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Introduction to Proton Exchange Membrane Fuel Cells

1.1 Overview of Proton Exchange Membrane Fuel Cells Technology

Proton exchange membrane fuel cells (PEMFCs) are at the forefront of clean energy innovation, offering a sustainable and efficient means of power generation that is pivotal in addressing the challenges of global energy demands and environmental sustainability. PEMFCs work by converting the chemical energy of hydrogen directly into electrical energy through an electrochemical process, with water and heat as the only by-products. PEMFCs have widespread attention among clean energy technologies, renowned for their high efficiency, low operating temperatures, and rapid start-up times, making them suitable for a wide range of applications, from automotive and stationary power generation to portable power devices [1, 2]. As the world increasingly shifts toward renewable energy sources, PEMFCs provide a compelling alternative to traditional fossil fuel–based energy systems. Their ability to generate power with zero-greenhouse-gas emissions makes them an essential component in the global efforts to combat climate change and reduce the carbon footprint of energy production.

1.1.1 Brief History and Development of Proton Exchange Membrane Fuel Cell

The concept of fuel cells dates back to the nineteenth century when Sir William Grove first demonstrated the "gaseous voltaic battery" in 1839. However, it wasn't until the mid-twentieth century that significant advancements were made in fuel cell technology, primarily driven by the need for efficient power sources in space missions. While PEMFCs are a distinct type of fuel cell, their development is intrinsically linked to hydrogen as the primary fuel source. The exploration of hydrogen as a clean energy carrier has paralleled the advancement of PEMFC technology [3]. This synergy is crucial for the widespread adoption of fuel cell technologies, as hydrogen provides the necessary energy source that powers PEMFC systems. However H_2 as a low-carbon-energy system is not new; the wave of enthusiasm

Electrospinning for Proton Exchange Membrane Fuel Cells, First Edition.
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for hydrogen began in the early 1970s due to the first global energy demand and environmental crisis; thus, many hydrogen energy-based research programs were launched. For instance, the International Energy Agency (IEA) was established in 1974, the *International Journal of Hydrogen Energy* launched in 1976, and the IEA Hydrogen and Fuel-Cell Technology Collaboration Programme in 1977. Since then, a growing number of researchers, international organizations, and companies have supported the hydrogen-based economy to address the fossil fuel demand and control greenhouse gas (GHG) emissions [4]. The historical key milestone of hydrogen and fuel cells is depicted in Figure 1.1.

Today, hydrogen and fuel cell technologies offer a promising path toward sustainable energy. Ongoing research and development aim to overcome current challenges, such as reducing the reliance on precious metals and improving system efficiency and durability. Continued investment in research and infrastructure is essential to realizing the full potential of hydrogen as a clean energy carrier. Moreover, hydrogen is a versatile energy carrier, not an energy source, having potential applications to provide energy services across all sectors: transportation, power, building, and industry. Hydrogen is itself a carbon-free carrier, but a significant amount of carbon footprint occurs during its production [1, 4]. Presently, hydrogen is produced from various primary energy sources such as fossil fuels, biomass, and renewables. Low-carbon technological options like carbon capture and storage (CCS) and electrolyzers require extensive development to reduce carbon dioxide (CO_2) emissions during hydrogen production. As an energy carrier, hydrogen can overcome the variable renewable energy flexibility issue on the energy supply-and-demand side by enabling the linkage between them by connecting various transmission and distribution networks [5]. Hydrogen and fuel cell technologies are an excellent solution to decarbonize the transport sector. Green hydrogen produced from renewable energy sources such as solar photovoltaic (PV) and wind power could be integrated into fuel cell vehicles as a promising alternative to internal combustion engines [1, 5].

1.1.2 Need for H_2-Powered Fuel Cell Technology in Today's World

In the face of addressing global environmental challenges and an urgent need for sustainable energy solutions, hydrogen-powered fuel cell technology has emerged as a critical component in the global energy transition. The pressing issues of climate change, air pollution, and energy security have highlighted the necessity of moving away from fossil fuel dependency and toward cleaner, renewable energy sources [6]. The transport sector is one of the fast-growing and key driving forces of anthropogenic environmental pressure, contributing nearly 20% of GHG emissions, with fossil fuels accounting for almost 90% of total energy consumption. One-quarter of all energy-related GHG emissions are related to transportation, with around 72% of these overall emissions generated from road transport. Recently, the COVID-19 pandemic decreased global transport emissions by 10%, or 7.2

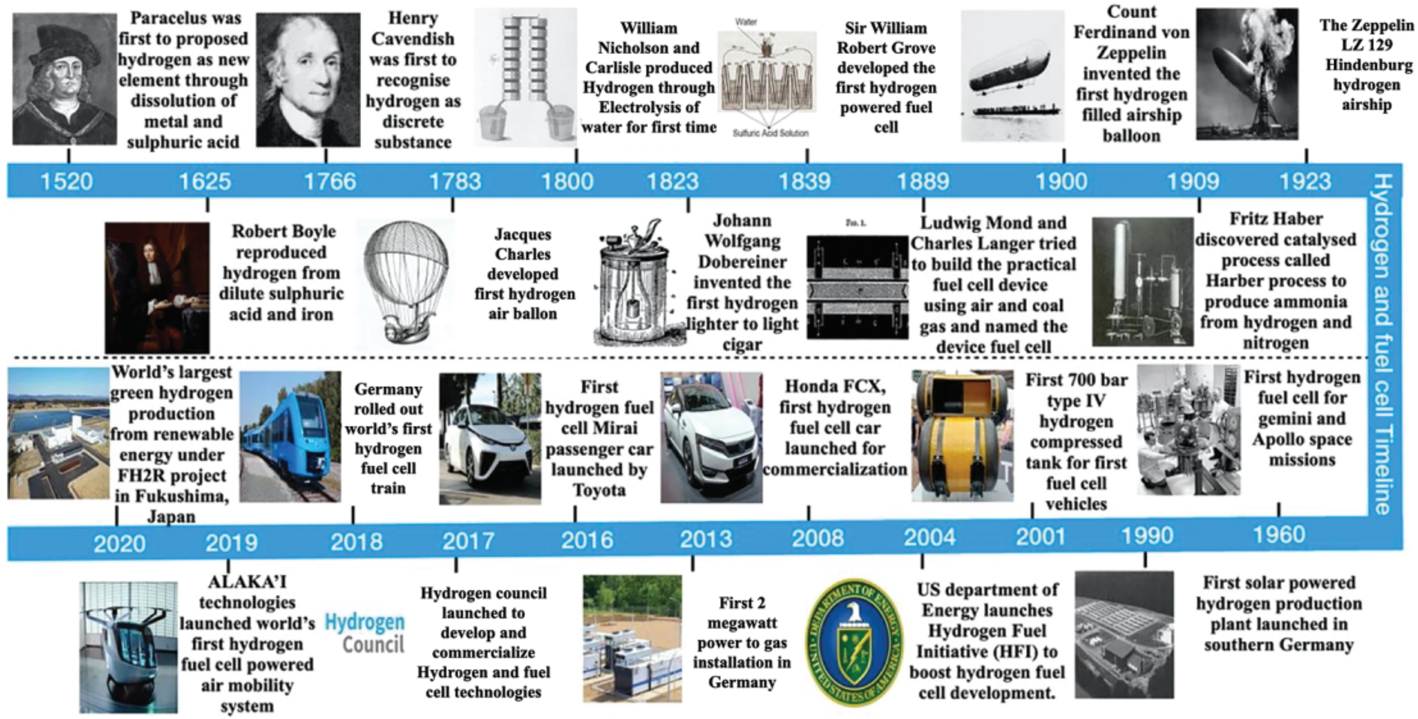

Figure 1.1 Hydrogen and fuel cell technology timeline. Source: Mohideen et al. [4]/with permission of Elsevier.

gigatonne (Gt) of carbon dioxide (CO_2) in 2020, compared to 8.5 Gt of CO_2 in 2019, due to the pandemic-related restrictions on domestic and international travel. However, in 2022, the CO_2 emissions associated with the transport sector began to rebound with the lifting of travel restrictions around the world [1, 4].

Today, a well-to-wheel passenger vehicle generates an average of 300 g of CO_2 per kilometer. According to the IEA, achieving a net-zero-emission transport sector requires a further drop in carbon emissions by 20% to 5.7 Gt by 2030 from the current level. Achieving such a drastic emission drop highly depends on the policies driving the revolutionary shift from fossil-fuel-based vehicles to clean and green mobility. Today, several low-carbon road transport technologies are readily available in the market, including plug-in hybrid vehicles, battery electric vehicles, and fuel cell electric vehicles (FCEVs). However, all these technologies are at various commercialization phases, and the significance of each in the sustainable future transport sector is a topic of discussion. Hydrogen-powered FCEV has the potential to decarbonize the transport sector compared to other low-carbon transport technologies. The proton exchange membrane (PEM) fuel cell stack is mostly used in FCEVs, offering high power density, high efficiency, and cold-start capabilities. In addition, hydrogen-powered FCEVs have widespread advantages, including high range and short refueling time (~500 km and 3 min), high well-to-wheel efficiency, smooth operation (low noise), and quick start-up. Owing to such overwhelming benefits, hydrogen-powered FCEVs will be a competitive edge in future transportation, especially for heavy-duty vehicles, trucks, buses, maritime shipping, and aviation sectors. However, compared to gasoline-powered and electric-powered vehicles, the number of FCEVs on the road is comparatively small, due to its high production cost of materials and infrastructure.

On the road to net-zero-emission scenario, it is anticipated that the hydrogen demand will reach almost 2.6% of the total transport sector energy demand by 2030 and over one-quarter by 2050. Nevertheless, in the current scenario, the use of hydrogen in the transport sector is much lower than that in other sectors, accounting for $<0.01\%$ of the energy consumed. For instance, if all the 1 billion cars, 25 million buses, and 190 million trucks on the road are replaced by FCEVs in the future, then the demand for global green hydrogen will be fourfold higher than the current level. From 2017 to 2020, the global share of FCEVs stock skyrocketed by an annual average of 70%, and as of June 2021, more than 40,000 FCEVs were on the road, mostly in the United States and Japan. The United States accounts for the second largest FCEV fleet, with more than 9,200 vehicles sold at the end of 2020. Japan presently has 4100 FCEVs on the road and is targeted to manufacture 800,000 passenger light-duty vehicles (PLDVs) by 2030. It was followed by Korea, which took the lead in the FCEVs market between 2019 and 2020, and by the end of June 2020 alone, 4400 PLDVs had been registered, and the government targeted 200,000 and 2.9 million light-duty FCEVs by 2025 and 2040, respectively.

Although FCEVs hold tremendous advantages in decarbonization transport sector, the cost of fuel cell components is a key barrier that hinders the widespread commercialization of FCEVs. For instance, the high cost of

Table 1.1 Approximate cost of platinum content in PEMFC vehicles based on current target platinum loading.

Stack power (kW)	Application	Example	Total Pt (g)	Total cost of Pt (USD)
1–25	Portable power and scooters		0.3–8	10–240
25–75	Range extenders, buses, and trucks		8–25	240–750
>75	Passenger vehicles		25–35	750–1050

the expensive platinum metal used as a cathode catalyst in a fuel cell stack itself is responsible for 56% of its total cost of ownership. As shown in Table 1.1, for mid-sized passenger FCEVs, 25–35 g of Pt is required, which is 10-fold higher than a diesel autocatalyst. Therefore, reducing the platinum loading of the catalyst in the fuel cell stack is critical for the economic viability of FCEVs. In this direction, Daimler has significantly reduced platinum usage in their FCEVs by nearly 90% of platinum by ~8 g to just 5 g per vehicle [8]. Similarly, Toyota's Mirai FCEV cuts platinum utilization by 50% through alloying with cobalt (Pt/Co), an approach that plays.

In this context, electrospun nanofibers, prepared via the electrospinning technique, have garnered considerable attention to reduce the cost of the key components as well as improve the performance of fuel cell. The concept of electrospinning experienced a resurgence in the 1990s as nanomaterials became a research priority. The technique has since found diverse applications in biotechnology, filtration, energy storage, medicine, aerospace, and electronics [9]. As illustrated in Figure 1.2, a typical electrospinning setup includes a high-voltage power supply, a spinning apparatus (composed of a feed pump and syringe), and a collector. The process involves generating a strong electrostatic field between the spinning apparatus and the collector. When the electrostatic force acting on the polymer solution overcomes its surface tension and viscosity, a charged jet forms at the apex of the Taylor cone. This jet stretches, undergoes solvent evaporation and solidification, and finally deposits on the collector as nanofibers. The resulting fiber diameters typically range from tens of nanometers to several microns [11].

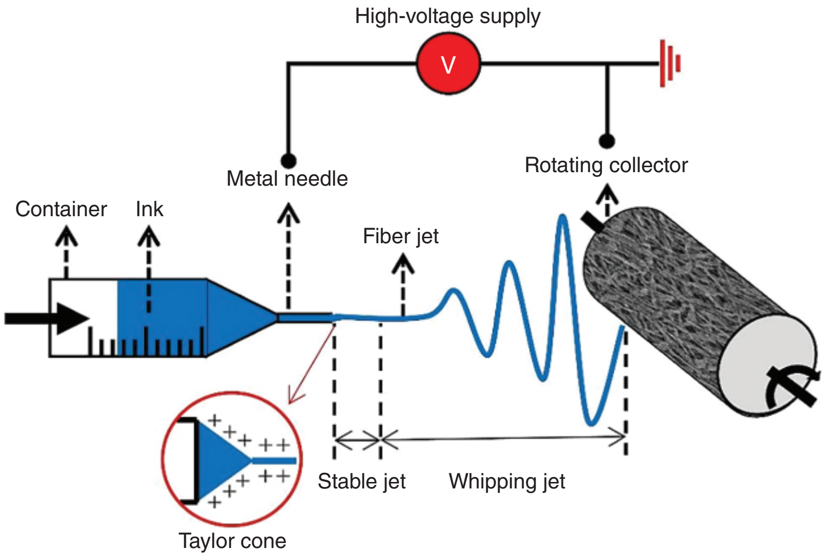

Figure 1.2 Schematic diagram of electrospinning device. Source: Yong et al. [10]/with permission of Elsevier.

1.2 Key Components of Proton Exchange Membrane Fuel Cell

PEMFCs are complex systems that rely on the seamless integration of several critical components to convert hydrogen into electrical energy efficiently. Each component plays a vital role in ensuring the effective operation of the fuel cell, with maximum efficiency and durability. A deeper understanding of these components is crucial for advancing PEMFC technology and optimizing its performance across various applications. The core components of a PEMFC include the PEM, catalyst layer (CL), gas diffusion layer (GDL), bipolar plates, and the flow field. Together, these elements form a cohesive system that facilitates the electrochemical reactions necessary for power generation in FCEVs, as illustrated in Figure 1.3.

1.2.1 Catalyst Layer

The CL is typically a thin, porous structure consisting of catalyst particles, an ionomer, and a carbon support. The platinum or platinum alloy catalyst particles are dispersed on a high-surface-area carbon support to maximize the available catalytic surface area. The ionomer, often Nafion, is interspersed throughout the layer to aid proton conduction and ensure effective contact with the membrane [12–15]. The primary function of the CL is to accelerate the electrochemical reactions within the fuel cell, ensuring efficient conversion of hydrogen and oxygen into water and electrical energy. The efficiency and performance of the PEMFC are heavily dependent on the activity and stability of the CL. The catalysts must exhibit high