

Materials Innovations and Advanced Fuel Cell Technologies for Addressing Global Energy Needs

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Abstract: The increasing global energy demand, depleting fossil-fuel resources, and growing concerns about climate change and environmental pollution have accelerated the development of efficient, sustainable energy-conversion technologies. Fuel cells are promising alternatives owing to their high energy-conversion efficiency, low emissions, modularity, and broad applicability in transportation, stationary power generation, and industrial systems. This review presents an overview of major fuel-cell technologies, focusing on their operating principles, key components, material requirements, technological developments, and performance limitations. It emphasizes designing and selecting functional materials for electrodes, electrocatalysts, electrolytes, membranes, and interfaces, considering catalytic activity, ionic and electronic conductivity, chemical stability, mechanical strength, and durability. The review discusses recent progress in non-precious-metal electrocatalysts, advanced polymer electrolyte membranes, and high-temperature fuel-cell materials in relation to improving efficiency, reducing costs, and minimizing dependence on critical resources. The review further examines emerging fuel-cell systems, commercialization trends, and global patent developments across major technological domains. It highlights current challenges and future research opportunities, particularly in materials innovation, system optimisation, durability, cost reduction, and large-scale commercialisation. Overall, the review offers insights into the evolving fuel-cell landscape and its potential to contribute to sustainable energy generation.

Keywords: Fuel cells, Sustainable energy, Energy generation, Materials selection, Patent analysis.

1. INTRODUCTION

In the world, just eight countries have 81% of all crude oil and 89% of all coal reserves; six countries have 70 % of natural gas reserves. Globally, energy consumption has been tremendously increasing, which results in the diminishing of natural resources like gas, oil, coal, etc. Additionally, global warming is increasing on account of rapid industrialisation and the widespread use of natural resources like water, coal and fossil fuels. Besides these, the world population is increasing, and by 2050 the world population is “

expected to reach 12 billion; 6 on account of this, there is a great demand for energy for future needs [1]. To overcome these peoples have paid much attention to developing alternative or renewable energy sources, which include solar, wind, bio-energy, hydropower, ocean energy, hydrogen and fuel cells (FCs), which play a significant role and meet consumers' demands. Among the different kinds of renewable energy generators, one is fuel cells. Due to their potential to provide both power and heat. Basically, a fuel cell (FC) is an energy conversion device that converts chemical energy directly into electrical energy and produces water as a byproduct [2, 3]. However, an FC differs with battery in which they require a continuous source of fuel and oxygen to sustain the chemical reaction and produce electricity continuously as long as these inputs

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are supplied, whereas in the case of a battery, the chemicals react with each other to generate an electromotive force. The efficiency of FC is high in comparison with conventional engines (CE), in which there is an intermediate mechanical step that reduces efficiency while converting chemical energy into electrical energy, but in the case of FC, without any intermediate step, chemical energy can be directly converted into electrical energy [4]. So far, there are different types of FCs that exist, and each FC should consist of an anode, a cathode, and an electrolyte, which allows positively charged hydrogen ions (or protons) to move between the two electrodes. The anode is where oxidation occurs and generates positively charged H^+ ions and electrons; moves through the external circuit and reach the cathode, where reduction reactions take place and generate H_2O as a byproduct by using externally supplied oxygen (O_2). However, the main difference among fuel cell types is the electrolyte, which is the deciding factor regarding the classification. Fuel cells have noticeable benefits like energy security (reducing oil consumption), reliability, low operating cost, choice of fuel, high efficiency (converts 50-70% of available fuel to electricity and 90% with heat recovery), generates power continuously, with clean output emissions (mainly H_2O); with these peoples anticipated that it can be a smart and suitable material for futuristic energy applications. However, the working capability of a fuel cell mainly depends on its design components, like the electrolyte (which plays a crucial role in FCs), the type of fuel used, anode and cathode materials [5] and some constraints on these material sections were disclosed in the literature [6]. Based on the choice of electrolyte and input fuel named different types of fuel cells are named as proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and direct methanol fuel cell (DMFC). In the cases of AFC, PEMFC and phosphoric acid fuel cells, they essentially require relatively pure hydrogen (as input fuel) to be supplied to the anode; therefore, an external fuel processor is required, and this introduces complexity, increases the cost and decreases the efficiency of the fuel cells. In other cases, MCFC and SOFCs operating at higher temperatures have the advantage that both CO and H_2 are electrochemically oxidised at the anode. Additionally depends on the electrolyte used, which creates a difference in start-up time ranging from 1 second for proton exchange membrane fuel cells (PEMFC) to 10 minutes for solid oxide fuel cells

(SOFC). Moreover, the efficiency of the fuel cell also depends on the stacking of individual cells in all cases. Upon keen observation, hydrogen is the main input fuel in most of the fuel cells in order to produce electricity. The choice of fuel will also influence the commercialisation of fuel cells. In this aspect, we should focus on hydrogen storage materials and also the cheapest technology for the large-scale production of hydrogen [7]. The rising global demand for energy, along with concerns about fossil-fuel depletion, greenhouse-gas emissions, and climate change, has heightened the search for efficient and sustainable energy-conversion technologies. Conventional energy systems that largely rely on fossil fuels have notable environmental impacts, including carbon dioxide emissions and other pollutants. As a result, more attention is being paid to renewable-energy technologies and low-carbon energy-conversion systems to help transition to more sustainable energy infrastructure. Among the technologies being explored, fuel cells have attracted significant interest because they convert the chemical energy of a fuel directly into electrical energy through electrochemical reactions, without requiring an intermediate combustion or mechanical conversion step. In a hydrogen-oxygen fuel cell, the overall reaction generates electricity and water, although the system's overall environmental performance also depends heavily on how the hydrogen fuel is produced. Unlike traditional batteries, fuel cells are not mainly limited by the amounts of reactants stored within the electrochemical device. When fuel and oxidant are provided continuously, electrical energy can be generated continuously. This quality makes fuel cells appealing for a wide range of uses, such as transportation, stationary electricity generation, combined heat and power, backup power, and portable energy systems. The performance of a fuel-cell system depends significantly on the characteristics and compatibility of its individual components. The electrolyte or membrane determines which ion is transported through the cell, thereby influencing operating temperature and electrochemical reactions. Electrode and catalyst materials affect reaction kinetics, while gas-diffusion layers and bipolar plates influence reactant transport, electrical conduction, water management, heat transfer, and mechanical integrity. Thus, material selection is a central factor affecting fuel-cell efficiency, power density, durability, and cost [8, 9]. Recent research increasingly aims to improve these characteristics through better membranes, electrocatalysts, electrodes, and other functional materials. Among the

various fuel-cell technologies, PEMFCs have gained substantial attention for transportation and other applications that require high power density, compact design, and a quick response. Current research focuses on reducing the need for platinum-group metals, improving proton-exchange membranes, optimizing gas-diffusion layers and low-field structures, and increasing bipolar plates that are resistant to corrosion. Advances in PEMFC materials between 2021 and 2025 have comprised single- and dual-atom catalysts, advanced proton-exchange membranes, better gas-diffusion layers and multilayer bipolar plates. Fuel cells operating at high temperatures, especially solid oxide fuel cells, have several advantages including high electrical efficiency, fuel flexibility and the ability to produce both heat and power. On the other hand, the high operating temperatures can cause thermal stresses, lead to material incompatibility, result in electrode degradation, cause problems with sealing and give rise to long-term durability issues [10, 11]. Due to this, current research is increasingly concentrating on operating at intermediate temperatures, using advanced ceramic electrolytes, improving the electrodes and employing proton-conducting ceramic materials. The development of the hydrogen economy is also closely linked to the role of fuel cells. Hydrogen can function as an energy carrier by connecting renewable electricity, energy storage and electrochemical power generation. However, it should not be automatically regarded as a zero-emission energy carrier since its environmental impact

varies according to the method of its production. The International Energy Agency (IEA) states that global demand for hydrogen exceeded 100 million tonnes in 2025, although demand from new applications such as mobility and power generation is still limited when compared with conventional fossil-based products. Heavy trucks remain the only very fast-growing market for fuel cell electric vehicles, with China leading in deployment [12].

1.1. Review Scope and Literature-Selection Methodology

This article is a narrative review rather than a systematic review or meta-analysis. It discusses foundational studies and the cited literature on fuel-cell chemistry, electrodes and membranes, bipolar plates, durability, commercialization, hydrogen supply, and patent activity. The discussion prioritizes peer-reviewed research and review articles, established technical handbooks, and identifiable patent-statistics sources. The manuscript record available for this revision does not document a reproducible database search or formal screening protocol; therefore, the review is presented as a narrative synthesis and no claim of exhaustive database coverage is made. For transparency, this revision was informed by a targeted supplementary search of publicly accessible scholarly records and official technical sources including Scopus, Web of Science, ScienceDirect and Google Scholar, through 20 October 2026. Figure (1) presents an overview of the fuel-cell system architecture, reactant flow,

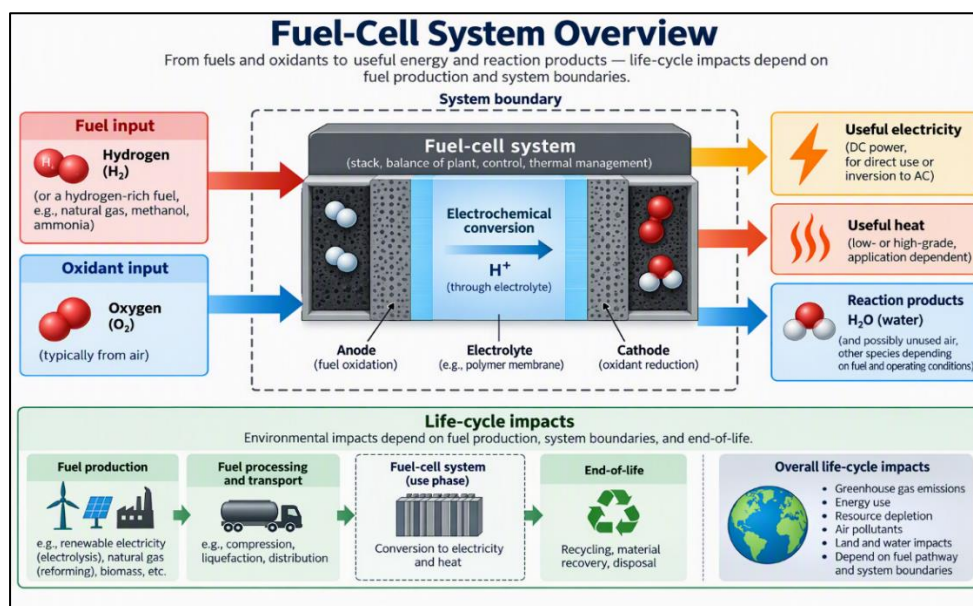


Figure 1: Fuel-cell system overview showing fuel and oxidant inputs, electrochemical conversion, useful electricity and heat, and reaction products.

electrochemical conversion process, and life-cycle considerations. Search concepts included fuel-cell types and charge carriers; electrocatalyst activity and durability; polymer-electrolyte conductivity and fuel crossover; solid-oxide operating temperature and degradation; sources were retained when they directly addressed fuel-cell chemistry, materials, component design, device performance, degradation, system deployment, hydrogen infrastructure, commercialization, or the interpretation of patent and techno-economic evidence. Materials research, device engineering, commercialization, hydrogen infrastructure and patents are included because material performance alone does not determine deployability: component properties affect cell performance and durability, while fuel availability, system cost, manufacturing and intellectual-property activity influence practical adoption. This is a targeted narrative update, not a protocol-driven systematic search counts or exhaustive-screening claim is made.

In this review, we focus on different types of fuel cells and recent developments in their design components, especially electrolytes, fuel types, operating temperatures, efficiency comparisons, and maintenance costs. We also focus on developments in graphene-based metal materials used as anode and cathode components in fuel cell technology for high energy storage. All these are based on literature available on fuel cell technology [13-25]. Overall, this review discusses the basic principle of operation, classifications, advantages, developments and suitability of applications.

2. HISTORICAL NOTES ON FUEL CELL TECHNOLOGY

As for historical notes on fuel cells, first of all, Alessandro Volta (1745-1827) was the first scientist who observed the electrical phenomena on a scientific footing and later continued by J. W. Ritter (1776-1810) to develop an understanding of electricity on those issues. In the year 1802, Sir Humphrey Davy designed a simple fuel cell based upon a compound C/H_2O , $NH_3/O_2/C$, which carries a weak electric shockwave. The basic principle of the fuel cell was first revealed by Christian Friedrich Schonbein in the year 1838, and the next year Sir William Grove developed the first fuel cell constructed by reversing the electrolysis of water [26]. After a long time, in 1899, Nernst discovered solid oxide electrolytes [27] and in 1937, the first ceramic-based solid oxide fuel cell operated at 1000 °C by Baur and Preis [28]. Later, in 1945, a few research groups

took over the studies on fuel cells to improve their technologies towards industrial development. After that, in 1950, Francis Bacon first introduced the alkaline fuel cell of 5 kW. Additionally, people found that FCs had much more intensive applications in space program technology, and NASA spent tens of millions of dollars on hydrogen-based fuel cells, and they succeeded. In the year 1980, the USA, Canada, and Japan governments significantly increased their funding for the fuel cell R&D sector. Starting in the 1990 Ballard used fuel cell technology and ran buses on the basis of compressed hydrogen. Nowadays, fuel cell devices are common in transportation and power generation.

3. WORKING PRINCIPLE

As we mentioned above, a fuel cell is a device that converts chemical energy directly into electrical energy, where the fuel is hydrogen; the only by-products are pure water and heat. The core of each fuel cell consists of an electrolyte and two electrodes (anode and cathode). At the negative anode, hydrogen (a fuel) is oxidised, whereas at the positive cathode, oxygen is reduced, and ions are transported through the electrolyte from one side to the other. The electrochemical conversion takes place by means of two separate half-cell reactions at the anode and cathode. At the anode, hydrogen molecules undergo oxidation by releasing protons and electrons. The electrolyte allows suitable ionic species to pass between the electrodes while at the same time stopping any direct electronic conduction through the electrolyte. The charge carrier depends on the fuel-cell type. PEMFCs, PAFCs and DMFCs conduct protons (H^+), AFCs conduct hydroxide ions (OH^-), MCFCs conduct carbonate ions (CO_3^{2-}), while conventional SOFCs conduct oxide ions (O^{2-}) and proton-conducting SOFCs conduct H^+ ions. Electrons do not pass through the electrolyte; instead, they travel through the external circuit, producing useful electrical power. The electrons which are released therefore have to pass through an external electrical circuit, producing useful electrical power. At the cathode, oxygen is reduced and reacts with the protons and electrons which have been transported to form water. The simultaneous electrochemical reactions therefore enable the direct conversion of the chemical energy stored in hydrogen into electricity without any combustion or mechanical process [29].

The actual voltage obtained from a fuel cell is less than the theoretical equilibrium voltage due to a number of irreversible losses; these losses are

generally associated with activation polarization, ohmic losses and mass-transfer or concentration polarization. The activation losses are linked to the kinetics of the electrode reactions, especially those concerning the oxygen reduction reaction at the cathode. Ohmic losses arise from resistance to proton transport through the electrodes and the current-collecting components. At high current densities, limitations in the transport of reactant gases and in the removal of water can cause concentration losses and further lower the cell voltage [30]. Hence, the performance of a fuel cell is very much dependent on various operating parameters such as temperature, pressure, current density and the characteristics of the electrolyte and electrode materials. In the case of PEMFCs, effective water and thermal management are especially important since membrane hydration affects proton conductivity, but too much accumulated water can hinder the transport of the reactants. As a result, recent studies have concentrated on optimizing the properties of the membrane, the catalyst layers, the gas-diffusion layers and the operating conditions in order to achieve stable performance, particularly at high current density [31].

4. CLASSIFICATION OF FUEL CELLS

The fuel cells are classified based on the choice of electrolyte as well as type of fuel. Presently, six major types of fuel cells are available, as follows. These are further differentiated on the basis of operating temperature. A comparative summary of the major fuel-cell technologies, including electrolytes, charge carriers, operating temperatures, strengths, and limitations, is shown in Figure (3). The minimum operating temperature ranges from room temperature to 250 °C for PEMFC, PAFC, and AFC, and the high operating temperature ranges from 650-1000 °C for SOFC and MCFC. In addition to electrolyte and fuel type, temperature, charge-carrier species, and fuel-processing requirements. Low-temperature systems such as PEMFCs, AFCs and DMFCs generally offer rapid start-up, whereas high-temperature systems such as MCFCs and SOFCs provide greater tolerance toward hydrocarbon fuel cells. They can also be distinguished according to their operating fuels and enable effective utilization of waste heat. These characteristics strongly influence the selection of materials, system design and potential applications of each fuel-cell technology [32].

4.1. Proton Exchange Membrane Fuel Cell (PEMFC)

The proton-exchange membrane fuel cell (also known as the solid polymer fuel cell) consists of two

electrodes separated by an electrolyte. Depends upon the choice of electrolyte and type of fuel used, which differs from other fuel cells. It has unique operational properties due to the presence of a polymer membrane-based electrolyte, and it has significant advantages over other types of liquid-based electrolytic fuel cells, which are easy to manufacture, with cell designs and convenient stacking (depending on material selection). The PEMFC basically shows high power density [33], and it is a promising material for next-generation energy applications. The fuel used in PEMFC is less-pure hydrogen derived from hydrocarbons or methanol, and the electrolyte is a polymer proton exchange membrane (Teflon-like membrane). It is basically an insulator but conducts H⁺ ions well, and it operates at low temperatures in the range of 50- 80 °C [34], making it a convenient power system for commercial applications such as cell phones, laptop computers, and power generators. The operating principle and charge transport mechanism of a proton-exchange membrane fuel cell are illustrated in Figure (2). Besides this, bipolar plates play a key role in proton exchange membrane (PEM) fuel cells with multifunctional characteristics, especially uniform distribution of fuel gas as well as air, conduction of electrical current from cell to cell, elimination of heat from working regions, control of gas leakage, and also significantly improving the stack of PEM fuel cells [35]. Regarding electrocatalysts, Sheng Zhang et al. report on recent developments in nanostructured electrocatalysts of Pt and Pt-based components. Platinum is the most effective electrocatalyst for fuel cells, and Pt nanocrystals with smaller sizes will usually provide a high electrochemical surface area, which increases the catalytic activity [36]. Pt nanocrystals with specific surface structures will significantly improve the reduction reaction. The electrode reactions in the PEM fuel cell are as follows: the hydrogen from the input fuel gas is consumed at the anode, generates electrons (oxidation process), and produces H⁺ ions, which enter into the electrolyte and travel towards the cathode and combine with oxygen and electrons (reduction process) to produce water. Progressively, several programs have been going on to improve and develop the PEMFC stack technology for motive applications. Because of this, Qingfeng et al. developed a PEMFC with a high operating temperature (above 100 °C) using perfluorosulfonic acid (PFSA) polymer electrolytes [37]. The main advantage is quick start-up for automotive vehicles due to its high-power density. The major drawbacks of the PEMFC are that it shows low efficiency, just about 40-45%, the use of a high-

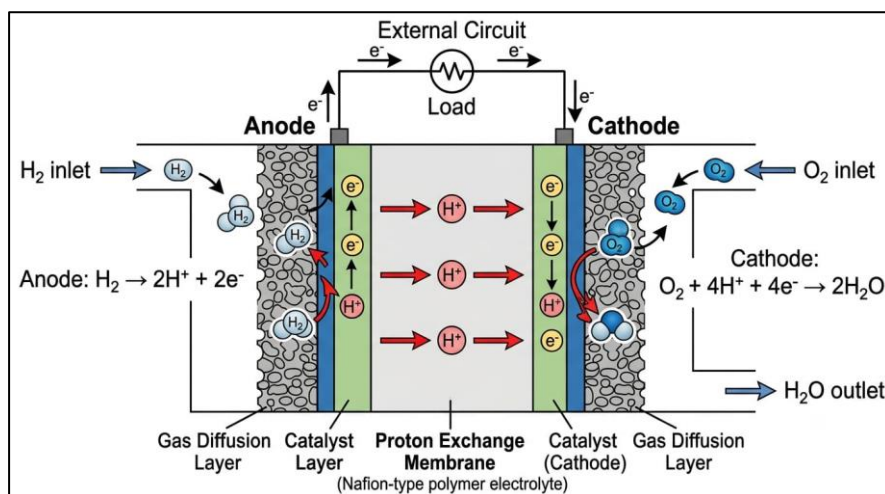


Figure 2: Schematic illustration of the operating principle of a proton-exchange membrane fuel cell (PEMFC), showing proton transport through the membrane and electron flow through the external circuit.

Fuel cell type (acronym)	Schematic	Electrolyte (material)	Charge carrier	Typical operating temperature (°C)	Key strengths	Key limitations
Proton Exchange Membrane Fuel Cell (PEMFC)		Polymer proton-exchange membrane (e.g., Nafion)	H^+ (protons)	60 – 100	<ul style="list-style-type: none"> High power density Rapid start-up Compact design Ideal for transportation 	<ul style="list-style-type: none"> Requires high-purity H_2 Expensive Pt catalysts Sensitive to fuel impurities
Direct Methanol Fuel Cell (DMFC)		Polymer proton-exchange membrane (e.g., Nafion)	H^+ (protons)	20 – 90	<ul style="list-style-type: none"> Uses liquid methanol directly Easy fuel storage and handling Suitable for portable devices 	<ul style="list-style-type: none"> Lower efficiency and power density Methanol crossover losses Catalyst degradation
Alkaline Fuel Cell (AFC)		Aqueous KOH solution or alkaline polymer membrane	OH^- (hydroxide ions)	50 – 200 (typically < 100)	<ul style="list-style-type: none"> Fast electrode kinetics High efficiency Lower catalyst cost possible 	<ul style="list-style-type: none"> Highly sensitive to CO_2 contamination in air and fuel Electrolyte management (aqueous systems)
Phosphoric Acid Fuel Cell (PAFC)		Concentrated phosphoric acid (H_3PO_4)	H^+ (protons)	150 – 220	<ul style="list-style-type: none"> Mature technology Good tolerance to fuel impurities Suitable for combined heat and power (CHP) 	<ul style="list-style-type: none"> Lower power density Expensive catalysts Slow start-up
Molten Carbonate Fuel Cell (MCFC)		Molten alkali carbonate salts (e.g., Li_2CO_3/K_2CO_3)	CO_3^{2-} (carbonate ions)	600 – 700 (≈ 650)	<ul style="list-style-type: none"> High efficiency Internal fuel reforming Fuel flexibility (e.g., natural gas) Suitable for large-scale power generation 	<ul style="list-style-type: none"> Corrosion and materials degradation Requires CO_2 management Long start-up times
Solid Oxide Fuel Cell (SOFC)		Ceramic oxide electrolyte (e.g., yttria-stabilized zirconia, YSZ)	O^{2-} (oxide ions)	500 – 1,000	<ul style="list-style-type: none"> Highest efficiencies Fuel flexibility (e.g., natural gas, biogas) No precious-metal catalysts required 	<ul style="list-style-type: none"> High operating temperature Thermal stress and materials challenges Slow start-up and shutdown

Figure 3: Comparative overview of six major fuel-cell types, their electrolytes, charge carriers, indicative operating-temperature ranges, and key strengths and limitations.

cost platinum catalyst, and its susceptibility to carbon monoxide. PEMFC power systems are also being developed for household electricity (3-7 kW for residential and 50 kW for buildings) and hot water applications. Recently, Ballard Power Systems (Canada) developed a 250 kW PEMFC power source. Currently, the development of a 7 kW PEMFC is carried

out by Plug Power for domestic applications. The American Department of Energy is funding a project [38] which is led by General Motors and includes Ballard Power Systems to develop a PEMFC fuel cell car operating on methanol as fuel. This has also announced a programme to develop a hydrogen-fuel PEMFC fuel cell. However, the researchers are still

focusing on following parameters regarding PEMFC forefficiency: high proton conductivity, low electronic conductivity, low permeability to fuel, good chemical thermal stability, good mechanical properties, and low cost. Current PEMFC technology is based on expensive perfluorinated PEMFCs that operate effectively only under fully hydrated conditions. Alternative PEMFCs are classified into the following categories: modified Nafion composite membranes, functionalized non-fluorinated membranes, acid base composite membranes [39]. Recent PEMFC research shows growing interest in reducing platinum usage while maintaining catalytic activity and durability. Researchers are exploring non-precious-metal catalysts based on transition metal-nitrogen-carbon (M-N-C) materials are promising substitutes as potential alternatives to conventional Pt-based electrocatalysts, especially for the oxygen reduction reaction. However, enhancing their long-term stability and performance under practical fuel-cell operating conditions remains an important challenge [40]. Although these catalysts can substantially reduce cost and in some cases approach the activity of Pt-based catalysts, their long-term durability under practical operating conditions generally remains inferior. Therefore, current PEMFC research focuses on balancing catalytic activity, durability, and cost rather than maximizing activity alone. Another crucial research direction focuses on developing advanced polymer electrolyte membranes and membrane-electrode assemblies with improved proton conductivity, mechanical strength, chemical stability, and reduced gas crossover. Composite and hydrocarbon-based membranes are being investigated as potential alternatives or supplements to standard perfluorosulfonic-acid membranes, particularly to improve performance at higher temperatures and lower humidity levels [41]. The recent advances in non-precious metal catalysts (CS Fe/N-C), which have a curved-surface single-atom iron catalyst and feature a special outer protection + inner catalysis microenvironment, allow for replacing platinum catalysts in PEMFCs with excellent output performance and long-term stability. Moreover, hierarchically porous Co-N-C electrocatalysts, with improved mass transport and better cobalt utilization efficiency, have been developed for use in oxygen reduction in high-performance PEMFCs. Finally, a method for producing Co-N-C electrocatalysts in the solid phase on a kilogram scale by means of the Kirkendall effect has established a generally applicable and environmentally sustainable way of carrying out large-scale production [42].

4.2. Alkaline Fuel Cell (AFC)

Alkaline fuel cell (AFC) is also called a Bacon fuel cell, and it is similar to PEMFC but differs in electrolyte and fuel. In the case of AFC, potassium hydroxide is used as an electrolyte and pure hydrogen or hydrazine as an input fuel. It has a low operating temperature, which is around 100 °C which constitutes pollution-free energy conservation, and it shows high efficiency compared to PEMFC, which is around 60-70%. The major advantage is that it has a quick start-up nature, and the disadvantage is very sensitive to CO₂ gas, which has been investigated by several research groups and reveals poisoning of electrocatalysts in AFCs with rolled electrodes due to CO₂. It needs a separate system to remove the CO₂ from the air. In this AFC, different types of cells are present, which are a fuel cell with a free liquid electrolyte between electrodes; a cell with liquid KOH in the pore systems; a matrix cell where the electrolyte is fixed in the electrode matrix [43]. All types of AFCs consist of porous electrodes. There are several problems concerning AFCs have been reported in the literature. The noticeable problems are: the preparation method of the electrodes with noble metal catalysts is very expensive, which is reflected in terms of cost. The electrolyte is very corrosive, and the catalyst materials are sensitive, leading to high degradation of these catalysts, such as nickel and silver. The use of a corrosive electrolyte is one of the disadvantages because it has a shorter lifespan. Therefore, it is not very preferable for commercial applications like cell phones, computers, and household power systems. This type of fuel cell is used in transportation and space aircraft [44]. The Major drawbacks of traditional liquid-electrolyte AFCs are their vulnerability to carbon dioxide. CO₂ interacts with alkaline electrolytes to form carbonate compounds that can hinder ionic conductivity and alter electrode performance. To overcome some of the issues linked with corrosive liquid KOH electrolytes, anion-exchange membrane fuel cells (AEMFCs) have emerged as a key area of research direction. AEMFCs use solid polymer membranes that conduct hydroxide ions and offer the possibility of using more affordable non-platinum-group-metal catalysts. However, challenges like membrane stability, hydroxide conductivity and carbonate formation still need to be addressed [45].

4.3. Phosphoric Acid Fuel Cell (PAFC)

The operating temperature for a phosphoric acid fuel cell (PAFC) is around 160-210 °C. This

temperature is relatively high in comparison with PEMFC. The electrolyte is phosphoric acid, and the fuel is hydrogen from hydrocarbons and alcohols [46]. The electrochemical oxidation and reduction reactions are similar to those occurring in PEMFC and AFC systems. The cost of this fuel cell is high because it uses a platinum catalyst, which is a drawback. The advantage of PAFC is that it does not suffer from carbon dioxide-induced electrolyte degradation, as seen in the case of AFC, and it shows noticeable efficiency around 44-46 %. This fuel cell is used in stationary power generators with output in the range of 100-400 kW for commercial premises, and they are also a suitable application in large vehicles like buses. These PAFCs are used in heat applications and installed in various countries like Japan, the USA, and Europe. The new developments are in the management of phosphoric acid quantity, a new type of cell configuration, non-external replenishment of phosphoric acid, specifications like cell dimensions and voltage, and cooling parts [47]. The higher operating temperature of PAFCs compared with PEMFCs allows effective heat recovery, making them suitable for combined heat and power applications. However, their relatively low power density, slow start-up, and dependence on platinum-based electrocatalysts remain important limitations compared with other fuel-cell technologies [48].

4.4. Molten Carbonate Fuel Cell (MCFC)

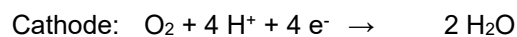
This molten carbonate fuel cell (MCFC) is a high-temperature fuel cell that operates around 600 °C and above, and which has promising high efficiency (60 %) and is a more sustainable power-generation fuel cell. The improved efficiency offers significant cost reductions over phosphoric acid fuel cells (PAFCs), which have efficiencies of just 44-46%. Besides this, when waste heat is captured and used, the overall fuel efficiencies can rise up to 85%. It consists of porous electrodes and a liquid electrolyte (molten carbonate) that consists of sodium and potassium carbonate. It has its own internal reforming (converted to hydrogen within the fuel cell itself) capability, and it separates hydrogen from the fuel; the remaining process is the same as other cells like PEMFC. The disadvantage of MCFC technology is low durability due to high-temperature operation and a corrosive electrolyte, decreasing cell life and causing slow startup. Currently, research is going on to explore corrosion-resistant materials for components for fuel cell designs that increase cell life without decreasing performance. The recent developments in key issues of MCFC

components like cathode, anode, matrix, current collectors and bipolar plates are discussed in the literature [49]. Currently, the focus of MCFC development is improving long-term durability. This involves issues like corrosion, electrolyte loss, and electrode degradation that can occur during high-temperature operations. Researchers are exploring better formulations for electrodes and electrolytes, as well as corrosion-resistant materials and innovative stack configurations. To enhance the operating life of these systems while maintaining high electrical efficiency and effective heat utilization [50].

4.5. Solid Oxide Fuel Cell (SOFC)

The SOFC is also a high-temperature fuel cell; in contrast to other fuel cells, it is designed to operate within a wide temperature range of 500-1,000°C. For the desired operating temperature, it is necessary to take into account parameters like the type of fuel and the properties of electrolytes; here we used solid electrolytes like yttria-stabilised zirconia and doped perovskite. The advantage of this fuel cell shows high efficiency of up to 60% and produces additional electricity by recycling operation process of waste heat [13]. The SOFC also exhibits internal reforming capability, as mentioned in MCFCs. In the case of SOFC, the stack is to be integrated with a gas turbine, so the system temperature exceeds about 850°C. The fuels used here are diesel, petrol, and propane to produce H₂ and CO gases for the anode, where the electrochemical oxidation reactions occur. However, the properties of the solid electrolyte will influence material selection as well as stack design, which depends on the stability of the electrode-electrolyte interface, optimal material composition, and the selection of bipolar plates and the arrangement of seals necessary for SOFC stacks. At present, research is focused on designing a 250kW commercial stack model. The drawbacks include high cost, slow start-up, and an inability to sustain highly fluctuating loads. Recently, proton-conducting SOFCs are being developed, which transport protons as an alternative to oxygen ions through the electrolyte, enabling operation at lower temperatures than traditional SOFCs [51].

The possible reactions at the anode, cathode, and overall reaction are as follows;



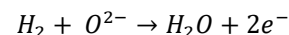
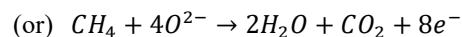
Recently, a growing interest in solid oxide fuel cell (SOFC) research has focused on lowering operating temperatures while still achieving high ionic conductivity and effective electrode performance. Proton-conducting ceramic fuel cells are particularly promising because they allow protons through the electrolyte, enabling them to function at lower temperatures compared to traditional oxygen-ion-conducting SOFCs. This shift to lower temperatures can help minimise thermal stresses, accelerate start-up and permit the use of a wider variety of materials for the cell components [51]. However, lowering operating temperature may reduce electrode reaction kinetics and ionic conductivity, leads to lowering in electrochemical performance. Thus, intermediate-temperature SOFCs are increasingly viewed as a compromise between high performance and long-term durability. Metal-supported solid oxide fuel cells (MS-SOFCs) have become a major development, providing improved efficiency and durability for use in biofuel-powered mobility applications. Research carried out between 2020 and mid-2025 has brought about a clearer understanding of electrocatalysis in MS-SOFCs [52]. Solid oxide fuel cells are further classified into two types, based on conducting charge species, as oxygen ion-conducting solid oxide fuel cells (O^{2-} -SOFC) and proton-conducting solid oxide fuel cells (H^+ -SOFC).

4.5.1. Oxygen-Conducting Solid Oxide Fuel Cells

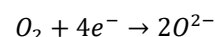
The operation of an oxide ion-conducting solid oxide fuel cell (O^{2-} -SOFC) is shown in Figure (4) states that when H_2 is used as fuel, the fuel is oxidized at the

anode. The external circuit is traversed by the released electrons. Oxygen ions (O^{2-}) are created on the cathode side when oxygen atoms absorb incoming electrons from the external circuit. After moving through a dense electrolyte to the anode, the oxygen ion joins forces with H^+ ions to create water.

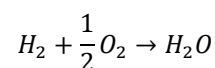
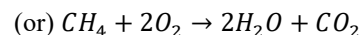
Anode reaction:



Cathode reaction



Overall cell reaction



The limitations of O^{2-} -SOFCs include high operating temperatures, which lead to cell component deterioration, a restricted selection of materials and their associated costs, and a lengthy start-up time [53, 54].

4.5.2. Proton-Conducting Solid Oxide Fuel Cells

H^+ -SOFCs are ceramic high-temperature proton conductors that have been attracting significant attention for a range of electrochemical applications, such as steam electrolyzers for hydrogen production,

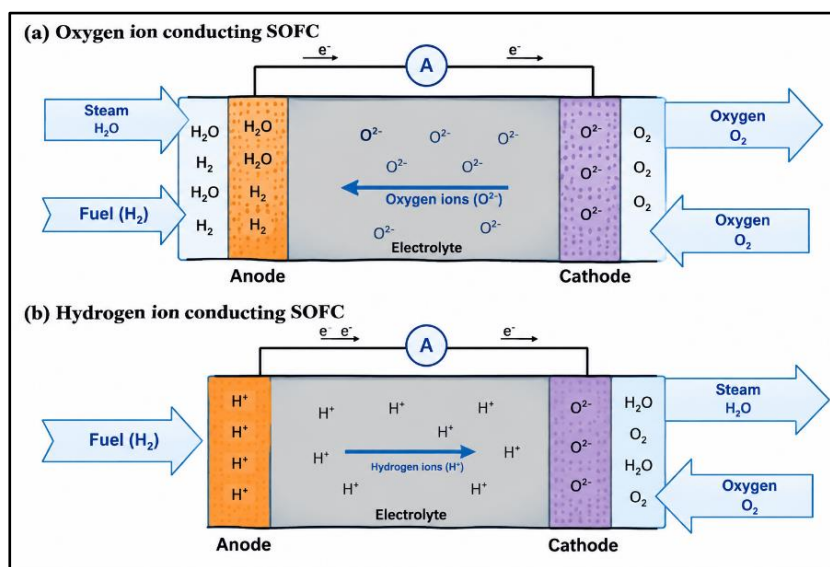
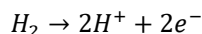
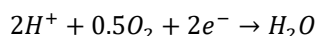


Figure 4: Conceptual diagram of a SOFC based on (a) an oxygen ion-conducting SOFC; (b) Hydrogen ion-conducting SOFC.

hydrogen pumps and membranes, hydrogen sensors, and as the electrolyte materials for intermediate temperature (500–750 °C) solid oxide fuel cells (IT-SOFCs) [55]. The first systematic study of high-temperature proton conductivity in doped strontium and barium cerate ceramic oxides was conducted in the 1980s [55]. Proton conduction has a lower activation barrier than oxide ion conduction due to the smaller size of the H^+ proton carrier (~ 0.9 Å) compared with the oxygen ion (1.4 Å). Thus, proton-conducting oxides have better conductivity than oxide-ion conductors. This gives proton-conducting solid oxide fuel cells a considerable benefit, namely lower operating temperatures, over oxide-ion solid oxide fuel cells. H^+ -SOFCs thus have a larger material selection for the cell and accessory components [56]. Figure (4) depicts the schematic diagram and operating principle of an H^+ -SOFC. H_2 molecules pass through the porous fuel electrode (anode) to the anode-electrolyte interface (triple phase barrier), where they break down into hydrogen ions and electrons (e^- and H^+). These hydrogen ions go across the thick electrolyte to the cathode. The electrons travel via the external circuit to the cathode side, where they react with oxygen molecules and protons to form steam. Unlike O_2 -SOFCs, water is produced on the cathode side, preventing fuel dilution and improving fuel cell performance [57].



The desired requirements of a proton conductor are:

(1) it should possess oxygen vacancies either structurally or by lower valence doping; (2) a favourable crystal structure for the fast transport of the protons [58, 59].

4.6. Direct Methanol Fuel Cell (DMFC)

Over the past few decades, DMFCs have been widely studied and are a promising energy conversion device. The DMFC is novel in comparison with other fuel cells. In this case, a polymer-based electrolyte is used, like in other cells, such as PEMFCs. The fuel used is a liquid fuel (methanol or alcohol) that can be derived from oil, natural gas, coal or biomass. The DMFC will also require platinum-based catalysts for the fuel electrode. The operating temperature is around 60–200°C. At the cathode, the recombination of the positive ions and negative ions takes place and produces water as by product and anode hydrogen

dissociation occurs. Polymer electrolyte-based DMFCs are directly supplied with methanol at the anode, where oxidation occurs; that is, methanol is directly oxidized to carbon dioxide and possible compounds such as formic acid, formaldehyde and other organic molecules, and these organic molecules decrease the fuel use [60–64]. The reaction process at the anode, cathode and the overall reaction process occurring in a DMFC equipped with a proton-conducting electrolyte is followed below:



This fuel cell has a unique advantage because methanol is safe for storage and transportation, and besides this cell produces a fast anodic reaction rate because methanol does not break bond between C-C and it has high energy density. The current technology concerning catalysts is not sufficient to support and develop a large-scale production of cost-effective and highly efficient DMFCs. A single DMFC can produce only 0.3–0.5 V under laden conditions. It is mainly used to replace batteries for cameras, other portable electronic applications and notebook computers in the range of 1 W to 1 kW capacity. The Smart Fuel Cells Company has commercially created DMFCs from the completely portable system of 15 W to the semi-portable 250 W systems [65]. One of the major technical limitations of DMFCs is the issue of methanol crossover through the polymer electrolyte membrane from the anode to the cathode. This crossover can lead to reduced fuel efficiency, lower performance at the cathode, and can even cause mixed-potential losses. As a result, current research focuses on developing membranes that have lower methanol permeability, alongside developing highly active catalysts for both the anode and cathode that can tolerate methanol effectively [66]. A critical analysis has been carried out of recent developments in direct liquid fuel cells (DLFCs) employing various fuels such as methanol, ethanol, and dimethyl ether, and dimethyl ether has now appeared as a possible future energy vector for use in DLFC applications [67].

5. MATERIALS SELECTION FOR FUEL CELL

Before going to the material section, it is necessary to know about material constraints. The materials selection for a commercial product needs a repeatedly checking design and, which eventually becomes exact

for a particular product and application. However, it is likely to make a few common statements regarding the selection of materials for fuel cells. The overall area-specific resistivity (ASR) of the fuel cell components (anode, cathode and electrolyte) must be below $0.5\Omega\text{ cm}^2$ and ideally condition $0.1\Omega\text{ cm}^2$ to ensure high power densities, with targets of 1 kW dm^{-3} and 1 kW kg^{-1} often mentioned for transport applications. The high-power density is also an important parameter to reduce the cost of the fuel cell. The minimisation of cell resistive components plays a significant role in the selection of materials. To achieve minimized resistivity, these are the criteria one should consider: the gaseous reactants, electrocatalyst, electrolyte and current collector have to be brought into closer contact within a confined spatial region; for low-temperature systems, it is better to introduce hydrophobic polytetrafluoroethylene (Teflon), metal, carbon powders or porous carbon papers are good electronic pathways for further reduction of resistivity. Electrolytes like liquid KOH, phosphoric acid and molten carbonates ensure low ASR values based on their suitable design approaches and whose ionic conductivity values are greater than 1 S cm^{-1} ; besides these, the Nafion membrane, whose thin film ($100\text{ }\mu\text{m}$) is used in the PEMFC system, can reduce resistivity. When operating with pure hydrogen and air, platinum is the most active material and is used as a catalyst. To reduce the cost, nanoparticles of platinum on a carbon support have been developed.

This loading has been significantly reduced from 2 mg/cm^2 of electrode to values below 0.5 mg/cm^2 without much impact on performance and lifetime [68, 69]. The structural arrangement of the membrane-electrode assembly and the major material components used in PEM fuel cells are illustrated in Figure (5).

The other important component in the fuel cell is the bipolar plate, which plays a significant role in stacking individual cell components and functions as a distributor of fuel and air to electrodes (anode and cathode). In the case of PEMFC and PAFC systems, graphite material is used as bipolar plates and, recently, for better functioning, carbon-based materials which are produced by injection moulding or coated stainless steels. The additional constraints influencing material selection will also depend on reliability and durability issues; in combined heat and power system parameter plays important role. The section on fuel in the case of AFC is pointed out in this report [70]. The materials currently being used in PEMFC, MCFC and SOFC prototype demonstrations are reported in the literature [71, 72]. In the case of SOFC, the design configuration components are yttria-stabilised zirconia (YSZ) as an electrolyte, $\text{La}(\text{Sr})\text{MnO}_3$ for the cathode, and Ni-YSZ for the anode. All these are successful technical compounds, relatively expensive, and efforts are still going on to replace them with alternatives. In all types of fuel cells, bipolar plates should be corrosion-

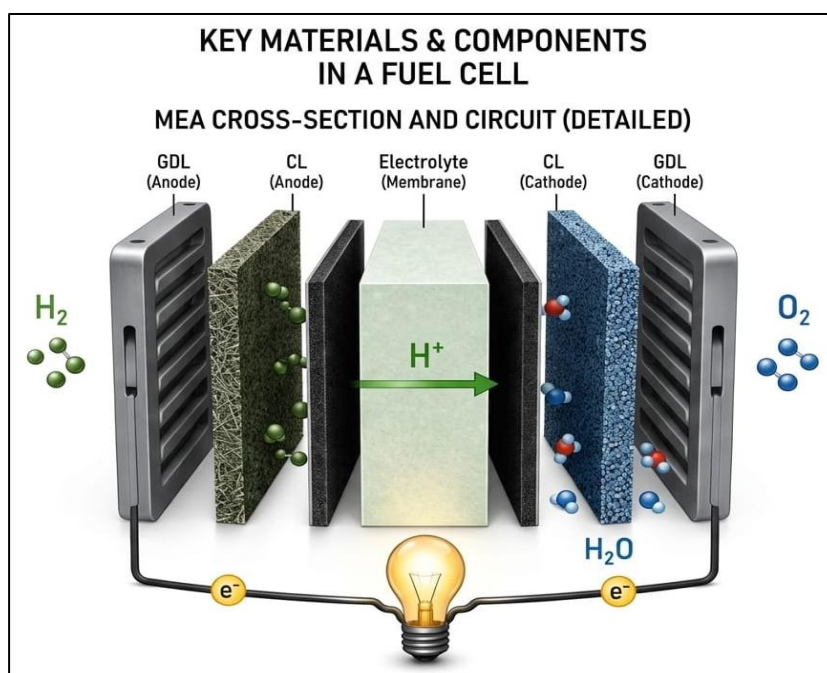


Figure 5: Structural architecture of a proton exchange membrane fuel cell (PEMFC) membrane-electrode assembly (MEA) showing material components, proton transport, electron flow, and electrochemical reaction pathways.

resistant; for this, graphite material is preferred. However, the conductivity of graphite materials is less than that of metallic materials, and the conductivity values are: C polymers, $\sim 1 \text{ S cm}^{-1}$; graphite, 10^3 S cm^{-1} . The polymer/graphite compounds are developed with a conductivity of 10 S cm^{-1} to reduce resistivity, and the graphite materials are porous and optimisation of carbon weight percentage is well reported [73, 74]. The most promising materials are stainless steels, as the other candidate metals such as titanium, niobium, tantalum and gold are too expensive. Stainless steels can provide satisfactory performance for several thousand hours [75, 76]. Recent developments in electrocatalyst materials have involved single-atom catalysts (SACs), among which Fe-N₄ sites are the best non-precious cathode catalysts have reached peak power densities of approximately 1.0 W cm^{-2} in H₂/O₂ fuel cells under optimized testing conditions. Dual-atom catalysts, in which the Fe-Co diatomic sites are modified by boron atoms, have also shown promising results. Moreover, carbon-based non-precious metal catalysts, such as those doped with heteroatoms and transition metals, are currently being developed to deal with the problems relating to cost and performance [77]. There has been considerable progress in advanced membranes and electrolytes. Membranes based on nanofibers have appeared, providing a range of approaches that make use of both electrospun and natural nanofibers as key elements in PEMs and AEMs. Composite electrolyte membranes incorporating functional polymer nanofibre frameworks are being developed in order to achieve high proton conductivity. Filter-crosslinked membranes for hydrogen fuel cells are advancing the generation of sustainable energy. Finally, hydrocarbon-based membranes are being studied as alternatives to perfluorosulfonic acid membranes [78]. Comparisons across fuel-cell classes show that no single material set is optimal for every application. Low-temperature polymer-electrolyte systems offer compact designs and rapid start-up, but they remain sensitive to catalyst cost, membrane crossover, water management, and degradation. High-temperature carbonate and oxide systems can use a wider range of fuels and recover useful heat, yet they face thermal-cycling stresses, sealing challenges, and demanding materials compatibility. Consequently, peak laboratory activity or conductivity alone is not sufficient for material selection: durability under realistic operating cycles, manufacturability, critical-material demand, and whole-system efficiency must also be considered. Compare performance figures only when fuel composition,

temperature, pressure, catalyst loading, active area, and test protocol are comparable.

6. RECENT DEVELOPMENTS IN FUEL CELLS

In recent developments, people are very focused on the optimal size of the fuel cell for specific applications, which can make it easier to synchronise and locate the fuel cell in a distributed system to meet the highest efficiency demands for different applications. In the present market, different fuel cells are available whose power ranges from 0.5 kW to 2 MW. Specifically, the research intensively focuses on MCFC, PEMFC and SOFC fuel cells to reduce the cost (by replacing the platinum catalyst with metal/carbon related material), and some research groups are heavily involved [79, 80]. And increase the lifespan of fuel cells to more than 40,000 h. Presently, PEM fuel cell capacity reaches about 7 kW, which is carried out by Plug Power for residential applications, and 250 kW power capacities are under testing conditions by Ballard Systems. Recently, SOFC has achieved success in stationary power applications. People have developed SOFCs and tested a 250kW hybrid system that has achieved an efficiency of around 52%, and the still efforts were going on to develop SOFCs in different ranges, starting from 1 and 25 kW, and they are also introduced high efficiency power system of capacity about 5 kW to reduce its installation cost. Moreover, further research is focusing on PEMFC and PAFC systems for combined heat and power generation [81, 82]. Besides, this research is also focusing on developing DMFCs for commercial applications and increased cell performance from 100 kW to 1 MW. Fuel Cell Energy, Inc. has researched MCFCs for stationary power generation applications and developed 1.2 MW power systems, which is the largest distributed generation power plant for commercial purposes. Germany has reached of 250, 300 and 400 kW for MCFCs [83]. Recently, the increase in fuel-cell development has increasingly directed towards enhancing durability, lowering system costs and increasing the use of non-precious-metal catalysts. Particularly, the focus is being given to improving the durability and catalyst efficiency of PEMFCs, while SOFC research is focused on lowering operating temperatures and enhancing the stability of cell components. These enhancements are crucial for ensuring that fuel-cell systems can operate reliably over the long haul and be deployed more widely in commercial settings [84]. From 2024 to 2026, there were developments in the commercial sector, such as Ballard Power Systems introducing its FCmove ®-SC hydrogen fuel cell engine at the end of 2025; this

is a high-efficiency platform designed for use in buses. Toyota declared its intention to put fuel cell-powered Class 8 trucks into its commercial logistics fleets by early 2027 and has also entered into a new agreement with Hyroad to carry out large-scale commercial deployment of hydrogen trucks in the United States. Powercell Group obtained a contract to provide fuel cell systems for two liquid hydrogen-powered cargo ships (with 4 MW of installed power) and for 14 Marine System 225 units, supplying more than 3 MW of power. Furthermore, Advait Energy Transitions reached a pact with Norway's TECO Fuel Cell Technology for the development of scalable hydrogen fuel cell systems for use in data centres, stationary power, heavy-duty transport, mobility and maritime applications. The current global market trends show that global demand for hydrogen reached about 100 million tonnes in 2024 and is expected to go beyond this figure in 2025. Among all sectors, heavy-duty trucks are the only one in which the number of fuel cell electric vehicles is growing rapidly, with China taking the lead in terms of deployment. Global investment in low-emissions hydrogen production neared \$8 billion in 2025, reflecting a year-on-year increase of 80 per cent, although electrolysis is expected to make up 80 per cent of the spending in 2025 even though it will only account for 56 per cent of the production from projects currently under construction [85, 86]. Fuel-cell commercialization should be application-based and based on the maturity of the evidence. Demonstrated operating installations, products launched to market, awarded contracts, announced partnerships, and proposed future deployments are different categories and should not be reported interchangeably. PEMFCs are commonly discussed for transport and distributed power, while SOFCs and MCFCs are relevant to stationary generation and combined heat and power; maritime and heavy-duty applications have their own requirements for fuel storage, system integration and durability. Reported power capacities and project status should be dated and tied to a traceable source. Hydrogen-demand, hydrogen-cost and low-emissions-hydrogen investment estimates also depend on geography, production pathway, reporting year and the inclusion or exclusion of storage and delivery. Because the supplied manuscript did not retain source-level documentation for all of its specific market figures, those figures are not repeated here as verified facts. Future updates should prioritize official statistics and clearly distinguish announcements from commissioned systems and sustained operation.

7. COUNTRIES AND THEIR PATENTS ON FUEL CELLS

The number of fuel cell patents increased by 51% from 1806 in 2010 to 2732 in 2011; it was 3% more than the combined United States Patent and Trademark Office (USPTO) and European Patent Office (EPO) patents, and 10% higher than the overall granted patents worldwide. The number of patent filings also increased by 58% in 2011 compared to 2010, which is more than the total worldwide applications (8%) or combined USPTO and EPO applications (1%). USA and Japan dominated in granted patents, accounting for 69% of total patents in 2011. Most of them are related to the automotive sector, showing their commitment towards better fuel cell technology. Asia has emerged as a dominant patenting force with double-digit growth in applications from Japan and China. More than two million applications were filed worldwide in 2011 under the Patent Cooperation Treaty (PCT) system (direct and PCT national phase entries) [87]. The combined USPTO and EPO figures reported by Fuel Cell Today were 1801 granted fuel-cell patents in 2010, rather than 1806. In between 2010-2011, the total number of worldwide patents increased by 10%, while fuel cell patents increased by 51%, equating to growth in fuel cell-related intellectual property (IP). The US and European patent offices published a combined total of 2,732 granted fuel cell patents in that year. The effects of the global economic crisis were not reflected in 2011 granted patents (65%) due to the filing of the majority of applications before 2007. A recommended workflow for conducting a reproducible fuel-cell patent-landscape analysis is presented in Figure (6). Japanese companies like Honda, Toyota, Panasonic, Nissan, Hitachi and others make up half of the top ten global holders of granted patents in 2011. Japanese companies are interested in fuel cell technology due to automotive development and residential micro-combined heat and power (micro-CHP) applications. In the USA, General Motors heads the granted patents list for 2011 with 23% of the country's total patents and other patents are from UTC Power, Delphi Technologies, Bloom Energy, Fuel Cell Energy, IDA Tech and Honeywell, each contributing 24 or more to the total. In Germany, the Clean Energy Partnership (CEP) is a national organisation focusing on developing standards for hydrogen production, infrastructure and mobility. Daimler and Siemens are members of CEP; these companies work together to overcome their competitive boundaries and advance hydrogen technologies. In

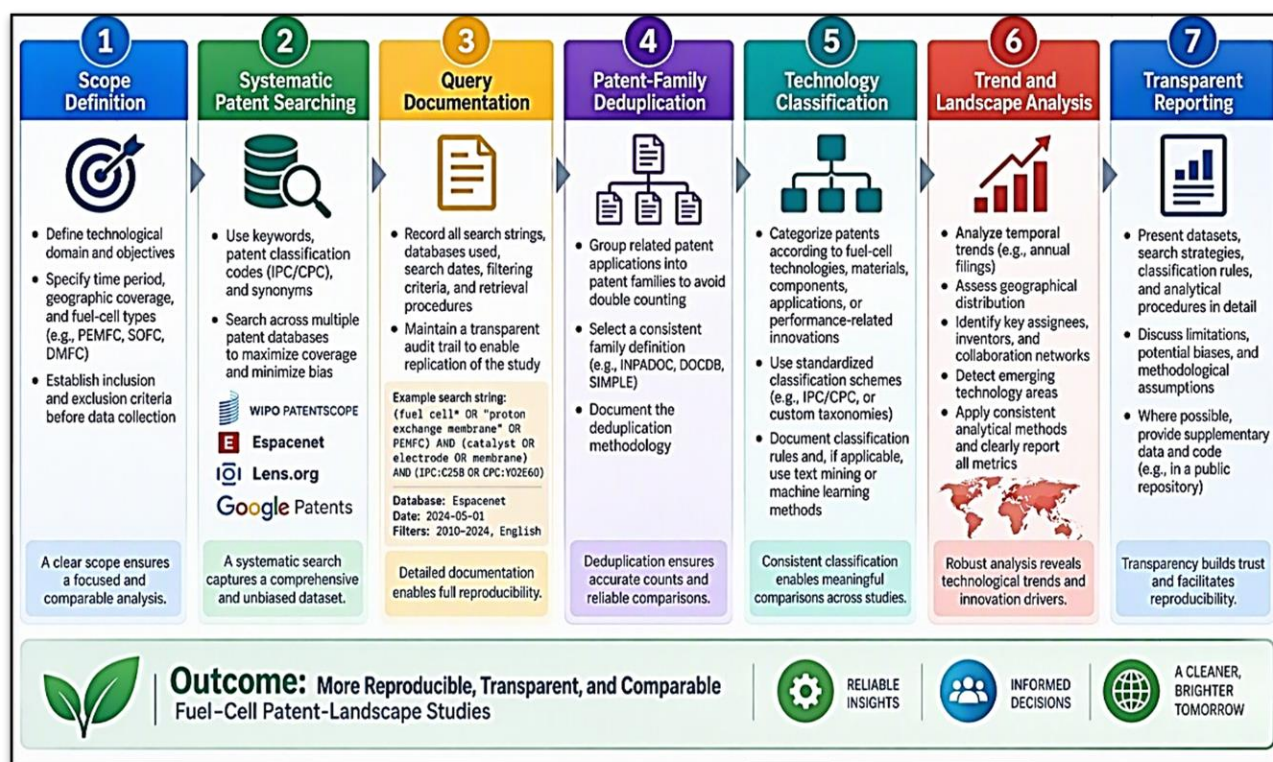


Figure 6: Schematic overview for the recommended workflow for reproducible fuel-cell patent-landscape analysis.

South Korea, Samsung has 80% of granted patents in the country; Hyundai and LG Chemical Ltd contribute smaller amounts to the total. In France, CEA (Atomic Energy Commission) contributed 40% to the total. Along with society BIC (Ballpoint Pens Company), Renault and Air Liquide, these companies account for 75% of French fuel cell patents. In Canada, Versa Power Systems, which works on solid oxide fuel cell systems and the development of 2 to 10 kW stationary systems for CHP (combined heat and power) applications, is leading the list of granted patents with around 20% of the total. In the UK, Johnson Matthey (JM) has 20% of the country's total granted patents. JM specialises in platinum-based products and sells fuel cell catalysts and membrane electrode assemblies (MEA) for fuel cell systems. For five years, there has been a large increase in the number of granted fuel cell patents in China (included in PCT in 1994). The recent development of IP in the country highlights it as an important end-user of fuel cells. By 2010, China was involved in 78% of all granted patents, a significant shift in IP protection by fuel cell researchers and developers. This percentage dropped in 2011, with an absolute reduction of 78 despite an increase in total granted patents, but it still shows the importance of IP protection in the country. Asia remains the dominant region in granted patents; most of them are from Japan

and Korea. North America holds second place, led by the USA, and the rest of the world region continues to lag behind the other regions. But adoption of the technology in the rest of the world is growing. In 2011, Japan, USA, Germany and Korea showed their dominance in both fuel cell patent applications and granted patents published during the year. The top ten companies of granted patents (Table 1) are from the automotive sector, with other companies including residential micro-CHP fuel cell manufacturers and well-known multinationals. Automotive fuel cell technology is expected to reach commercialisation during the next three years; they are all developing products for sale. Japanese manufacturers like Panasonic, with the continued success of residential micro-CHP, will be at the top of the patent statistics as they further optimise their products for sale both domestically and overseas. If we look back over the past ten years, typically less than 1% of granted patents included China, but a shift has taken place in the industry with strong emphasis on IP protection in China. To improve the existing technology, allowing longer lifetimes, increased durability, and lower cost, intense research is being carried out. This effort will continue alongside the discovery of new materials with the potential to improve fuel-cell technology; these discoveries will lead to continued growth in patent activity also.

Table 1: Leading Assignees of Fuel-Cell Patent Applications in 2010, 2011, and 2024 [88]

S. No.	Company	No. Fuel cell Patents-2010	No. Fuel Cell Patents-2011	No. Fuel Cell Patents-2024
1	Samsung	68	191	245
2	Honda	50	217	289
3	General Motors	48	194	201
4	Toyota	26	188	312
5	Panasonic	24	92	156
6	Nissan	22	87	98
7	Hitachi	22	36	67
8	Delphi	17	33	45

Table 2: Ratio of Applications to Granted Patents [89]

S. No	Country	2010 Applications	2010 Granted	2010 Ratio	2011 Applications	2011 Granted	2011 Ratio	2024 Ratio
1.	Japan	1374	618	2.2	2376	1040	2.3	2.1
2.	USA	1080	601	1.8	1495	841	1.8	1.7
3.	China	15	N/A	N/A	20	N/A	N/A	1.9
4.	Germany	341	187	1.8	552	285	1.9	1.8
5.	South Korea	206	177	1.2	418	240	1.7	1.6
6.	France	126	46	2.7	179	72	2.5	2.4
7.	UK	67	30	2.2	120	46	2.6	2.5

Apart from this, recently in annual review on fuel cells and hydrogen energy (2015) has revealed [90] a graphical overview of fuel cells. In which they reported on several points concerning fuel cells, which are as follows: the number of countries with policies that are directly or indirectly pro-fuel cells or hydrogen has increased in 2014; global fuel cell shipments and regions of manufacture from the year 2009-2015, share of companies in the fuel cell industry by various countries like Europe, North America, Canada, and Asia (Japan, China). They revealed that the usage of fuel cells from the past decade onwards drastically increased in industry, transportation, domestic, and power generators. The review also reports on various electrolytic mixers which improve the performance of fuel cells. The increase in patent activity as described above reflects the broader development of fuel-cell technologies in transportation, stationary power generation and domestic applications. Therefore, continued research on new materials, catalysts, membranes and cell components is expected to support improvements in fuel-cell durability and cost-efficiency [91]. Patent trends between 2020 and 2025

indicate that China has become the main source of innovation and the primary target market for hydrogen fuel cell stack technology. By 2024, China held 78 of all the granted patents in certain fuel cell categories. Japan remains at the forefront of fuel cell patent applications, a position it has maintained due to its work in the automotive sector and in residential micro-CHP applications. South Korea has also been very active in terms of patents, with Samsung, Hyundai, and LG Chemical Ltd making significant contributions. India has demonstrated growing patent activity in alternative fuels, particularly in the areas of hydrogen fuels and hydrogen internal combustion engines, as shown by the patent publications from January 2024 to March 2025 [92].

8. CHALLENGES AND FUTURE PERSPECTIVES

8.1. Technical Challenges

The durability of fuel cells is a major obstacle to their commercialization. For stationary applications, PEMFCs need to have a lifespan of more than 40,000

hours, and for automotive applications, that range is 5,000 to 10,000 hours. The ways they degrade are through catalyst dissolution, membrane thinning, and bipolar plate corrosion [93]. The reduction of costs involves platinum-group metal catalysts, since they make up a major part of the expense of fuel cells. Although non-precious metal catalysts have potential,

Table 3: Number of Patent Applications Per Country of Origin [89]

Country	2010	2011	2024
Japan	1,374	2,376	3,890
USA	1,080	1,495	2,456
Germany	341	552	856
South Korea	206	418	890
France	126	179	245
UK	67	120	198
Taiwan	71	112	98
Canada	57	72	134
Denmark	29	57	76
Italy	25	44	67
Netherlands	34	43	56
Switzerland	24	42	65
Finland	17	42	54
Sweden	22	32	48
Austria	7	21	34
China	15	20	4,200
Israel	13	20	32
Australia	8	17	28
Spain	4	13	21
Singapore	10	12	19
Norway	4	8	14
South Africa	3	6	11
Greece	2	6	9
Belgium	1	6	8
Brazil	3	5	12
India	3	5	67
Turkey	2	5	8
Russia	3	3	7
Estonia	1	2	4
Cayman Islands	3	1	2
Ireland	2	0	3
Czech Republic	1	0	2
Hong Kong	1	0	2
New Zealand	1	0	2
Saudi Arabia	1	0	3
Total	3,561	5,734	14,832

their long-term stability and performance when operated under practical conditions are major problems [94]. The hydrogen infrastructure situation is such that the absence of an extensive network for producing, storing and distributing hydrogen hinders the deployment of fuel cells. Although global demand for hydrogen is still increasing, demand for hydrogen is still increasing, demand from new applications is still limited when compared to that of conventional fossil-based products. The ongoing obstacles are high production costs, a lack of refilling facilities, energy losses, complex storage requirements, and regulatory uncertainty [95]. The problems associated with high-temperature operation include thermal stresses, incompatibility of materials, degradation of the electrode, sealing difficulties, and issues concerning long-term durability when using SOFCs and MCFCs. Thermal stress and mechanical cracking result from repeated heating and cooling cycles because of the mismatch between the coefficients of thermal expansion of the electrolyte, electrodes, and interconnect materials. Material degradation takes place via grain growth, delamination at the interfaces, and interdiffusion between the layers [96]. Polymer electrolyte membranes encounter various problems such as degradation due to humidity cycling and thermal degradation when the temperature is high [97].

8.2. Commercialization Barriers

Regarding economic viability, fuel cell systems must compete with established alternatives on total system cost, durability, and infrastructure requirements. Costs are shaped not only by platinum-group-metal catalysts but also by stack manufacturing, power electronics, maintenance, fuel delivery, and hydrogen production. Reported green-hydrogen costs vary substantially with region, renewable-electricity price, electrolyser utilization, financing, and whether storage and delivery are included; a single figure should therefore not be presented as a universal price. Techno-economic assessments and hydrogen-pathway analyses should be interpreted within their stated scenarios [98, 99]. Battery-electric vehicles are strong competitors in light-duty transport, whereas fuel cells may remain competitive; however, the comparison remains application-specific [100].

8.3. Future Research Directions

Fuel cell research targets efficiency, durability, lower-cost manufacturing, reduced dependence on critical materials, and integration with renewable-

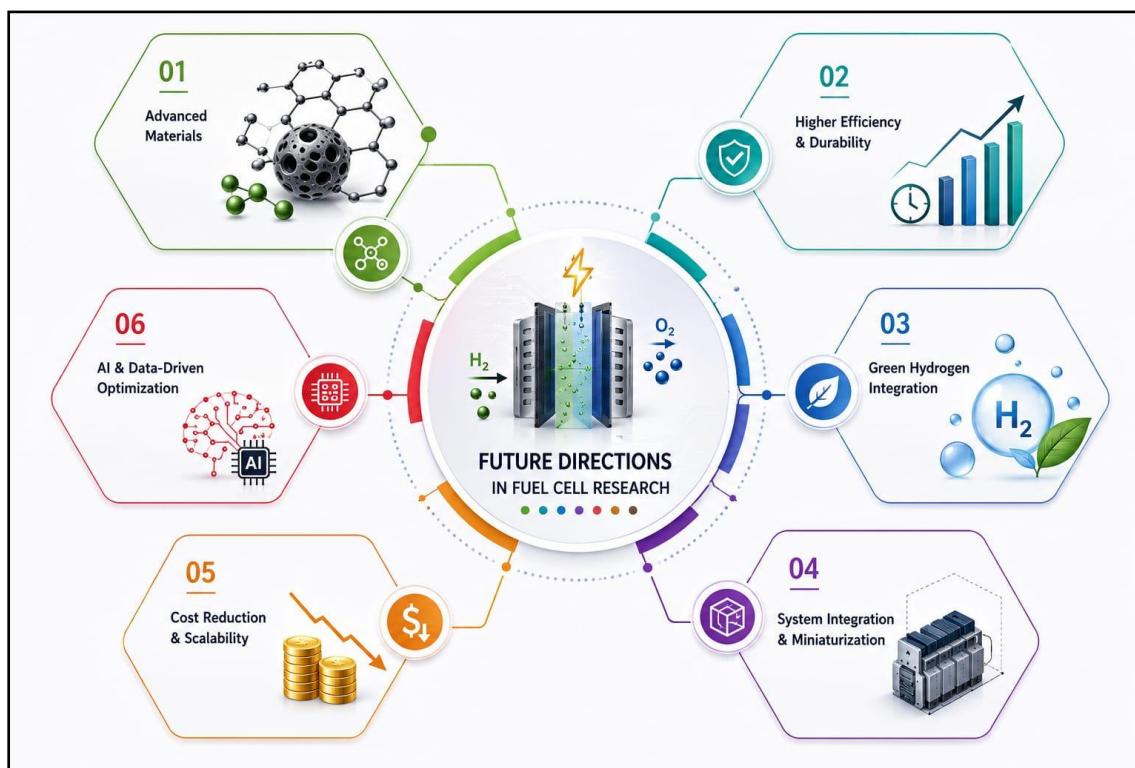


Figure 7: Schematic overview of the six key strategic pillars shaping the future of fuel cell research, encompassing advanced materials, operational efficiency, AI-driven optimization, system miniaturization, cost reduction, and green hydrogen integration.

energy systems. Machine-learning methods are being explored for materials discovery, catalyst design, diagnostics, and system optimization, but their practical value depends on validation against experimental data. Recycling and critical-metal supply are also relevant to scale-up. Integration with renewable electricity and low-emission hydrogen can improve system-level performance, provided that hydrogen production and delivery are included in the environmental assessment [101-105]. The major strategic directions expected to drive future fuel-cell research and commercialization are summarized in Figure (7).

9. CONCLUSIONS

In conclusion, we presented a comprehensive review of various types of fuel cells, their working principles, and the components (fuel, electrolyte type, and catalyst), chemical reactions, operating temperatures, advantages, and drawbacks. From the literature, we observed that high efficiency, lifespan, durability, and reliability depend on suitable material selection and on constraints imposed on the material. In recent developments, various companies have tried and achieved high power outputs ranging from kilowatts to megawatts, which reflect the advanced

developments in material components. It is observed that globally the number of fuel-cell-related patents has drastically increased over the years. From these things, one can understand that extensive research has been going on to improve the performance of fuel cells, and researchers are continuously working to achieve higher efficiency, durability, reliability and cost-efficiency. The ongoing development of advanced catalysts, electrolytes, electrodes and other functional materials is essential for the wider commercialization of fuel-cell technologies. The key developments mentioned in this review are non-precious metal catalysts, particularly single-atom and dual-atom catalysts, which show promise in replacing platinum. Advanced membranes include those based on nanofibres and composite membranes that have better proton conductivity and durability. Intermediate-temperature solid oxide fuel cells, such as proton-conducting and metal-supported types, are allowing for lower operating temperatures. There has been progress towards commercialization with major deployments in the automotive and stationary power sectors currently in progress. Future research should aim at further reducing costs, improving durability, and developing sustainable methods of producing hydrogen and the associated

infrastructure in order to achieve widespread fuel cell deployment.

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AUTHORSHIP CONTRIBUTION STATEMENT

All authors contributed to the conception and design of the review article. The concept has been conceived and implemented by the Dr. RKJ, review article corrections and supervision has been done by the Dr. C.A. Pawar (Dr. CAP). Review article drafting has been carried out by the Ms. MD.SA. Formal monitoring and formatting was done by the Dr. DVS, Dr. SRG and Dr. SHP. All authors reviewed and approved the final draft of review article for publication.

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DECLARATION OF COMPETING INTERESTS

The authors declare that they have no competing interests.

APPENDIX A. SUPPLEMENTARY DATA

The data is available free of charge at the journal website or from the journal editor or corresponding author upon reasonable request.

REFERENCES

- [1] Carrette L, Friedrich KA, Stimming U. Fuel cells: principles, types, fuels, and applications. *ChemPhysChem*. 2000 Dec; 1(4): 162-193. doi: 10.1002/1439-7641(20001215)1:4<162::AID-CPHC162>3.0.CO;2-Z.
- [2] Grove WR. On voltaic series and the combination of gases by platinum. *London and Edinburgh Philosophical Magazine and Journal of Science*. 1839 Sep; 14(85): 127-130. doi: 10.1080/14786443908649684.
- [3] Boudghene SA, Traversa E. Fuel cells, an alternative to standard sources of energy. *Renewable and Sustainable Energy Reviews*. 2002 Jun; 6(3): 295-304. doi: 10.1016/S1364-0321(01)00015-6.
- [4] Carrette L, Friedrich KA, Stimming U. Fuel cells-fundamentals and applications. *Fuel Cells*. 2001 May; 1(1): 5-39. doi: 10.1002/1615-6854(200105)1:1<5::AID-FUCE5>3.0.CO;2-R.
- [5] Hermann A, Chaudhari TK, Spagnol P. Bipolar plates for PEM fuel cells: A review. *International Journal of Hydrogen Energy*. 2005 Dec; 30(12): 1297-1302. doi: 10.1016/j.ijhydene.2005.04.016.
- [6] Steele BCH, Heinzel A. Materials for fuel-cell technologies. *Nature* 2001 Nov 8; 414: 345-352. doi: 10.1038/35104620.
- [7] Huang X, Zhang Z, Jiang J. Fuel cell technology for distributed generation: An overview. *Proceedings of the IEEE International Symposium on Industrial Electronics*. 2006 Jul; 2: 1613-8. doi: 10.1109/ISIE.2006.295748.
- [8] Qasem NAA. A recent overview of proton exchange membrane fuel cells: Fundamentals, applications, and advances. *Applied Thermal Engineering*. 2024 Aug; 252: 123746. doi: 10.1016/j.applthermaleng.2024.123746.
- [9] Shao Z, Ni M. Fuel cells: Materials needs and advances. *MRS Bulletin*. 2024 May; 49(5): 451-463. doi: 10.1557/s43577-024-00722-9.
- [10] Sikstrom D, Thangadurai V. A tutorial review on solid oxide fuel cells: fundamentals, materials and applications. *Ionics*. 2026 Jan; 32(1): 5-30. doi: 10.1007/s11581-024-05824-7.
- [11] Qasem NAA, Abdulrahman GAQ. A recent comprehensive review of fuel cells: history, types, and applications. *International Journal of Energy Research*. 2024 Aug; 2024: 7271748. doi: 10.1155/2024/7271748.
- [12] Eikeng E, Makhsoos A, Pollet BG. Critical and Strategic raw materials for electrolyzers, fuel cells, metal hydrides and hydrogen separation technologies. *International Journal of Hydrogen Energy* 2024 Jun; Paris: 71: 433-464. doi: 10.1016/j.ijhydene.2024.05.096.
- [13] Ellis MW, Von Spakovsky MR, Nelson DJ. Fuel cell systems: efficient, flexible energy conversion for the 21st century. *Proceedings of the IEEE* 2001 Dec; 89(12): 1808-1818. doi: 10.1109/5.975914.
- [14] Farooque M, Maru HC. Fuel cells-the clean and efficient power generators. *Proceedings of the IEEE* 2001 Dec; 89(12): 1819-29. doi: 10.1109/5.975917.
- [15] Yeom J, Mozsgai GZ, Asthana A, Flachsbarth BR, Waszczuk P, Choban ER, Kenis PJA, Shannon M. A silicon microfabricated direct formic acid fuel cell. In: *ASME 2003 1st International Conference on Fuel Cell Science, Engineering and Technology*. 2003 Apr 21-23; 267-272. doi: 10.1115/FUELCCELL2003-1729.
- [16] Coors WG. Protonic ceramic fuel cells for high-efficiency operation with methane. *Journal of Power Sources* 2003 May; 118(1-2):150-156. doi: 10.1016/S0378-7753(03)00072-7.
- [17] Jamard R, Salomon J, Martinet BA, Couanceau C. Life time test in direct borohydride fuel system. *Journal of Power Sources* 2009 Sep; 193(2): 779-787. doi: 10.1016/j.jpowsour.2009.03.057.
- [18] Colominas S, McLafferty J, Macdonald DD. J. Electroanalytical Studies of sodium borohydride in alkaline aqueous solutions using a gold electrode. *Electrochimica Acta* 2009 Jun; 54(13): 3575-3579. doi: 10.1016/j.electacta.2009.01.021.
- [19] Sullivan JB. Fuel cells in distributed generation. In: 1999 IEEE Power Engineering Society Summer Meeting. Vol. 1. 1999 Jul;568-572. doi: 10.1109/PESS.1999.784293.
- [20] Yakabe H, Sakuri T, Sobue T, Yamashita S, Hase K. Solid oxide fuel cells as promising candidates for distributed generators. In: *2006 IEEE International Conference on Industrial Informatics*. 2006 Aug;369-374. doi: 10.1109/INDIN.2006.275828.

- [21] Pasricha S, Keppler M, Shaw SR, Hashem NM. Comparison and identification of static electrical terminal fuel cell models. *IEEE Transactions on Energy Conversion*. 2007 Sep; 22(3): 746-754. doi: 10.1109/TEC.2007.895465.
- [22] Alejandro JR, Alicia A, Carlos B. Development and experimental validation of a PEM fuel cell dynamic model. *Journal of Power Sources* 2007 Nov; 173(1): 310-324. doi: 10.1016/j.jpowsour.2007.04.066.
- [23] Correa JM, Farret FA, Popov VA, Simoes MG. Sensitivity analysis of the modelling parameters used in simulation of proton exchange membrane fuel cells. *IEEE Transactions on Energy Conversion*. 2005 Mar; 20(1): 211-218. doi: 10.1109/TEC.2004.842382.
- [24] Laughton MA. Fuel Cells. *IEEE Power Engineering Journal*. 2002 Feb; 16(1): 37-47. doi: 10.1049/pe:20020105.
- [25] Kirubakaran A, Shailendra J, Nema RK. A review on fuel cell technologies and power electronic interface. *Renewable and Sustainable Energy Reviews*. 2009 Dec; 13(9): 2430–2440. doi: 10.1016/j.rser.2009.04.004.
- [26] Talukdar A, Chakrovorty A, Sarmah P, Paramasivam P, Kumar V, Yadav SK, Manickam S. A review on solid oxide fuel cell technology: An efficient energy conversion system. 2024; 6443247. doi: 10.1155/2024/6443247.
- [27] Nernst WZ. Über die elektrolytische Leitung fester Körper bei sehr hohen Temperaturen. *Zeitschrift für Elektrochemie*. 1899 May; 6(2): 41-43. doi: 10.1002/bbpc.18990060205.
- [28] Baur E, Preis HZ. Über Brennstoffketten mit Festleitern, *Elektrochemie und angewandte physikalische Chemie*. 1937 Sep; 43(9): 727-732. doi: 10.1002/bbpc.19370430903.
- [29] Ali ABM, Nemah AK, Al Bahadli YA, Kianafar E. Principles and performance and types, advantages and disadvantages of fuel cells: A review. *Case Studies in Chemical and Environmental Engineering*. 2024 Jun; 10: 100920. doi: 10.1016/j.csee.2024.100920.
- [30] Kahraman H, Akin Y. Recent studies on proton exchange membrane fuel cell components: a review of the literature. *Energy Conversion and Management*. 2024 Mar; 304: 118244. doi: 10.1016/j.enconman.2024.118244.
- [31] Cai F, Cai S, Tu Z. Proton exchange membrane fuel cell (PEMFC) operation in high current density (HCD): Problem, progress and perspective. *Energy Conversion and Management*. 2024 May; 307: 118348. doi: 10.1016/j.enconman.2024.118348.
- [32] Wang Y, Chen KS, Mishler J, Cho SC, Adroher XC. A review of polymer membrane electrolyte fuel cells: Technology, applications and needs on fundamental research. *Applied Energy*. 2011 Apr; 88: 981-1007. doi: 10.1016/j.apenergy.2010.09.030.
- [33] Prater KB. The renaissance of the solid polymer fuel cell. *Journal of Power Sources* 1990 Jan; 29(1): 239-250. doi: 10.1016/0378-7753(90)80023-7.
- [34] de Bruijn FA. The current status of fuel cell technology for mobile and stationary applications. *Green Chemistry*. 2005 Feb; 7: 132-150. doi: 10.1039/B415317K
- [35] Tawfik H, Hung Y, Mahajan D. Metal bipolar plates for PEM fuel cell-A review. *Journal of Power Sources* 2007 Jan; 163 (2): 755-767. doi: 10.1016/j.jpowsour.2006.09.088.
- [36] Zhang S, Shao Y, Yin G, Lin Y. Recent progress in nanostructured electrocatalysts for PEM fuel cells. *Journal of Materials Chemistry A*. 2013 Mar; 1(5): 4631-4641. doi: 10.1039/C3TA01161E.
- [37] Qingfeng L, Ronghuan H, Jens OJ, Niels JB. Approaches and recent development of polymer electrolyte membranes for fuel cells operating above 100 °C. *Chemistry of Materials*. 2003 Dec; 15(26): 4896-4915. doi: 10.1021/cm0310519.
- [38] Helms HE, Haley PJ. Development of a PEM fuel cell system for vehicular application. *SAE Technical Paper Series* 921541. 1992 Aug;1: 1-11.
- [39] Srinivasan S, Mosdale R, Stevens P, Yang C. Fuel cells: Reaching the era of clean and efficient power generation in the twenty-first century. *Annual Review of Energy and the Environment*. 1999 Nov; 24:281-328. doi: 10.1146/annurev.energy.24.281.
- [40] Krishnan SR, Verstraete D, Aguey-Zinsou F. Performance of non-precious metal electrocatalysts in proton-exchange membrane fuel cells: A review. *ChemElectroChem*. 2024; 11(17). doi: 10.1002/celec.202400299.
- [41] Wani AA, Shaari N, Kamarudin SK, Raduwan NF, Yusoff YN, Khan AM, Yousuf S, Ansari MNM. Critical review on composite-based polymer electrolyte membranes toward fuel cell applications: Progress and perspectives. *Energy & Fuels*. 2024 Oct; 38(19): 18169-18193. doi: 10.1021/acs.energyfuels.4c02516.
- [42] Baek J, Son H, Lee E, Yoo SJ, Kim M, Lee G. Hierarchically porous Co-N-C electrocatalysts with enhanced mass transport and cobalt utilization efficiency for oxygen reduction reaction in high-performance PEMFCs. *Journal of Materials Chemistry A*. 2025 Apr; 13(16): 11445-11457. doi: 10.1039/D5TA00827A.
- [43] Winsel A, Führer O, Rühling K, Fischer C. Elox fuel cells and electrolysis cells. *Berichte der Bunsengesellschaft für Physikalische Chemie*. 1990 Sep; 94: 926-931. doi: 10.1002/bbpc.19900940909.
- [44] Führer O, Rieke S, Schmitz C, Willer B, Wollny M. Alkaline elox fuel cells and electrolysis cells using a new kind of gas diffusion electrodes. *International Journal of Hydrogen Energy*. 1994 Apr; 19(4): 343-348. doi: 10.1016/0360-3199(94)90066-3.
- [45] Varcoe JR, Atanassov P, Dekel DR, Herring AM, Hickner MA, Kohl PA, Kucernal ARJ, et al. Anion-exchange membranes in electrochemical energy systems. *Energy & Environmental Science*. 2014 Oct; 7: 3135-3191. doi: 10.1039/C4EE01303D.
- [46] Kulkarni A, Giddey S. Materials for solid oxide fuel cells. *Journal of Solid State Electrochemistry*. 2012 Oct; 16(10): 3123-3146. doi: 10.1007/s10008-012-1771-y.
- [47] Wasmus S, Kuver A. J. Methanol oxidation and direct methanol fuel cells: A selective review. *Electroanalytical Chemistry*. 1999 Jan; 461(1): 14-31. doi: 10.1016/S0022-0728(98)00197-1.
- [48] EG&G Technical Services, Inc. *Fuel Cell Handbook*. 7th ed. Morgantown, WV: U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory; 2004. 427 p. doi: 10.2172/834188.
- [49] Sharon CT, Xiaoming R, Shimshon G, Piotr Z. Recent advances in direct methanol fuel cells. *Electrochimica Acta*. 2002 Oct; 47(22): 3741-3748. doi: 10.1016/S0013-4686(02)00344-4.
- [50] Pervaiz E, Ali H, Noor T, Baig MM. A perspective on development of fuel cell materials: Electrodes and electrolyte. *International Journal of Energy Research*. 2022 May; 46(7): 8981-9001. doi: 10.1002/er.7853.
- [51] Chen S, Li Q, Li W, Liu X. Advancement in materials and strategies for reliable and high-efficiency proton-conducting electrolytes in solid oxide cells. *Chemical Engineering Journal*. 2025 Sep; 519: 164664. doi: 10.1016/j.cej.2025.164664.
- [52] Antunes FC, de Oliveria JPP, de Abreu RS, Dias T, Brandao BBNS, Goncalves JM, Ribeiro J, Hunt J, Hunt J, Zanin H, Doubek G. Reviewing metal-supported solid oxide fuel cells for efficient electricity generation with biofuels for mobility. *International Journal of Hydrogen Energy*. 2024; 103: 48-95. doi: 10.1016/j.ijchem.2024.10.056.
- [53] Liu Y, Guo Y, Ran R, Shao Z. A new neodymium-doped BaZr_{0.8}Y_{0.2}O_{3-δ} as potential electrolyte for proton-conducting solid oxide fuel cells. *Journal of Membrane Science*. 2012; 415-416: 391-398. doi: 10.1016/j.memsci.2012.05.062.
- [54] Xu J, Lu X, Ding Y, Chen Y. Stable BaCe_{0.5}Zr_{0.3}Y_{0.16}Zn_{0.04}O_{3-δ} electrolyte-based proton-conducting solid oxide fuel cells with layered SmBa_{0.5}Sr_{0.5}Co₂O_{5+δ} cathode. *Journal of Alloys and*

- Compounds. 2009; 488(1): 208-210. doi: 10.1016/j.jallcom.2009.08.080.
- [55] Iwahara H, Esaka T, Uchida H, Maeda N. Proton conduction in sintered oxides and its application to steam electrolysis for hydrogen production. *Solid State Ionics*. 1981; 3-4: 359-353. doi: 10.1016/0167-2738(81)90113-2.
- [56] Tseng CJ, Chang JK, Hung IM, Lee KR, Lee SW. BaZr_{0.2}Ce_{0.8-x}YxO_{3-δ} solid oxide fuel cell electrolyte synthesized by sol-gel combined with composition-exchange method. *International Journal of Hydrogen Energy*. 39(26): 14434-14440. doi: 10.1016/j.ijhydene.2014.02.024.
- [57] Dang J, Zhu Z, Qian J, Liu W. A stable BaCe_{0.7}Ta_{0.1}In_{0.2}O_{3-δ} electrolyte membrane for proton-conducting solid oxide fuel cells. *Ceramics International*. 2013; 39(4): 4287-4292. doi: 10.1016/j.ceramint.2012.11.008.
- [58] Bassano A, Buscaglia V, Viviani M, Bassoli M, Buscaglia MT, Sennour M, Thorel A, Nanni P. Synthesis of Y-doped BaCeO₃ nanopowders by a modified solid-state process and conductivity of dense fine-grained ceramics. *Solid State Ionics*. 180(2-3): 168-174. doi: 10.1016/j.ssi.2008.12.026.
- [59] Jang I, Carneiro JSA, Crawford JO, Cho YJ, Parvin S, Gonzalez-Casamachin DA, Baltrusaitis J, Lively RP, Nikolla E. Electrocatalysis in solid oxide fuel cells and electrolyzers. *Chemical Reviews*. 2024; 124(13): 8233-8306. doi: 10.1021/acs.chemrev.4c00008.
- [60] Fabbri E, Pergolesi D, Traversa E. Materials challenges toward proton-conducting oxide fuel cells: A critical review. *Chemical Society Reviews*. 2010 Nov; 39: 4355-4369. doi: 10.1039/B902343G.
- [61] Xiaoming R, Piotr Z, Sharon T, John D, Shimshon G. Recent advances in direct methanol fuel cells at Los Alamos National Laboratory. *Journal of Power Sources* 2000 Mar; 86(1): 111-116. doi: 10.1016/S0378-7753(99)00407-3.
- [62] Dillon R, Srinivasan S, Arico AS, Antonucci V. International activities in DMFC R&D: Status of technologies and potential applications. *Journal of Power Sources*, 2004 Mar; 127(1): 112-126. doi: 10.1016/j.jpowsour.2003.09.032.
- [63] Hansan L, Chaojie S, Lei Z, Jiujun Z, Haijiang W, David P W. A review of anode catalysis in the direct methanol fuel cell. *Journal of Power Sources*, 2006 Apr; 155(2): 95-110. doi: 10.1016/j.jpowsour.2006.01.030.
- [64] Christopher K, Stanislaus SW. A promising structural paradigm for direct methanol fuel cells. *Energy and Environmental Science*, 2011 Apr; 4: 1161-1176. doi: 10.1039/CC0EE00197J.
- [65] Karl K, Viktor H, Josef G *et al*. Alkaline Fuel Cells Applications. *Journal of Power Sources*. 2000 Mar; 86(1): 162-165. doi: 10.1016/S0378-7753(99)00429-2.
- [66] Kordesch, K. & Simader, G. *Fuel Cells and Their Applications*. Weinheim, Germany: VCH; 1996. 375 p.
- [67] Subbiah G, Tripathy S, Guntaj J, Kaliappan N, Nagappan B, Patel DJ, Kamakshi PK. Advancements in electrocatalytic technologies for metal-supported solid oxide fuel cells: Enhancing efficiency and durability for biofuel-powered mobility applications. *Materials for Renewable and Sustainable Energy*. 2025 Aug; 14: 51. doi: 10.1007/s40243-025-00322-w.
- [68] Kamarudin SK, Achmad F, Daud WRW. Overview on the application of direct methanol fuel cell (DMFC) for portable electronic devices. *International Journal of Hydrogen Energy*. 2009 Aug; 34: 6902-6916. doi: 10.1016/j.ijhydene.2009.06.013.
- [69] Tsvetkov N, Kim D, Jeong I, Kim JH, Ahn S, Lee KT, Jung WC. Advances in materials and Interface Understanding in Protonic Ceramic Fuel Cells. *Advanced Materials Technologies*. 2023 Oct; 8(20): 2201075. doi: 10.1002/admt.202201075.
- [70] Tariq U, Khan MZ, Gohar O, Baar ZUD, et al. Bridging the Gap between fundamentals and efficient devices: Advances in proton-conducting oxides for low-temperature solid oxide fuel cells. *Journal of Power Sources*. 2024 Sep; 613: 234910. doi: 10.1016/j.jpowsour.2024.234910.
- [71] O'Hayre R, Cha SW, Colella W, Prinz FB. Fuel cell fundamentals. *Fuel Cells*. 2005; 5(2):1-15. doi: 10.1002/fuce.200500014.
- [72] Borup, R. L. and Vanderborgh, N. E. Design and testing criteria for bipolar plate materials for PEM fuel cell applications. MRS Online Proceedings Library. 1995. 393, 151-155. doi: 10.1557/PROC-393-151.
- [73] Scholta J, Rohland B, Trapp V, Focken U. J. Investigations on novel low-cost graphite composite bipolar plates. *Journal of Power Sources* 1999; 84(2): 231-234. doi: 10.1016/S0378-7753(99)00322-5.
- [74] Robert CM, Arno HHJ, Frank AB, Ronald KAMM. Use of stainless steel for cost competitive bipolar plates in the SPFC. *Journal of Power Sources* 2000 Mar; 86(1): 274-282 (2000). doi: 10.1016/S0378-7753(99)00460-7.
- [75] Davies DP, Adcock PL, Turpin M, Rowen SJ. J. Stainless steel as a bipolar plate material for solid polymer fuel cells. *Journal of Power Sources* 2000 Mar; 86(1-2): 237-242. doi: 10.1016/S0378-7753(99)00524-8.
- [76] Ashok P, Maheswari S, Ramaprabhu S. Platinum on boron doped graphene as cathode electrocatalyst for proton exchange membrane fuel cells. *International Journal of Hydrogen Energy*. 2015 Aug; 40(32): 10251-10261. doi: 10.1016/j.ijhydene.2015.06.020.
- [77] Zhang et al. (2024). Fe-based dual-atom catalysts for the oxygen reduction reaction. *Journal of Materials Chemistry A*; 12; 87-112. doi: 10.1039/D3TA05147A.
- [78] Nguyen et al. (2022). Fully hydrocarbon membrane electrode assemblies for proton exchange membrane fuel cells and electrolyzers. An engineering perspective review. *Advanced Energy Materials*; 12: 2103559. doi: 10.1002/aenm.202103559.
- [79] Imran Jafri R, Rajalakshmi N, Dhathathreyan KS, Ramaprabhu S. Nitrogen-doped graphene prepared by hydrothermal and thermal solid-state methods as catalyst supports for fuel cell. *International Journal of Hydrogen Energy*. 2015 Apr; 40(12): 4337-4348. doi: 10.1016/j.ijhydene.2015.02.008.
- [80] Divya P, Ramaprabhu S. Platinum-graphene hybrid nanostructure as anode and cathode electrocatalysts in proton exchange membrane fuel cells. *Journal of Materials Chemistry A*, 2014 Apr; 2: 4912-4918. doi: 10.1039/C3TA15181F.
- [81] Corigliano O, Pagnotta L, Fragiaco P. On the technology of solid oxide fuel cell (SOFC) energy systems for stationary power generation: A review. *Sustainability*. 2022 Nov; 14(22): 15276. doi: 10.3390/su142215276.
- [82] Swider-Lyons KE, Carlin RT, Rosenfeld RL, Nowak RJ. Technical issues and opportunities for fuel cell development for autonomous underwater vehicles. Proceedings of the Symposium on Autonomous Underwater Vehicle Technology. 2002 Jun: 61-64. doi: 10.1109/AUV.2002.1177204.
- [83] Garcia BL, Sethuraman VA, Weidner JW, White RE, Dougal R. Mathematical model of a direct methanol fuel cell. *Journal of Fuel Cell Science and Technology*. 2004 Feb; 43-48. doi: 10.1115/1.1782927.
- [84] Golkhatmi SZ, Asghar ML, Lund PD. A review on solid oxide fuel cell durability: Latest progress, mechanisms, and study tools. *Renewable and Sustainable Energy Reviews*. 2022 Jun; 161: 1-34. doi: 10.1016/j.rser.2022.112339.
- [85] Hidayat EF, Juliandri, Zain SM, Noviyanti AR, Advances in proton exchange membrane fuel cell (PEMFC) materials: A review of developments from 2021 to 2025. *Journal of Power Sources* 2025 Nov; 657: 238124. doi: 10.1016/j.jpowsour.2025.238124.
- [86] Le DD, Nguyen HL, Yu S, Le HH, Hoang TD. Progress and outlook of solid oxide fuel cell technology for stationary power general applications. *Frontiers in Energy Research*. 2025 Sep; 13. doi: 10.3389/fenrg.2025.1650696.
- [87] Xie Z, Wang J, Zhao Q, Fan H, Zeng A, Ding W. Key components of PEM fuel cells. Catalysis: A review on

- durability. *Catalysis Science & Technology*. 2024 Aug; 14(16): 4420-4431. doi: 10.1039/D4CY00351A.
- [88] Mo S, Du L, Huang Z, Chen J, Zhou Y, Wu P, Meng L, Wang N, et al. Recent advances on PEM fuel cells: From key materials to membrane electrode assembly. *Electrochemical Energy Reviews*. 2023 Aug; 6:28. doi: 10.1007/s41918-023-00190-w.
- [89] Yang G, Lee C, Qiao X, Babu SK, Martinez U, et al. Advanced electrode structures for proton exchange membrane fuel cells: Current status and path forward. *Electrochemical Energy Reviews*. 2024 Mar; 7:9. doi: 10.1007/s41918-023-00208-3.
- [90] Zucconi A, Hack J, Stocker R, Suter TAM, Rettie AJE, Brett DJL. Challenges and opportunities for characterization of high-temperature polymer electrolyte membrane fuel cells: A Review. *Journal of Materials Chemistry A*. 2024 Mar. 12:8014-8064. doi: 10.1039/D3TA06895A.
- [91] Ramachandran R, Chen TW, Veerakumar P, Anushya G, Chen SM, Kannan R, Mariyappan V, Chitra S, Ponmurugraj N, Boominathan M. Recent development and challenges in fuel cells and water electrolyzer reactions: An overview. *RSC Advances*. 2022 Oct; 12(43): 28227-28244. doi: 10.1039/D2RA04853A.
- [92] Arun M, Giddey S, Joseph P, Dhawale DS. Challenges and mitigation strategies for general failure and degradation in polymer electrolyte membrane-based fuel cells and electrolyzers. *Journal of Materials Chemistry A*. 2025 Mar; 13: 11236-11263. doi: 10.1039/D4TA08823A.
- [93] Huang C, Wang F, Chen X, Li J, Shao M, Wei Z. Innovative strategies for designing and constructing efficient fuel cell electrocatalysts. *Chemical Communications*. 2025 Jan; 2658-2683. doi: 10.1039/D4CC05928J.
- [94] Xu H, Han Y, Zhu J, Ni M, Yao Z. Status and progress of metal-supported solid oxide fuel cell: Towards large-scale manufactory and practical applications. *Energy Reviews*. 2024; 3(1):100051. doi: 10.1016/j.enrev.2023.100051.
- [95] Li J, Cai Q, Amini Horri B. Highly conductive and stable electrolytes for solid oxide electrolysis and fuel cells: Fabrication, characterisation, recent progress and challenges. *Materials Advances*. 2025 Jan; 6: 39-83. doi: 10.1039/D4MA00690A.
- [96] Sheikh AA, Bianchi FR, Bove D, Bosio B. A review on MCFC matrix: State-of-the-art, degradation mechanisms and technological improvements. *Heliyon*. 2024 Feb; 10(4): e25847. doi: 10.1016/j.heliyon.2024.e25847.
- [97] Sahu S, Kanwal R, Ratnawat I, Mir A, Abrar I. Hydrogen fuel cells: Technical, economic, and policy pathways toward net-zero integration. *Sustainable Energy & Fuels*. 2025 Oct; 9(24): 6601-6630. doi: 10.1039/D5SE01080B.
- [98] Vallejo Cervantes C, Espinoza Andaluz M, Iranzo Paricio JA. Technical review of commercial LT-PEMFC technologies: Performance, applications and challenges. *International Journal of Hydrogen Energy*. 2025 Oct; 176: 151480. doi: 10.1016/j.ijhydene.2025.151480.
- [99] Blessing Y, Blessing O. Challenges and future directions of fuel cells. In: Babaniyi BR, Aransiola SA, Maddela NR, editors. *Fuel Cells in Environmental Sustainability*. Boca Raton, FL: CRC Press; 2025 Nov. 269-276. doi: 10.1201/9781043640958-16.
- [100] Sasej N, Cleeman LN, Torres T, Azizi K. Advancing HT-PEM fuel cell technology: Durability and performance under start-stop conditions. *Journal of Materials Chemistry A*. 2025 Nov; 13: 40500-40536. doi: 10.1039/D5TA07002C.
- [101] Paixao da Costa G, Garcia DME, Nguyen THV, Lacharmoise P, Simao CD. Advancements in printed components for proton exchange membrane fuel cells: A comprehensive review. *International Journal of Hydrogen Energy*. 2024 Jun; 69:710-728. doi: 10.1016/j.ijhydene.2024.05.072.
- [102] Li Y, et al. The supply of critical metals could constrain China's low-carbon transition in hydrogen production. *Resources, Conservation and Recycling*. 2025 Jun; 219: 108295. doi: 10.1016/j.resconrec.2025.108295.
- [103] Lu X, Gang W, Tu Z. Recent developments in control and integration of solid oxide fuel cells: From stack to system. *Renewable and Sustainable Energy Reviews*. 2025 Nov; 223: 116000. doi: 10.1016/j.rser.2025.116000.
- [104] Lin K, Chen B, Liu Z, Fu L, Hao S, Li J, Zhang Y, Xie H. Toward efficient, low-carbon, and cost-effective hydrogen production shifting from fossil fuel-based to renewable water electrolysis: A perspective and outlook. *Applied Energy*. 2025; 401: 126661. doi: 10.1016/j.apenergy.2025.126661.
- [105] Sadeghian O, Mohammadpour Shotorbani A, Ghassem Zadeh S, Mohammadi-Ivatloo B. Energy management of hybrid fuel cell and renewable energy-based systems: A review. *International Journal of Hydrogen Energy*. 2025 Mar; 107: 135-163. doi: 10.1016/j.ijhydene.2024.03.134.

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