FUEL CELLS — A REALISTIC ALTERNATIVE FOR ZERO EMISSION?

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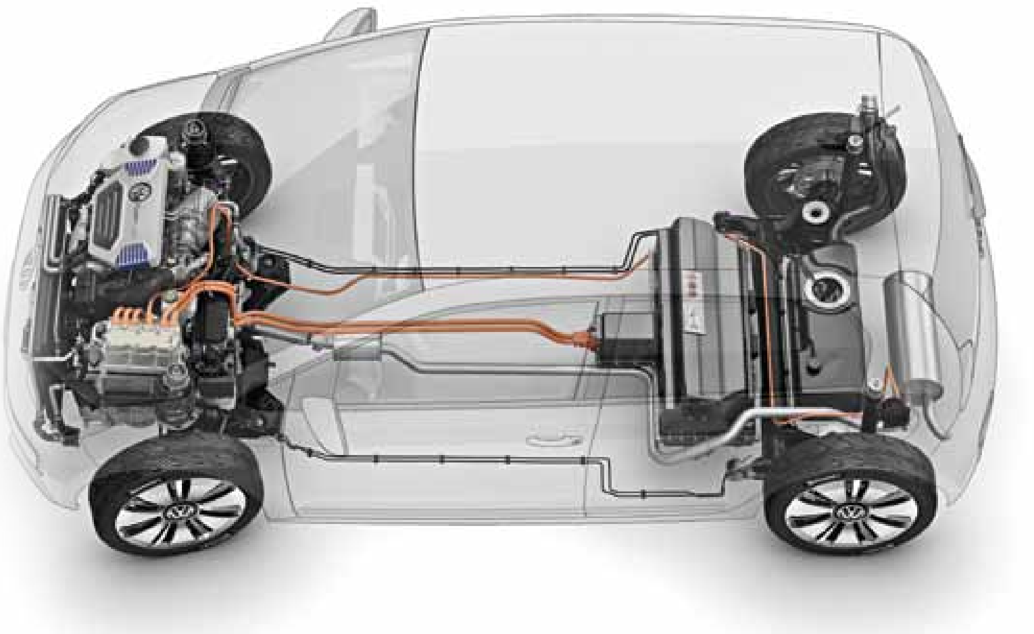


EXECUTIVE SUMMARY

For several decades, OEMs have dreamed of making zero-emission vehicles a reality – needing only a breakthrough in fuel cell technology. This dream finally seems to be within their grasp as the first market-ready vehicles roll off the production line, and OEMs have committed to considerable volumes for the coming years.

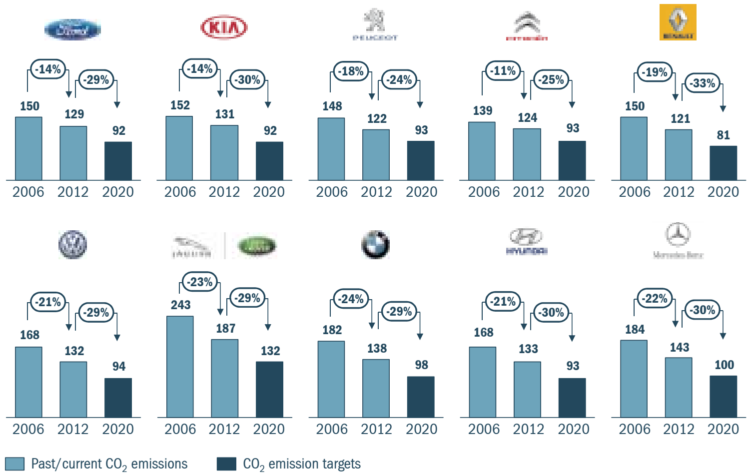
While fuel cell electric vehicles (FCEVs) represent an attractive alternative to battery electric vehicles in meeting the CO_2 challenge, the costs of a fuel cell system are still estimated at a hefty €45,000. A major share of those costs (~35-45 %) is made up by the membrane electrode assembly (MEA). As the MEA also forms the technical heart of the fuel cell, it is a subject worth of detailed investigation.

The MEA converts hydrogen into electrical energy and consists of a polymer electrolyte membrane (PEM), precious-metal catalyst layers and gas diffusion layers. Bringing these three components together is relatively simple; however, manufacturing the individual components is not. Synthesising the PEM in particular is complex and costly.

Our analysis shows that in a scenario of 300,000 FCEVs produced annually, a single MEA would cost € 7/unit. Costs are dominated by material costs, stemming from the special polymer required (€ 125/kg) and the platinum-based catalyst layer (€ 2,500/kg). Improvements in the MEA could potentially reduce costs to € 3/unit, or € 1,000/vehicle for the entire MEA system.

An optimistic future scenario shows both MEA and fuel cell system costs dropping by a further 80 % to approximately € 9,000/vehicle, although not for at least another decade from today. Despite this huge drop, it is doubtful whether this technology will be able to compete with enhanced battery technologies on cost. This scenario also assumes a significant decrease in the platinum load, down to less than 10 g/vehicle. Once this is achieved, the scenario forecasts annual production of 5 mn FCEVs, forcing demand for platinum up significantly to a level difficult to meet at today's prices.

Fuel cell technology offers significant



Source: Roland Berger calculation

① CO$_2$ emissions 2006, 2012 and targets for 2020 in EU-27 [g/km]

potential and we expect it to occupy certain automotive niche markets within the next decade. However, costs and platinum-based technology will limit mass market penetration. Instead, battery-based and plug-in hybrid powertrains are expected to become the major factors in the medium term on the path to zero-emission mobility.

In this first of a two-part series, we look at alternative powertrains, and the dream of zero emissions. This part also describes how fuel cell technology works.

ALTERNATIVE POWERTRAINS – THE DREAM OF ZERO EMISSIONS

Today's vehicles are predominantly based on conventional combustion engines fed by diesel or gasoline fuels. Over the last decade, the automotive industry has achieved significant improvements in powertrain energy efficiency, driven mainly by stricter regulations and rising fuel prices. However, CO$_2$ regulations from 2020 onward (as proposed by the European Commission in June 2013, currently under evaluation) will further increase the need for powertrains that demand less carbon-based fuel, ①.

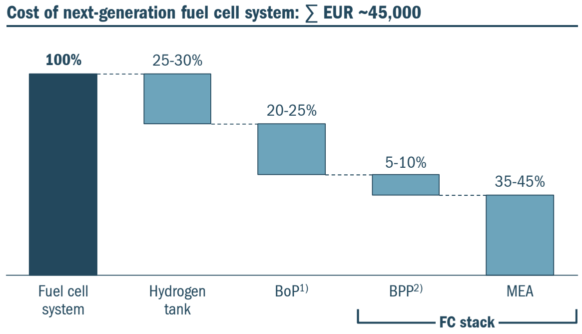
Besides increasing the efficiency of conventional combustion engines, three major technologies can be used to reduce CO$_2$ emissions:

:: Alternative fuel types, e.g., natural gas;
:: Partial powertrain electrification, e.g., serial and parallel hybrid solutions, also as plug-ins (PHEV);
:: Pure electric vehicles, based on:
  √ Energy absorption, storage and release through batteries;
  √ On-board energy generation through fuel cell technology.

Of these options, only fully electric vehicles offer the possibility of zero-emission mobility. However, if zero-emission technology is to attain broad market appeal, it must first become competitive in terms of costs and mobility options.

For more than a decade, fuel cell vehicles have been announced to be on the verge of a breakthrough. The next generation of fuel cell vehicles is set to debut in 2015. However, although this next generation is expected to be manufactured in a small series production of 3,000 vehicles per year, the cost of a fuel cell system for the OEMs is still high at an estimated € 45,000 per vehicle, or about € 500 per kW. Significant portions of the overall cost are due to the fuel cell tank and the balance of plant (BoP), an umbrella term for various required support components such as a humidifier, pumps, valves and compressor. The fuel cell stack, especially the membrane electrode assembly (MEA), accounts for the lion's share of the cost, ②.

The BoP and the fuel cell tank are relatively established technologies and so their cost development is fairly predictable. Therefore, it is the MEA that will decide the success – or failure – of

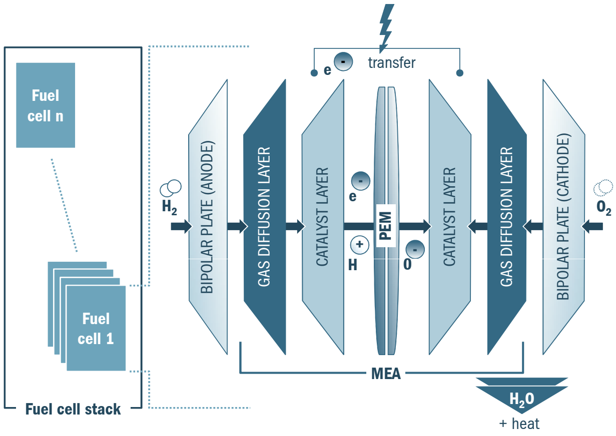


Comments

- Total cost of next-generation fuel cell system estimated at EUR 45,000 – market entry expected from 2015 onward
- Baseline of cost break-down is a system with 90 kW power and low serial production volume of approx. 3,000 vehicles per year
- MEA has the highest cost share, driven especially by platinum, a catalyst material [platinum load: approx. 0.3-0.4 mg/cm^2]

1) Balance of plant 2) Bipolar plates
Source: Expert interviews; Roland Berger

② Cost breakdown fuel cell system



Comments

- Single fuel cell with low voltage (~1 V) – Normally "piled" together into a fuel cell stack
- Current fields of improvement:
  - High amount of platinum required for catalyst
  - Reactant air needs to be humidified
- Next generation of fuel cells operate at higher temperature and will need less catalyst material and no humidification

Source: Roland Berger

③ Schematic view of a PEMFC

cost-competitive fuel cell technology. For this reason, our study focuses on both the technical and cost core of the system: the MEA.

HOW FUEL CELL TECHNOLOGY WORKS

A fuel cell system typically consists of auxiliary components (humidifier, pumps, valves, etc. grouped together as BoP) and a fuel cell stack, which is made up of hundreds of bipolar plates and MEAs. The leading fuel cell type for automotive applications is the polymer electrolyte membrane fuel cell (PEMFC).

A PEMFC is characterised by a MEA that is embedded between bipolar plates, which form the cathode and anode of the fuel cell. The MEA converts reactants into electrical energy, facilitates the performance of the stack, and therefore forms the heart of the system, ③.

The general operating principle is as follows:

:: Hydrogen (H_2) is fed into the fuel cell anode;
:: H_2 is split into protons (H+) and electrons (e-) by means of a catalyst;
:: The membrane lets only protons (H+) pass – the electrons (e-) are forced to follow an external circuit, creating a flow of electricity;
:: Oxygen is fed into the fuel cell at the cathode;
:: Oxygen, electrons from the external circuit and protons combine to form water and heat.

This results in the net reaction:

$2H_2 + O2 = 2 H_2O$

To achieve enough electrical power to propel a vehicle, multiple fuel cells have to be compiled into a fuel cell stack. Let's take a closer look at the MEA and its three components:

:: Polymer electrolyte membrane (PEM);
:: Catalyst layer (CL);
:: Gas diffusion layer (GDL).

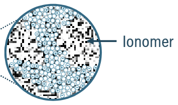
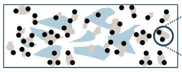
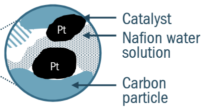
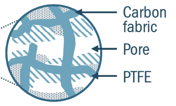
Each of these components has a specific purpose, summarised ④.

Today, the most common form of PEM used in automotive applications is based on perfluorinated sulfonic acid membranes, or PFSAs. With strong reduction and oxidation stability, PFSA polymers are most commonly known under the name Nafion [1]. They are composed of a hydrophobic backbone and hydrophilic side chains terminated with sulphonic acid groups.

In the CL, the most common catalyst is platinum, supported by a substrate such as highly active carbon black (Pt/C catalyst). The advantage of supported catalysts lies in higher efficiency, e.g., by providing high electrical and thermal conductivity as well as chemical and mechanical stability. About 20-60 % of the weight of these Pt/C catalysts is made up of platinum in order to deliver high electrochemical activity, and incurs the bulk of the MEA costs. The typical size of a Pt/C particle is 3-5 nanometres (nm). In addition to Pt/C, the catalyst layer usually contains an additional amount of PFSA and a solvent.

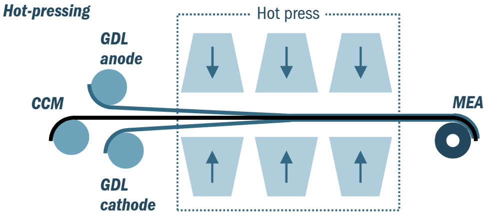
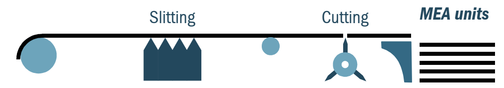
The third component, the GDL, is made predominantly of carbon paper. Carbon is highly porous and possesses good electrical conductivity and mechanical strength. In general, the GDL is relatively mature and has a simpler structure than the PEM and CL. This study focuses on the most widely used process for creating an MEA, ⑤:

:: Catalyst ink is applied to the PEM using a die coating process, resulting in a catalyst-coated membrane, or CCM;
:: Two GDL layers are integrated on the top and bottom of the CCM with a hot-pressing process;
:: Finally, a simple cutting process produces single MEA units.

Comp.	Purpose and features	Structure of layers	Composition
PEM	> When saturated with water, conducts/transports protons (water transport) and blocks electrons > Is impermeable to anode and cathode gas > Common ionomer is Nafion, with a polytetrafluoroethylene (PTFE) backbone and perfluorinated vinyl polyether side chains		
CL	> Facilitates and accelerates the chemical reaction by reducing activation energy > Conducts protons to membrane and electrons to GDL > Catalyst particles (e.g. platinum, platinum alloys) are mixed with carbon black as substrate (support material)		
GDL	> Effectively/evenly diffuses hydrogen and oxygen to the CL > Transports electrons to and from the catalyst layer > Keeps PEM moist while allowing produced water to exit > Porous carbon paper or cloth usually wet-proofed with PTFE to avoid water saturating the pores		

Source: Thampan; Roland Berger

④ Purpose and features of MEA components

Description	Process
1. Layers of CCM and two identical GDLs are unwound from rolls and merge to form a five-layer MEA assembly 2. The rolls are pressed between hot plates at ~130°C and 200-350 kPa per cm² 3. After opening the press, the hot-pressed membrane and electrode are rewound onto a spool	*Hot-pressing* 
4. Hot-pressed MEA roll is unwound 5. MEAs are slit into several streams depending on MEA geometry 6. MEA streams are cut into rectangles of defined size 7. MEAs are formed into stacks	*Slitting & cutting* 

Source: Directed Technologies, Inc.; Ramasamy; Roland Berger

⑤ MEA manufacturing process

REFERENCE:

[1] Typical density 1.979 g/cm^3

(The second part of this study would appear in our March 2014 edition.)

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