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Study

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 EUR 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. Synthesizing 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 EUR 7/unit. Costs are dominated by material costs, stemming from the special polymer required (EUR 125/kg) and the platinum-based catalyst layer (EUR 2,500/kg). Improvements in the MEA could potentially reduce costs to EUR 3/unit, or EUR 1,000/vehicle for the entire MEA system.

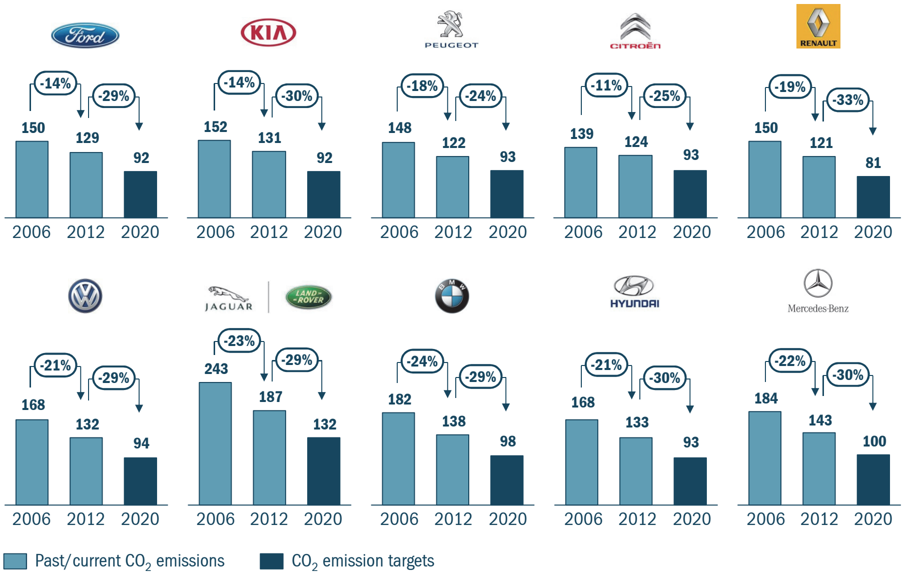
An optimistic future scenario shows both MEA and fuel cell system costs dropping by a further 80% to approx. EUR 9,000/vehicle, although not for at least another decade from today. Despite this huge drop, it is doubtful whether this technology will be able to compete with enhanced battery technologies 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 million FCEVs, forcing demand for platinum up significantly to a level difficult to meet at today's prices.

Fuel cell technology offers significant potential and we expect it to occupy certain automotive niche markets within the next decade. However, costs and platinumbased 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.

A. 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 (see Figure 1).

Figure 1: CO_2 emissions 2006, 2012 and targets for 2020 in EU-27 [g/km]



Source: Roland Berger calculation

Besides increasing the efficiency of conventional combustion engines, three major technologies can be used to reduce CO_2 emissions:

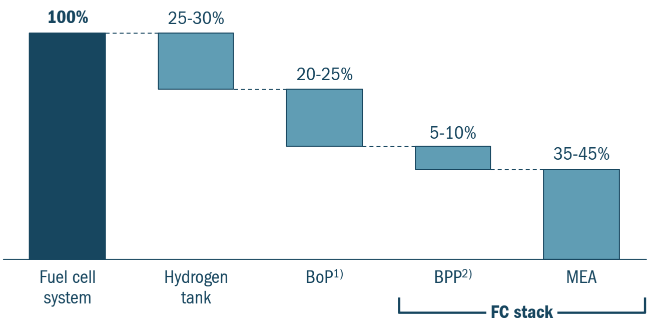
> Alternative fuel types, e.g. natural gas
> Partial powertrain electrification, e.g. serial and parallel hybrid solutions,
  also as plug-ins (PHEV)
> Pure electric vehicles, based on
  – Energy absorption, storage and release through batteries
  – On-board energy generation through fuel cell technology

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 EUR 45,000 per vehicle, or about EUR 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 (see Figure 2).

Figure 2: Cost breakdown fuel cell system

Cost of next-generation fuel cell system: ∑ EUR ~45,000



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

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]

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 cost-competitive fuel cell technology.

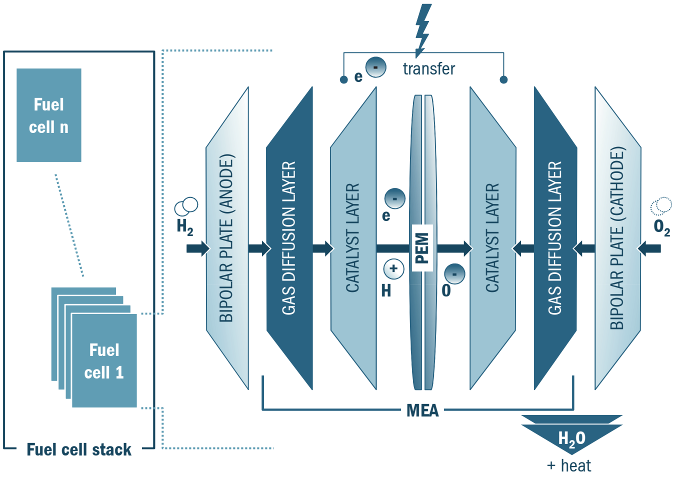
For this reason, our study focuses on both the technical and cost core of the system: the MEA.

B. 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 characterized 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 (see Figure 3).

Figure 3: Schematic view of a PEMFC



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

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

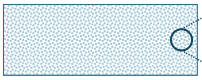
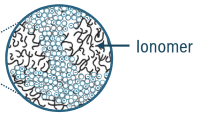
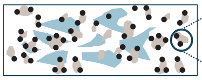
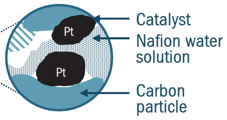
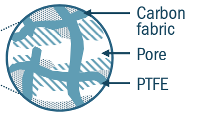
This results in the net reaction: $2H_2 + O_2 = 2\ H_2O$

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, summarized in Figure 4.

Figure 4: Purpose and features of MEA components

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

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 Nafion1). They are composed of a hydrophobic backbone and hydrophilic side chains terminated with sulfonic 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 nanometers. In addition to Pt/C, the catalyst layer usually contains an additional amount of PFSA and a solvent.

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1) Typical density 1.979 g/cm³

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.

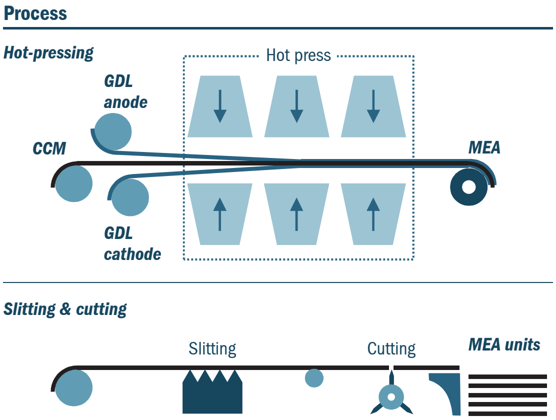
This study focuses on the most widely used process for creating an MEA (see Figure 5):
> Catalyst ink is applied to the PEM using a die coating process, resulting in a catalyst-coated membrane, or CCM
> Two GDL layers are integrated on the top and bottom of the CCM with a hot-pressing process
> Finally, a simple cutting process produces single MEA units

Figure 5: MEA manufacturing process

Description

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

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



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

C. The cost of developing fuel cells – who can afford zero emissions?

All discussions about opportunities for fuel cell vehicles raise the question of economies of scale. Therefore, our MEA cost analysis is based on a scenario with annual global production of 300,000 fuel cell vehicles.

At first glance, the cost structure of MEA seems fairly straightforward: three components are joined by an ordinary pressing and cutting process. However, upon closer inspection, things change: While GDLs are highly commercialized and therefore balanced in their pricing, CL costs depend heavily on the amount of required platinum. However, the biggest mystery lies in the cost of PEMs. There are currently very few providers of PFSA polymers and PEMs on the market, and the leading PFSA-based product, Nafion, is sold for EUR 950-1,000 per kg. Understanding its cost structure is a necessary first step to understanding cost reduction potential from a technology perspective.

Deep-dive: PEM cost structure

In our scenario, the automotive industry pushes PFSA demand up to roughly 500 tons per year, twice today's estimated total world market volume. Assuming five plants in the world market have the necessary know-how in specialty chemistry, the approximate net production capacity is 100 tons per year. Given a utilization rate of 72%, a plant's nameplate capacity for PFSA production is assumed to be 140 tons per year (see Figure 6).

Figure 6: Assumptions for PFSA polymer demand

PFSA polymer demand

Chlor alkali industry	Installed membrane area [m^2]	700,000
	Lifecycle [years]	4
	Replacement business [m^2/year]	175,000
	Additional business [m^2/year]	35,000
	Ionomer weight [kg/m^2]	1
	Market production PFSA polymer [tons/year]	**210**
Automotive demand	Ionomer weight [g/m^2]	47.5
	MEA area [cm^2]	460
	MEAs per vehicle [units]	350
	FCEV production [units]	300,000
	Total membrane area – net [m^2]	4,830,000
	Membrane scrappage [%]	25
	Total membrane area – gross [m^2]	6,037,500
	Ionomer demand [tons/year]	**287**
∑	**approx. 500 [tons/year] / 5 plants = 100 [tons/year]**	

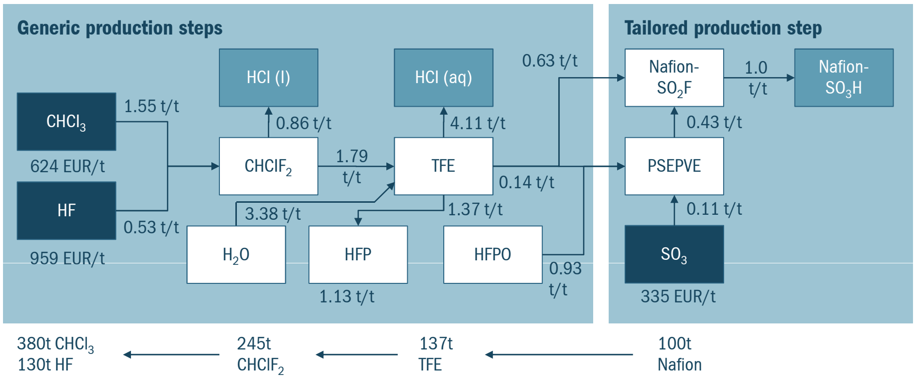
Comments

- With an underlying **demand** of **300,000 FCEVs** per year, PSFA polymer demand is expected to increase from 210 tons to approx. **500 tons** per year
- The analysis assumes **five existing production facilities** for Nafion
- As no single facility currently dominates, yearly **net production** of **approx. 100 tons** was chosen for further cost analysis
- For the purposes of this study, we chose **Nafion nameplate production** capacity of **140 tons**, derived from a typical **utilization rate** of **72%** in the specialty chemicals industry (5,760 hours out of 8,000)

Source: Jülich; Expert interviews; Roland Berger

We also assumed that PFSA is synthesized on the premises of a fully integrated chemical industry park, at which some precursors of PFSA are manufactured for several products and only the last few steps are tailored to PFSA production. Aiming for a target output of 100 tons of polymer material per year, all necessary raw materials have been quantified in a comprehensive material flow analysis as depicted in Figure 7. Additionally, investment costs for all production facilities, including auxiliary facilities, have been included for production of all intermediates. The cost calculation includes bottom-up production costs for each individual chemical production step, briefly described below:

Figure 7: Material flow in PFSA synthesis



Assumed nameplate production capacity: $CHClF_2$: 12.5 ktpa, TFE: 7 ktpa, HFP: 1.7 ktpa, HFPO: 1.4 ktpa

■ Purchased materials ▨ By-products and end ☐ Intermediate

Source: BTS; Roland Berger

At its core, PFSA production consists of a single process step: copolymerization of tetrafluoroethylene (TFE) and a special co-monomer called PSEPVE. Prefabrication of these two materials, however, is complex and involves fluorine chemicals.

TFE is primarily a source material for the production of PTFE, which is more commonly known under the brand name Teflon. PTFE is made by combining chloroform ($CHCl_3$) and hydrofluoric acid (HF) to yield chlorodifluoromethane ($CHClF_2$) – toxic and explosive materials and processes that only a handful of chemical manufacturers deal with. $CHCl_3$ and HF are considered input materials for which purchasing costs are assumed.

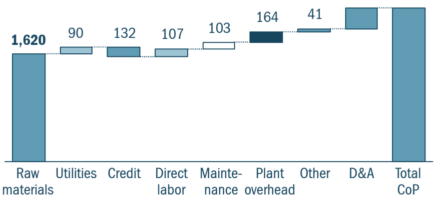
PSEPVE is a unique fluorointermediate made by synthesizing three special input materials: TFE, sulfur trioxide (SO_3) and hexafluoropropylene oxide (HFPO), the latter synthesized from TFE by rearrangement and oxidation. Even fewer manufacturers worldwide have mastered the highly complex synthesis processes of PSEPVE. The derived co-monomer and TFE then copolymerize to result in the PFSA polymer, which is formed into its useful physical shape and converted to the usable SO_3H form through hydrolysis and acid treatment. In contrast to TFE, PSEPVE is used solely for production of PFSA polymers and nothing else.

In our scenario, PFSA polymers can be produced for approximately EUR 125/kg, a fraction of current market prices. The majority of the cost – EUR 78/kg – is for raw materials, reflecting the complex production of the precursors as described above. These costs are fully included as input for the final PFSA polymer synthesis. Other significant costs are plant overhead (EUR 13/kg) and depreciation and amortization (EUR16/kg). Maintenance and direct labor costs account for EUR 15/kg. Remaining costs, for utilities (electricity, natural gas and steam) or for cooling or process water, are negligible.

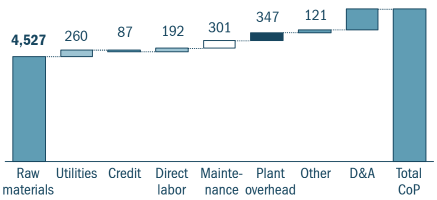
The breakdown of the cost of production for the PFSA polymer and its precursors is shown in Figure 8.

Figure 8: Cost of PFSA polymer production

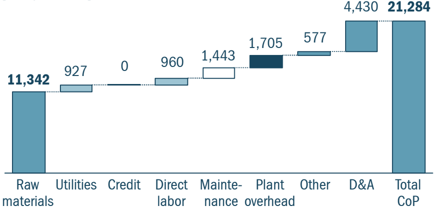
$CHClF_2$ – Cost of production
[EUR/t $CHClF_2$]



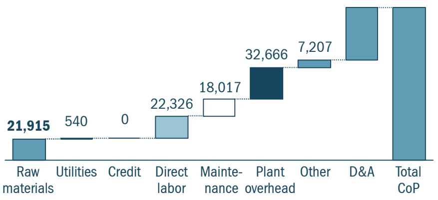
TFE – Cost of production
[EUR/t TFE]



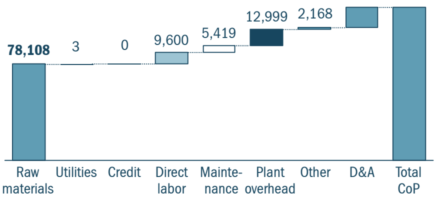
HFPO – Cost of production
[EUR/t HFPO]



PSEPVE – Cost of production
[EUR/t PSEPVE]



PFSA Polymer – Cost of production
[EUR/t PFSA polymer]



Source: BTS; Roland Berger

Main assumptions for cost calculation	
Raw materials	Include 10% markup for chemicals and catalysts
Utilities	Cost of gas, steam and electricity – Includes 10% markup for other utilities such as cooling water, etc.
Maintenance	5% of investment
Plant overhead	Indirect labor within plant, set as fixed costs – 10% of direct labor & 45% of maintenance costs
Other	Cost of insurance and health & safety – 2% of investment
D&A	10% of capital investment (linear) 10% interest rate

The big picture – MEA cost structure

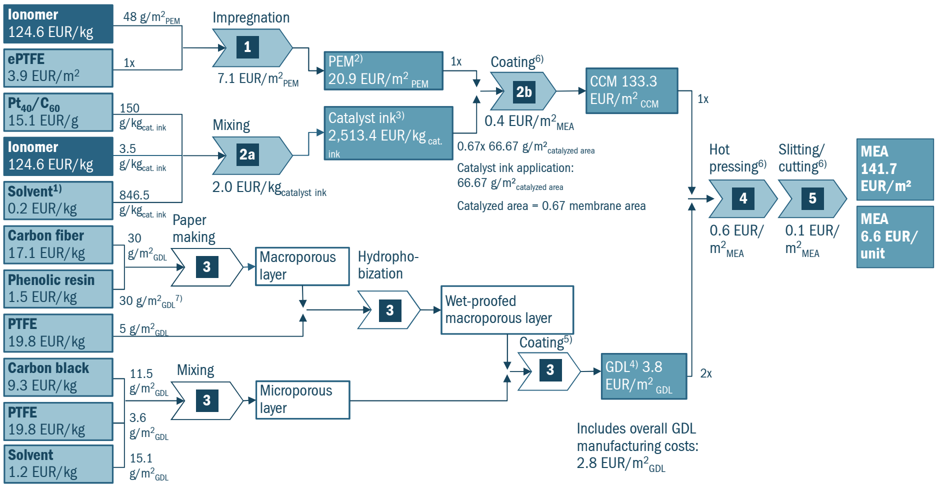
The production of PFSA is expected to remain with specialized chemical companies. In contrast, MEA manufacturing processes do not require such specific expertise and generally can be done by automotive OEMs or their suppliers. Therefore, the basis for the MEA cost structure is an OEM with a production volume of 30,000 vehicles (requiring approximately 500,000 m^2 MEA at current performance), reflecting a 10% market share of the scenario's 300,000 fuel cell vehicles per year.

Starting with the raw materials for the three components PEM, CL and GDL, the MEA cost structure can be broken down as follows:

The PEM ionomer costs were calculated at EUR 125/kg. The PFSA is reinforced with an ePTFE web, which costs roughly EUR 4 per m^2. When this impregnation process is included, the PEM costs EUR 21/m^2

The catalyst layer is the most expensive part of the MEA and heavily driven by platinum2). For this study, we chose a Pt_{40}/C_{60} catalyst, which is mixed with the ionomer and the solvent to create a catalyst ink. Overall, the costs for catalyst ink exceed EUR 2,500/kg.

Figure 9: Breakdown of MEA costs



1) Weighted average of all solvents 2) Including 30% material scrap rate 3) Including 10% material scrap rate
4) Including 20% material scrap rate 5) Sum of all GDL process costs 6) Negligible scrap rate of below 1% 7) Incl. 50% yield

■ Cost-based ▨ Price-based ■ Material and manufacturing costs ▶ Manufacturing/process costs ▷ ☐ No deep-dive analysis

Source: Roland Berger

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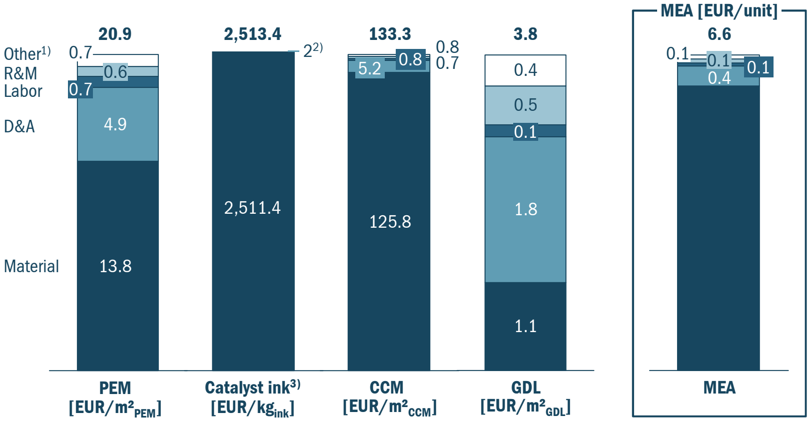
2) Calculated using a platinum price of EUR 37,646/kg

The most commonly used GDLs consist of a macroporous and a microporous layer. The macroporous layer is wet-proofed by adding PTFE via a hydrophobization process. The microporous layer consists of carbon black, PTFE and a solvent. The two layers are joined to the GDL using a coating process, which costs a total of 4 EUR/m² at high volume production, the lowest for any of the MEA components.

As previously described, the PEM is coated with catalyst ink in a process with negligible costs. For this part of the study, we assumed a catalyst-to-membrane ratio of 0.67 and consumption of 0.67g/m² catalyzed area, reflecting a platinum load of 0.4 mg/cm². As a result, the CCM cost base adds up to EUR 133/m². Including pressing the GDL onto the top and bottom of the CCM and the cutting process, MEA costs add up to EUR 142/m², or roughly EUR 7/unit as shown in Figure 9.

Considering each component individually, materials are the dominant cost factor, accounting for roughly 90% of overall MEA costs (see Figure 10). Platinum in particular is a driving factor. For this study, we assumed platinum usage of 0.4 mg/cm².

Figure 10: Cost structure by MEA component



1) Energy and miscellaneous
2) D&A: 0.4; Labor: 1.5; R&M: 0.1; Other: 0.1; Total: 2 EUR/kg_{ink}
3) Incl. 10% material scrap rate
Source: Roland Berger

However, even in a scenario with a global production volume of 300,000 fuel cell vehicles, production of MEAs alone add up to approximately EUR 2,500/ vehicle[3].

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[3] *Reflecting pure production cost without any margins or transfer prices between companies*

In the future, improvements in stack operations, design and production technology may reduce MEA costs. We have identified 5 major levers that can have a positive effect on the MEA cost structure:

> Reducing scrap rates: Current manufacturing processes have significant scrap rates of up to 30%[4]. Cutting these by half would yield significant cost savings

> Optimizing MEA design: The current membrane/catalyst area ratio of 0.67 can be increased further, with a positive effect on required membrane material

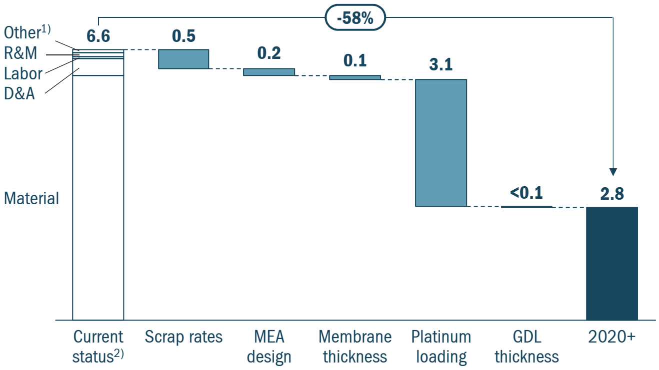
> Decreasing membrane thickness: Reduce current thickness from 25.4 µm to 15 µm

> Adjusting platinum loading: Further reduce the required amount of platinum from today's 0.4 mg/cm^2 to 0.15 mg/cm^2

> Reducing GDL thickness: Decrease current thickness from 210 µm to 130 µm

Naturally, the technical design and component specifications can only be made if they do not negatively affect the MEA's durability and performance.

Figure 11: MEA long term cost optimization levers 2020 [EUR/unit]



Comments

> Due to the high price and cost share of platinum, changes in the platinum loading have the greatest effect on cost

1) Energy and miscellaneous 2) Aggregate values from single processes
Source: Roland Berger

Implementing all these levers would decrease estimated MEA costs by 58%, down to roughly EUR 3/unit or about EUR 1,000 per vehicle (see Figure 11).

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4) Scrap rates: Membrane production ~30%; catalyst application ~10%; GDL manufacturing ~20%

D. Platinum – the central problem of the fuel cell story

Today's fuel cell systems use platinum as a catalyst, and this is likely to remain so over the next decade. Global reserves of this rare and expensive material are estimated to be one-thirtieth the size of gold reserves, with roughly 90% concentrated in just two countries, South Africa and Russia.

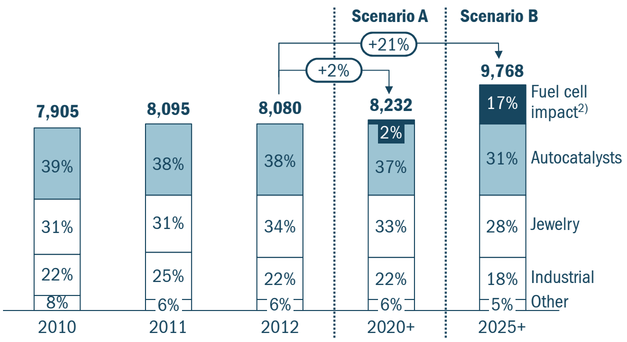
The platinum industry is characterized by volatile production volumes and limited investment potential. For example, labor disputes in South Africa caused a loss of 400,000 ounces in 2012, or roughly 8% of the country's export volume. What's more, low margins and highly fluctuating production volumes limit the potential for new investment in platinum mining.

These unfavorable business conditions, coupled with platinum's scarcity, mean that the price is not expected to decrease. An expansion in the supply base is also rather unlikely. Overall, platinum demand over the past few years has been more or less stable. The highest demand comes from the automotive industry, and demand would rise still further if fuel cell vehicles were put into series production.

Let us therefore consider two scenarios. Scenario A reflects the base scenario of the cost analysis conducted above: global production of 300,000 fuel cell vehicles from 2020 onward with a platinum load of about 16 g/vehicle[5]. Assuming that the annual global production of light vehicles exceeds 100 million units by 2020, this scenario allocates less than 0.3% of the market to fuel cell vehicles, a rather conservative estimate. However, even in this scenario, the demand for platinum would increase by 2% compared to 2012 levels (see Figure 12).

Figure 12: Impact of fuel cell vehicles on platinum demand

Platinum demand1) by application ['000 oz]



Comments

Scenario A:
Next-generation technology will reach 0.15 mg/cm² platinum load in the MEA – By 2020, a global production volume of 300,000 vehicles is assumed

Scenario B:
FCEVs will improve significantly in costs and required platinum load decreases to <0.10 mg/cm² in the MEA. FCEVs become a global success story with a yearly production volume of 5 million units

1) Excluding movement in stocks 2) Underlying assumption: 300,000 FCVs with each 16 g platinum in Scenario A, 5 million FCVs each with <10 g platinum/vehicle in Scenario B

Source: Johnson Matthey; Roland Berger

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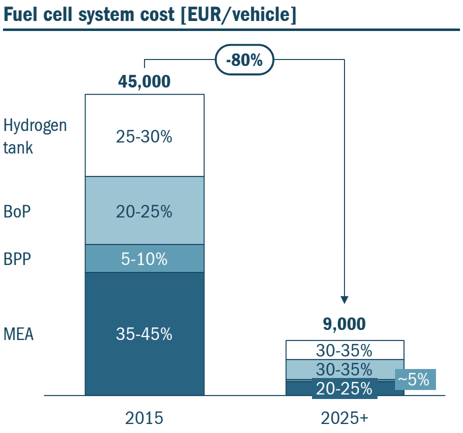
[5] *Based on a platinum load of 0.15 mg/cm², 300 cm² active area per MEA and 350 MEAs per fuel cell stack*

Scenario B assumes that fuel cell vehicles will become a fully cost-competitive alternative and therefore forecasts global annual production of 5 million fuel cells no earlier than a decade from today. The underlying cost improvements to fuel cell systems are based on technological and financial levers:

> Platinum load further decreased to <10 g per vehicle
> Simplifying BoP will streamline individual components
> Improved production technologies enable mass production of today's lowscale producible components (e.g. hydrogen tanks)
> Full leverage of economies of scale, including optimized development and implementation of modular kits by OEMs

With these improvements, Scenario B forecasts an 80% reduction in today's fuel cell system costs (see Figure 13).

Figure 13: Assumed fuel cell system costs in scenario B



Source: Interviews; Roland Berger

Comments

Scenario B assumes that both technological and financial levers can significantly decrease fuel cell system cost:

> Reducing platinum demand to <10g per vehicle has a positive effect on material costs
> Streamlining components by simplifying BoP decreases costs and manufacturing complexity
> Improved production technologies enable mass production of today's low-scale producible components, such as hydrogen tanks
> Economies of scale will significantly reduce share of fixed costs and push learning effects

As mentioned above, this cost improvement may result in 5 million units being produced, accounting for about 5% of the global market. What's more, each vehicle will require only 10 g of platinum per vehicle instead of 16 g as in Scenario A. As a result, platinum demand would rise 21% from 2012 levels (see Figure 12). Considering the current state of the platinum industry, it seems unlikely that this demand will be met at today's price levels.

Therefore, the potential for fuel cell vehicles will lie in niche applications and markets, as it is doubtful whether there is enough platinum for broad-based use of fuel cells in automotive applications. In addition to reducing the cost of components, a technological solution without platinum will be necessary to achieve the vision of zeroemission mobility through the comprehensive use of fuel cells.

E. Conclusion – fuel cells: an interesting alternative, but only in the long term

Due to their basic characteristics, FCEVs will continue to be viewed as an attractive option for meeting the CO_2 challenge. Our analysis revealed that in a mass production scenario, fuel cell system costs can be decreased by ~80% to approximately EUR 9,000/vehicle. A deep dive into the most opaque parts of the MEA (membrane electrode assembly) cost structure supplemented this approach. However, the platinum-based technology currently favored will put a massive strain on global availability of this raw material, reinforcing the doubts about this technology. Non-platinum solutions are currently still in the fundamental research stage. It will be at least another decade before prototypes can be expected to produce meaningful results.

Therefore, in light of the formidable costs, fuel cells will make it into broader applications only if a suitable substitute for platinum can be found. OEMs need to balance the development of FCEVs for small series production with rolling out a sustainable zero-emission technology suitable for the mass market. At the moment, no non-platinum fuel cell technology has emerged as a frontrunner, so prioritizing and approving the advanced engineering budget will be an important first step for successful FCEV penetration.

Fuel cells remain an interesting element in the quest for zero-emission mobility, but the prohibitive costs plus dwindling supply of platinum mean that they are currently unlikely to prove the magic bullet OEMs dreamed of.

Contact

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