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REVIEW PAPER

The Effectiveness of Membrane Materials in Green Alternative Energy and Environmental Technologies

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Abstract

Green process engineering, which is founded on the concepts of the process intensification approach, can make a significant contribution to industrial sustainability. Green process engineering refers to new equipment and procedures that are intended to result in significant improvements in chemical and other manufacturing and processing elements. It entails lowering production costs, equipment size, energy consumption, waste creation, as well as boosting remote control, information flow, and process flexibility. Membrane-based technology aids in the pursuit of these ideals, and the potential of membrane operations has recently been extensively acknowledged. The efficacy of fuel cells is dependent on the correct design of the electrodes and membrane, which allows for simple access to oxygen and protons. The use of non-precious catalytic electrodes based on recyclable carbon nanostructures is critical for producing clean energy and increasing the commercialization potential of fuel cells. Green hydrogen will play a significant part in future fuel supply chains, covering 15% to 20% of the world's energy demands. A proton exchange membrane (PEM) fuel cell is one method, where hydrogen may be utilized to generate electricity. This paper begins by providing an overview of membrane electrolytes in fuel cells and the generation of energy. Moreover, the proton exchange membrane fuel cell (PEMFC) is regarded as one of the most promising power generators capable of providing clean energy sources, particularly for transportation and stationary cogeneration applications. Finally, it will shed light on the role of green or renewable hydrogen in future fuel cells and achievement sustainability.

Keywords: sustainability, fuel cells, clean energy, PEMFC, membrane-based technology, green hydrogen

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1. Introduction

The world's most severe challenges are energy and air pollution. Pollution affects the entire planet rather than just one country [1]. Furthermore, due to the scarcity of fossil fuel supplies and the ever-increasing need for electrical power, it is critical to discuss alternative power sources as a strategy to combat global warming and reduce air pollution [2]. These sources are distinguished by high efficiency (up to 50%) low operational temperature (between 25 °C and 100 °C), high power densities (up to 2 W/cm^2) rapid start-up, low noise, solid membrane, long life, and are often used [3]. Membranes have become a viable alternative to traditional separation unit activities such as cryogenic distillation, chemical, and physical absorption. During the last two decades, membrane gas separation has played an important role in a variety of environmental and energy processes, including CO_2 capture, VOC recovery, natural gas sweetening, biogas upgrading, and hydrogen production, and it has the potential to compete with some traditional separation methods in terms of energy requirements and economic costs [4]. Common polymers, microporous organic polymers (MOPs), fixed-site-carrier (FSC) membranes, mixed matrix membranes (MMMs), carbon molecular sieve membranes (CMSMs), and inorganic (ceramic, metallic, zeolites) membranes are known to be utilized in gas separation procedures [5]. As a result, the PEMFC is regarded as one of the most promising power generators capable of providing clean energy, particularly for transportation and stationary cogeneration applications [5]. The domain of fuel cells is an objective for major automobile corporations in terms of reducing reliance on fossil fuels, with direct consequences for the greenhouse effect, by significantly contributing to pollution reduction levels [1]. As a result, the research, integration, and enhancement of fuel cells are inextricably linked to the area of electric cars. Polymer electrolyte membrane fuel cells (PEMFC), also known as proton exchange membrane fuel cells (PEMFC), use Nafion-based polymer electrolyte membranes (PEMs) to conduct protons for ion exchange. PEMFC mostly utilizes hydrogen, methanol, or formic acid [6]. During operation, the anode chamber's hydrogen, methanol, or formic acid is oxidized, while the cathode chamber's oxygen is reduced. Several researchers have been interested in developing membrane electrode assembly prototypes into commercially relevant products in recent years by improving overall efficiency, increasing current density, and lowering the cost of the membrane and catalytic materials utilized.

When compared to normal unit operations, membrane separation systems utilize none or very few chemicals. They are also simple to scale, energy-efficient and are already widely employed in a variety of gas and liquid separation processes. In the last two decades, many membranes such as common polymers, microporous organic polymers, fixed-site-carrier membranes, mixed matrix membranes, carbon membranes, and inorganic membranes have been explored for CO_2 capture/removal and other energy processes [7]. Furthermore, proton exchange membrane electrolyzers have been used to generate H_2 [8]. Pressure retarded osmosis (PRO) technology for power generation (based on knowledge of reverse osmosis (RO)) or forward osmosis (FO) membranes) has recently shown significant promise for sustainable energy production [9].

2. *Membrane electrolytes fuel cells*

The membrane is the thin electrolyte layer (usually 10–100 μm) that conducts protons between the anode and cathode, e.g., 18 μm for Gore 18 and 175 μm for Nafion117 [10]. Desired membrane materials with high ionic conductivity while avoiding the transportation of the electron and the crossover from the cathode of hydrogen fuel. Besides, in an environment with HO- and HOO-radicals, they must be chemically resistant and mechanically robust during all operating temperatures [11]. Membranes are based on perfluorosulphonic acid, which was developed first by the DuPont Company during the 1960s, Nafion, a leading one, then. The problem with this substance is its heavy dependence on the water as the transport of protons occurs in a random structure in pathways filled with water and emerges upon contact with water with polymeric components that are hydrophobic and hydrophilic [12]. Therefore, it is not enough for us to understand how protons travel inside a moist medium at the molecular level, but also, have to recognize how sectors filled with water are linked with each other in a filtration network [6]. The backbone of Nafion is polytetrafluoroethylene structure (PTFE) that offers physical strength to the membrane. The functional groups of sulfonic acid in Nafion provide proton transport loading sites [13]. Perfluorinated polymer materials are used for PEM fuel cell applications such as Neosepta-FTM Tokuyama, Gore-SelectTM (W.L. Gore and Associates, Inc.), Flemion TM (Asahi Glass Company), Asiplex TM (Asahi Chemical Industry). Moreover, high-temperature PEM fuel cell membrane materials are preferred for the operation (100–200 °C), which offers the advantages of better CO catalyst tolerance and fuel cell cooling strategy [14]. In the entire course of fuel cell development, investigations have been underway on cost-efficient, high-performance electrolyte materials. Solvay Solexis develops Hyflon ionomers, also known as ionomers, with a short side chain (SSC) was developed and subsequently abandoned by Dow Chemical Company, as severe degradation was observed [15]. Because of its high proton conductance at temperatures up to 200 °C and low methanol/ethanol permeability, the Phosphoric acid-doped polybenzimidazole (PBI) membrane is a promising material for a high-temperature membrane. However, the low conductivity of protons at low temperatures (essential for a cold start) and the low solubility of oxygen, as well as assessment of stacking components such as bipolar panels, dyes, and coolants, heat and water management, are concerned [16]. Poly Fuel was used for fuel cell hydrocarbon-based membranes [17]. Proton and water transport are the two principal modes of transport that take place in membranes. The polymeric membrane is called a cluster model, described by Gierke and Hsu as inverted micellar. The structure is separated from the fluorocarbon backbone in which ion-exchange sites constitute spherical clusters (pores) connected by short, narrow channels [18]. The size of the clusters is determined by the amount of water in the region. The electrolyte's electrical potential gradient is the primary driving force for proton transport. Protons are transported across the membrane primarily because of an electrolyte potential gradient; diffusion has a minor effect. Proton transport, that requires water in the membrane is known as "vehicular" diffusion. Protons can transport from high to low proton concentration regions by forming hydronium ions (H_3O^+), a process known as vehicular diffusion [19]. As a result, the diffusivity of water in membranes plays a significant role in this process. Another way is via the "hopping" process, which occurs when adequate H_2O is present to bind the side chains of sulfonic groups, allowing protons to pass directly from one site to another [20].

Low durability is the major challenge hindering the large-scale implementation of the Proton Exchange Membrane Fuel Cell (PEMFC) technology. Likewise, decomposition of the carbon backing materials from the current catalysts is the principal-agent [21]. The high durability is based on a hollow nano-carbon developed with high graphite and concurrent doping to enhance resistance to oxidation and uniform precipitation of Pt micro-particles and intense Pt-support reaction [22]. The sped-up decomposition test shows that this designed catalyst possesses superior electrochemical activity and long-term stability of both hydrogen oxidation and oxygen reduction relative to industry standards for current catalysts. Further tests under practical operation conditions for fuel cells show almost no degradation during the long-term cycling cycle. Such a high activity catalyst, specifically high durability, opens the door for PEMFC's next generation of real-world applications [23].

2.1. Polymer electrolyte membrane fuel cell (PEMFC)

PEMFC converts the fuel chemical (such as hydrogen) energy into electricity [24]. Polymer PEMFC is a power conversion device for energy. Because of several attractive properties such as high effectiveness and close to nil emissions, it was considered to be one of the most promising energy generation technologies for transport, stationary and portable applications [25]. A negatively charged electrode (anode) and a positively charged cathode are separated by a polymer electrolyte in the form of a membrane in the PEMFC. This solution has the advantages of high current density, low operating temperature, quick start-up time, low weight, and dimensions. The anode receives hydrogen, whereas the cathode receives oxygen. The membrane is only pierced by protons from the anode to the cathode, whereas electrons travel from the anode to the cathode in the external circuit, bypassing the membrane. As previously stated, the input substrates are $2H_2$ (hydrogen) and O_2 (oxygen), and the end product is $2H_2O$ (water). However, crucial issues such as high cost and low durability continue to stymie PEMFC's widespread commercialization. Thus, the production of advanced materials such as high electroactive catalysts and alternative polymer exchange membranes will dramatically boost the cell efficiency of PEMFCs at a fraction of the cost of traditional materials (Pt/C and perfluorinated membranes), facilitating their commercialization [26].

Planar PEMFC is equivalent to a fuel cell class with minimized volume and weight, which reduces physical burden while increasing the density [27]. Planar PEMFC usually has open-air cathodes to permit a passive, self-respiring operation with no air/O_2 fan. The equivalent circuits (EC) approach is the most frequently used model of PEMFC impedance-based diagnostic tools [28]. Simplicity and versatility, to accommodate a large variety of operational conditions and low calculation costs, make up the chief advantage of this model. In the last few years, several onboard monitoring techniques based on EC models have been proposed.

2.2. The fuel cell catalysts

The catalyst for hydrogen oxidation at the elevator and oxygen returns at the cathode is an essential component for the efficient operation of the fuel cell [29]. The catalyst in PEFC fuel cells consists of a layer of platinum nanoparticles distributed in a carbon matrix with a large surface area. The colloidal dispersion of platinum nanoparticles aided by carbon and dissolved ionic polymer particles of the membrane causes them to arrange themselves (i.e., the particles) into a compound of different phases during manufacture, enabling electrons, protons, and gases to pass through [30]. The electric current and the movement of reactants in the cell cause the return and oxidation reactions to move away from electrochemical equilibrium, resulting in irregular spatial distributions. Such shifts lead to a loss of voltage in the cell and reduce cell efficiency by between 30% and 40% [31]. Therefore, the goal is to find highly effective catalysts and create layered structures that mitigate these losses. The location and attachment of the porous substrate or nanostructure on the catalyst is critical since it determines the stability of the bonds between the catalyst and its substrate and the stability of the catalyst layer structure and carrier properties [32]. Theoretical estimates suggest that the yield or efficiency of catalysts in current fuel cells is less than 10%. It is noteworthy that Mark Debe and his co-workers have developed catalytic layers that take the form of a thin film with a nano structure and have higher efficiency and better durability than the current designs [33]. We expect to increase return rates by ten to a hundred times if we consider the number of these examples in the engineering of stimulation at the nanoscale level and in designing their layers. Although platinum is chosen as a catalyst in most types of fuel cells due to its stability and activity, a less costly alternative should be sought. As a result, palladium took its position. Reduced particle size is one method for increasing the active surface areas of catalysts.

Many studies have employed nanotechnology to create porous nanocatalysts that eliminate the need for a bulk catalyst and a gas diffusion layer. Consequently, PEFC fuel cells need as little as ten to 100 times less platinum, which reduces the cost of fuel cell stacks by 25% while maintaining the same amount of output power. Incorporated Pt catalysts, also known as non-Pt catalysts, reduces the cost of Pt [34]. It remains crucial to maintain or improve catalyst activity and durability when Pt loading is reduced or eliminated. With the current modern technology, the most significant PEMFC-based electrocatalysts are still nanoparticles distributed on carbon supports. However, these catalysts suffer from performance degradation during practical operation because of the high voltage, acidic and oxidative environment in PEMFC [34]. Although other modes such as decomposition, dissolution and toxicity of Pt particles have contributed to failure, the corrosion of the carbon support materials has been identified as the imperative cause of the weakness of the catalyst. In the case of the cathode catalyst, oxidation of the carbon support may occur in the presence of oxygen, resulting in the separation of the Pt molecules and, as a result, a decrease in fuel cell efficiency. For the anode catalyst, the carbon supportive can also be oxidized in an acute deficiency of hydrogen [35]. Because of these degradation processes, the stability of the Pt catalyst was below the lowest durability target of 5,000 h for automotive applications, based on the PEMFC compound test monitored by the United States Department of Energy [36]. Because of the marketing power of fuel cells, the need for materials that are both intrinsically stable and easy to replace existing carbon stents becomes urgent not only to extend the serving life but also to enhance the reliability and reduce the total lifetime cost of the PEMFC. Significant efforts have been made to explore stable alternatives to replace the carbon materials (Vulcan XC-72R and Ketjen) currently used with fuel cell catalysts [37]. These are based on some basic requirements, including high surface area, preferred dispersion of catalytic metals, high oxidation resistance, high electrochemical stability under fuel cell operating conditions, as well as high electrical conductivity. The challenges are that the support materials hardly meet these requirements at the same time. While graphene has been studied only recently, carbon materials with one-dimensional nanostructures (CNTs and carbon nanofibers-CNFs) have long received attention as catalytic support because of their unique structure and properties [38]. It was concluded that structural defects play an important role in improving catalytic activity. However, the erosion of carbon materials always begins at detecting sites. The enhanced durability of Pt/CNTs was observed for CNTs with a good graphite structure and is attributed to the strong resistance of CNTs to corrosion and the specific interaction between Pt nanoparticles and CNTs (the positional electrons of CNTs and Pt d-electron particles) [39].

The highest methanol oxidation mass activity reached 323 A/g with a cycling rate of 50 mV/s for Pt/GCNFs/graphite electrode in 2 mol/l CH_3OH +1 mol/l H_2SO_4

solutions. The Pt/GCNFs/graphite electrodes had high oxidation activity (129.5 A/g) and good stability even at low Pt loading (8.79 μg/cm^2). Catalytic activity loss after 500 cycles can be due either to methanol consumption, toxicity, and a structural change in platinum nanoparticles or disturbances in the potential of the aqueous solutions [40]. The highest current density is 55.4 mA/cm^2 higher than long-term cycling ends, and 91% of the value of maximum peak current (60.94 mA/m^2) after the Pt/GCNTs/ graphite electrode has been stored in a twin distilling water during 24 h [41]. The distribution and morphology of nanostructures of noble metal on advanced materials help in achieving high-performance catalysts effectively. The promising catalyst support materials should fulfill the following characteristics (1) high specific surface area and efficient interaction with metal nanoparticles (NPs) to achieve high and stable dispersion (2) excellent stability under harsh electrochemical conditions to keep the structural integrity of the composites; (3) high electrical conductivity to promote electron transfer during the electrode reaction process [42]. As has been demonstrated repeatedly in experiments, supporting materials in the catalytic system can significantly enhance electrocatalytic activity and reduce noble metal consumption [43]. Given the high graphitization of the inherent carbon material surface, it is hard to achieve direct deposition of highly dispersed NPs with high efficiency of loading on such surfaces [44]. The surface functionality of carbon materials usually is indispensable to activate the inert surface (producing more anchorage sites for NPs). Two pathways exist to change the carbon surface: (1) the covalent fastening by chemicals in reactions to the α-combined carbon skeleton, and (2) non-covalent interactions or packaging of different organic functional fragments. Supported Pt and Pt alloy catalysts showed excellent performance in electrode reactions, because of the high and uniform dispersion of the catalytic metals and improved mass transfer. To improve electrical conductivity and stability, mesoporous carbon should be treated by high-temperature annealing and graphite catalytic [45]. However, these treatment strategies must be implemented at the expense of specific porosity and surface area, which makes it difficult to deposit metal nanoparticles. To address the issue of carbon oxidation, a major effort has been made in recent years to develop non-carbon materials to support catalysts, including nitrites, carbides, mesophoric silicates, conductive polymers, and metal oxides [46]. Although there has been some progress, there are still significant disadvantages compared with carbon materials such as low electronic conductivity, high acidic solubility, and low surface area. Some non-carbon materials have intrinsic inertness in high temperature and electrochemical corrosive environments, which improves the stability of the supports and the supported catalysts [47].

The durability of the catalyst is mainly determined by the corrosion resistance of the support material. Graphite reinforcement is useful for improving durability. The abuse of nitrogenous doping has been known to improve the stability of carbon materials. It was found that the high nitrogen content would reduce the stability of carbonaceous substances, because of the structural disturbance caused by N in the carbon lattice [48]. With an increase in the nitrogen content, the resistance to oxidation of the Amesbury carbon could decrease because excessive doping of nitrogen may accelerate the conversion of the oxidized carbon oxidation gas. The durability of the catalyst is also determined by the interaction of the support with Pt molecules. It is believed that increasing the degree of graphite support to carbon leads to enhanced sites on carbon, which act as binding centers for Pt nanoparticles. Thus, graphite to a higher degree strengthens the interaction between the PT molecules and the carbon support [49].

2.3. Layers of gaseous diffusion

The gas diffusion layer serves as an electrical conductor between the carbon-supported catalyst and the current collector plates. Thin gas diffusion layers with the lowest resistance to electricity are preferred [50]. Between the catalyst layer and the two oxygen and hydrogen gas inlets in the fuel cell is a porous gas-carrying layer. This layer allows the reactants to leak into the catalyst layer while allowing electrons to move away from the anode and extract water from the cathode. Otherwise, the flow of reactants at both electrodes would be impeded. So that the gas-carrying layer is with caudate and holes ranging between 10 and 100 μm, while the layer with micro-holes has dimensions of hundreds of nanometers. Improving the performance of fuel cells to perfection is a multi-level issue, from the molecular dynamics of the transport of protons across the membrane and the chemical reactions taking place in the catalyst to the macroscopic properties of the complex media that control gas scattering, water permeability, and charge transport. At the level of the entire fuel cell or stack, these mechanisms interact with each other complexly that may lead to undesirable effects such as the irregular distribution of the reactants, the ineffective use of the catalyst besides the flooding of the cell with water, or the dehydration and depletion of the fuel.

It is known that 2D graphene can function as a proton exchange membrane in fuel cells. Among the many beneficial properties of graphene (sturdy material, electrical conductivity, self-repair ability, flexibility, etc.), it will take billions of years for hydrogen, the smallest molecule, to penetrate the graphene monolayer [51]. This makes it a considerable substance-containing material, especially for the small gas molecules known to escape quickly into the atmosphere. For example, hydrogen cars need to store their fuel inside a container that does not diffuse hydrogen, which is proving challenging.

It has been found that monomers of graphene and boron nitride are very permeable to thermal protons under ambient conditions [52]. This means that thin films can be manufactured, the most reliable ones as graphene are a full-proof gas

Table 1. Hydrogen storage in nanomaterials.

Material	**Pore diameter**
Nanoporous materials	<100 nm
Microporous	<2 nm
Mesoporous	2–5 nm

separator. The hydrogen collected was in small volumes, but these are only the first steps—proof of concept. Imagine a car using hydrogen assembled from the air, plus fuel stored in tanks—it would be exciting.

Great efforts went into the mass production of graphene, for use in many applications, thanks to its extended properties, and if the industry falters in making it in large quantities, we may witness a whole new technological revolution [53].

Between the main macroporous layer and the catalyst layer, a microporous layer is often added. This microporous layer's function is to help with the distribution of reacting gases, improve mechanical compatibility between layers, minimize contact resistance, and improve water management. Carbon is used for electrical conductivity, and PTFE is used for hydrophobicity in this microporous layer. The commercial Gas diffusion layers (GDLs') in-plane and through-plane resistivity are between mΩ cm and 6–20 mΩ cm^2, respectively [54]. The GDL microstructure determines the plane and aircraft's resistances. The flat resistance determines the cell strength, and the flat resistance affects the reaction uniformity. The GDL's position in the anode is not the same as its role in the cathode. For instance, cathode water must be removed from the catalyst surface easily for flood prevention (i.e., liquid water formation). The liquid water prevents catalyst sites from entering the catalyst and inhibits oxygen. The anode must retain some water so that the membrane does not dry up and this applies in particular to the dry anode gas stream.

Hydrogen storage nanomaterials such as carbon tubes have been developed as they have a higher storage capacity than ordinary solids (table 1).

Titanium is now used in Liquid/gas diffusion layers (LGDLs) on the PEMEC anode side. It has a thickness of more than 300 m and a substantial electrical conductive route as well as fluidic resistance [55]. Furthermore, their random architectures make controlling the water/electron/thermal distribution difficult, and their intricate pore shape leads to exceptional interfacial contact resistance. For the first time, titanium in thin and well-tunable LGDLs with flat interfacial surfaces are produced and deployed in a PEMEC, demonstrating enhanced multifunctional performance over traditional LGDLs. At a current density of 2.0 A/cm^2, the operating voltages were as low as 1.69 V, with an efficiency of up to 88% and efficiency by more than 9% [56]. Mo *et al.* [56] conducted both ex-situ and in-situ characterizations to better understand the mechanisms. The well-tunable LGDL with flat surface characteristics might also be used to increase the performance and efficiency of PEMFCs. Furthermore, reducing the LGDL thickness from 350 m of typical LGDLs to 25 m would significantly reduce the weight and volume of PEMEC stacks, thus opening up new avenues for future development of low-cost PEMECs with improved performance. Its customizable properties, such as pore size, pore shape, pore distribution, and permeability, will be extremely useful for constructing PEMEC models and testing simulations of PEMECs with optimal and repeatable performance [57].

3. The drawbacks, challenges, and future visions

One of the newly proposed alternative energy sources is the fuel cell (FC) which generates energy using high-value metal catalysts. This method has sufficient advantages over other types of power generators, such as no emissions of polluting gases to the environment (such as SO_x, NO_x, CO_2, and CO), higher efficiency, no moving parts, and thus no sound pollution [58]. However, the high cost is the critical disadvantage of this method. Not all experts agree that hydrogen fuel cells are a clean enough energy source to warrant global enthusiasm for them. Many still wonder if this pattern of operating cars, planes, and trains will help slow climate change, and some even worry that hydrogen production will speed up the pace of climate change [59]. As for emissions, burning hydrogen for energy does not harm the environment, as the only by-products released by this process are heat and water. But the problem of emissions arises when trying to separate hydrogen, not when burning it. We must isolate hydrogen from water, coal, natural gas, or animal or vegetable waste before using it as fuel. Most of the 9 million metric tons produced by the United States of hydrogen comes from methane through steam reforming, and this process emits greenhouse gases [60]. However, it can also separate hydrogen from water through a process called electrolysis, which is a process that wind power, solar energy, or other renewable energy sources can power [61]. Hydrogen fuel cells produce electricity through electrochemical reactions when hydrogen combines with air. Inventors and engineers have experimented with using hydrogen as a source of clean energy for decades and are three times more efficient than gasoline when used as a fuel for cars, which tempts many to pursue the development of hydrogen fuel technologies [62]. Besides the cost challenges related to producing clean hydrogen fuel, there is the risk of gas leakage into the atmosphere during storage or transportation, as hydrogen is difficult to transport, as it needs to be stored under high pressure.

If there is no efficient method for producing, storing, and transporting hydrogen, 10 to 20% of the gas will leak into the atmosphere [63]. The researchers concluded that it is equally possible to imagine extreme scenarios, but the potential impact on the hydrogen cycle will always be significant. The oxidized hydrogen would cool the stratosphere and create more clouds, which would affect the polar vortex and increase the holes in the ozone layer. We need to make some considerable changes in the energy we consume, and there is great hope for switching to hydrogen [64]. To reach solutions for hydrogen production from renewable energies, scientists have developed an electrochemical device driven by solar energy to produce hydrogen from industrial wastewater [65]. This presents an opportunity for pharmaceutical companies to eliminate the harmful environmental and health effects of industrial wastewater while also providing renewable fuel that the world will depend on in the future to fill the expected fuel shortage caused by the depletion of petroleum fuels. They developed a new technology that overcomes the challenges in developing hydrogen fuel cells from water, such as the high cost of preparation and use, also the lack of reliability and long-term stability under harsh conditions. New technology is easy to prepare, cheap, and it is more efficient than its predecessors in exploiting the energy of the sun besides it is more stable and withstands harsh conditions. We can use it in industrial wastewater, which makes the production of hydrogen fuel with this technology less costly and economically viable. Most of the previously developed devices and fuel cells produce hydrogen fuel using pure water only, which creates the application of these technologies on the ground very limited; Purifying water to prepare it to generate hydrogen fuel is expensive [66].

3.1. Green hydrogen and fuel cells

Climate change is one of the most critical environmental issues that concern governments today, given the economic, social, and health risks this issue entails. Experts agree that vigorous international attempts must be made to limit global warming to prevent the negative impact of climate change on our planet's environment. Global carbon emissions must be reduced to zero by the year 2050, prompting some governments to take immediate measures to adopt alternative energy means [67]. Green hydrogen is one method that has gained momentum in recent times for its reliance on producing hydrogen from sewage waste [68]. Hydrogen and fuel cells are commonly recognized as one of the most important energy options for the twenty-first century. These technologies will greatly contribute to reduced environmental impact, increased energy security (and variety), and the development of new energy sectors. Transport, distributed heat and power generating, and energy storage systems may all benefit from hydrogen and fuel cells. The shift from a carbon-based (fossil fuel) energy system to a hydrogen-based economy, on the other hand, entails considerable scientific, technological, and economical challenges to the deployment of hydrogen and fuel cells as future clean energy solutions.

Hydrogen can be generated in a variety of ways, including electrolysis, which involves breaking down water into oxygen and hydrogen using an electric current

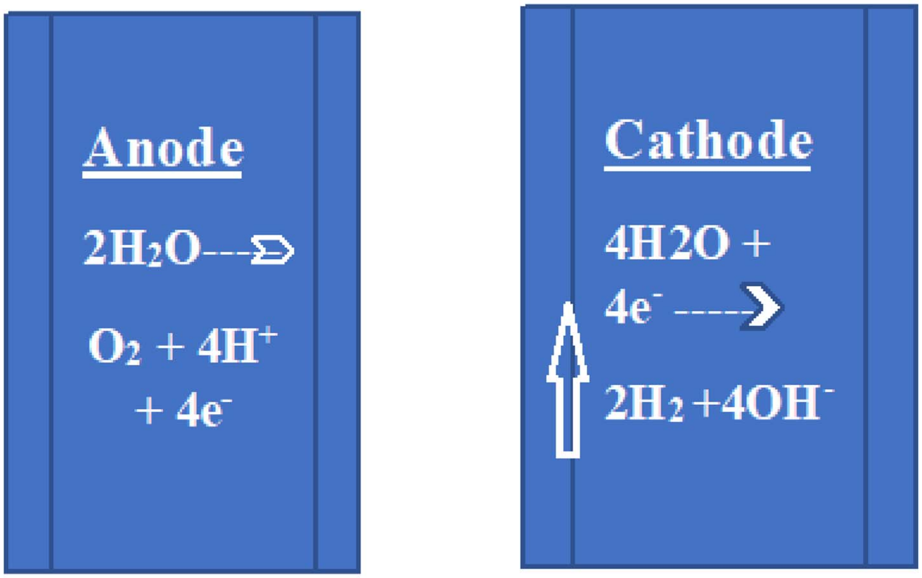

Figure 1. The process of dissociation of water and formation of hydrogen gas at the cathode.

(figure 1). Green or “renewable” hydrogen is created when the energy used in the process comes from a renewable source such as wind [69].

Currently, three significant technological obstacles must be solved to shift from a carbon-based (fossil fuel) energy system to a hydrogen-based one. First, the cost of producing and delivering efficient and sustainable hydrogen must be greatly decreased. Second, new generations of hydrogen storage technologies must be created for both automotive and stationary uses. Finally, the cost of hydrogen-based fuel cells and other devices must be decreased.

Hydrogen is labeled gray, blue, and green, according to the amount of carbon emitted during the industrially prepared hydrogen. Gray hydrogen is hydrogen that is made from fossil sources like natural gas. Hydrogen derived from low-carbon sources is known as blue hydrogen. Green hydrogen is hydrogen that is made from renewable energy sources [70]. Unfortunately, gray hydrogen accounts for about 95% of the hydrogen produced in the world today. The natural gas formation mainly produced gray hydrogen in industrial applications. In a combustion chamber with the presence of a co-factor, natural gas that has been treated with water vapor is used at high temperatures, ranging from 800–1700 °C. This method gives off a lot of carbon dioxide. The fact remains that much of the world’s hydrogen production is linked to natural gas. Blue hydrogen (low carbon dioxide), is more expensive, as most of the carbon dioxide emissions are captured and stored, up to 90%, during gray hydrogen production [71]. The most common method for producing green hydrogen is by the electrolysis of water, in which water molecules are broken down into oxygen and hydrogen. Electrolysis is a proven method, but it is not mature enough for widespread use, and it is relatively expensive. The cost of producing green hydrogen is two to three times higher than that of gray hydrogen produced from natural gas, so it is not competitive [72]. Even though green hydrogen plays a minor role in the overall energy mix, accounting for just 0.1% of global hydrogen output in 2020, costs for generating green hydrogen could drop by as much as 64% by 2040 [73]. According to the degree to which hydrogen is free of carbon, there are three principal forms of hydrogen: (1) electrolysis created Green hydrogen with renewable energy sources, including solar and wind. (2) Blue hydrogen is made by evaporating methane, the principal component of natural gas rock, and removing the carbon during the process. (3) Gray hydrogen is made by reforming methane with steam without removing the fuel. According to the International Energy Agency, grey hydrogen, which is derived from fossil fuel sources, accounts for 95% of the total global supply of hydrogen, and electrolysis produces the rest they together account for around 4% of final energy consumption [74]. In 2019, the total global demand for hydrogen was about 120 million metric tons (60% for pure hydrogen and 40% for hydrogen-based fuels), with an estimated economic value of $135.5 billion [75]. According to an European plan, 6 GW of electrical hydrogen analyzer facilities will be launched in the first phase (2020–2024) to generate up to one million tons of green hydrogen, with the second phase (2025–2030) increasing production capacity by 40 GW to produce up to ten million tons of green hydrogen, and the European Union will spend between 180 and 470 billion euros to encourage the use of green hydrogen until 2050 [76]. By replacing gas and coal with clean electricity, current technology, such as used in the production of solar and wind energy, can reduce carbon dependence in the energy sector by up to 85%. Some other economic sectors, such as shipping and manufacturing, face more difficulty moving into electricity dependence. They usually require a fuel that has a high energy density or the heat it produces at high temperatures. However, green hydrogen (GH) is the future in these sectors. GH is one of the four technologies necessary to achieve the goal of the Paris Climate Agreement, which is to reduce over 10 billion tons of carbon dioxide emissions per year in the industrial sectors that pose the biggest challenge such as the mining, construction and building, and chemical industries [76].

Figure 2 depicts an assessment of future cost trends for green and blue hydrogen based on BNEF data [77]. The graphic shows the expenses in terms of hydrogen mass (on the left axis) as well as energy content, which takes into account hydrogen's lower heating value (120 MJ/kg, or 33.3 kWh/kg).

3.2. Microbial fuel cells (MFCs)

By 2050, the world's population is expected to reach 9.5 billion people. Given that most of our current energy is generated from fossil fuels, providing adequate,

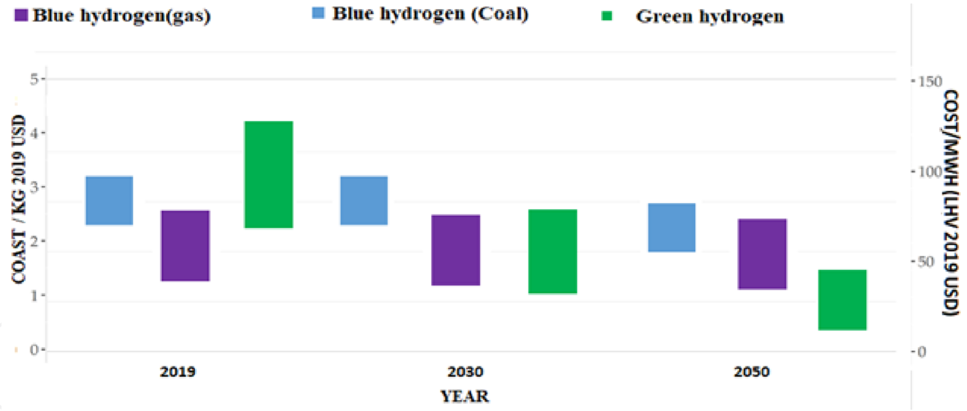

Figure 2. Future hydrogen prices for various approaches are estimated. Hydrogen-based energy has a lower heating value (LHV). Data from the BNEF, 2020. Adapted from [77].

sustainable electricity while mitigating climate change is a significant challenge [78]. One idea that has gained momentum in recent years is generating electricity using bacteria in devices called microbial fuel cells (MFCs). These fuel cells rely on the capacity of some naturally occurring microorganisms that can exchange electrons to generate electricity [79]. It can feed this process using materials called substrates to include the organic materials found in the wastewater. MFCs use a system of anodes and cathodes—electrodes that pass a current either in or out. MFC systems comprise an anode chamber and a cathode chamber separated by a membrane. Bacteria grow on the anode and convert the substrates into carbon dioxide, protons, and electrons [80].

The electrons are then moved to the cathode chamber through an external circuit, while the protons move through the membrane. The reaction between protons and electrons in the cathode chamber absorbs oxygen and produces vapor. Electrons can flow out as long as the substrates are shifted, which is what electricity means. There are some advantages in electricity generation from MFCs, systems can be developed in any place; they create a lower sludge than traditional wastewater treatment methods, including active sludge systems [81]. They can be small, but they can be modular in construction for larger systems; they have a high salt tolerance. It is possible to work at room temperature. The availability of a wide range of renewable substrates that can be used to generate electricity in MFCs has the potential to revolutionize future electricity production. These substrates include urine and organic matter in wastewater. Inorganic waste, like sulfides, and even gaseous pollutants, excrete into the soil (root secretions). A renewable substrate that MFCs can use to generate electricity plants root secretions in so-called plant MFCs. When plants grow, they produce carbohydrates such as glucose, some of which are excreted into the root system [82]. Microorganisms near the roots convert carbohydrates into protons, electrons, and carbon dioxide. In the MFC plant, protons are transported through a membrane and recombined with oxygen to complete the electron transfer circuit. By connecting the load to the circuit, the generated electricity can be harnessed. Multifunctional plant cells could revolutionize electricity production in isolated communities without access to the grid. In cities, streets can be lit with trees. Another type of microbial fuel cell is microbial desalination cells. These devices use bacteria to generate electricity, for example, from wastewater, while desalinating the water at the same time [83]. The water to be desalinated is placed in a chamber confined between the anode and cathode chambers of MFCs using negative (anion) and positive (positive) ions membranes. When the bacteria in the anode compartment consume the wastewater, protons are released. These protons cannot pass through the anion membrane, so the negative ions from the saltwater are transferred to the anode chamber. Protons are consumed in the cathode, and thus the positive ions of the salt are moved into the cathode chamber which causes the middle chamber to desalinate [84]. The ions released into the anode and cathode chambers help to improve the efficiency of electricity generation. Anaerobic digestion microorganisms are used to break down degradable materials, or waste without oxygen to recover energy from wastewater by producing biogas, which is made of methane, the principal component of natural gas [85]. Nevertheless, this process is usually ineffective. Research shows that the microbial groups used within these digesters share electrons with the so-called electron transfer between species—which opens the possibility of using positive energy to influence metabolism [86].

4. Conclusion

PEMFC fuel cells are among the best types of fuel cells for use as an electrical source that powers transportation, which may be used as an alternative to internal combustion engines that use diesel or gasoline as fuel. A proton exchange membrane- fuel cell uses a water-based acid polymer membrane as the electrolyte has a platinum-based electrode. PEMFC operates at relatively low temperatures (below 100 °C) and can customize the electrical output to meet dynamic power requirements. Because of the relatively low temperatures and the use of electrodes made of precious metals, these cells must be operated under pure hydrogen. The life of a PEMFC can be extended if it is treated with care and faults are avoided using fast and accurate fault diagnosis. Flooding and drying faults are the most common faults in the PEMFC system.

The world has agreed to move toward sustainable and alternative energy sources in response to rising energy demand and severe climate change risks. Hydrogen, which is created by electrolysis of water using renewable energy, has the potential to be the clean, sustainable, and hence climate-neutral energy carrier of the future, eventually eliminating greenhouse gas emissions from the energy industry. Fuel cells reduce the destruction of the environment associated with petroleum extraction and processing, with hydrogen extraction from renewable energy sources. In the event of a hydrogen leak, it will evaporate immediately since the hydrogen is lighter than air, leaving only water behind. However, hydrogen is significantly different from today's common fuels because of its ability to migrate through very small channels, and also in its combustion properties—again very different from carbon-based fuels. These aspects demand diverse safety precautions and an appropriate culture for operations in which customers will interact directly with hydrogen and fuel cell technologies. Furthermore, hydrogen and fuel cells can eliminate carbon dioxide emissions in the green energy area. These technologies provide a huge chance to eventually change the global carbon-based energy system into a clean, renewable, and sustainable hydrogen-based economy throughout the whole spectrum of energy usage. The difficulties are enormous, necessitating scientific discoveries and huge technical improvements, as well as ongoing social and political commitment.

Data availability

The data presented in this study are available on request from the corresponding author.

Conflict of interest

The authors declare no conflict of interest.

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