partnership between METI and several Japanese fuel cell companies is established and called JHFC project. The intention of this project was mainly focused on the development of a FCV and surrounding infrastructure like hydrogen production, storage and filling. The development is characterized by a high

**METI** : Ministry of Economy, Trade, and Industry (Japan)

**JHFC** : Japan Hydrogen and Fuel Cell

**FCV** : Fuel Cell Vehicle

**JTI** : Joint technology initiative

<sup>37</sup> Cornelia R. Karger and Richard Bongartz, "External determinants for the adoption of stationary fuel cells—Infrastructure and policy issues," *Energy Policy* 36, no. 2 (2008), doi:10.1016/j.enpol.2007.10.024, <http://www.sciencedirect.com/science/article/pii/S0301421507004806>

<sup>38</sup> Brown, Hendry and Harborne

<sup>39</sup> International Energy Agency Staff, *Energy Policies of Iea Countries Japan: 2008* (Washington, Biggleswade: Organization for Economic Cooperation & Development; Turpin Distribution Services Limited [Distributor], 2008)

<sup>40</sup> Brown, Hendry and Harborne

<sup>41</sup> Manoj Pudukudy et al., "Renewable hydrogen economy in Asia – Opportunities and challenges: An overview," *Renewable and Sustainable Energy Reviews* 30, no. 0 (2014), doi:10.1016/j.rser.2013.11.015, <http://www.sciencedirect.com/science/article/pii/S1364032113007648>

<sup>42</sup> Brown, Hendry and Harborne



degree of cooperation between government and industry, which is significant for high corporatist countries. The plan was divided in three phases. The first phase from 2002 to 2005 was intended to develop a hydrogen infrastructure and to determine performance statistics. The aim of the second phase from 2006 to 2010 was to develop standards investigate about policies and reduce costs. Besides this plan there was an agreement of the Japanese car manufacturers to release fuel cell vehicles by 2015.<sup>43</sup> In 2002 the Japanese government announced the target to reach 15 GW produced by stationary fuel cells in 2030. Besides funding, another influence of the government, is the research on the practical use of fuel cells. Japan has a clear focus on creating new markets for fuel cell CHP. The Japanese effort is among the highest.<sup>44</sup>

Using FCV and stationary appliances, Japan intends to use \$ 4 billion for hydrogen usage and is expecting that by 2020 all road vehicles are powered by hydrogen fuel cells. The government is also funding manufacturers and an estimated value of 380 million \$/year is done for research and commercialization of FC.<sup>45</sup>

## 4.2 Situation in the USA

The electricity market in the US is decentralized and also the framework for fuel cells is different in the states. California, Connecticut, New York, Ohio and South Carolina are the most supporting countries.<sup>46</sup> In contrast to Germany or Japan there is less support for creating a market for fuel cell CHP. The SECA program is focusing on SOFC for small stationary use. While SOFC may be the best choice for electricity generation it is lacking behind PEMFC. Besides the US Department of Defense is also investigating about residential fuel cells in military related fields.<sup>47</sup> The US department of energy has started a Hydrogen Program. Furthermore there is a direct subsidy support for manufacturing facilities.<sup>48</sup> In 2009 the American Recovery and Reinvestment Act (ARRA) funded a fuel cell program with

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<sup>43</sup> Gareth E. Haslam, Joni Jupesta, and Govindan Parayil, "Assessing fuel cell vehicle innovation and the role of policy in Japan, Korea, and China," *HYFUSEN Special Issue for the 4th National - 3rd Latin American Conference on Hydrogen and Sustainable Energy Sources (HYFUSEN)*, 6-9 June 2011, Mar Del Plata, Argentina 37, no. 19 (2012), doi:10.1016/j.ijhydene.2012.06.112, <http://www.sciencedirect.com/science/article/pii/S0360319912015315>

<sup>44</sup> Brown, Hendry and Harborne

<sup>45</sup> Lako P. and Ros M.E.

<sup>46</sup> U.S. Department of Energy, "State of the States: Fuel Cells in America 2014," news release, December 2014

<sup>47</sup> Brown, Hendry and Harborne

<sup>48</sup> Dodds et al.



around \$ 42 million.<sup>49</sup> Until 2014 an annually expense of \$640 was made and in addition a \$3,000/ kW purchase incentive tax credit was granted.<sup>50</sup>

### 4.3 Situation in Germany

As a part of the EU the German policies have also to be seen in the context of the European framework, as the national framework is largely shaped by the European context. The general consent within the EU is that the “further development and market introduction” is desirable, as it can be a carbon neutral substitute for fossil fuels. One of those projects which empower fuel cell is the JTI in which frame 1 billion € will be spend from 2008 to 2017.<sup>51</sup> It was shown that Germany is one of the most innovative regions regarding fuel cells.<sup>52</sup> <sup>53</sup> The public federal funding amounts 8-10 million every year. For the time 2001-2003 additionally 15 million were added in the “program on investment into the future”. The Helmholtz foundation, which undertakes basic research is supported with 15 million annually. Besides financial support, politicians promote hydrogen power, e.g. by presenting newest technologies.<sup>54</sup> The German government often proved to create new markets for new energy forms, e.g. with the “feed in law” from 1991 which guarantee a specific price for electricity generated by renewable energies. Germany is creating a market for fuel cell CHP within a broader range of technologies. To further develop fuel cells for the residential market there is an extensive ZIP program. Another indicator is how much new technologies are encouraged as this is creating an atmosphere in which firms will experiment more. Japan and the US may have the highest spending for R&D, but the highest use of renewable energies is reached in Germany. A main reason for this is the feed-in law.<sup>55</sup> Another influence is the taxation, in Germany hydrogen is taxed when used as a motor fuel.<sup>56</sup> Furthermore there is the NOW program. Germany also makes use of subsidies for capital cost and give feed in tariffs for fuel cell CHP.<sup>57</sup> In difference to the USA or Japan Germany heavily pushes R&D in fuel cells but has now

<sup>49</sup> Nancy L. Garland, Dimitrios C. Papageorgopoulos, and Joseph M. Stanford, “Hydrogen and Fuel Cell Technology: Progress, Challenges, and Future Directions,” *Fuel Cells 2012 Science & Technology – A Grove Fuel Cell Event* 28, no. 0 (2012), doi:10.1016/j.egypro.2012.08.034,  
<http://www.sciencedirect.com/science/article/pii/S1876610212013902>

<sup>50</sup> Canadian Hydrogen and Fuel Cell Association, “10 Reasons to Support Hydrogen and Fuel Cell Funding,” accessed May 6, 2015,  
[http://www.chfca.ca/media/10\\_Reasons\\_Support\\_Funding.pdf](http://www.chfca.ca/media/10_Reasons_Support_Funding.pdf)

<sup>51</sup> Bleischwitz and Bader

<sup>52</sup> Anne N. Tanner, “Regional Branching Reconsidered: Emergence of the Fuel Cell Industry in European Regions,” *Economic Geography* 90, no. 4 (2014), doi:10.1111/ecge.12055

<sup>53</sup> Lako P. and Ros M.E.

<sup>54</sup> *ibid.*

<sup>55</sup> Brown, Hendry and Harborne

<sup>56</sup> Bleischwitz and Bader

<sup>57</sup> Dodds et al.





subsidies for e.g. buying a FCEV.<sup>58</sup> Till 2017 an investment sum of \$1.1 billion is calculated.<sup>59</sup> Furthermore there is a rebate to the end customer after the purchase. In Japan this was introduced in 2005, in Germany in 2012.<sup>60</sup>

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<sup>58</sup> Katharina Hamberger, "Die Chancen der Brennstoffzellen-Technologie," *Deutschlandfunk*, February 7, 2015, [http://www.deutschlandfunk.de/antrieb-der-zukunft-die-chancen-der-brennstoffzellen.724.de.html?dram:article\\_id=310237](http://www.deutschlandfunk.de/antrieb-der-zukunft-die-chancen-der-brennstoffzellen.724.de.html?dram:article_id=310237)

<sup>59</sup> Canadian Hydrogen and Fuel Cell Association

<sup>60</sup> Iain Staffell and Richard Green, "The cost of domestic fuel cell micro-CHP systems," *International Journal of Hydrogen Energy* 38, no. 2 (2013), doi:10.1016/j.ijhydene.2012.10.090, <http://www.sciencedirect.com/science/article/pii/S0360319912024147>



## Part 5

## 5. FUTURE PERSPECTIVES

### 5.1 Fuel Cells as Off-Grid Power Source<sup>61</sup>

Prior to the London's Olympic Games, the UK government decided that the security level in roads and motorways could still be increased by installing CCTVs on strategically important locations. However, the people involved in the project of providing energy sources for these CCTV realized that connecting these cameras to the grid would cost an absurdly high amount of budget from the government even without considering the maintenance cost of the grid itself. The construction engineers also argued that the construction would take up two years provided that sufficient manpower, materials and budgets are provided.

The government then turned to off-grid power as the ultimate solution to minimize the cost and time spent in installing the CCTVs system. Two fuel cell companies called 'FCS' and 'UPS systems' came into interest of the government. The companies installed stationary fuel cells at remote location in order to supply power for the fuel cells 24/7 the technology is superior to other renewable energy sources like wind energy and solar energy as the energy produced is stable regardless of the changing weather or climate conditions as long as fuel hydrogen is continually supplied. From the client's perspective, the fuel cells are easier to deal with than batteries mainly because of the lighter weight, relatively more compact size and longer unit

<sup>61</sup> <http://www.fuelcellsystems.co.uk/fcapplications/case-studies/remote-off-grid-power-for-road-network-cctv/>





lifetime. This means that the maintenance team can actually perform maintenance more easily and economically. The fact that the country did not have to consider about the space and equipment for recharging the batteries for the entire highway itself made fuel cells easily became the solution for the UK government.

From our point of view, fuel cells can also be used in similar scenarios where off-grid power systems are needed under the fact that weather and climate conditions are unstable. The technology is even more appealing to environmentalists as it produces zero noise and air pollution.

## 5.2 Hydrogen Infrastructure<sup>62</sup>

Before hydrogen fuel cell vehicles can become a successful commercialization of international scale, an update in infrastructure and equipment must be established with the support of government institutions and society: hydrogen pipeline transport, as the name implies, is the transportation of hydrogen gas through a pipe. Sufficient length, quantity and area coverage of the piping system is mandatory in order to supply sufficient amount of hydrogen to all the vehicles in the country; hydrogen refueling stations, these stations will be used to refuel vehicles with hydrogen thus essentially it functions acts more or less the same as a petrol station, the main difference between the two is simply the fuel type. As for major countries, the USA for example, The National Renewable Energy Laboratory believes that U.S. counties have the potential to produce more renewable hydrogen for fuel cell vehicles than the gasoline they consumed in 2002. Thus, fuel cell maybe a sensible alternative or a potential replacement of conventional fuels.<sup>63</sup>

**Internet of things:**  
This term refers in this case to the project of enabling objects to interact with each other in order to minimize “useless” human interventions and to optimize their applications on a large scale.

This infrastructure would be all the more beneficial for the implementation if it integrated smart devices automatizing control and communication between the different components. Indeed, because fuel cells are often installed in systems involving renewable energy sources, it is to be managed in an optimized way that maximizes efficiency. Such results can be reached only if components are able to communicate with energy management systems (EMS) that make strategic decisions for the electrical networks. Such systems can be decentralized. In this case, it is each device that has its own microcontroller and is responsible for interacting with others. It today remains very complex to design such systems because of the rules that the components are to respect, but also the reliability of the communications. Fortunately, similar issues are present in more general internet of things applications. A potential way to solve this is given in a lately used technology: Block Chains. Indeed, thanks to cryptography, communication and transactions taking place on block chains are more secure and reliable, but

<sup>62</sup>

[http://www.researchgate.net/publication/233987484\\_Fuel\\_cell\\_electric\\_vehicles\\_and\\_hydrogen\\_infrastructure\\_status\\_2012](http://www.researchgate.net/publication/233987484_Fuel_cell_electric_vehicles_and_hydrogen_infrastructure_status_2012)

<sup>63</sup> <http://www.nrel.gov/docs/fy07osti/41134.pdf>



also be controlled in a decentralized and preprogrammed way. Such technologies therefore would enable better integration of fuel cells in smart networks and to bring more comprehensive benefits to end-users.

### 5.3 Technology

In the technology domain, there is one innovation that regards electrodes and therefore is awaited because it gives the possibility to reduce the manufacturing price a lot. Core-Shell electrodes are indeed offering to keep the properties presented by platinum electrodes at the same time as reducing the amount of precious metal contained in the component. The idea is to concentrate the platinum at the surface of the electrode so that it remains in small quantity<sup>64</sup>. Such kind of techniques are particularly interesting because they can be applied for existing types of fuel cells which have already been found usage and therefore will not require any change in terms of standards. Other improvements could also be brought by minimizing the cost of the electrolyte or catalysts consisting of the fuel cell.

Those innovations will have an impact by making the product more accessible to customers. But fuel cells already present quite a few advantages compared to combustion engines. Indeed, because of the little movement pieces are submitted to, it is a system that requires little maintenance. Fuel cells however can fail for mechanical or thermal degradation, or from a loss of efficiency of the different components (catalyst, electrode, and electrolyte) <sup>65</sup>. As a consequence, research and commercialization will also help improve system reliability.

These innovations have to be carried out because of the remaining immaturity of the technology and infrastructure. And indeed in terms of infrastructure, the hydrogen production equipment is rare. A fuel cell is supposed to provide a zero-emission option. To remain consistent, the best hydrogen production modes then are the non-polluting ones. In addition to this, as hydrogen needs to be produced and then used, the process is not efficient in terms of energy expenses. This can be seen as a defect. However, because natural energy sources cannot be controlled and therefore are hard to exploit efficiently, making hydrogen out of them is a great opportunity to make good usage of their potential. Nowadays this is done through electrolysis. More efficient options are being developed, including a promising one: direct solar water splitting. It can be done thanks to cells similar to photovoltaic ones where the splitting is powered by the sunlight.

NREL's researchers are working on developing sustainable Hydrogen production on this YouTube page:

NREL's Hydrogen Program



[https://www.youtube.com/watch?v=ZQ8YR\\_4vC\\_k](https://www.youtube.com/watch?v=ZQ8YR_4vC_k)

<sup>64</sup> "Core-Shell Fuel Cell Electrodes - Energy Innovation Portal," accessed May 30, 2015, <http://techportal.eere.energy.gov/technology.do/techID=1257>

<sup>65</sup> Jinfeng Wu et al., "A review of PEM fuel cell durability: Degradation mechanisms and mitigation strategies," *Journal of Power Sources* 184, no. 1 (2008), doi:10.1016/j.jpowsour.2008.06.006



Another promising and original possibility is use microorganisms that will produce hydrogen through their photosynthesis process<sup>66</sup>.

## 5.4 Pricing

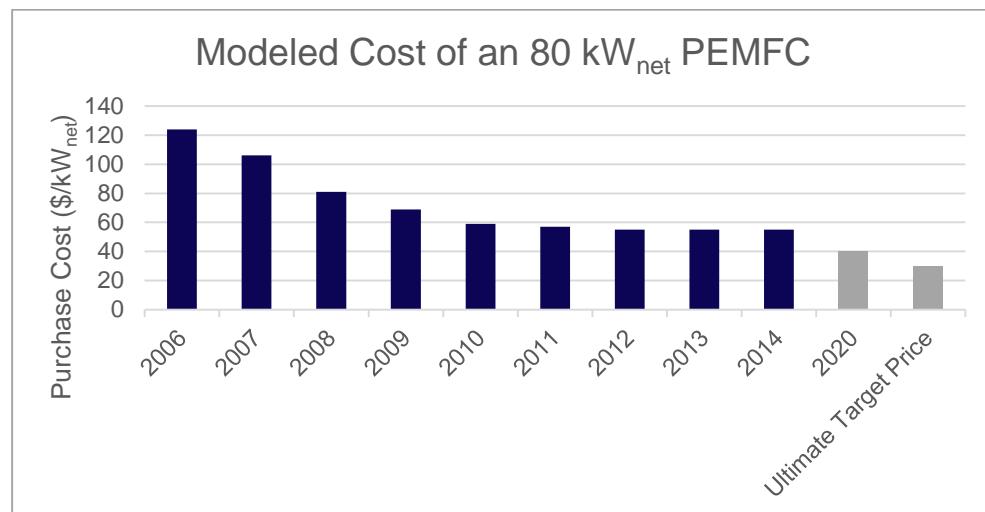


Figure 28 : FC Cost Reduction <sup>67</sup>

As shown in Figure 28 the cost of fuel cells declined significantly since 2006, by fifty percent. This is mainly based on R&D departments of many companies attempted and succeeded to some extents in making the fuel cell prices comparable with conventional energy sources. At the same time, it was discovered that durability of the cells has increased by two times in general.<sup>68</sup>

The future price is an important factor in the adoption of fuel cells and the price has to become competitive.<sup>69</sup> Although there are variations in the extent of the decrease nearly all source predict a decrease of the price, mainly for the fact of economies of scale. Reasons are for example the usage of fuel cells in public transportation,<sup>70</sup> or experiences made in former systems.<sup>71</sup>

<sup>66</sup> "Hydrogen Production Processes | Department of Energy," accessed May 30, 2015, <http://energy.gov/eere/fuelcells/hydrogen-production-processes>

<sup>67</sup> [http://www.hydrogen.energy.gov/pdfs/14014\\_fuel\\_cell\\_system\\_cost\\_2014.pdf](http://www.hydrogen.energy.gov/pdfs/14014_fuel_cell_system_cost_2014.pdf)

<sup>68</sup> [http://www.hydrogen.energy.gov/pdfs/11003\\_fuel\\_cell\\_stack\\_durability.pdf](http://www.hydrogen.energy.gov/pdfs/11003_fuel_cell_stack_durability.pdf)

<sup>69</sup> Wolfgang Bernhart, Stefan Riederle, and Manuel Yoon, "Fuel cells: A realistic alternative for zero emission?," 2013

<sup>70</sup> E4tech

<sup>71</sup> I. Staffell and R. J. Green, "Estimating future prices for stationary fuel cells with empirically derived experience curves," *2nd International Conference on Hydrogen Safety 2nd International Conference on Hydrogen Safety* 34, no. 14 (2009), doi:10.1016/j.ijhydene.2009.05.075,

<http://www.sciencedirect.com/science/article/pii/S0360319909008039>

## Future perspectives



Also the standardization process for unified infrastructure will lower the cost.<sup>72</sup>

The future price stated in Figure 28 is a forecast of the US government and is based on a high volume manufacturing of 500.000 units per year.<sup>73</sup> Another prediction for the price of fuel cells in FCEV is heavily based on the price of platinum. At the moment the whole fuel cell system in a car is estimated to be priced at around EUR 45,000. Around 35-45% of this is needed for the MEA, which is built out of different layers whereof the PEM is the most complex and costly part. Other parts like tanks and bipolar plates are already established and the possible price decrease is estimated to be low. A breakdown of the supply chain and analysis of the main influences on the price has shown that the main lever to decrease the price for MEA is the platinum. Platinum is a rare material with a difficult production environment. For example it is only found in Russia and South Africa, which creates a high dependency and volatility in prices. Assuming that FCEV become a cost competitive the production volume will increase up to 5 million units in a decade. Within this scenario the price is estimated to drop by 80% to EUR 9,000 per vehicle, assuming the full use of identified levers, like reducing the needed platinum (to <10g/vehicle), improving production technologies and the use of economies of scale. But at the same time this would increase the platinum demand by 21% compared to 2012, which would make it hard to keep the today's prices. Therefore the broad use of fuel cell is problematic and highlights the importance of finding a fuel cell technology not using platinum, which was already mentioned in **PART 5.3.**<sup>74</sup>

Also the cost for CHP is predicted to decrease. The target of the US Department of Energy is a price of \$ 1000 by 2020 for domestic fuel cell micro CHP. The price in the last years tend to decrease. The decrease is varying from manufacturer to manufacturer due to the effect of experiences of prior production. In general the price decrease is higher in the early stages of production. Nevertheless it is unlikely that it will reach the price of \$ 1000. One of the reasons is that the size of the market would have to quadruple (up to 10 billion) and even then with declining learning rates the price would not be reached. Furthermore the price doesn't reflect the complexity and doesn't include the whole system of a domestic CHP. When including all parts needed in the periphery around such a system it is more likely that a price of \$ 3500 by 2020-2030 is reached. Of course this price can be lower or reached earlier, if big technological improvements are achieved.<sup>75</sup>

For both the domestic CHP as well as FCEV the competitiveness of the price is influenced by the price of fossil fuels and electricity.<sup>76</sup> But also the user

**MEA:** membrane electrode assembly, the part converting H<sub>2</sub> and O<sub>2</sub> into energy

**PEM:** polymer electrolyte membrane

<sup>72</sup> Yang Chia-hao, "Fuel Cell Manufacturing," news release, July 29, 2014

<sup>73</sup> [http://www.hydrogen.energy.gov/pdfs/14014\\_fuel\\_cell\\_system\\_cost\\_2014.pdf](http://www.hydrogen.energy.gov/pdfs/14014_fuel_cell_system_cost_2014.pdf)

<sup>74</sup> Bernhart, Riederle and Yoon

<sup>75</sup> Staffell and Green

<sup>76</sup> ibid.





habit will influence the adoption. Forecasts for total cost of ownership of FCEV vary depending on e.g. the mileage which is driven in one year. In general the TCO by 2030 will be around the same level as other technologies like combustion or electric cars.<sup>77</sup>

### 5.5 Policy

All three countries have announced to continue their investment in fuel cells. With its three phases of commitment Japan set a plan for 2020 where it wants to reach that all road vehicles are powered by hydrogen. In the US several states announced further commitment to fuel cells, New York for example set the aim of 100 hydrogen stations to fuel 50000 FCEV cars in 2020.<sup>78</sup>

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<sup>77</sup> Alain Le Duigou and Aimen Smatti, "On the comparison and the complementarity of batteries and fuel cells for electric driving," *International Journal of Hydrogen Energy* 39, no. 31 (2014), doi:10.1016/j.ijhydene.2014.08.077, <http://www.sciencedirect.com/science/article/pii/S0360319914023775>

<sup>78</sup> Garland, Papageorgopoulos and Stanford





## Part 6

### 6. CONCLUSION

The history of fuel cell reaches back to the 19th century. Yet the commercialization for private customer only started in the recent past. Therefore the market is in an early stage. On the market there are several technologies available. All of them have different operating characteristics, among which the power output and temperature range are mainly determining the application possibilities. The type of material involved for the electrodes is the critical criteria cost wise. One of the objectives in R&D projects therefore is to reduce the quantity of precious metals used so that fuel cells become more affordable. Such an effort is essential for the technology to spread. Indeed, fuel cells already have various applications in our everyday lives thanks to the wide range of power it can provide. While MCFC can supply high power demands up to 5 MW other fuel cells like DMFC work in the lower output range down to 1 mW. Their adoption by the general public is not complete because of the price issues mentioned previously, but also due to the infrastructure they require to work with a maximum effectiveness. This infrastructure shall include distribution facilities and an organized surrounding network that enables the shipping of the gas, but also production plants. Several techniques can be used to generate hydrogen, from gas reforming which emits greenhouse gas, to more innovative ones such as solar direct water splitting, which mimics green natural processes. Electrolysis, on another hand, offers a great opportunity which is to exploit fully renewable - and thus often not controllable - energy sources. The potential for fuel cells therefore is enormous both in applications, but also in fulfilling the promise of a zero emission energy.





## Conclusion

The market size continuously increased in the past years. There were several interesting notable steps. As an example, the worldwide fuel cell industry sales surpassed \$ 1 billion for the first time in 2013. Fuel cell power parks were continually opening in many countries including Japan, Germany, USA, but most importantly in Korea where the world's largest fuel cell power plant of 59 MW capacity was constructed. The demand for telecommunications backup fuel cells were high in the Middle East, China, the Philippines and other international markets, which resulted in favorable business conditions for stationary fuel cell manufacturers. The major players on the market are Bloomenergy, Ballard Power Systems, FuelCell Energy, Plugpower and SFC Energy AG. All of these companies collaborate with firms from other industries to build a supply chain and bring varieties of fuel cell products into the global market. As a result, many financial and educational institutions started to pay close attention to the evolution of fuel cells.

The strong development of fuel cells in some countries is also based on governmental policies, which are playing a big role in the emerging of a new technology. Japan heavily pushed the R&D as well as the market introduction. Therefore it is now the leading country with regard to the fuel cells shipped by MW. Germany is mainly supporting R&D efforts. What with the USA, after using fuel cells already for early NASA missions, they now also started to support fuel cells for daily use especially in New York and some other states.

Fuel cells started to make an appearance in many off-grid power systems around the globe. This is because of multiple countries follow the UK government approach, which utilized stationary fuel cell in powering its off-grid CCTV. This technology is conceived to be very versatile under unstable geographical circumstances. Hydrogen infrastructures on the other hand, are being developed sparsely in many countries but most interestingly in the US, California where there have been ongoing demonstration programs of fuel cell transport vehicles supported by the state government.

In the future fuel cells have to hold their ground against other emerging technologies like the electric car. A factor which is helpful for this development is, that it is forecasted that the price will drop in the long run, mainly through the mentioned improvement of the technology and economies of scale. Yet the adoption is highly influenced by the price of the competing technologies like electric cars. Still some problems like the high dependency on platinum will remain unsolved in the near future.





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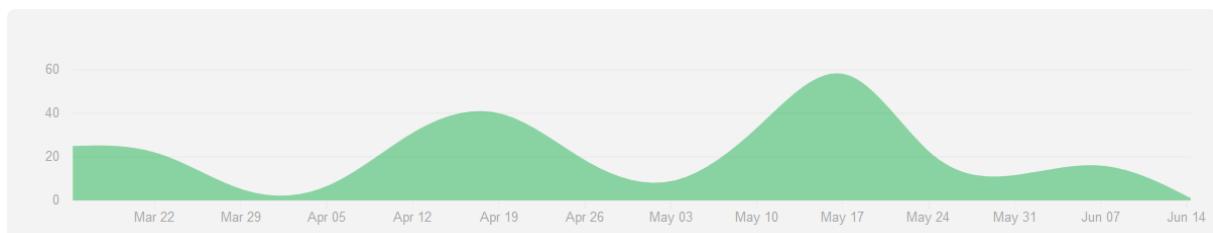


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## Appendix



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