

Review

Advances in Solar-Derived Chemical Fuel Systems

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Abstract: Fuel cells are essential components of a large portfolio for developing a competitive, secure, and sustainable clean energy economy as they possess the ability to efficiently convert a variety of fuels into electricity. They convert chemical energy from fuels into electricity through chemical reactions with an oxidizing agent. Fuel cells are highly efficient and can produce electricity with very little pollution. They are used in a variety of applications, including powering buildings and vehicles, and as a backup power source. However, the infrastructure for fuel cells is still not fully developed and the cost of fuel cells is currently high, hindering their widespread adoption. This article discusses various advanced fuel cell types with descriptions of their working principles and applications. It provides some insights on the requirements of solar-derived chemical fuel cells as well as some novel materials for the fabrication of solar-derived chemical fuel cells. Discussions on the limitations of solar-derived fuel cells were provided in relation to environmental hazards involved in the use of these cells.

Keywords: fuel cells; solar-derived fuel cells; chemical fuel cells; clean energy; sustainable energy



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1. Introduction

Energy is essential for human survival; ever since the initial use of fire, which has become an indispensable resource for the survival of our species. Initially, primitive humans burnt easily accessible timber to meet their basic needs. Technological advancements in the mining of coal, which had higher energy densities, increased the popularity of coal as an energy source. Later, coal became the primary source of energy in the 1850s. The invention of the combustion engine by Daimler in 1886 stimulated a greater increase in demand for more efficient oil and gas as fuel. Advances in oil and gas exploration and refining technologies substantially increased the production of oil and gas until it became the primary source of energy in the 1960s [1]. The demand for sustained energy has led to the emergence of a low-carbon society with a third energy revolution of “new energy” [1], which can reduce global warming, and the depletion of petroleum reserves [2].

Transitioning to non-fossil energy sources from fossil has generally followed three trends, such as from high-carbon to low-carbon fuels, from low-tech to high-tech production, as well as from one-time use to reusability [1]. Currently, sources of energy can be categorized primarily as fossil fuels, nuclear energy, and renewable energy. In contrast to nonrenewable energy sources (fossil and nuclear), renewable energy sources can be replenished rapidly by nature. In 2021, renewable energy constituted 7.23% of the global total energy supply [3]. Solar, wind, geothermal, marine energy, biomass, and biofuels are the most common types. Figure 1 shows the renewable energy outlook in the USA until the end of 2050 [4].

These are typically more dependable, eco-friendly, and cost effective. While most of these technologies are currently in use, many are still in their infancy. Three main drivers are responsible for human adaptation to renewable energies, such as (1) burning huge quantities of coal causes the release of thick fog; (2) increments in the entire oil and gas value; and (3) decrements in the price of renewable energies, especially solar energy [3].

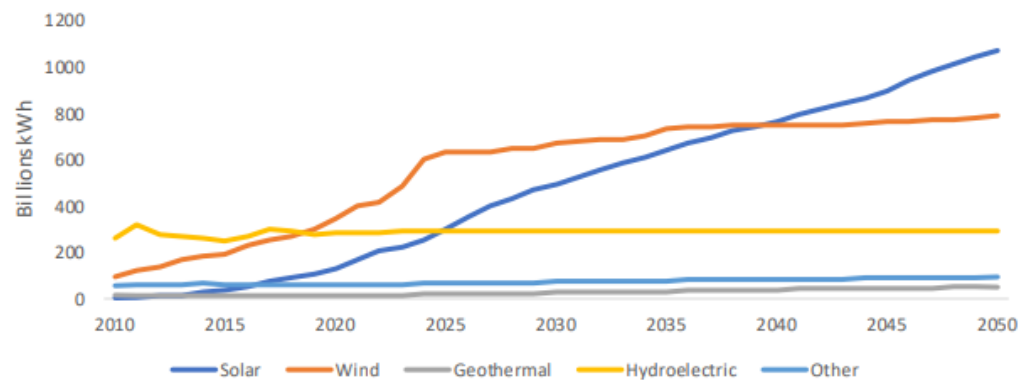


Figure 1. Renewable energy outlook in the USA until the end of 2050 [4]. Accessed online with permission (open access) from United States Energy Information Administration (2021).

Among these renewable energy sources, solar energy is widely used in various countries, in and around the equator region, except the polar regions, where the prevalence of solar energy is almost throughout the year [5]. Further, several novel technologies have been introduced to harvest solar energy into potential usable energy, which can be classified mainly as “Power Plant Types” and “Nonpower Plant Types”, as shown in Figure 2. Despite the considerable advancements made during the “New Energy Revolution,” the rate of clean energy deployment has been modest. This is partly because there are not enough long-term, affordable storage facilities, which has forced the development of new storage technologies. One of the most potential options is the conversion of solar energy into chemical fuels. This would make it easier to deliver energy to the consumer on demand, independent of the time or place [6].

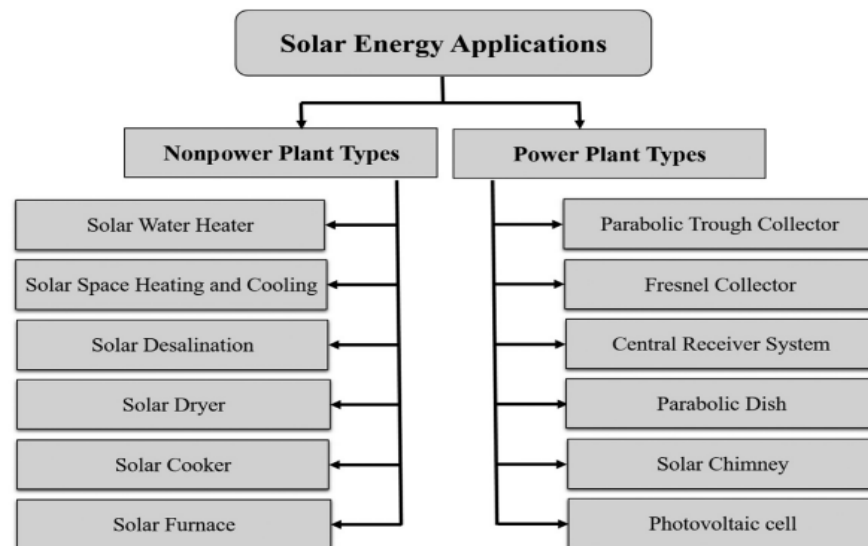


Figure 2. Applications for various forms of solar energy [3]. Reproduced with permission from Ajarostaghi and Mousavi (2022), © Academic press, 2022.

An electrochemical device called a fuel cell is used to directly convert the chemical energy of the fuel into electrical energy. The one-step energy conversion process used in fuel cells (from chemical to electrical) has several advantages over the multistep process used in combustion-based engines (e.g., from chemical to thermal to mechanical to electrical). In 2019, the United States Department of Energy began a \$30 million research and development program on fuel cells. A wide range of fuel cell technologies were included in this program to enable low-cost, robust, and high-performance fuel cell development for a variety of applications. Catalysts and electrodes, membranes, fuel cell performance and durability, and assessments are some of the early-stage research and development

(R&D) areas that were covered. Figure 3 shows the research investments for the various fields [7,8].

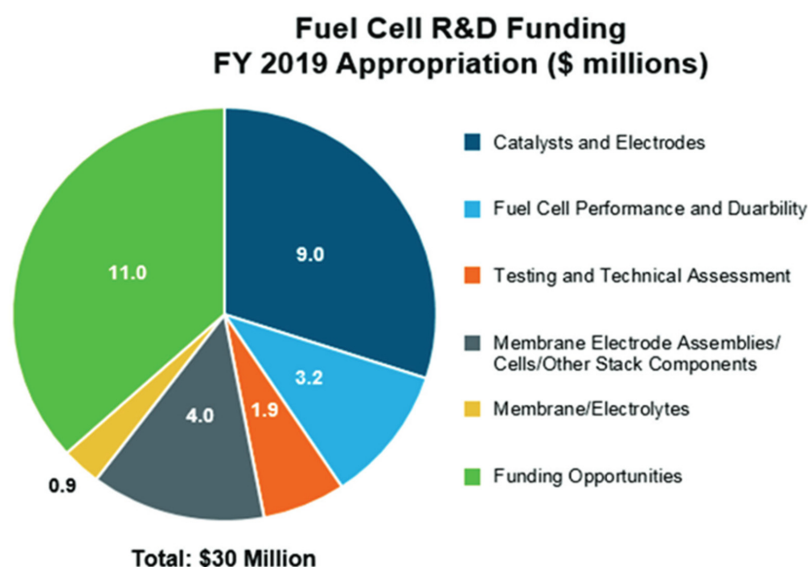


Figure 3. USDOE Research investment supporting fuel cell R&D Program [8]. Adapted and reproduced from the report by United States Department of Energy (2020), © Office of Scientific and Technical Information, 2020.

Fuel cells provide an effective and clean energy conversion mechanism and a sustainable substitute for fossil fuels. Fuel cells are also compatible with current energy carriers and clean or renewable energy sources, which include solar energy, notably for the development and sustainability of energy [9]. As a result, this paper provides an overview of different fuel cell types, including proton exchange membranes, silicon oxide, phosphoric acid, and alkaline fuel cells with a brief description of their working principles and applications. Furthermore, the requirements of solar-derived chemical fuel cells were categorized and discussed. Moreover, novel materials for the fabrication of solar-derived chemical and biochemical fuel cells were also addressed. Additionally, the limitations of solar-derived fuel cells were highlighted to understand the environmental hazards that are involved in the use of these cells.

Solar-Derived Chemical Fuel Cells

Solar-derived chemical fuel cells utilize solar energy to produce electrical energy through an electrochemical reaction. The basic principle of these fuel cells is to convert solar energy into chemical energy through the photoelectrochemical reaction, where sunlight excites electrons in a photoelectrode, creating a flow of electricity. This technology has the potential to revolutionize energy storage, providing a more sustainable and efficient alternative to traditional battery technologies. One of the most common types of solar-derived chemical fuel cells is the dye-sensitized solar cell (DSSC), also known as the Grätzel cell [10]. DSSCs use a dye-sensitized semiconductor to absorb photons from sunlight, which creates an electron–hole pair. The electrons are then transferred to an electrode, while the holes are consumed by a redox couple, generating a current flow. DSSCs have several advantages over other solar cells, including low manufacturing costs, high conversion efficiency, and flexibility. These cells can be used in a variety of applications, from powering small electronics to large-scale energy storage systems [10,11]. Another type of solar-derived chemical fuel cell is the photoelectrochemical cell (PEC). PECs use a photoelectrode to absorb photons, creating an electron–hole pair, which is then separated by a potential difference across the cell. The electrons are transferred to an external circuit, generating electricity, while the holes are used in a redox reaction to produce a chemical product. PECs have the potential to store energy on a large scale, and they can be combined with other

renewable energy sources, such as wind and hydro power, to create a stable and reliable energy grid [12].

A premier solar-derived chemical fuel cell developed was the artificial photosynthesis system, which uses a combination of photovoltaic cells and chemical catalysts to convert CO₂ and water into usable fuels. These systems typically use a photovoltaic cell to convert light into electrical energy, which is then used to drive a chemical reaction that converts CO₂ and water into fuel. Another type of solar-derived chemical fuel cell is the photochemical fuel cell, which uses light energy from the sun to drive chemical reactions that produce fuel. These systems typically use a combination of photovoltaic cells and chemical catalysts to produce hydrogen or other fuels [12]. For example, a photochemical fuel cell can use light energy from the sun to produce hydrogen through the process of water splitting. More recently, there have been efforts to develop hybrid solar-derived chemical fuel cells that combine the strengths of both artificial photosynthesis and photochemical fuel cells. These systems typically use a combination of photovoltaic cells, chemical catalysts, and biological catalysts to produce usable fuels, such as hydrogen [13]. In addition to these traditional methods for the development of solar-derived chemical fuel cells, there has been a growing interest in the use of biological catalysts, such as enzymes, in these systems. Another important area of research in the development of solar-derived chemical fuel cells is the use of novel materials and nanomaterials. These materials can offer improved efficiency, stability, and scalability, which are critical for the commercialization of these fuel cells. Despite the progress that has been made in the development of solar-derived chemical fuel cells, there are still many challenges associated with these systems. One of the key challenges in this field is to find new materials that can absorb a wider range of light and improve the overall conversion efficiency of the cells. Researchers have also focused on improving the stability of these cells, which can degrade over time due to exposure to light and air. Despite the challenges, solar-derived chemical fuel cells have significant potential to provide a more sustainable and efficient energy storage solution. These cells can help reduce our dependence on non-renewable energy sources, reduce greenhouse gas emissions, and provide a more reliable and stable energy grid.

2. Types of Chemical Fuel Cells and Their Recent Advancements

2.1. Proton Exchange Membrane Fuel Cells (PEMFCs)

In a PEMFC, it is often that hydrogen and atmospheric oxygen are electrochemically combined over a solid polymer membrane to generate electricity, water, and heat [14]. PEMFCs are widely utilized in the portable power, military power, stationary power, and transportation industries, among others. Due to their advantages of being small, light, highly efficient, and durable, portable fuel cells are frequently used in smartphones, computers, and toys [15]. Recent research has investigated the limitations of PEMFCs under unconventional conditions, including variable vibration intensities, low pressure, and low ambient temperatures [15]. Although no definitive solutions have been identified, additional research would result in significant advances in the exploration of PEMFCs.

2.2. Alkaline Fuel Cells (AFCs)

The initial functional fuel cells that generate sizable amounts of power were AFCs [16]. These devices use hydrogen gas as fuel, oxygen (or air) as an oxidizer, and aqueous solutions of sodium or potassium hydroxide as electrolytes. They typically function at temperatures below 100 °C. Their electrodes are constructed of metals, such as nickel and carbon. Zinc or aluminum may be utilized as an anode if by-product oxides were removed and the metal was constantly delivered as a strip or powder. Later, water must be eliminated from the system via the electrodes or a different evaporator [16,17]. The interest in AFCs has grown as polymer anion exchange membranes (AEM) have become more advanced. Using these AEMs is anticipated to significantly increase the use of fuel cells since its reactions are accelerated more quickly under alkaline conditions relative to acidic settings. This reveals numerous potential anode and cathode materials, since non-platinum catalysts perform

well in such an environment. Comparing it to PEMFC, this implies a possibly affordable technique [16].

2.3. Solid Oxide Fuel Cells (SOFCs)

SOFC's are considered as moist carbonate technology, where most of the cell components are composed of nickel-infused specialty ceramics. A zirconia material that has been treated with yttria serves as the electrolyte. Hydrogen and carbon monoxide will fuel these experimental molten carbonate cells, with the cell products being water vapor and carbon dioxide. The high operating temperatures (900–1000 °C) were identified to rapidly induce electrode reactions. Due to its variety of fuel sources, environmental friendliness, and high efficiency, solid oxide fuel cells (SOFCs) have become one of the most promising power production technologies after thermal, hydro, and nuclear power. The SOFC/GT combined system, which has a higher energy efficiency than either SOFC or gas turbine (GT) alone, is the predominant research focus at present [18].

2.4. Phosphoric Acid Fuel Cells (PAFCs)

Orthophosphoric acid is the electrolyte used in PAFCs, which allows operation up to about 200 °C. PAFCs can utilize carbon dioxide-contaminated fuel made of hydrogen and an air or oxygen oxidizer. A series generation circuit is created by pairing together and placing back-to-back catalyzed carbon electrodes. Graphite is used to frame this cell assembly, which dramatically raises the cost [9–18]. PAFCs have an advantage over PEMFCs, where PAFCs do not require ultrapure hydrogen fuel, as hydrogen can be produced on-site from methanol, and CO poisoning has no effect on PAFC catalytic activity, unlike PEMFCs. PAFCs are regarded as the first generation of fuel cells to be effectively marketed due to their high CO tolerance rates. Future research in PAFC systems can focus on developing less expensive catalysts and increasing the use of different fuel types, which can pave the way for realistic and widespread commercial use [19].

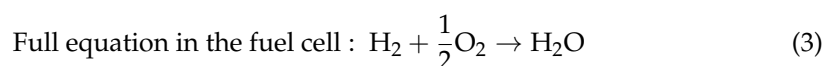
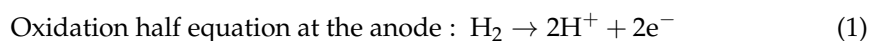
2.5. Solar-Derived Biochemical Fuel Cells

Solar-derived biochemical fuel cells use biological processes to convert carbon dioxide (CO₂) and water into usable fuels, such as hydrogen, using solar energy as the source of energy for these reactions [20]. One type of solar-derived biochemical fuel cell is the photosynthetic fuel cell, which utilizes photosynthetic organisms, such as algae or bacteria, to convert CO₂ and water into fuel. The photosynthetic organisms use light energy from the sun to produce organic matter through photosynthesis, which can then be converted into fuel. For example, algae can be used to produce hydrogen through the reduction of CO₂, while bacteria can be used to produce biofuels, such as ethanol or butanol [21]. While this concept has shown promise in laboratory settings, there have been limited real-world demonstrations of the effectiveness of photosynthetic fuel cells. There are also concerns about the scalability and sustainability of these systems, as well as the potential for contaminants in the water to negatively impact the performance of the photosynthetic organisms. The use of biocatalysts is another type. Enzymes or biocatalysts can facilitate the chemical reactions that produce the fuel. Enzymes can be used to convert CO₂ into fuels, such as formic acid, formaldehyde, or methanol. For example, the enzyme carbonic anhydrase can be used to convert CO₂ into formic acid, which can then be converted into hydrogen or other fuels. While biocatalytic fuel cells have shown promise in laboratory settings, there are still many challenges associated with these systems, including the need for high-quality biological catalysts and the stability of these catalysts under the conditions required for fuel cell operation. There is also limited data on the scalability and long-term performance of biocatalytic fuel cells [22]. To fully realize the potential of these fuel cells, more research investment, particularly in the areas of improving the efficiency and stability of biological catalysts and demonstrating the scalability and long-term performance of these systems, is required.

3. Proton Exchange Membrane Fuel Cells

Proton exchange membrane fuel cells convert chemical energy from acidic electrolytes, to electrical energy, through the reduction–oxidation (redox) reaction process [23]. Proton exchange membrane fuel cells usually consist of a selective polymeric membrane, with gas diffusion layers, catalysts (mainly platinum based), and electrodes on either side [24]. On the other hand, there is the anode current and channel, and there is the cathode current and channel on the other. Hydrogen is supplied to the anode part as fuel while air is introduced on the cathode side. Hydrogen oxidizes as it reaches the surface of the membrane, to produce electrons, as shown in the oxidation Equation (1). The released electrons travel through conductors at the outer part of the cell, through a load, then to the cathode side of the cell. Hydrogen ions (protons) are produced due to the oxidation process and travel through the selective polymeric membrane to the cathode side.

Atmospheric oxygen, present at the cathode side, is reduced as it encounters the electrons from the anode as shown in the reduction Equation (2). The reduction creates oxygen ions, which later react with the hydrogen in the cathode side, through the selective polymeric membrane. This reaction, sped up by the catalyst on the membrane surface, and leads to the formation of water. The movement of the electrons through the load, as a result of this redox reaction in the fuel cell, to generate an electrical current [25].



Unused gases and produced water present at the cathode are evacuated from the cell. Since the processes of the proton exchange membrane fuel cells do not involve any combustion, there is a net zero production or emission of greenhouse gases, making it a greener and cleaner source of energy. Thus, the production and use of these fuel cells are primarily focused on the transport sector to aid in the control of greenhouse gas emissions as shown in Figure 4. However, there are certain issues associated with the use of proton exchange membrane fuel cells [26]. Some of the most common issues are stated in this section.

Initially, contaminants present in either air or fuel are produced due to the corrosion of plates in the cell, which can compromise the integrity of the cell membranes. Furthermore, cell membranes are sensitive to certain contaminants, such as metal ions. Some of these metals include nickel, iron, and chromium. The presence of these metal ions causes the rate of cell voltage decrease to be about two times higher than in their absence [27]. This may, eventually, have an effect on the conductance of the membrane to the protons [28]. The presence of carbon monoxide is also another issue associated with the purity of the reactors. Furthermore, the platinum-based catalysts are reactive to carbon monoxide and this interaction causes a reduction in their activity. Later, this inhibits future redox reactions that are required for the operation of the fuel cells [29]. It is, therefore, necessary to purify the fuel and air used in this fuel cell to curb the complications associated with these contaminants.

It is noteworthy that the management of produced water in the cell may have an effect on the processes of the fuel cell [30]. This is due to the rate of evaporation of water that must be discharged from the cell as gas. In this scenario, the cell's operating temperature is usually above 100 °C to have water and convert it into steam for easy evacuation. However, the system may be flooded if the evaporation process is slower, which is directly related to the rate of water production. On the other hand, resistance in the cell is also increased if the rate of evaporation is higher than that directly related to the water production rate. The use of an electroosmotic pump has been proposed as one of the ways to overcome the challenges related to the flooding of the system and increased resistance.

Moreover, calculated amounts of clamping force (based on internal pressure, surface area, torque on bolts, and bolt diameters) are exerted on the plates of the fuel cell to create a leak-free system during fabrication and assembly [31]. The ability of the cell to draw current and increase voltage losses may be severely constrained by a lack of contact between the collector and field plates as well as the GDL and field plates. As a result, the amount of power that can be produced by the cell is also constrained. However, if the amount of pressure exerted on the plates is excessive, breakages may occur, and this may lead to damage in the diffusion layer, thereby reducing the conductance of the fuel across the membrane. This situation can be curtailed via optimum pressures that are applied during the assembly of the fuel cell parts. Additionally, the internal pressure of the cell must be properly controlled through effective regulation of humidity and thermal conditions in the cell [32].

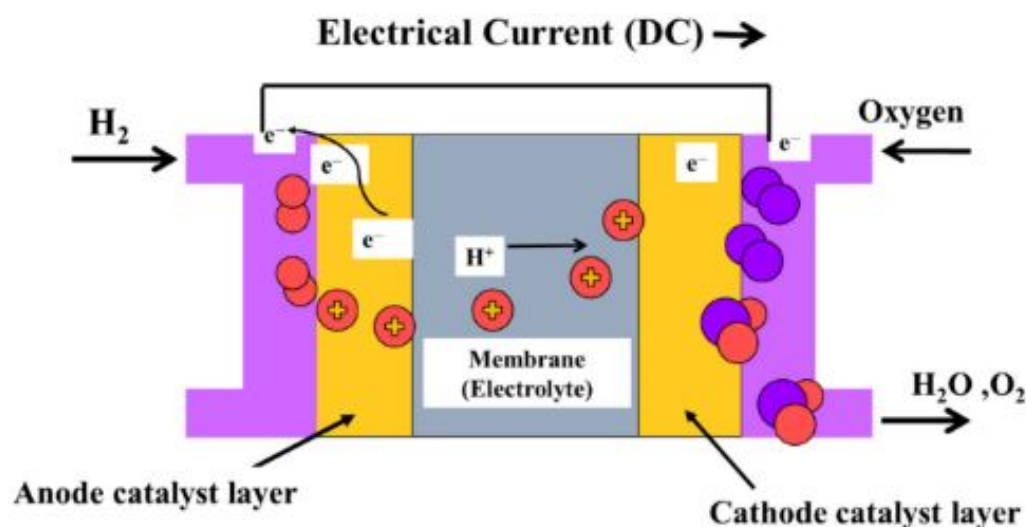
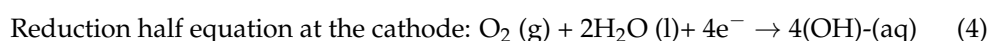


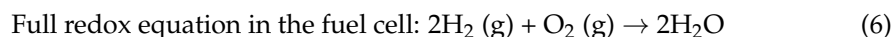
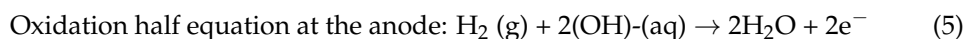
Figure 4. Schematic representation of proton exchange membrane fuel cells [33]. Reproduced with permission from Alashkar et al. (2022), © MDPI, 2022 (Open access—Creative commons attribution 4.0).

4. Alkaline Fuel Cells

Alkaline fuel cells convert chemical energy from alkali electrolytes into electrical energy as shown in Figure 5. Similar to proton exchange membrane fuel cells, alkaline fuel cells also have selective membranes with gas diffusion layers, catalysts (mainly platinum-based), and electrodes on either side of the electrolyte. However, the main difference in alkaline fuel cells is the presence of alkali electrolytes instead of an acidic electrolyte that is mainly made of potassium hydroxide in water. Hence, this fuel cell has led to a change in the reaction process that is involved in the conversion of energy from chemical to electrical [34]. On the contrary, reactions in the fuel cell were initiated in the cathode. On the cathode side, oxygen undergoes a reduction reaction with water to produce hydroxide ions (or carbonate ions, depending on the anionic composition of the electrolyte) as shown in reduction Equation (4). The hydroxide or carbonate ions produced from the reduction reaction passes through the electrolyte to the other side, which is the anode.

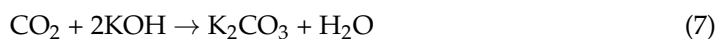
Hydrogen fuel is fed to the anode of the cell. After passing through the electrolyte and upon reaching the anode, the hydroxide ions initiate an oxidation reaction for hydrogen. The reaction is speeded up by the catalysts present on either side of the membrane, which causes the release of electrons in the anode of the cell. This oxidation equation is shown in Equation (5). The electrons are transferred to the external part of the cell, through conductors, to load the circuit. The movement of the electrons through the load, as a result of this redox reaction in the fuel cell, to generate electric current [35].





Alkali fuel cells are cheap, and the presence of an alkali medium for easier oxygen reduction reaction as compared to the proton exchange membrane fuel cells gives them higher commercial prospects. Therefore, a wide range of cheap prospective catalysts has been identified to be used at the cathode to improve the efficiency of this fuel cell type [36]. These catalysts include noble metals, such as gold and platinum. Previously, alkaline fuel cells used to operate at high temperatures were in the range of 100 °C and 250 °C. However, there have been alkaline fuel cells that have been designed with highly active catalysts such as platinum, high surface nickel, and silver. This has given them the ability to operate at lower temperatures around 70 °C, and even closer to ambient temperatures around 23 °C, in recent times, due to the improved activity of catalysts [37].

One of the biggest downsides of alkaline fuel cells is its susceptibility to CO₂ poisoning conditions. Though its efficiency is high, the presence of carbon dioxide, as part of air that enters the cell, has been identified to be responsible for the degradation of electrolytes [38]. The electrolyte solution, which is usually made of potassium hydroxide, undergoes a quick reaction with carbon dioxide in air to produce potassium carbonate or potassium bicarbonate. The chemical reaction equations are shown in Equations (7) and (8). The air used in these alkaline fuel cells has to undergo purification to eliminate carbon dioxide before being used, due to this susceptibility. This increases the costs involved in the operation of alkaline fuel cells [39].



In addition to the formation of carbonates due to CO₂ poisoning, there are also certain drawbacks in the manufacture and use of alkaline fuel cells. These include the high rate of degradation of catalysts and electrodes due to a corrosion, high cost of electrodes, high cost of catalysts, and poor durability [40].

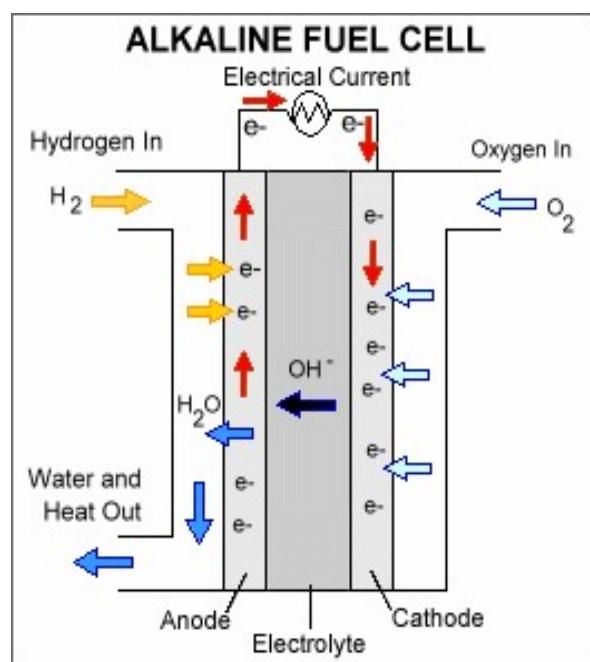


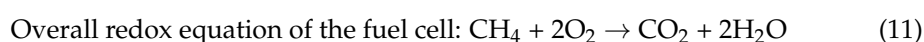
Figure 5. Schematic representation of alkaline fuel cells [41]. Reproduced with permission from Vaghari et al. (2013), ©Springer, 2013 (open access—Creative common attribution 2.0).

5. Solid Oxide Fuel Cells

Solid oxide fuel cells possess the basic composition of every fuel cell as shown in Figure 6. They have electrodes (cathode and anode) on either side of the electrolytes. Unlike the previously mentioned fuel cells, these fuel cells have solid electrolytes (as the name implies), which are usually made of ceramic materials [42]. These solid electrolyte must have the properties as mentioned below to appropriately perform its function in the operation of the solid oxide fuel cells [43].

- Low electronic conductivity prevents higher loss in voltage and leakage in oxygen, which may lead to the production of low or no electricity.
- Great strength to withstand high mechanical stress.
- High oxide ion conductivity to prevent resistance.
- Great chemical stability.
- Great thermal stability in the presence of air and fuel.
- Low cost of raw materials and construction.

Another specific property that makes solid oxide fuel cells different from the other fuel cells is the use of natural gas instead of only hydrogen. Natural gases, such as methane, ethane, and propane can be reformed into hydrogen and carbon monoxide, to be used in these fuel cells. Air is fed into the cell through the cathode part, where the oxygen component undergoes a reduction reaction to produce oxide ions as shown in the reduction reaction Equation (10). The oxide ions pass through the solid ceramic electrolyte to the anode side of the cell. Hydrogen, carbon monoxide, and methane from reformed natural gas are fed to the anode side of the cell. On this electrode, these fuels encounter the oxide ions that have travelled from the cathode side and through the ceramic electrode. They catalytically react with the oxide ions to undergo an oxidation reaction to produce water, carbon dioxide, and electrons. The electrons released are transferred to the cathode by passing through the external circuit, thereby producing electricity. These electrons recreate more oxide ions as they undergo another reduction reaction with oxygen in the cathode. The oxidation reaction equation is shown in Equations (9)–(11).



The water produced from this reaction in the form of steam can be recycled to be used in the reformation of the natural gas to hydrogen and carbon monoxide, for another redox reaction in the fuel cell [44].

The energy conversion efficiency of solid oxide fuel cells is high, compared to other fuel cells. About 60% of the energy in the fuel cell can be converted into electrical energy. Apart from energy conversion, the heat and steam that are generated as byproducts of the energy conversion process can also be used as a source of energy for other processes, such as driving turbines, reformation of natural gas, and a source of heat. This could raise the efficiency of solid oxide fuel cells to about 80% [45]. Hence, the solid oxide fuel cell program was initiated by the United States department of energy in 2000, to manufacture environmentally friendly and low-cost solid oxide fuel cells for both small-scale and large-scale power generation via natural and synthesized gases. The project aims at attaining a degradation rate of less than 0.2% for every 1000 h, and an energy efficiency of higher than 60%, without carbon capture and sequestration [46].

Another advantage of the solid oxide fuel cell is the solid state of its electrolyte, which makes it possible for the fuel cell to be able to tolerate the presence of impurities, provided the impurities do not alter the permeability and porosity of the components of the cell. Solid oxide fuels usually operate at temperatures within the range of 800 °C to 1000 °C. There are few solid materials such as Chromium (melting point of 1615–1860 °C) and Cupronickel (melting point of 1170–1240 °C) that are readily available and come close to withstanding

these high temperatures. Beryllium (melting point of 1280 °C), for instance, has a relatively higher thermal resistance, but it is rare. Ceramics are the most suitable materials to be used in this fuel cell type due to their availability and high thermal resistances. Therefore, special and exotic ceramic materials should be used in the construction of solid oxide fuel cells at high temperatures. This leads to an increase in the cost of construction [47].

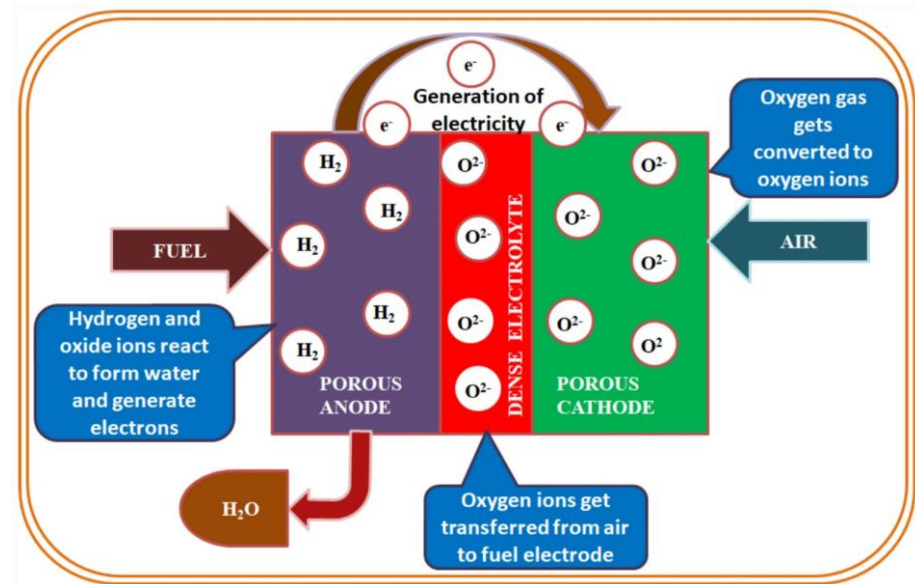
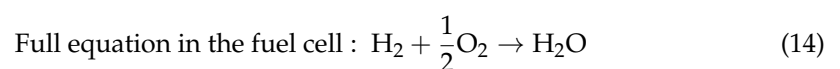


Figure 6. Schematic representation of solid oxide fuel cells [48]. Reproduced with permission from Hussain et al. (2020), © Springer, 2020 (Open access—Creative commons attribution 4.0).

6. Phosphoric acid Fuel Cells

Phosphoric acid fuel cells transform chemical energy from acidic electrolytes to electrical energy through the reduction–oxidation (redox) reaction process with hydrogen and oxygen, as shown in Figure 7. The electrolyte used in this type of fuel cell is a highly concentrated phosphoric acid, which is saturated in a matrix of silicon carbide [49]. Hydrogen is fed as a fuel to the anode of the fuel cell. The hydrogen present at the anode catalytically reacts and undergoes an oxidation reaction to produce electrons, as shown in the oxidation reaction Equation (12). The electrons produced due to the oxidation reaction travel through the circuit outside the cell through a load to the cathode side of the cell. Hydrogen ions (protons) that are produced due to the oxidation process travel through the silicon carbide and the phosphoric acid electrolyte to the cathode side.

In this fuel cell, oxygen is introduced to the cathode side of the fuel cell. On this side of the cell, the oxygen gas catalytically undergoes a reduction reaction, as it encounters the electrons from the anode as shown in the reduction Equation (13). The reduction reaction produces oxygen ions, which then react with the hydrogen that comes to the cathode side, through the phosphoric acid electrolyte as shown in Equation (14). The interaction between the hydrogen ions and the oxygen ions produce water. The movement of the electrons through the load as a result of this redox reaction in the fuel cell to generate electric current [50].



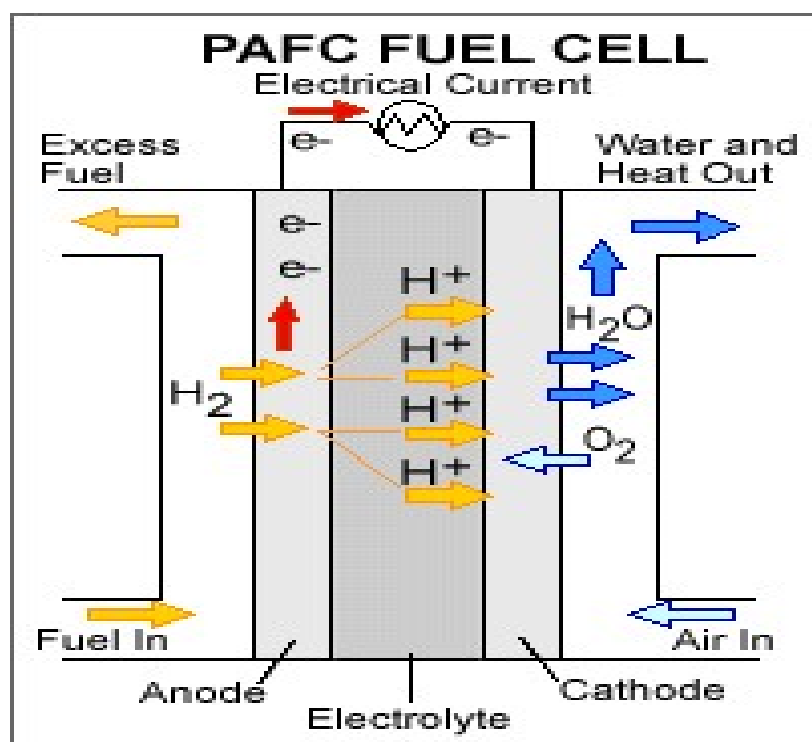


Figure 7. Schematic representation of phosphoric acid fuel cells [41]. Reproduced with permission from Vaghari et al. (2013), ©Springer, 2013 (open access—Creative common attribution 2.0).

The phosphoric acid fuel cell (PAFC) and the proton-conducting electrolyte membrane fuel cell are both fuel cells that utilize hydrogen ions as the charge carrier. The necessary thermal, chemical, and electrochemical stability, the low volatility, and the lack of the CO_2 reaction to generate carbonate ions are the only benefits of phosphoric acid. The electrolyte of the fuel cell must be maintained substantially above the freezing point of phosphoric acid ($42\text{ }^\circ\text{C}$), which results in typical operating temperatures between $150\text{ }^\circ\text{C}$ and $200\text{ }^\circ\text{C}$. The silicon carbide matrix in which the electrolyte is contained is made up of particles with an average size of $1\text{ }\mu\text{m}$, which enables the matrix to be between 0.1 and 0.2 mm of thickness and offers remarkably reduced ohmic losses, while being thick enough to avoid reactant gas crossover. Gas diffusion electrodes for the PAFC are made of a porous carbon matrix with platinum acting as a catalyst [51].

There are certain factors that must be met to improve the performance of PAFCs. The materials of the anode must maintain their stability in phosphoric acid at high working temperatures. The anode material undergoing reverse polarization and electrochemical corrosion while under operation are also possible effects of hydrogen scarcity. The materials must also be reasonably priced to be commercialized. Cell performance may suffer from carbon monoxide in the fuel gas, which is hydrogen-rich, especially at reduced operation temperatures [52]. Further, the platinum–ruthenium alloy on a support of graphitized carbon is the suggested anode catalyst. The optimal concentration of phosphoric acid must be maintained for the operation at high temperatures. Depleted reactant gases must also be able to leave the anode structure without obstructing the flow of new reactants. The microstructure of the anode, including the catalyst layer and substrates, is crucial to boost the usage of anode catalysts and to enhance anode performance [53].

Commercial phosphoric acid fuel cell (PAFC) development began in the US TARGET program in 1967, and PAFC for on-site application was introduced into the market in 1995. A variety of applications were created and successfully used in industries, hospitals, hotels, sewage treatment plants, schools, and other facilities, in addition to being a cogeneration system [54]. Among the numerous varieties of fuel cells, the PAFC is the only plant with a durability of more than $40,000\text{ h}$ that has been proven in the real world. The advancements

in cost reduction, reliability, and durability enhancements, as well as the creation of new applications, has made PAFC the choice to reduce carbon dioxide, which is the leading factor of global warming [55].

7. Requirements of Solar-Derived Chemical Fuel Cells

In solar-powered fuel cells, artificial chemical fuels are made from solar energy. Photoelectrochemical, photobiological, thermochemical, and photochemical processes can be used to produce solar-powered fuels. Photoelectrochemical processes involve the activation of certain chemical reactions, such as electrolysis by photons. Further, photobiological processes involve the use of photosynthetic microorganisms to produce energy. An example is the use of microalgae and bacteria in a bioreactor. Photochemical processes involve the direct use of sunlight to produce energy without any electricity. Likewise, thermochemical processes involve the direct use of solar heat to produce energy without any electrical processes. Light is employed as an energy source in all these processes with solar energy converted into chemical energy, often by reducing protons to hydrogen.

7.1. Photoelectrochemical Processes

Solar energy conversion directly into chemical energy in the form of hydrogen occurs during the photoelectrochemical water splitting process using semiconductor materials. Such semiconductors are similar to those used for photovoltaic solar electricity generation. For photoelectrochemical applications, the semiconductor is immersed in aqueous electrolyte, where photons from the sun accelerate the water-splitting process. With the ability to convert solar energy into chemical energy at a high efficiency, low operating temperatures, and the utilization of readily available thin-film and/or particle semiconductor materials, photoelectrochemical water splitting is a viable method for producing hydrogen. As with photovoltaic panels, photoelectrochemical reactors can be fabricated as electrode systems, slurry-based particle systems, or panels, each of which has benefits and drawbacks of their own [56]. For unbiased solar water splitting applications to produce hydrogen, connecting a standard photoelectrochemical cell with a photovoltaic cell can also be accomplished if the photovoltaic compartment can contribute enough photovoltage to make up for the photoelectrochemical cell's potential deficiencies. For practical photoelectrochemical solar hydrogen generation, dependable photoelectrode materials that meet the criteria for effective charge carrier use, reduced overpotential, a wide range of solar spectrum harvesting, improved stability, and lower cost are required [57].

7.2. Photobiological Processes

The requirements for the photobiological processes involve a culture for energy producing micro-organisms (cyanobacteria and micro-algae), oxygen and hydrogen). In these processes, cyanobacteria and/or green microalgae use sunlight to divide water into oxygen and hydrogen. Hydrogen gas may be released as a result of direct or indirect interactions between the hydrogen ions. The drawbacks of this process include the low hydrogen production rates and oxygen production, which quickly stymies the hydrogen generation reaction and can be dangerous when mixed with hydrogen at certain levels. A lot of research has been conducted to develop the mechanisms that will let the bacteria produce hydrogen more quickly and for extended periods. Through a process known as photofermentative hydrogen production, some microbes that are capable of photosynthesis use sunlight as a source of energy to break down organic molecules and create hydrogen. Photobiological production technologies are promising for cost-effective hydrogen generation from sunlight with reduced carbon emissions. It is possible to grow algae and bacteria using water that cannot be used for drinking or agriculture [58].

7.3. Thermochemical Processes

For a thermochemical process to occur, sources of high temperature, water, and metal oxides are required. High-temperature heat (500 °C–2000 °C) is used in thermochemical

processes to power a series of chemical reactions that yield hydrogen as a chemical fuel. Each cycle's chemical input is recycled, resulting in a closed loop that uses only water and generates hydrogen and oxygen [59]. The high temperatures are either obtained from nuclear waste heat or, in the case of this study, solar heat. The recovered chemicals employed to create a closed-loop process utilize only water as a feedstock and solar heat. A two-step procedure characterizes the simplest thermochemical process. One endothermic process and one exothermic redox process involving metal oxides are present. The first transformation of the metal oxide is into a reduced-valence metal oxide and oxygen. This metal oxide and water, subsequently, combine to form hydrogen and oxygen as well as the original metal oxide. Consequently, the metal oxide is recycled [60].

7.4. Photochemical Processes

The photochemical technique of producing hydrogen as a chemical fuel is similar to photosynthesis in nature. The main requirements for this process are a source of light and photoactive compounds. The source of light (which for the purpose of this study is solar) must have a wavelength emission corresponding to the transition of electrons in the photoactive compounds. The photoactive compounds that operate as synthetic reaction centers have been the strategy used for photochemical systems. These molecules absorb light and undergo charge separation, which leaves a hole on one side and an electron on the other side. However, the maintenance of the charge-separated condition for a long time to fuel the chemical reaction that produces hydrogen is difficult [61]. A light absorber, a catalyst, and an electron source are the required components of a system for the photogeneration of hydrogen from water [62].

8. Novel Materials for the Fabrication of Solar-Derived Chemical Fuel Cells

A unique positive-type (p-type) lanthanum ferrite (LaFeO_3) photoelectrode was fabricated by Pawar and Tahir (2018), utilizing a scalable and affordable spray pyrolysis technique. The resultant nanostructured LaFeO_3 photoelectrode produced spontaneous evolution of hydrogen from water in the absence of any external bias. Additionally, the photoelectrode demonstrated outstanding stability over 21 h and had a faradaic efficiency of 30%. LaFeO_3 may have a conduction band of -1.11 V beyond the hydrogen reduction potential and may cross the water redox potential, according to the band diagram generated from optical and impedance measurements.

In the study, a low-cost LaFeO_3 photoelectrode was also created. This device is a viable source of renewable hydrogen because it can spontaneously produce hydrogen from water using sunlight [63].

In another study by Safaei and Teridi (2018), graphitic carbon nitride ($g\text{-C}_3\text{N}_4$) was used in a Z-scheme configuration to boost the performance of bismuth vanadate (BiVO_4). Density Functional Theory (DFT) simulations were used to assess the experimental results. The performance of a titanium dioxide (TiO_2)/ BiVO_4 heterojunction and a $g\text{-C}_3\text{N}_4$ / BiVO_4 heterojunction were examined in this work. The $g\text{-C}_3\text{N}_4$ / BiVO_4 device with the highest photocurrent among Z-scheme heterojunction devices based on $g\text{-C}_3\text{N}_4$ was found to be at 0.42 mAcm^{-2} at 1.23 V versus a reversible hydrogen electrode (RHE). The $g\text{-C}_3\text{N}_4$ based heterojunction showed low resistance charge transfer, increased light absorption, and more vacant sites for oxygen. The simulation results supported the formation of a van der Waals heterojunction between $g\text{-C}_3\text{N}_4$ and BiVO_4 , where an internal electric field made it simpler to separate electron-hole pairs at the $g\text{-C}_3\text{N}_4$ / BiVO_4 interface, further reducing carrier recombination. The resulting heterojunction displayed modest effective electron masses of 0.01 effective mass (m_e) and holes of 0.10 m_e with ideal band edge placements, where both the conduction band maximum (CBM) and valence band maximum (VBM) were significantly above and below the redox potential of water [64].

Similar to this, nanostructured photoelectrodes constructed of zinc ferrite were proposed by Tahir and Pollet (2013) as a novel way to regulate the texture of substances (ZnFe_2O_4).

In research on the effect of the deposition solution composition, the chemical and physical parameters that are significant in the generation of aerosols and their subsequent decomposition during the chemical vapor deposition of ZnFe_2O_4 electrodes, assisted by aerosols, were examined (methanol, the deposition solvent, and ethanol). The ZnFe_2O_4 electrode texture was found to have undergone a considerable change as a result of the composition of the deposition solution, according to investigation using a field emission scanning electron microscope (FESEM).

The ZnFe_2O_4 electrodes produced using methanol and predominantly methanolic solvents have a relatively compact shape [65].

A p-type cobalt tetra-oxide (Co_3O_4) with a high efficiency of photoelectrochemical processes in aqueous media was proposed by Ebadi et al. (2015). This study used starch particles floating in a chloride bath to electrodeposit various amounts of CuO-doped p-type Co_3O_4 photocathodes on fluorine-doped tin oxide (FTO). For water splitting applications, artificial samples containing 0.5 M of sodium sulfate (Na_2SO_4) were photoresponsive under artificial sunlight. We evaluated the performance of the photoelectrochemical cell (PEC) using light shelf photovoltaics (LSPV), chronoamperometry, and electrochemical impedance spectroscopy (EIS) methods. The samples created using the electrodeposition/annealing methodology had a lower photocurrent response than those created using the electrodeposition/anodizing/annealing method. Co: 24.9, Cu: 25.0, and O: 50.1 atoms made up the sample with the highest overall photocurrent response (6.5 mA cm^{-2} against spatial collection efficiency (SCE) at -0.3 V). Using the x-ray diffractometer (XRD), field-emission scanning electron microscope (FESEM), energy dispersive x-ray (EDX), and ultraviolet-visible (UV-Vis) techniques, the structure, morphology or composition, and optical response of the photocathodes were each discovered [66].

To comprehend the characteristics of the bismuth vanadate (BiVO_4) heterojunction with selenium–bismuth vanadate, Nasir et al. (2017) performed a comprehensive experimental and periodic density functional theory (DFT) simulations (Se- BiVO_4). Additionally, they showed that Se can influence the morphology and light absorption and charge transfer properties in heterojunctions to support improved performance. Additionally, the CBM and VBM of BiVO_4 were both demonstrated by electronic property simulations that were composed of oxygen in 2p and vanadium in 3d orbitals, respectively. The photocurrent density at 1.3 V vs. SCE increased by three times due to the Se/ BiVO_4 heterojunction, from 0.7 to 2.2 mA cm^{-2} . Electrochemical impedance and Mott–Schottky analysis produced positive charge transfer characteristics, which explained why Se/ BiVO_4 performed better than BiVO_4 , and Se Spectroscopic, photoelectrochemical, and DFT observations have shown that Se and BiVO_4 can form a straight Z-scheme by band alignments in the photoexcited electrons of BiVO_4 after interacting with the VBM of Se. Due to this, the electron–hole at Se and BiVO_4 separates, increasing the photocurrent [67]. Table 1 is the summary of various novel materials for the preparation of solar-derived chemical fuel cells and their exclusive properties.

Table 1. Novel materials for the preparation of solar-derived chemical fuel cells and their exclusive properties.

Novel Materials	Solar-Derived Chemical Fuel Cells	Reference
P-type lanthanum ferrite photoelectrode	<ul style="list-style-type: none"> - Stability over 21 h - 30% of faradic efficiency - Water redox potential with the conduction band at -1.11 V. - Hydrogen generation via sunlight 	[63]
Graphitic carbon nitride-bismuth vanadate and titanium dioxide-bismuth vanadate heterojunction	<ul style="list-style-type: none"> - Z-scheme arrangement to improve bismuth vanadate's performance for four times - Maximum photocurrent at 0.42 mA cm^{-2} - Lower resistance of charge transfer - Greater absorption of light - High vacancy sites for oxygen 	[64]

Table 1. Cont.

Novel Materials	Solar-Derived Chemical Fuel Cells	Reference
Nanostructured zinc ferrite photoelectrodes	- Synthesized via aerosol-assisted chemical vapor deposition - Rod-like structure	[65]
Copper oxide-doped p-type cobalt tetra-oxide	- Fabricated on fluorine-doped tin oxide - Electrodeposition of starch particle in a chloride bath - 6.5 mA cm ⁻² against spatial collection efficiency (SCE) at −0.3 V of photocurrent response	[66]
Selenium-bismuth vanadate heterojunction	- Photocurrent density at 1.3 V vs. SCE - Photocurrent density increased by three times from 0.7 to 2.2 mA cm ⁻² - Electron–hole separation at selenium and bismuth vanadate	[67]

9. Limitations of Solar-Derived Chemical Fuel Cells

9.1. Environmental Hazards

Solar-derived biochemical fuel cells or photovoltaic systems have been identified as clean, long-lasting energy sources in recent times relative to other sources. However, these systems have negative effects on the land, air pollution, hazardous materials and noise, which cannot be considered to be entirely emission-free, environmentally beneficial systems [68].

9.2. Land Use

Numerous research and analyses revealed that the highest energy intensities in terms of land use are seen in photovoltaic systems and concentrated solar power [69,70], relative to alternative technologies. Additionally, the rapid expansion of solar systems will result in the acquisition of thousands of acres in the United States (US) alone, according to Almomani and Bhosale (2020) [71].

9.3. Air Pollution

Solar-derived biochemical fuel cells or photovoltaic energy is a clean energy source that has a relatively lower climate impact and air quality, compared to other conventional power generation technology, especially during application. Consequently, it can help to eliminate several environmental challenges caused by the use of fossil fuels [72]. Carbon dioxide, methane, sulfur oxides, and nitrogen oxide emissions from photovoltaic systems are completely eliminated during operation [73], with little impacts on climate change and air pollution. For instance, PV systems can minimize CO₂ emissions by 0.53 kg per kWh of electricity [74]. However, this is predicated on how PV systems operate, which ignores every stage of the lifetime. Therefore, the total emissions over time in all phases of the lifespan of solar power systems from production to disposal or decommissioning should be considered. Nugent and Sovacool (2014) demonstrated the breakdown of PV's total lifecycle greenhouse gas emissions in percentages, where fabrication or manufacturing were reported to have maximum emission contributions of 71.3% [75].

9.4. Hazardous Materials

Several hazardous materials are employed in the manufacturing of solar cells either during etching process of semiconductors or solar cells extraction and cleaning of surface [76]. Certain raw materials that are employed include silicone, gallium, selenium, cadmium, and tellurium. The manufacture, extraction, purification, separation, and cleaning operations for various types of solar cells also include the use of chemicals and solvents. HCL and HNO₃ are examples of certain chemicals that are employed for this process. Since the majority of these substances are toxic, corrosive, combustible, and carcinogenic, they must be handled carefully to minimize environmental hazards [68].

9.5. Noise

Noise is considered as one of the pollution types due to its environmental impact. It is reported as unwanted sound, per WHO standards. The sources of noise waves were determined by Dehra (2018) [77], based on the rate of noise interference. The solar-based system makes noise by virtue of power intensity differences between two PV setups. PV models do not have rotating parts, which means their operation does not give rise to noise [78]. However, numerous large vehicles and machinery operate on the building, and this contributes to noise pollution in the environment (residents and wildlife).

10. Novel Materials for the Fabrication of Solar-Derived Biochemical Fuel Cells

Lin and Seokheun (2020) [79] reported the use of photosynthetic bacteria as biocatalysts to show a straightforward and durable organic solar cell made of paper the first time. For a very long time, the paper has been used extensively in biological and chemical research [80,81]. The ground-breaking feature of paper-fluidics is the employment of a water-repellent wax to build three-dimensional microfluidic methods for doing several simultaneous bioassays by dispersing microliter amounts of analytes into various sensing sections of the paper [82]. Paper-fluidics is the most desirable method for single-use as a result of certain advantages, such as power-free fluidic control and its ability to be disposed through cremation [83,84]. Electronics made of paper, also referred to as paper-electronics, have made notable advancements at the same time as paper-fluidics. Because paper has a higher dielectric constant than most other materials, papertronics employs it as a substrate for electrical components [85–87].

Papertronics' capacity to biodegrade has garnered interest as the cutting-edge in environmentally friendly electronics, which reduces a sharp rise in electronic waste. It is ideal for such potential uses as the Internet of Disposable Things and electronics for security (IoDT) due to its simple and secure disposability [88,89]. Paper-fluidic-electro-systems, which are merged systems with paper-fluidics and papertronics, are capable of producing highly potent diagnostics. The fluidic and electrical connectivity was made possible by a revolutionary electro-fluidic production technique on paper, which also provided a numerous novel designs [90].

Paper-based electronics are gaining attention among researchers as a straightforward, cheap, and biodegradable model for temporary electronics, and they might be a great method to lessen the sudden increase in waste from electronics. Electronics from paper that are independent and self-sufficient require batteries, where these batteries should ideally be biodegradable, affordable, and able to deliver usable power. Paper-based microbial bio-batteries stand out among other paper-based batteries due to their economical, self-sustaining, and friendly to the environment being. However, their development has not fulfilled its potential in producing useful power applications due to their poor performance. Additionally, their biodegradability is yet debatable.

Mohammadifar et al. (2018) [89] reported that a unique, high-performance microbial battery is built using a readily biodegradable paper-polymer substrate. Further, the bio-battery is biodegradable without the requirement of specialized infrastructure, environmental factors, or the addition of more microbes. Additionally, Lin and Seokheun (2020) [79] reported the efficiency of biological solar cells from paper as they maximize the capabilities of controlled electricity-producing bacteria in a microchamber.

Application of Novel Materials and Nanomaterials

The efficiency and performance of fuel cells are largely dependent on the materials used, and researchers have been exploring novel materials and nanomaterials to improve the performance of these systems. One important component of solar-derived chemical fuel cells is the catalysts, which facilitate the chemical reactions that produce the fuel. Metal nanoparticles, such as copper and platinum, have been extensively studied for this application due to their high efficiency at catalyzing the reaction. For example, copper nanoparticles have been shown to be efficient for the reduction of CO₂ to formate

or formaldehyde, while platinum nanoparticles are efficient for the hydrogen evolution reaction (HER). Furthermore, metal nanoparticles can be synthesized with a high degree of control over their size, shape, and composition, allowing for further optimization of their performance [91]. Semiconducting materials, such as titanium dioxide (TiO₂), are also commonly used in solar-derived chemical fuel cells as photoelectrodes. TiO₂ has a high absorption coefficient in the visible region of the spectrum and can be easily doped with other elements, such as nitrogen or carbon, to improve its performance. For example, nitrogen-doped TiO₂ has been shown to exhibit enhanced photoactivity and improved stability compared to undoped TiO₂, making it a promising material for solar-derived chemical fuel cells [92]. Nanomaterials of graphene and carbon nanotubes in solar-derived chemical fuel cells are also of interest. Graphene, a single layer of carbon atoms, has high electrical conductivity, mechanical strength, and thermal stability, making it a promising material for use as a support material or as a catalyst. Carbon nanotubes, meanwhile, have high mechanical strength and can be used as support materials for catalysts, as well as catalysts themselves. Another promising area of research is the use of hybrid materials, such as metal-organic frameworks (MOFs), for solar-derived chemical fuel cells. MOFs are porous materials that can be synthesized with a high degree of control over their structure and composition and have been shown to exhibit high performance as catalysts and supports for catalysts. In particular, MOFs that incorporate metal nanoparticles have been shown to exhibit improved activity and stability compared to metal nanoparticles alone, making them promising candidates for use in solar-derived chemical fuel cells [93].

11. Real Applications of Solar-Derived Chemical Fuel Cells

Solar-derived chemical fuel cells have shown promising outcomes with the potential to revolutionize the renewable energy industry. There have been some real demonstrations of solar fuel cells in recent years, which have shown promising results in terms of their efficiency and stability. One example was reported in *Renewable Energy World* in 2023. The researchers, led by the National Renewable Energy Laboratory, demonstrated a new type of perovskite solar fuel cell that had the benefits of high efficiency and stability. The design enabled a stabilized efficiency of 24%, which is a significant improvement over previous designs [94]. Another example is the HySPRINT project, which is a European research initiative aimed at developing high-performance solar fuel cells for hydrogen production. The project has developed a new type of photoelectrochemical cell that uses a combination of photovoltaic and catalytic processes to produce hydrogen with high efficiency and stability. In addition to energy production, solar-derived chemical fuel cells can be used to produce a variety of fuels, including hydrogen, methanol, and formic acid, depending on the materials and designs used. This makes them suitable for a wide range of applications, including energy storage, transportation, and industrial processes.

12. Integration of Artificial Intelligence and Solar Fuel Cells

Artificial intelligence (AI) has emerged as a powerful tool in the field of energy research, and the integration of AI with solar fuel cells has the potential to significantly improve their efficiency and performance. One area where AI can be particularly beneficial is in the optimization of photocatalysts. Researchers have explored the use of different materials and structures for photocatalysts, with the goal of maximizing their performance. However, the large number of possible combinations and the complexity of the underlying physical and chemical processes make it difficult to predict which materials and structures will be most effective. AI can help address this challenge by using machine learning algorithms to identify the most promising materials and structures.

Chen et al. (2018) [94] demonstrated the power of this approach by using a deep learning algorithm to predict the performance of different materials for use as photocatalysts. The researchers used a combination of experimental data and theoretical calculations to train the algorithm, which was then able to accurately predict the performance of new materials that had not yet been synthesized. The results suggested that AI can significantly

accelerate the search for new and more efficient photocatalysts for solar fuel cells [95]. AI can also be applied in monitoring and performance control. Solar fuel cells are highly sensitive to changes in the environment, and even small variations in temperature, humidity, or light intensity can have a significant impact on their performance. AI can be used to analyze data from the fuel cell in real-time, allowing for the rapid identification of any issues and the adjustment of the operating conditions to optimize performance. Ardo and Winkler (2020) showed the potential of using AI to monitor the performance of a solar fuel cell in real-time. They used a combination of machine learning algorithms and advanced sensors to monitor a range of parameters, including the intensity and spectrum of incident light, temperature and humidity of the environment, and the performance of the fuel cell. The system was able to rapidly identify changes in the environment and adjust the operating conditions of the fuel cell to optimize performance [96]. The integration of AI and solar fuel cells has the potential to significantly improve their efficiency and performance.

13. Conclusions

As discussed, fuel cells are devices that convert chemical energy directly into electrical energy. They are considered to have a close to zero carbon footprint, as their working principle is based on sustainable chemistry, and they do not involve any combustion process that can release greenhouse gases into the atmosphere. Additionally, the feedstock for fuel cells is clean and readily available, especially when using hydrogen, which can be produced from renewable sources. Solar fuel cells use a photocatalyst to convert the energy from sunlight into chemical energy, which is then used to power the fuel cell. The use of solar energy is highly beneficial as a natural resource because it is abundant, widely available, and sustainable. The use of solar energy can also reduce dependence on non-renewable sources of energy, such as fossil fuels. However, the operational specificity of certain types of fuel cells requires the use of special materials, which can increase the cost of production. Extensive research is needed to develop cost-effective fuel cells that maintain high integrities while using materials that are readily available and affordable. It is also important to note that the use of fuel cells does not necessarily amount to zero environmental impact. Reports indicate that the manufacturing process of fuel cells can result in environmental pollution and other negative effects, including land use, air pollution, hazardous materials, and noise from on-site machinery. The use of hydrochloric acid, nitric acid, and isopropanol in the production of fuel cells can result in the release of harmful emissions and wastes. As such, it is important to implement proper manufacturing practices and develop sustainable solutions to minimize the negative impacts of fuel cell production.

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