ISSN: 2754-6675

Journal of Chemistry & its Applications

Review Article

Open Access

Hydrogen Fuel Cell Technology

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ABSTRACT

A hydrogen fuel cell generates energy by combining hydrogen and oxygen, making it a potential source of an electric power. The following paper presents the characteristics, operating theory, implementations, benefits, and drawbacks of the novel hydrogen fuel cell technologies available. It also covers the techniques for producing and storing hydrogen, which is the main fuel for a fuel cell. Additionally, a brief comparison of internal combustion vehicles (ICEV) and hydrogen fuel cell vehicles (FCV) is presented. The findings indicate that hydrogen fuel cell technologies have a general framework, a high-performance range of 40 to 60%, an optimal temperature range of 70 to 1000oC, and a reduced natural effect. At the end, a comparative study of five major power generating system is also performed.

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Received: June 21, 2023; **Accepted:** August 18, 2023; **Published:** August 28, 2023

Introduction

The development of clean energies is a critical component of developing low-carbon technologies for green industries. In the clean energy market chain, wind, solar, and tidal energy are the main generators of electricity. Moreover, the need for a viable solution to the oil-based economy has been demonstrated by the continuous and steady depletion of crude oil prices [1]. The world's energy demand is that in lockstep with economic growth, more or less. Many areas across the world, such as East Asia, Europe, and the Gulf Region, have seen rapid economic growth in recent decades. Rapid urbanization resulted in a significant rise in the living conditions of major communities, as well as a significant increase in global energy demand.

To solve this issue, a sustainable and renewable energy-based power efficient solution is needed. Hydrogen fuel cell power production in the car industry and stationary power plants is becoming an ever more effective alternative in various potential innovations [1]. The fuel cell is the best option for overcoming the challenges of resource sustainability. The quest for the best energy conversion started in the 18th century and continues today [2]. A hydrogen fuel cell is an electrochemical cell that converts chemical energy into usable electricity via an electrochemical reaction [3].

In this paper, literature review on the hydrogen fuel cell technology, production, storage, pros and cons and challenges will have discussed. Moreover, the comparative studies of fuel cell with other alternatives are represented below.

Hydrogen Fuel Cell Technology

The fuel of the future is hydrogen. Hydrogen is now widely regarded as a non-polluting energy source because it does not affect the climate when derived from renewable sources [4]. Hydrogen fuel cell is one of the promising technologies for the production of pollution free energy. The electrochemical reaction of hydrogen with air (oxygen) in the hydrogen fuel cell transforms hydrogen or hydrogen-based fuels directly into heat and electricity [5,6]. Figure 1 shows the typical representation of fuel cell reaction [7].

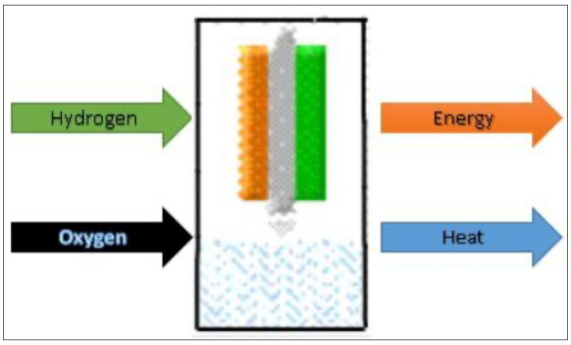

Figure 1: Representation of fuel cell reaction

An ion transmitting electrolyte, a cathode, and an anode are the main elements of a fuel cell, as seen schematically in Figure 2. A material must meet a number of requirements in order to serve as an electrolyte in a fuel cell. [4] described that an electrolyte should has high stability, melting and boiling points, and less toxicity. The types of electrolytes are varied into three main categories i.e. solid, liquid and gases. Moreover, the reactions are taking placed on the catalyst side of cathode and anode of a fuel cell. The oxidation and reduction reaction are carried out on anode and cathode respectively. The electrodes (catalyst layers) contain catalyst particles to speed up the cell's reaction cycle. An electrode usually has a thickness of 5– 15 m and a charge of 0.1–0.3 mg/ cm^2 [8].

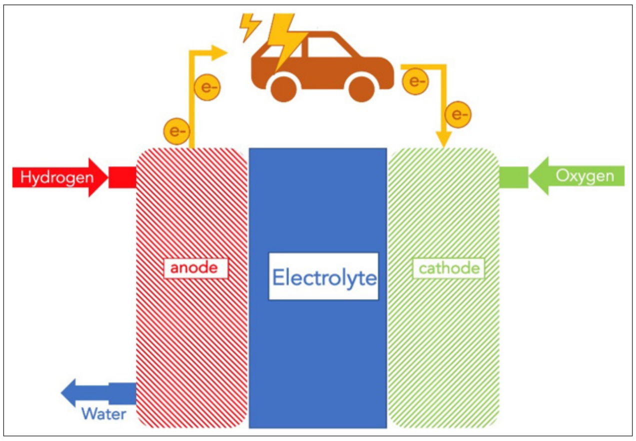

Figure 2: Regenerated Picture of Hydrogen Fuel Cell Components Based On (haile, 2003) Production and Storage

Hydrogen can be produced mainly via three sources i.e. electrolysis of water, fossil fuels and renewable energy resources [9]. Currently, half of the hydrogen fuel is produced using fossil fuel methodology, particularly steam reforming of methane. In this reaction, the hydrocarbon source such as methane is reacted at very high temperature with water to produce hydrogen energy gas along with other byproducts [10].

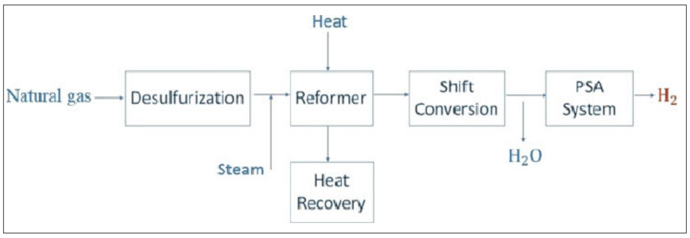

Figure 3: Process Flow of Steam Reforming

The schematic diagram of the steam reforming shown in Figure 3 [10].

Secondly, the production of hydrogen is carried out by using renewable energy resources such as biomass. But both of the above method causes high of emissions of greenhouse gases. However, the most environmentally friendly process for the production of hydrogen fuel is the electrolysis of water [11]. Moreover, it is the most efficient process to produce a pure hydrogen fuel gas. In this process, water is splitted into hydrogen and oxygen gases by the application of 237 kJ of electrical energy. Following is the electrochemical reaction that takes place during the splitting of water molecule and schematically shown in Figure 4 [12,7].

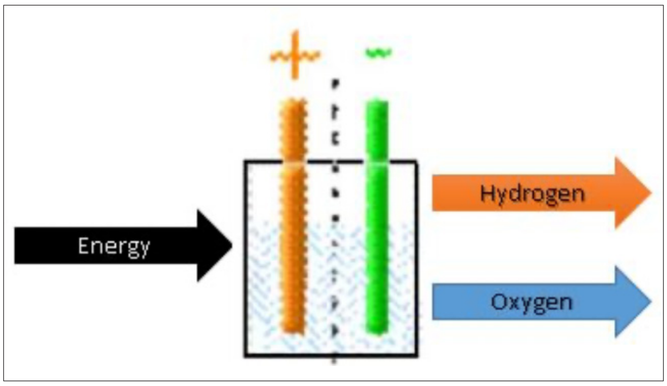

Figure 4: Representation of Electrolysis

After the production of hydrogen gas via electrolysis, it is converted into energy by the oxidation of hydrogen in a hydrogen fuel cell. A fuel cell behaves like a battery. But one significant difference is that batteries store energy, while fuel cells will consistently generate electricity as long as fuel and air are available [13]. Different types of hydrogen fuel cells may use any hydrogen-rich fuel. Following is the electrochemical reaction that takes place and previously shown in Figure 1 as well.

$$2H_2 + 0_2 \rightarrow 2H_20 + \text{Energy (0.1 to 3 MW)}$$

It is important to understand the operating segments to evaluate the significance of all the phenomena that occur in a fuel cell. Some major components of hydrogen fuel cell include electrolyte, cathode, anode, and catalyst layer [4]. In Figure 5, it can be seen that hydrogen produced from hydrogen rich source is fed to the anode side of the fuel cell whereas oxygen in terms of air is fed to the cathode side of cell. A porous carbon shield is used as the electrodes of a hydrogen fuel cell, on which the catalyst layer is embedded. The function of anode coated catalyst layer is to separate the electron from the hydrogen gas. The electrons are transported towards the cathode with the help of electrolyte solution and electric circuit. These electrons are then combined with oxygen gas that is entering from the cathode and as a result energy (electricity) of 0.1 to3 MW and water (byproduct) are produced [15].

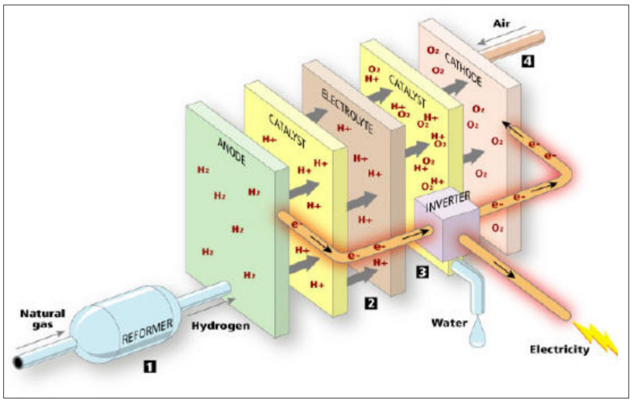

Figure 5: Schematic Diagram of Hydrogen Fuel Cell

Electrochemical reaction that occurs at the anode is the oxidation reaction whereas reduction reaction is occurred at anode [5].

At anode:

$$H_2 \rightarrow 2H^+ + 2e^-$$

At cathode:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$

The hydrogen electrode (the anode) must ensure the adsorption of the hydrogen molecule, its activation, and the promotion of the reaction with the hydroxyl ion. The reason behind is that the electrochemical reaction will not take place without proper activation. Furthermore, molecular adsorption of oxygen must be permitted by the cathode section of fuel cell.

Intellectual researchers are drawn to the fact that effective storage of hydrogen energy is a true technical challenge as hydrogen has a low volumetric storage density [16,12]. Various physical storage methods for raising the volumetric storage density such as compression and liquefaction of hydrogen gas have been developed. According to, the most popular standard gas cylinder for the storage of compressed hydrogen gas has a capacity of 50 liters [17]. New cylinders are designed to withstand a pressure of 300 bar. Moreover, several storage cylinders with a pressure of 200 bar are still being used.

For hydrogen compression, positive displacement devices, primarily reciprocating (classic piston or membrane) compressors with maximum withstanding pressures of 1000 bar, are currently used [17]. Theoretically, rotating positive displacement devices (scroll or screw) can also be used. Because of the low density of hydrogen gas, the resulting complexities and expense, and the high number of compressor stages needed than in positive displacement compressors, dynamic

compressors (centrifugal and axial) are not quite feasible for hydrogen [17]. More research in this area is needed.

Liquefaction is another way of storing hydrogen. Liquefied hydrogen (LH2) has a range of benefits, including high hydrogen energy density [17]. Various researchers have reported a literature on cryogenic liquefied hydrogen storage tanks [18,19]. The capacity of liquefied hydrogen tanks ranges from a few liters to 3,800 m3. Depending on tank capacity, usual boil-off drops range from 0.1 to 1% per day [20]. The schematic representation is of liquefaction of hydrogen is shown in Figure 6.

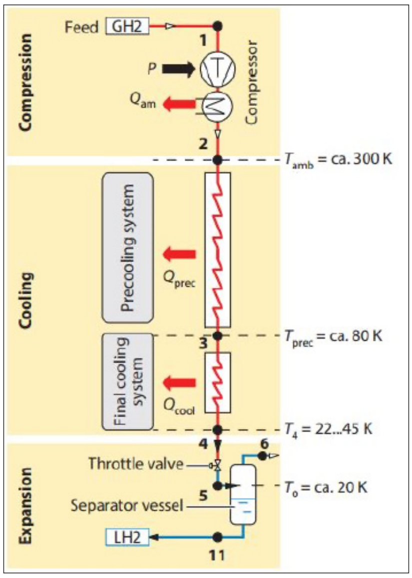

Figure 6: Liquefaction Process

Why Hydrogen Fuel Cells?

Fuel cells incorporate the desirable attributes of engines and batteries: like that of an engine, they can keep going as long as there is fuel, and just like a battery, they generate energy completely from fuel without combustion (which reduces emissions and disturbance) without any intermediate phases (efficient). Figure 7 illustrates some of the most significant benefits of hydrogen fuel cells. Although hydrogen fuel cell technology is beneficial for the world according to the above listed advantages, it has also some main drawbacks [21].

- Because of the low output voltage, control electronics devices may be needed as an interface between both the FC and the load, hampering the system's configuration.
- Because of its sluggish response time, it is unable to satisfy fast-variation requirements.
- There is no network for mass-market hydrogen fuel supply.
- As opposed to current substitutes, the price is too high

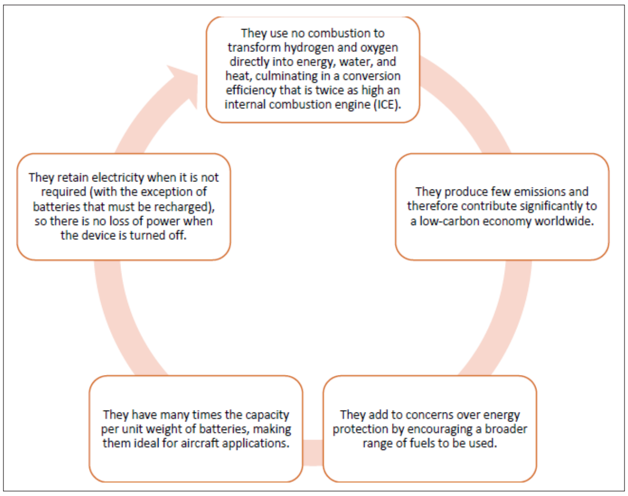

Figure 7: Generated graph of Benefits of hydrogen fuel cell (Ali, et al. 2006). Applications of Hydrogen Fuel Cells

Fuel cells have a wide range of applications. Each application has its own set of specifications. The application range of fuel cell systems can be divided into the following categories [8]:

- In the field of telecommunication, and data processing field
- In the field of transportation vehicles.
- In the field of renewable and sustainable energy production.

Results and Discussion

Six major types of hydrogen fuel cell technology based on their operating temperature conditions were reported in research studies and are shown below in Table 1 [5,22].

Table 1: Comparison of Types of Hydrogen Fuel Cells

Type of fuel cell	Operating temperature
Direct methanol fuel cell (DMFC)	60 to 130 ˚C
Alkaline fuel cell (AMFC)	70 ˚C
Proton exchange membrane fuel cell (PEMFC)	100 to 200 ˚C
Phosphoric acid fuel cell (PAFC)	180 to ˚C
Molten carbon fuel cell (MCFC)	650 ˚C
Solid oxide fuel cell (SOFC)	800 to 1000 ˚C

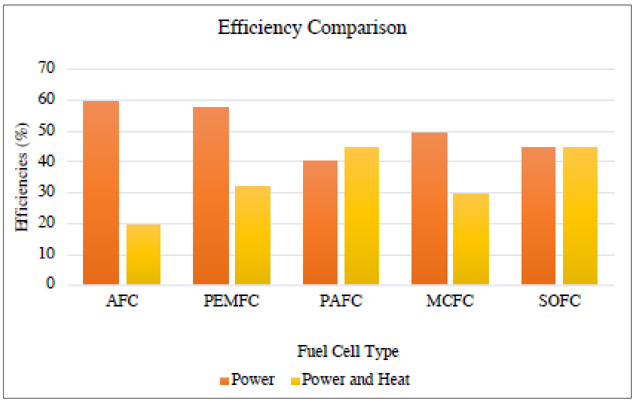

Figure 8: Efficiencies comparison

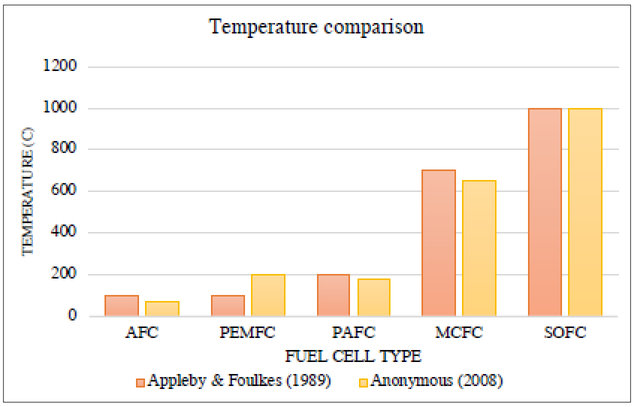

Figure 9: Generated chart Temperature comparison based on values from [5,22].

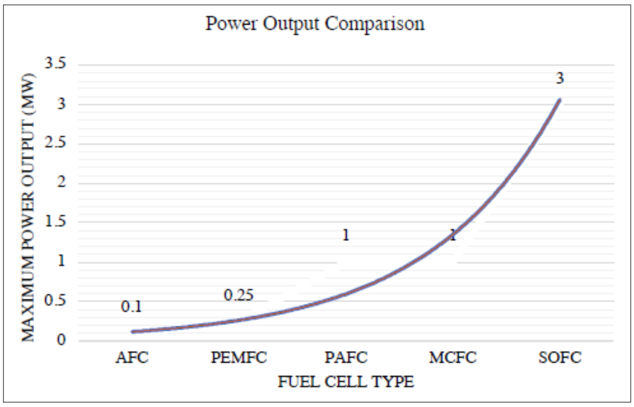

Figure 10: Generated Chart for Power Output For Different Fuel Cells

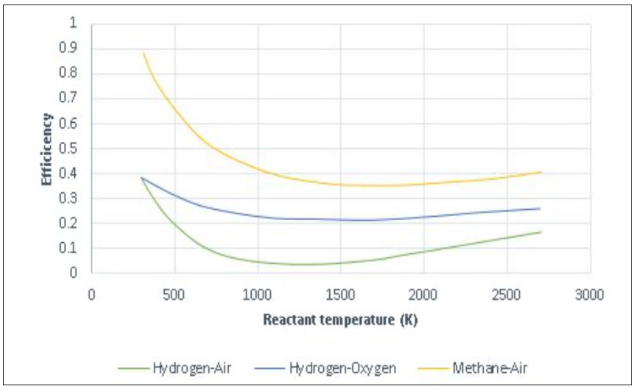

Figure 11: Effect of Reactant Temperature on Efficiency

Compared the highest conversion efficiencies of three types of fuel cell combination on the basis of type of reactants used i.e. hydrogen-air, hydrogen-air, and methane-air fuel cells. Moreover, he also depicted that on all three types of fuel cells, the optimum efficiency varies with the temperature of the reactants in Figure 11 [24].

[25] also worked on the reactant types of the five major types of fuel cells and they reported all the necessary parameters of the fuel cells that are listed in the form of Table 2.

Table 2: Comparison of Types of Hydrogen Fuel Cells

Type of fuel cell	Electrolyte	Reactant	Carrier ion
Alkaline fuel cell (AMFC)	KOH	H_2	OH^-
Proton exchange membrane fuel cell (PEMFC)	Sulfonated polymers	H_2, CH_3OH	H^+
Phosphoric acid fuel cell (PAFC)	H_3PO_4	H_2	H^+
Molten carbon fuel cell (MCFC)	K_2CO_3, Na2CO3	Hydrocarbon, CO	$CO_3 2^-$
Solid oxide fuel cell (SOFC)	ZrO_2, YO_2	Hydrocarbon, CO	O2$^-$

Compared the performance of hydrogen fuel cells and conventional gasoline engines. They declared that the efficiency of a fuel cell is 30–90% higher than that of a conventional gasoline internal combustion engine. The most important and clear benefit of hydrogen fuel cells is that they produce no pollution. To be more precise, since fuel cell vehicles only generate heat, water, and electricity, they have little or minimal environmental effects. In comparison to internal combustion engine vehicles (ICEVs), fuel cell electric vehicles (FCEVs) have a very basic structure. Since they are solid state instruments with no moving parts, they are naturally low vibrations and noise free. Through eliminating mechanical components from FC systems, the need for lubrication oil is removed, lowering maintenance costs [6].

Proposed the comparison of five major power generating system. The experimentation was performed on the diesel engine, turbine generator, photovoltaic cell, and wind turbine and hydrogen fuel cells [22]. The following result shown in Table 3 were obtained in the end. All the systems were evaluated based on their capacity to generate electric power, combined heat and power (CHP) efficiency and economical costs.

Table 3: Comparison of Power Generating System

Type of power system	Capacity (kW)	CHP Efficiency (%)	Capital cost ($/kW)
Diesel engine	500 – 5000,000	35	200 – 350
Turbine generator	500 – 5000	29 – 42	450 – 870
Photovoltaic cell	1 – 1000	6 – 19	6600
Wind turbine	10 – 1000	25	1000
Hydrogen fuel cell	100 – 3000	30 – 90	1500 – 3000

As far as the discussion of the results is concerned, various research works mentioned in the results have proved that hydrogen fuel cell technology is one of the best technologies for the production of electric power. The data of operating range of temperature were reported by the [5,22] in Figure 8. It can be seen that solid oxide fuel cell type has the highest temperature operating range. The temperature of 1000oC was recorded for the best operation of the solid oxide fuel cell. Alkaline fuel cells were found to has the least operating temperature range among all the five major types of hydrogen-based fuel cells.

The efficiencies of the hydrogen fuel cell in the production of electric power varies from the 40 to 60 % according to the above listed results. According to the results of the studies of presented in Table 1, it can be seen that alkaline fuel cells, polymer exchange membrane fuel cell, phosphoric acid fuel cells, molten carbon fuel cell and solid oxide fuel cells have the maximum power efficiency 40%, 50%, 45%, 55%, and 60% respectively. The similar trend was observed in case of the efficiencies as it was observed in the trend of the operating temperature of the hydrogen fuel cells. The solid oxide fuel cell has the maximum power generating efficiency whereas the alkaline fuel cell showed the least efficiency among all types of cell [5,22].

Most researchers focused majorly on the efficiency parameter of fuel cells. Mainly compared the efficiencies of power and the combined heat and power (CHP) in Figure 9. It was observing that the alkaline fuel cells and molten carbon fuel cells have the comparable combined heat and electricity production efficiency and was found as 80% [8,23]. Furthermore, similar trend was observed in polymer exchange membrane and solid oxide fuel cells and the efficiencies f both were founded near to 90%. Moreover, compared to the previous works that is discussed earlier, it can be clearly seen in the Figure 9 that the alkaline fuel cell was proved more efficient than all other types and its efficiency was reported almost to 60%.

Power output is also one of the major factors to access the performance of a fuel cell [8]. explained the comparison of power output of the cells. From Figure 10, it is clear that solid oxide fuel cell gives the maximum output of power which is 3 MW (or 3000 kW). Previously, similar behavior of profiles of temperature and efficiencies of fiver major categories of fuel cells were observed. Moreover, phosphoric acid fuel cell and molten carbon fuel cells gave one megawatt power but alkaline fuel showed the traditional behavior in power output as well as it was observed in previous studies. The maximum power obtained from the alkaline fuel cell was 0.1 MW (or 100 kW).

The primary reactant of the fuel is hydrogen through which energy production is carried out. The reactant depends on the various operating parameters such as temperature and pressure. Similar kind of work was performed by and it is presented in Figure 11 of the results section in which the three major types of fuel cells based on the difference in the reactants fed to the fuel cell, are compared [24]. The inverse curve behavior was seen for all the types of cells discussed. The CH_4-air fuel cell has the highest overall efficiency at a given reactant temperature, while the H_2- air fuel cell has the lowest, and the H_2- O_2 fuel cell is somewhere in the middle. The lowest optimum efficiency values are 82.1 percent, 75.7 percent, and 79.3 percent for methane-air fuel cell, hydrogen-oxygen fuel cell, and hydrogen-air fuel cell, respectively, while the highest total efficiency values are 92.7 percent, 82.7 percent, and 82.7 percent. The optimum conversion efficiency occurs at a temperature of 298.15 K for the reactants. However, increasing the temperature of the reactants reduces efficiency at first, then stays constant over a temperature spectrum, and gradually starts to increase. At 1350-1540 K, 1170-1300 K, and 1590-1730 K, the performance plateaus for hydrogen-oxygen, hydrogen-air, and methane-air, respectively. In Table 2, the comparison of different types of fuel cell types is carried out on the basis of their salient features by [25]. A fuel cell has the major component i,e, electrolyte which composes of carrier charge ion. Most of the fuel cells have the hydrogen ion as their mobile ion.

In Table 3, primary power generating devices ere compared by [22] and it was observed that hydrogen fuel cells are the most efficient device in terms of efficiency of combined heat and power generation. Moreover, it was also seen that diesel engine has the highest capacity among all to produce the electric power. On the other hand, photovoltaic cells produced the smallest electric power among all the systems. However, hydrogen fuel cells have the comparable energy production capacity. In the end, photovoltaic cells are the most expensive device of power generation whereas diesel are the least expensive one among all according to the data presented in Table 3.

Challenges

Costs consistency, and end-user adoption are the three major obstacles to any new product's commercialization. Fuel cells, on the other hand, lack natural opposition, unlike other innovative technologies [26].

Hydrogen fuel cells, as a relatively emerging battery system, have yet to make a major impact on the energy industry. The key obstacles in commercializing fuel cells are cost, durability, and reliability [27]. According to, government subsidies are almost exclusively responsible for the introduction of all hydrogen fuel cells in order to provide commercial opportunities for fuel cell deployment [28]. The impact of materials and efficiency of catalysts on fuel cell longevity has been thoroughly researched [29,30]. Scaling-up problems, according to these reports, are mostly content and catalyst efficiency issues, which have resulted in higher costs. Investigated fuel cell scaling-up in a series of experiments [31]. A major impediment to investment in this emerging energy-conversion technology is the failure to scale a pilot plant up to deployment due to poor reliability. To solve the problem of reliability, a systemic integration has been suggested.

Has also emphasized the role of reliability in the commercial viability of fuel cells [31]. In order to overcome durability and reliability problems, he proposed three operating windows to link components: flow-field layout, individual cells, stack and software design of the process, and device control.

Water and heat problems cause cumulative deterioration of materials and catalyst, resulting in poor longevity and reliability [32-34]. Weak water control, fuel and oxidant malnutrition, erosion, and chemical reactions of cellular constituents that trigger dehydration or flooding are the major causes of material and electrode deterioration.

After reviewing all the traditional and contemporary available data of the hydrogen fuel cell technology, it can be observed that there is a research gap for the cost estimation of this technology. This research area needs more attention.

Recommendations and Suggestions

Despite the above discussed challenges, there are compelling reasons to encourage continued development and deployment of hydrogen and fuel cell technologies. The benefits may be substantial in the longer run. Fuel cell vehicles will play an essential part in achieving greenhouse gases emission targets for light duty vehicles in 2050, according to the IEA's Energy Technology Perspective analyses review on light duty automobile transformations. More broadly, according to a recent IEA report, the advantages of moving to a renewable energy system exceed the drawbacks as far as policy mechanisms allow for stability and adaptation [35]. Moreover, stakeholders and energy departments of the countries all over the world should closely follow the technology of hydrogen fuel cell technology. Hydrogen fuel cells technology may play a part in a potential low-carbon energy grid, allowing for more alternatives to be used in fuel markets.

Therefore, I would recommend the following suggestions which need to be implement for the safe implementation of hydrogen fuel cell technology and the production of sustainable energy production. For several decades, policy consistency, coordination, and consistency would be needed. Hydrogen and fuel cells should be considered as part of a broader strategy for reducing carbon emissions in the energy infrastructure and achieving net zero emissions.

Conclusions

This paper presents a literature review of hydrogen fuel cell technology and its evolution to the present. It provides a critical overview of recent traditional and contemporary research on manufacturing and storage processes, types, and implementations of hydrogen fuel cell technology. For the past fifteen years, hydrogen and fuel cell technologies have improved significantly. Globally, this field continues to pose major obstacles (technical, commercial, economical and infrastructure-related) that must be addressed before fuel cells can achieve their full potential. With the ability to supply food, transportation, and power system utilities, hydrogen could play an essential part accompanying energy in the reduced economy.

It is not subject to the underlying requirement of instant stockpile balance, and thereby facilitates parallel pathways to further carbon reduction by supplying low carbon stability and preservation. It was also seen that five major types of hydrogen or hydrocarbon-based fuel cells for has the operating range of temperatures and efficiencies ranges from 70 to 1000 oC and 40 to 60% respectively. All in all, the single largest obstacle in realizing the hydrogen and fuel cell promise is to develop a concentrated, reliable, and coherent energy framework. Countries must create and implement on a complete framework for hydrogen fuel cell technology that provides the lengthy certainty required to make substantial, revolutionary commitments.

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