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Economics of Polymer Electrolyte Membrane Fuel Cells

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Abstract: Hydrogen is considered a key component of the renewable energy transition for the 21st century, with potential applications using fuel cells in the transportation sector, decentralized heating systems, and energy storage. However, the conversion from fossil fuels to hydrogen implies comprehensive research to address technological and socio-economic challenges, enabling its widespread adoption. This paper discusses the economics of fuel cells. A cost analysis of the polymer electrolyte membrane fuel cells (PEMFC) is performed, and current market data and developments are presented.

Keywords: cost breakdown; economics of fuel cells; market analysis; PEMFC; polymer electrolyte membrane fuel cells

1 INTRODUCTION

One of the fundamental concerns of our time is the accelerating climate change, which is primarily driven by increasing global energy demand and the use of fossil fuels [1]. This underscores the need for renewable and clean alternative energy sources [2]. One solution to these challenges is hydrogen, which serves as an emission-free energy carrier. The fact that hydrogen, with a lower heating value of up to 120 MJ/kg, exhibits an expectedly high energy to mass ratio compared to other fuels shows the enormous potential of this element [3]. As hydrogen is particularly suitable as an energy carrier, its production must be based on renewable energies to ensure sustainability. Producing hydrogen using fossil fuels is observed to offer no advantage over the direct use of fossil fuels; consequently, the production of hydrogen by electrolysis is regarded as the most rational course of action [4].

Hydrogen is considered a key component of the renewable energy transition for the 21st century, with potential applications using fuel cells in the transportation sector, decentralized heating systems, and energy storage. However, the conversion from fossil fuels to hydrogen implies comprehensive research to address technological and socio-economic challenges, enabling its widespread adoption [1, 5].

2 STATE OF THE ART

Fuel cells, which transform the chemical energy stored in fuels directly into electricity through electrochemical processes, are widely recognized as advanced power devices due to their remarkable efficiency and minimal emissions. They are classified based on their electrolyte type into (PEMFC), solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC), and alkaline fuel cells (AFC) [6]. From a technical point of view, the PEMFC has advantages of up to 80 % electrical efficiency and low operating temperatures between 60 °C and 85 °C [7]. The operating principle of the PEMFC shown in Fig. 1 is based on the utilization of hydrogen and oxygen to generate electrical energy and oxygen. The splitting of hydrogen at the anode into protons (H+) and electrons (e–) is a central process. The protons, which are positively charged due to the splitting of the hydrogen, pass through a polymer electrolyte membrane (PEM) to the cathode, while the electrons, which are negatively charged due to the splitting of the hydrogen, flow through an external circuit and generate electrical energy; at the cathode, the protons and electrons react with oxygen and produce water.

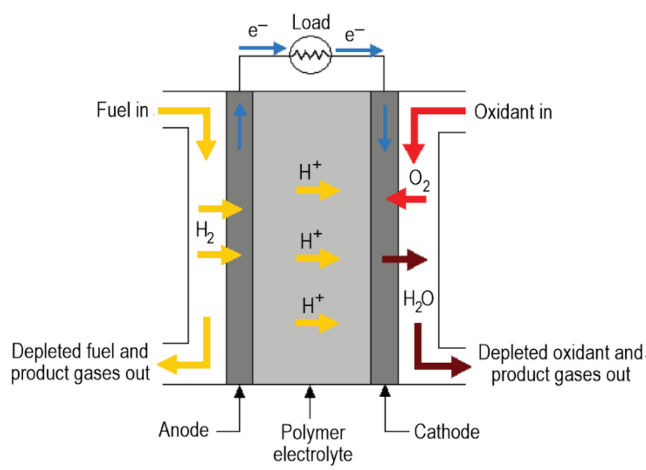

Figure 1 PEMFC schematic operating principle [12]

The PEMFC market volume also shows that the PEMFC is the dominant fuel cell technology today in terms of shipments and power output [8]. Low temperature operation enables rapid start-up and reduces wear on system components, improving overall durability. This approach involves the use of a noble metal catalyst, usually platinum, to facilitate the separation of hydrogen's electrons and protons, which contributes to higher system costs [9]. The PEMFC is considered a potential future type of power source for transportation, stationary and portable applications due to its easy scalability and high-power density. The PEM is used as a conductor for the protons and an electrochemical catalyst to enable reactions at low temperatures [10]. The PEM is coated on both sides with a catalyst layer, which is referred to as catalyst coated membrane (CCM). The CCM is surrounded by two sub gasket layers and is covered on both sides by a gas diffusion layer (GDL). Together this forms the membrane electrode unit (MEA) [11]. Another key component is the bipolar plates (BPP). The MEA is compressed by the BPP that provide a homogeneous supply of reaction gases and is cooling the active area [12, 13]. The individual cells are assembled into a fuel cell stack with the seals, the current collectors, endplates and the gaskets as shown in Fig. 2.

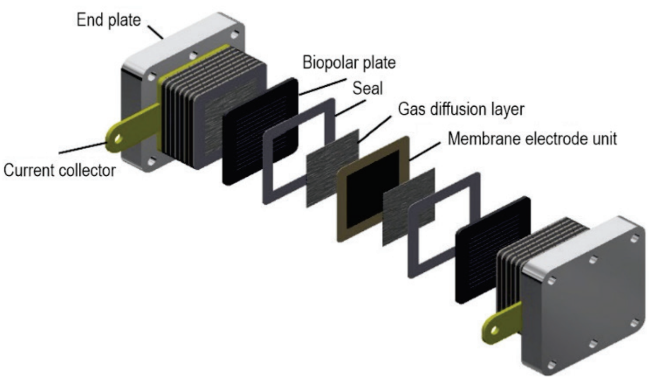

Figure 2 Components of a PEMFC stack [14]

3 METHODOLOGIES

To provide a comprehensive basis for the analysis of the economics of fuel cells, data from several recent relevant studies were used. Firstly, the studies were compared and evaluated based on their methodological approaches to ensure that the underlying data were comparable. For the cost analysis, studies from the Batelle Memorial Institute, Fraunhofer Institute IPT, and RWTH Aachen University were used. Quantitative data from these studies were consolidated into the present results and then presented visually in the form of charts and graphs. These visualizations allow a clear presentation of the relative cost distributions and contribute to a better understanding of the results. To conduct a comprehensive cost analysis, the current material costs associated with the production of PEMFCs were presented. The market analysis was based primarily on ERM's Fuel Cell Industry Review. Three recent market studies on different fuel cell sectors were used to present the prospects.

4 RESULTS
4.1 Cost Breakdown

As part of the Batelle Memorial Institute's 2017 study, a cost analysis was conducted for PEMFC’s with power outputs ranging from 1 kW to 25 kW.

In this study, the costs were analyzed for different numbers of units produced from 100 to 50 000 per year. The cost breakdown focuses on the 10 kW PEMFC and examines the general cost structure on the one hand and the costs related to the components on the other hand.

Assumptions for the cost analysis of a 10-kW fuel cell stack:

- Platinum (Pt) loading: 0,4 mg Pt/cm²
- Power density: 0,54 W/cm²
- Current density: 0,8 A/cm²
- Membrane material: Perfluorinated acids (PFSA), polytetrafluoroethylene reinforced
- Membrane thickness: 0,2 mm
- Number of cells: 106

Fig. 3 shows that as production increases, the cost per unit decreases significantly due to economies of scale. For example, as production volume increases from 100 to 50 000 units per year, the total cost per 10 kW PEMFC stack drops from 7 986 € to 1 490 €, a dramatic reduction of 81,35 %.

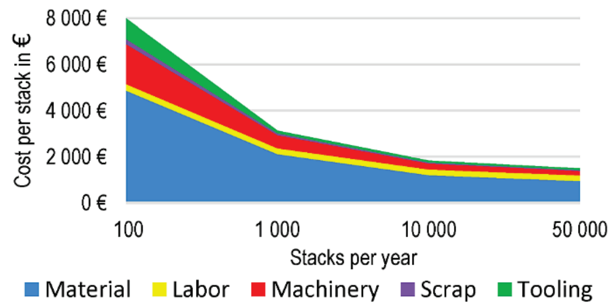

Figure 3 Cost scaling effects for 10 kW PEMFC (adopted from [15])

Fig. 4 shows an example of the cost breakdown for a stack production of 1 000 units per year. Over 67 % of the costs are material costs and over 18 % are machinery costs.

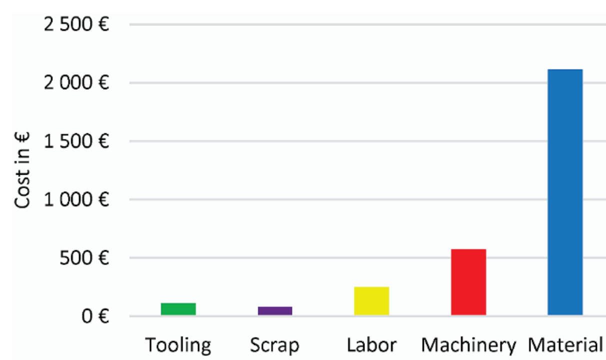

Figure 4 Cost breakdown for 1 000 stacks [15]

In the same study, the specific costs of the components were analyzed for different power outputs and production volumes (Fig. 5). The findings highlight significant economies of scale, as unit costs decrease considerably with higher production volumes. For smaller production volumes of 100 stacks per year, total manufacturing costs amount to 762 €/kW, whereas at 50,000 stacks per year, costs drop to just 142 €/kW. The MEA remains the most expensive component, but its share of total costs decreases as production volume increases. Particularly large cost reductions are observed in assembly, testing, and conditioning, indicating efficiency gains not only in material costs but also in production and quality control. In contrast, the relative cost reduction of the BPP is less pronounced. Generally, scaling effects are more significant for systems with lower production volumes [15].

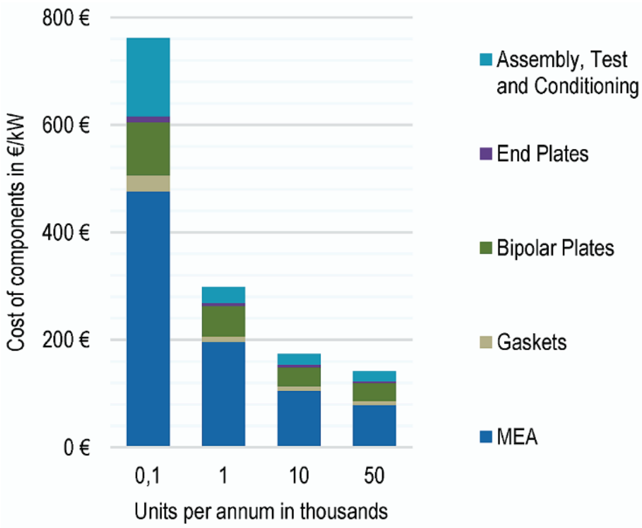

Figure 5 Cost breakdown of components for a 10 kW PEMFC [15]

According to the NOW study conducted by the Fraunhofer Institute for Production Technology IPT, the recurring components of a PEMFC can be qualitatively assessed based on their cost, lifespan, and manufacturing complexity. The end plates, gaskets, and current collectors exhibit relatively low manufacturing complexity and production costs while offering a comparatively long lifespan. In contrast, the MEA, BPP and GDL are identified as the most critical components in PEMFC manufacturing, with the GDL being considered separately from the MEA in this analysis. Among these, the MEA presents the greatest challenges, as it involves a highly intricate manufacturing process, incurs substantial material costs, and has a relatively short operational lifespan. Given these factors, optimizing MEA production techniques and material selection remains a key focus in improving the overall economic viability and durability of PEMFC technology.

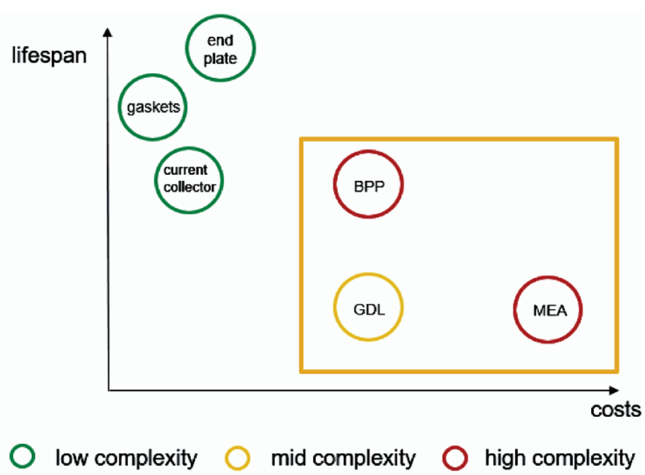

Figure 6 Qualitative evaluation of components according to lifespan, cost, and complexity (adapted from [16])

The material and machine costs for these three components, which are considered significant in the overall cost structure of the study from the Batelle Memorial Institute, are shown below.

Tab. 1 presents the conventional materials used in a PEMFC stack along with their current prices (September 2024). The cost of the catalyst, a key component of the MEA, significantly impacts the overall price. Additionally, there is a notable price difference between metal-based and graphite-based materials for the BPP, leading to a trade-off between cost, durability, and efficiency [11]. To facilitate cost comparisons, membrane prices are given in €/m², while all other materials are listed in €/kg. This approach allows for a clearer assessment of material cost impacts and highlights differences between components, such as the high cost of catalysts or the varying prices of BPP substrates and MEA membranes. Furthermore, the physical properties provided in the table offer valuable insight into the required material quantities and dimensions, which directly influence both the cost structure and the overall fuel cell stack design.

Table 1 Costs of the PEMFC stackstast components [13, 17-25]

Component	Material	Price	Physical properties
MEA Membrane	Nafion NR212 SPEEK-K Aquivion E98-15S	~ 3 306 €/m² ~ 172,95 €/m² ~ 12 800 €/m²	50,8 µm 105 µm 150 µm
MEA Catalyst	Platinum Rhodium	~ 28 790 €/kg ~ 147 740 €/kg	0,2 mg/cm² 0,01 mg/cm²
GDL	Carbon-fiber-based porous paper	~ 7 941 - 13 235 €/kg	0,3 - 0.5 g/cm³
BPP Substrate	Stainless steel Titanium Aluminium Graphit	~ 8,5 - 8,8 €/kg ~ 120 - 170 €/kg ~ 12,3 - 23,3 €/kg ~ 1 €/kg	8 g/cm³ 4,5 g/cm³ 2,7 g/cm³ 1,9 g/cm³
BPP Coating	Gold-based Carbon-based Metal nitrides	> 47 000 €/kg ~ 0,7 €/kg ~ 500 €/kg	19,3 g/cm³ 2,3 g/cm³ 5,2 g/cm³

According to the study by the Batelle Memorial Institute, machine costs represented the second largest cost center in PEMFC production. The following analysis highlights the components with the highest machinery costs.

The report by RWTH Aachen University and VDMA evaluated the machine costs for individual process steps in the production of PEMFC components. Fig. 7 shows the machine costs to produce the CCM, with the highest costs of 1 million € for coating the decals, followed by 0,9 million € for attaching the sub gaskets.

Fig. 8 shows the machine costs to produce the GDL component. With a total cost of €2,8 million, coating and sintering account for the largest share at €1,4 million.

Fig. 9 displays the machine costs for the BBP, with forming and cutting accounting for the largest share at 4,1 million €.

Fig. 10 provides the total machine costs for all production steps and illustrates that the production of the BPP accounts for the largest share of the costs at 8.6 million €. The machine costs to produce the MEA, which includes the production of the CCM, the GDL, and the assembly of the MEA, amount to a total of 8.4 million €. These machinery costs, representing the investments in machines and equipment required for the manufacturing process, result in an overall investment requirement of approximately 17 million € to cover the machine costs to produce all components [26].

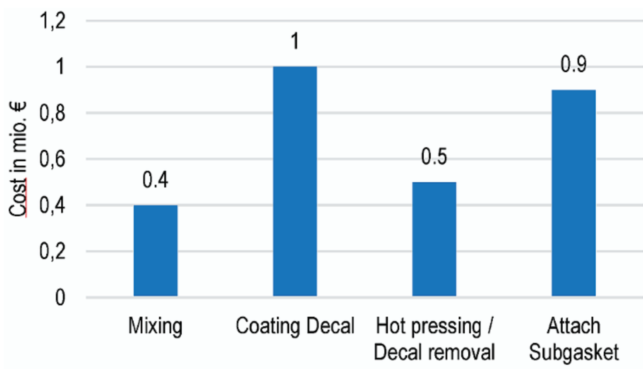

Figure 7 Machinery cost for CCM manufacturing [26]

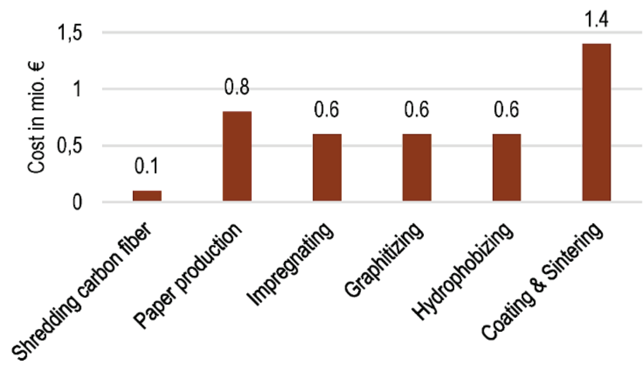

Figure 8 Machinery cost for GDL manufacturing [26]

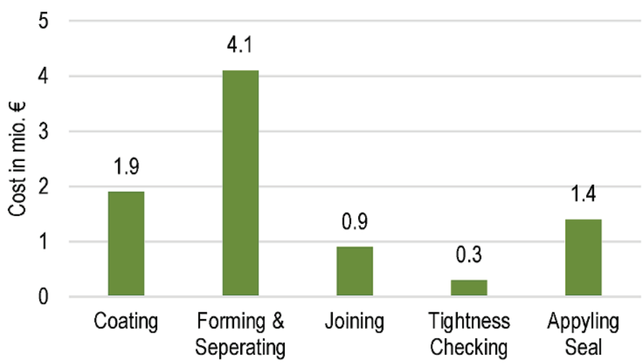

Figure 9 Machinery cost for BPP manufacturing [26]

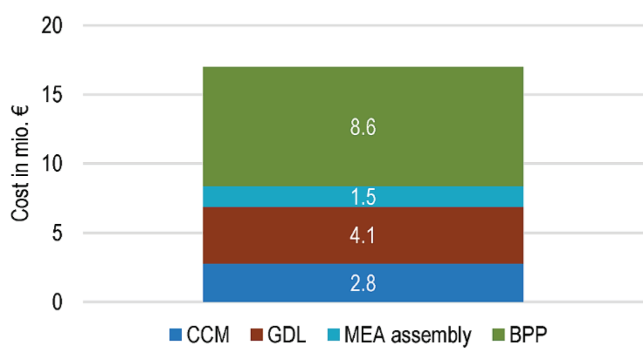

Figure 10 Total machinery cost for the PEMFC [26]

4.2 Market Analysis

The fuel cell market is highly diverse, with PEMFCs leading the sector. In terms of sales, PEMFC technology accounted for the largest share, representing 61 % of all fuel cells sold in 2022, amounting to a total of 89 200 units. SOFCs followed, capturing a 27 % market share as shown in Fig. 11.

With regard to installed capacity, PEMFCs are by far the most dominant. Fig. 11 shows the power output in 2022, which totalled over 2,49 GW. Of this, PEMFCs accounted for approximately 2,15 GW, representing around 86 % of the cumulative installed capacity in gigawatts.

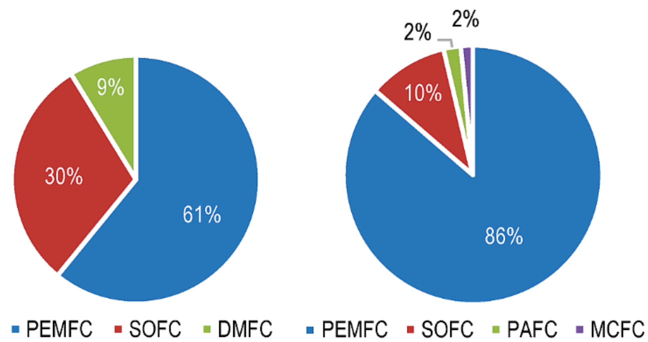

Figure 11 Shipments (left) and power output (right) by FC type [8]

Fuel cells play a crucial role across multiple industries and applications, with their deployment primarily concentrated in three key sectors. Tab. 2 provides an overview of the fuel cell types used and their typical applications within these sectors.

Table 2 Overview fuel cell sectors [6, 8]

	Transport	Stationary	Portable
Typical applications	fuel cell electric vehicles (FCEVs), buses, forklifts and trucks	power and heat generation for uninterruptible supplies in a permanent place	small-scale applications like portable chargers and small auxiliary power units
Fuel cell type	PEMFC	SOFC, PAFC, MCFC, AFC	PEMFC, AFC

In 2022, deliveries in the stationary sector were the most significant at over 57 %, followed by the transport sector, which accounted for just over a third of total shipments. In contrast, most megawatts were generated in the transportation sector (85 %) and 15 % in the stationary sector [8].

Table 3 Overview market analysis of fuel cells [27-29]

	Precedence research	Morder intelligence	Allied market research
Scope of investigation	Fuel cell market	PEMFC market	FCEV market
Investigation period	2024-2034	2024-2029	2022-2032
CAGR	26,2 %	18,4 %	43 %

There are several forecasts that assess the development of economics of fuel cells differently. Tab. 3 shows the different stages of development of the individual markets. The FCEV market has the highest growth potential with an impressive Compound Annual Growth Rate (CAGR) of 43 %, indicating the increasing demand for hydrogen vehicles and the decarbonization of transportation. In summary, the fuel cell market is forecast to record significant growth, although there are considerable differences in the growth rates of the individual market segments. The various segments are developing at different rates, which indicates different degrees of maturity.

The development of FCEV sales is another critical aspect, with significant growth expected in major regions like China, Europe, Japan, South Korea, and the USA. The cost of fuel cell stacks for automotive use is anticipated to decrease significantly, dropping by 84 % from 2006 to 2050 due to advancements in technology and increased production volumes [16, 28].

The prospects for fuel cells are driven by several factors:

1) **Technological Advancements:** Continuous improvements in fuel cell technology will lead to higher efficiency and lower costs [27].
2) **Government Policies:** Supportive policies and incentives for clean energy will boost market adoption [28].
3) **Infrastructure Development:** Investments in hydrogen infrastructure, including production, storage, and distribution, will facilitate the growth of the fuel cell market [29].
4) **Environmental Concerns:** Growing awareness and regulatory measures to reduce carbon emissions will drive the adoption of fuel cells [30].

5 CONCLUSION

The economic analysis presented in this report highlights the critical importance of scaling production, optimizing material and equipment expenditures, and evaluating market expansion potential. Material costs constitute the predominant portion of total stack costs and, while substantial reductions can be achieved through large-scale manufacturing, they remain the principal cost determinant. Among the various stack components, the MEA emerges as a primary cost driver, largely due to the high expenses associated with platinum and rhodium catalysts. The analysis further reveals inherent trade-offs between cost, efficiency, and durability, particularly in the selection of coatings for bipolar plates, where material composition significantly influences overall expenditure. Market projections indicate robust growth within the fuel cell sector, with PEMFCs expected to play a pivotal role in the future energy landscape, driven by ongoing technological advancements and supportive policy frameworks. Future research should focus on alternative catalyst materials to reduce dependency on platinum-group metals, advanced manufacturing techniques for cost-effective mass production, and innovative bipolar plate coatings that enhance both durability and performance while maintaining economic feasibility. Additionally, further analysis of supply chain resilience and policy-driven incentives could provide deeper insights into long-term market viability and investment strategies.

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