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Review

Fuel Cell Products for Sustainable Transportation and Stationary Power Generation: Review on Market Perspective

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Abstract: The present day energy supply scenario is unsustainable and the transition towards a more environmentally friendly energy supply system of the future is inevitable. Hydrogen is a potential fuel that is capable of assisting with this transition. Certain technological advancements and design challenges associated with hydrogen generation and fuel cell technologies are discussed in this review. The commercialization of hydrogen-based technologies is closely associated with the development of the fuel cell industry. The evolution of fuel cell electric vehicles and fuel cell-based stationary power generation products in the market are discussed. Furthermore, the opportunities and threats associated with the market diffusion of these products, certain policy implications, and roadmaps of major economies associated with this hydrogen transition are discussed in this review.

Keywords: energy scenario; renewable energy; hydrogen; fuel cells; fuel cell vehicles; electric vehicles; stationary fuel cells; fuel cell deployment; hydrogen roadmaps

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1. Introduction

Hydrogen and fuel cells have gained attention as a viable alternative energy system in recent years. In general, fuel cells work with fuels like hydrogen, methanol, or natural gas to convert the chemical energy in the fuel into direct current (DC) without intermediate combustion, as is the case with conventional engines [1]. Their improved efficiency and minimal emissions make fuel cells a candidate for a sustainable source of energy technology for the future [2]. The type of fuel cell, costs of raw materials, and methods of manufacturing determine the fuel cell market and hence the transition towards the hydrogen economy [3]. Over the past few years (since the 1990s), with the advent of technological advancements, the cost of fuel cells has decreased by 80%. Additionally, with the increased demand for raw materials, the cost of platinum is also expected to decrease [4].

One of the influential parameters deciding the economics of fuel cells is the method of production. High volumes of production can effectively reduce the cost due to economies of scale. However, higher production volumes involve higher investment in capital costs associated with production facilities and specialized equipment [5]. In terms of end-of-life management, the presence of noble metals such as platinum and some rare earth metals that are limited in supply must be properly utilized to extend the life of fuel cells. Certain techniques, such as recycling and re-furbishing fuel cell components, can minimize the total cost of these systems [6,7].

From a pure market perspective, investors are likely to maintain their portfolios un-der reduced subjective risks. Special purpose acquisition companies (SPACs) are becoming competitive in the market, with the sole purpose of raising capital for acquisitions [8]. The spill-over associated with this transition was modeled by Papathanasiou et al., and the strategy seemed to be effective in predicting market behavior [9]. Moreover, advanced research in the areas of materials, catalysts, performance, durability, and diagnostics associated with hydrogen energy and fuel cell systems is happening around the world. Most research articles in the literature deal with component-level technologies, illustrations, and research and development concerned with performance improvement and systems development.

In this article, we take into consideration the global commitment of nations to progress towards the hydrogen economy and from that standpoint, we discuss some of the key technological developments undertaken by some firms in this field. This review adds value to the prospect of starting research from the prospective of the need for energy transition and identifying the potential applications, products, and solutions in order to connect research goals with sustainable transportation and stationary markets. The purpose of this article is to provide a comprehensive overview of the transition towards a hydrogen-based economy using fuel cell technology. The global energy scenario and its inevitable shift to a different system of energy supply for the future are explored in the first section. The methods and systems for producing, storing, and using hydrogen as a fuel are covered in the following section. The potential for hydrogen to replace existing fossil fuels as a green energy carrier when generating processes are combined with renewable energy sources is strongly related to the prospect of developing a sustainable hydrogen economy. The next section addresses fuel cell technology in more detail, focusing on the applications, targets, configurations, demonstrations, and challenges related to fuel cell systems. This article's concluding section examines market elements that influence the transition to hydrogen fuel and notable hydrogen policies and roadmaps of various big economies.

The transition of the energy economy is pertinent to human nature [10]. A recent study undertaken by economists in Russia concluded that the attitude of citizens towards environmental issues plays a significant role in the pace of this energy transition. In this contemporary world, every nation is trying to adapt to newer technologies and consume alternative resources that are sustainable for mankind [11]. According to Ivan Illich, the fossil fuel energy system in the global market will reach a peak, and beyond a certain point, it will cause detrimental effects to humankind and the earth. In reality, the increase in greenhouse gas (GHG) emissions that has led to global climate change, increased air pollution, and associated disasters are now being associated with the exhaustive use of fossil fuels, which is considered to be a serious threat towards humankind [12]. The figure below (Figure 1) explains the growth in energy consumption through the years associated with varied energy sources. More than 76% of global energy use is created by fossil fuels, which are mainly composed of natural gas, coal, and oil in today's society. On a comparative scale, fossil fuel use accounted for a mere 1.72% in 1800, meaning an average increase of 6.8 TWh/year in the usage of fossil fuels over the last two centuries has contributed to scientific and industrial developments. Coal was the primary fuel amongst the fossil fuel subsets that contributed to these developments in the 19th century, but oil became one of the predominant fuels of the 20th century. In today's energy scenario, oil accounts for 31% of the global energy demand [13].

On the basis of production, it is believed that the per day production capacity of oil is approaching or has achieved its maximum [14]. Based on the production data from BP Statistical reviews, a local maxima was achieved that corresponded to 94,916 thousand barrels per day in 2019 [15] and considering reserves to be finite, the resource is expected to be emptied by the second half of this century. Clearly, on the other side, global energy consumption continues to increase with nations such as China and India going through economic development. However, developed countries are creating businesses that are less energy-intensive or are shifting their energy-demanding industries to developing nations [16]. This constant pressure on energy demand makes oil prices volatile and on the rise [17]. A report from the US Energy Information Administration showed that the price of oil at $7/barrel in 1974 reached $90/barrel in 2022 [18]. Historical patterns of energy transitions and predictions were made in the past about fuel shifts [19]. This present energy utilization scenario in the world is clearly inconsistent with nature and will lead to an energy crisis at a point. The environment, as a system that is critically stable, will fail once saturation is reached for the amount of pollution that the atmosphere can absorb. These factors create a serious need to shift the present energy supply scenario towards a greener, cleaner energy supply scenario.

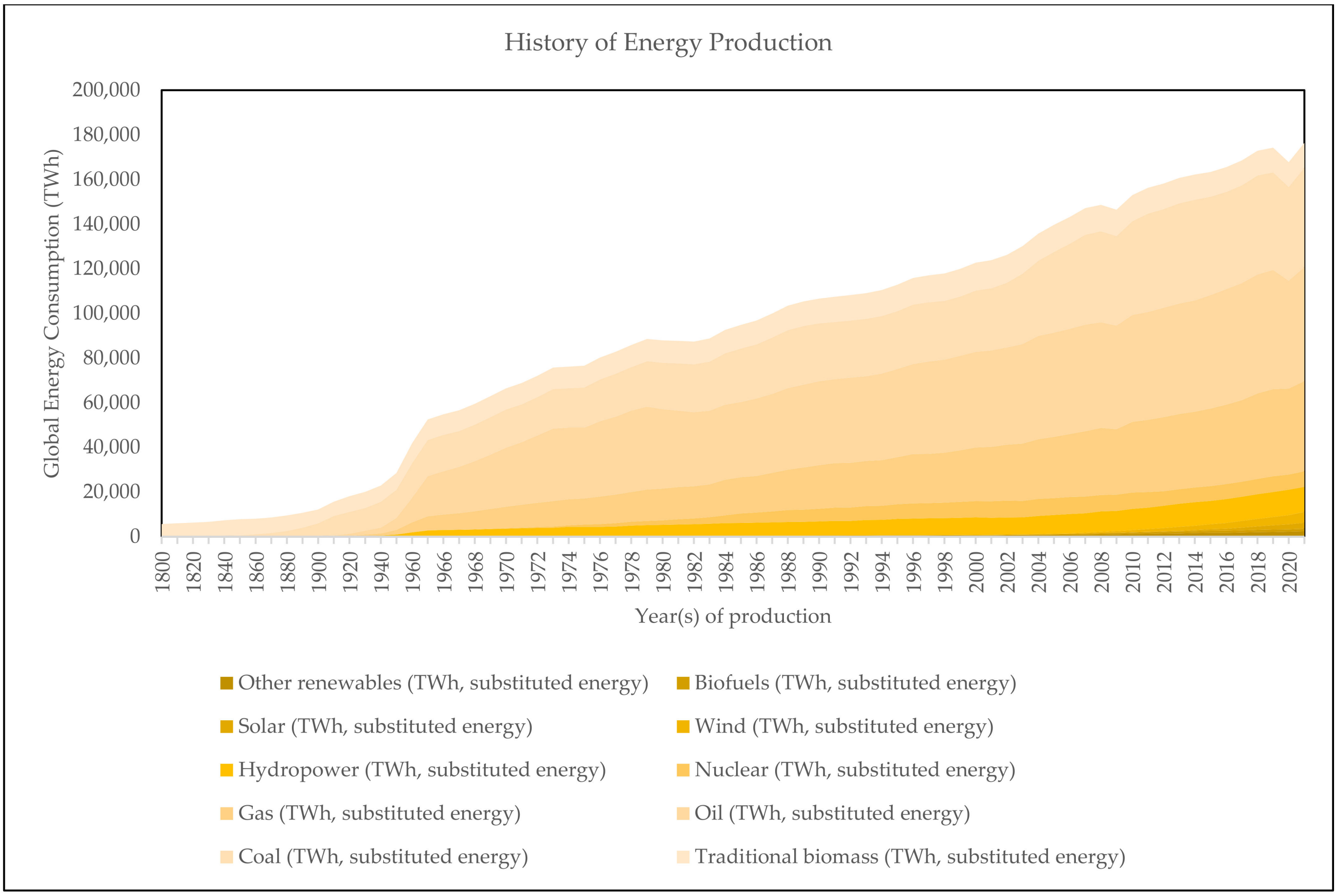

Figure 1. Global energy consumption (TWh) measured from varied energy sources over the past. (The graph was redrawn using data that are publicly made available for open source usage and proper citation is added to this text.)

One of the classic tools used to study the energy flows in an ecological system is an Odum's diagram (Figure 2). This tool is also used by researchers to study the behavior of global economic systems. In the case of non-renewable sources of energy in a system, the finite resources will be nullified depending on their usage. The upward movement of the associated utilization curve will be governed by technology development while the downward movement is associated with critical demands that lead to higher prices of fuel [20]. On the other hand, a sustainable model that uses renewable sources of energy has a flat availability and the usage usually reaches saturation depending on the technological limitations or the availability of a better energy source.

Certain modeling studies undertaken by Bert et al., on the availability of commercial energy indicated that the economic peak will be achieved in the first half of the 21st century [21] and then it will continue to decline as a result of depletion of fossil fuel resources. Another study undertaken by Nazim et al., estimated the possibilities of reversing the trend in commercial energy consumption and reducing the stress on the environment by using hydrogen-based renewable technologies. The projection estimated that if the hydrogen economy was made plausible at least by 2025, then the maximum peak in levels of CO_2 would be restricted to 550 ppm [22] as compared to the uncontrolled CO_2 levels of the fossil fuel economy. The transition towards a sustainable energy system for the future is inevitable considering the present energy scenario and forecasts, but there are several possible energy resources available, such as solar, wind, and hydro. The table below (Table 1) lists the potential and technical possibility of renewable energy sources that can significantly cater to the community [23].

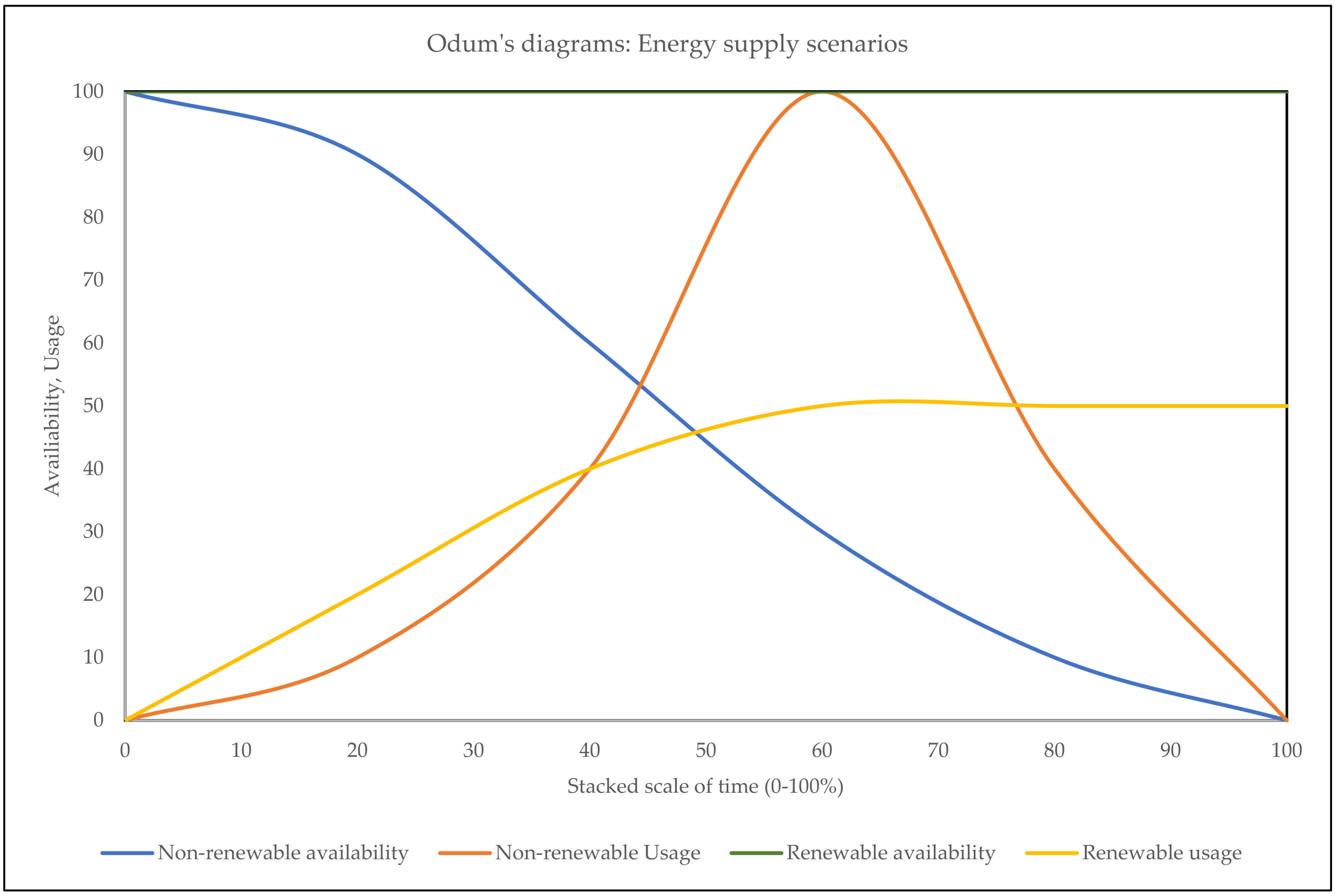

Figure 2. Odum's diagram based on the type of energy availability and usage. (This conceptual image is re-drawn based on the cited reference.)

Table 1. Potential and technical possibility of significant renewable energy sources (RES).

Energy Source	Potential (EJ)	Technical Possibility (TWh/yr)
Solar	3.85×10^6	4×10^5 *
Wind	1000	39,000
Hydro	144	15,000

* 1/10th of world deserts covered by PV panels.

Despite the fact that solar power as a resource can sufficiently satisfy the energy needs of today's society, which is 1.8×10^5 TWh/yr, the high initial cost of equipment, intermittency, and variable intensity associated with energy production pose an impedance to the market [24]. Each renewable resource is associated with such problems; these issues are addressed by converting the source into an energy carrier that can be transmitted through long distances in a clean manner. The direct conversion of renewable resources to electrical energy leads to storage and transportation losses. To solve this issue, hydrogen is proposed as an efficient energy carrier that can be locally produced by renewable energy sources, stored, transported, and then utilized for various applications through its integration with potential fuel cell technologies. The imminent transition from a commercial fossil fuel system to a renewable energy system is duly attributed to the creation of a hydricity economy.

2. Hydrogen: History, Production, Utilization, and Safety

2.1. History of Hydrogen and Fuel Cell Technologies

In 1839, Sir William Grove proposed the theory of the fuel cell effect [25] and developed the very first gas-based voltaic cell driven by the combination of hydrogen and oxygen. Attempts to popularize the cell were unsuccessful because of the concurrent revolution in internal combustion (IC) engines. Ostwald pioneered the theoretical underpinnings for the science of fuel cells in 1894. Van Santen explained the concept of step rule proposed by Ostwald that helps in the determination of the slowest step governing the reaction kinetics of chemical reactions [26], which is fundamental to explaining the rate of electrochemical reactions in fuel cells. The facets of global pollution and decreased efficiency of IC engines due to Carnot limitations were emphasized in his work. Lawaczek played a significant part in the development of pressurized electrolyzers and developed an array of layouts for hydrogen-powered cars, trucks, buses, trains, and engines in the 1920s [27].

Despite the fact that the concept of fuel cells evolved in the early 1840s, the reinvention of this technology came 100 years later when Francis T. Bacon [28] started working on fuel cells between 1932–1952 to develop and evaluate a 5 kW fuel cell stack for the first time. Later, this technology was developed for use in NASA's Gemini and Apollo programs for life support, guidance, and navigation systems [29]. With the increasing necessity for the development of a new fuel in the early 1990s, Scott and Hafele demonstrated the disruptions brought on by the excessive use of fossil fuels and showed that the shift to a hydrogen economy, whether achieved sequentially, overlapping, or directly, is necessary to reduce the contribution to greenhouse gas (GHG) emissions in the energy sector [30].

During the same period, fuel cell manufacturers such as Ballard and Energy Partners demonstrated their first fuel cell energy systems that were capable of powering buses and cars [31]. Due to tremendous advancements in the fuel cell industry over the past 20 years, there have been discussion about investing in hydrogen. Fuel cells and hydrogen energy are experiencing growth in their respective areas. The global fuel cell market is expected to grow from a USD 3 billion to 9 billion economy between 2022 and 2027, with a compound annual growth rate (CAGR) of 26.0% [32]. The interest in fuel cells in the scientific community has also increased over the past few years. The peak increase in the number of patents [33] filed in the hydrogen fuel cell community (23% increase) throughout 2016–2020 supports the above statement. Individual aspirations and global commitments drive the development of these technologies in countries such as the United States of America, China, India, Japan, South Korea, and some European nations.

2.2. Hydrogen Production Methods

The commercialization of fuel cell products requires the commercialization of hydrogen as an energy carrier, alongside the establishment of hydrogen infrastructure. The generation of hydrogen requires a prospective feedstock and energy to process. Hydrogen is presently produced in large scale through fossil fuels (natural gas, oils, coal) by methods such as steam methane reforming, partial oxidation, and auto thermal reforming. Currently, 78% of the world's hydrogen production is obtained through fossil fuels, considering the fact that it uses less energy to generate comparably greater quantities of hydrogen fuel [34]. From an economic standpoint, this method will be used during the transition to a hydricity economy. The addition of carbon capture units (CCUs) with these reformers is significant in providing a sustainability perspective to these systems.

Presently, only 4% of global hydrogen production is achieved through electrolysis, which is the process of directly splitting b water to produce hydrogen and oxygen. Obvious technologies that work well with electrolyzers include photovoltaics (PV) and wind turbines. A coupling efficiency of 93% was able to be achieved through PV-coupled electrolyzers [35]. The table below (Table 2) establishes a comparison between the consumption of energy, production capability, and levels of emission that are associated with hydrogen generation on per mole basis against the type of feedstock [36,37].

Table 2. Comparison of hydrogen production based on the source of feedstock and amount of energy to process.

Feedstock	Energy to Process (kJ/mole)	Production (Mole of H_2/Mole of Feed)	Emission (Ton of CO_2/Ton of H_2)
Natural gas	42.0	4.0	10.0
Oil products	50.0	2.7	12.0
Coal	60.0	2.3	19.0
Water	245.0	1.0	-

2.3. Hydrogen Storage and Utilization

Globally, storing hydrogen in high pressure cylinders at 200, 450, and even 690 bars has been reported [38]. The energy content of hydrogen on a mass basis is 120 MJ/kg; however, due to its poor volumetric density (4500 MJ/m^3), the storage of fuel requires much larger volumes and higher pressures. The areas of applicability of hydrogen are versatile, ranging from transport to power generation. One of the intermittent technologies that can diffuse the use of hydrogen in the market is H-ICE (hydrogen blended IC engines), which powers transport utilities with 20% more efficiency compared to gasoline powered engines. It has been reported that this blending also aids in fast and complete combustion of hydrocarbons [39]. Another associated technology that is more environment friendly and sustainable is fuel cells, which supports the direct conversion of hydrogen into electric power without combustion. Fuel cell electric vehicles (FCEVs) are becoming comparable to existing electric vehicles (EVs) in terms of driving range, speed, and acceleration.

2.4. Safety Aspects of Hydrogen

Hydrogen is considered to be as risky as any other fossil fuel [40,41]. The low volumetric density and higher diffusivity of hydrogen lead to comparably reduced losses in energy content (almost seven times lower) during leaks and makes the fuel less hazardous. Fuel cells are the least hazardous of the utilization methods for hydrogen-based products. The potential of fuel cells to suit various applications makes it a point of consideration in the global market for business and techno-social development.

3. Fuel Cells: Fundamentals and Applications

3.1. Fundamentals of Fuel Cells

Fuel cells are a direct electro-chemical energy conversion technology capable of generating direct current (DC) from low mW to higher kW applications. Fuel cells are comparable to batteries, considering the fact that they both have electrolytes, electrodes, and generate DC through electro-chemical reactions. The ultimate difference between them is that a fuel cell requires a constant supply of fuel and oxidant to generate power, whereas a battery discharges its stored potential per load demands. Faster recharging time for fuel storage and higher driving range in comparison with batteries makes fuel cells more versatile and comparable in the transportation sector [42,43].

3.2. Classification of Fuel Cells

Fuel cells are classified based on the type of electrolyte. The table below (Table 3) lists the significant categories of fuel cells with potential applications [44].

Table 3. Classification of fuel cells based on the type of electrolyte.

Fuel Cell Category	Electrolyte	Operating Temperature (°C)	Catalyst	Advantages	Weakness	Application
PEMFC	Polymer Electrolyte Membrane	60–80	Platinum	Quick startup Operation at room temperature Air as oxidant	Sensitive to CO Reactants need to be humidified	Vehicle power Portable power
AFC	35–85% wt. K-OH	120–250	Nickel/Silver	Quick startup Operation at room temperature	Needs pure O_2 as oxidant	Aerospace Military
PAFC	Phosphoric acid	150–220	Platinum	Insensitive to CO_2	Sensitive to CO Slow start	Distributed generation
SOFC	Y_2O_3-stabilized ZrO_2	650–1000	$LaMnO_3$/ $LaCoO_3$	Air as oxidant High energy efficiency	High operating temperature	Large distribution generation Portable power
MCFC	Molten carbonate	600–700	Nickel	Air as oxidant High energy efficiency	High operating temperature	Large distribution generation

Although most of the physics associated with fuel cells are common across types, PEMFCs stand out as the significant technology in the transport sector due to its quick startup, simplicity, and viability. These solid polymer membrane fuel cells are associated with an efficiency of 83%, which is much higher than IC engines. The technology, by itself, does not generate any emissions and the only byproducts are unused oxidant and water. The modularity and simple design of fuel cells allows for the mass production of individual units. Fuel cell stacks are built by adding each unit cell in series to provide a desired voltage and power. The concept of stacking fuel cell units in series to achieve the desired power became necessary in lieu of the cabling requirements and resistive losses associated with single cell-scaled up systems [45].

3.3. Basic Components and Working of Fuel Cells

A brief overview of the components that constitute a fuel cell unit along with its working principles are discussed in this section. The below figure (Figure 3) and associated tables (Tables 4 and 5) [23] explain the materials, functions, and processes associated with PEM fuel cells, considering that it caters to the transport market, which accounts for 90% of the global fuel cell market.

Table 4. PEM Fuel cell components, material usage, and specific functions (with reference to the color code in Figure 3).

Color Code	Name of the Component	Material Used	Function (s)
(blue)	Anode and cathode collector plate (s)	Copper	Collect electrons and transfer across the circuit
(yellow)	Anode and cathode flow channel (s)	Graphite	Conduct electrons and provide passage for reactant gases
(green)	Gas Diffusion Electrode	Pt/C	Provide the surface for electrochemical reaction to occur (Catalyst layer-CL) Equidistribution of reactant gases across the active area (gas diffusion layer-GDL)
(orange)	Membrane	Nafion	Conduct the protons

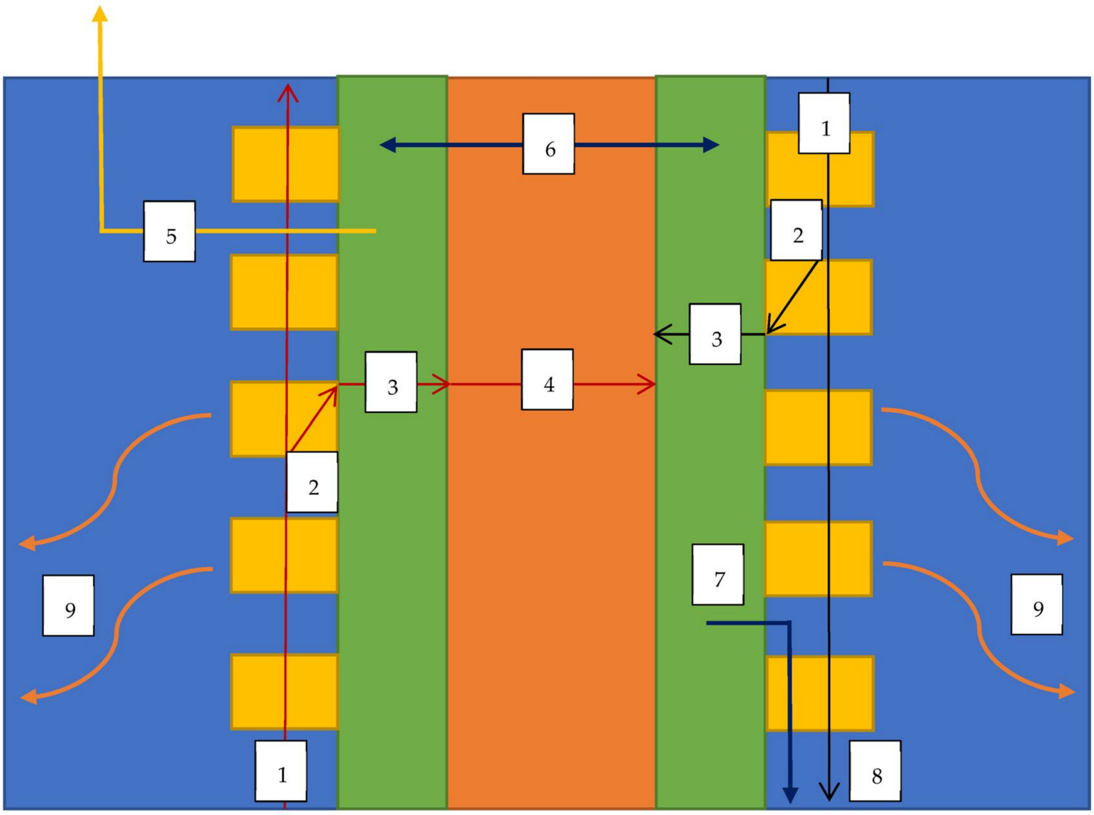

Figure 3. Schematic diagram of fuel cell components and associated processes. (This conceptual image is re-drawn from the cited reference).

Table 5. Fuel cell processes and description (with reference to Figure 3).

Process Code	Name of the Process	Description
1	Reactant gas flow	Hydrogen and oxygen are allowed to pass through the cell via gas flow channels
2	Reactant gas diffusion	These reactant gases diffuses through the GDL towards CL
3	Reactions at catalyst	At CL, the electrochemical splitting of hydrogen occurs at the anode and oxygen is held susceptible for completing the reaction at the cathode
4	Proton conduction	H^+ ions cross the membrane and react with O_2
5	Electron conduction	Electrons are conducted through the ribs of the anode flow channels and connected via an external load to combine at the cathode
6	Water transport (through membrane)	Due to electro-osmotic drag and back diffusion, there is a tendency to transport water between the anode and cathode through the membrane
7	Water transport (across GDE)	Water formed as a result of the combination of H^+, O_2, e^- constitutes this transport
8	Unused gas and water droplets	Unused gases and water droplets that fill the gas channels are usually purged out by the cathode gas itself
9	Heat transfer	The reaction is exothermic in nature and leads to building of temperature in these systems, hence proper cooling technology is essential to maintain system performance and prevent material failure

Some Design Challenges Associated with PEMFC Systems

Some of the key challenges in PEM fuel cell system design have been addressed by researchers worldwide. Certain studies on flow channel modifications showed improved performance of fuel cells due to the uniform distribution of reactants and effective water removal from cells. For example, one of the studies by Magesh Kannan et al., on the development of a sinuous flow field for the cathode exhibited a significant improvement in power density by 14% [46]. Certain experimental studies were performed to improve the temperature uniformity of PEMFCs in order to achieve better performance in the system. One such study was performed by Dineshkumar et al., to evaluate the optimal number of passes to be machined in the graphite plates with the objective of maintaining temperature uniformity in the system. This study reported that a 3-pass multi-serpentine flow field exhibited the best temperature uniformity characteristics [47]. Experiments investigating the voltage degradation of PEMFC systems were undertaken by Mathan et al., in order to evaluate and improve the end-of-life behavior of fuel cell systems. These authors reported that fuel cell performance was degraded based on flooding, catalyst contamination, and MEA delamination issues due to mechanical and thermal stresses [48].

3.4. Applications of Fuel Cells: Transportation Sector

A commercial vehicle that meets the expectations of fast refueling times and zero or low tail-pipe emissions is the fuel cell electric vehicle of today [49]. Presently, these FCEVs have a driving range of 240–435 miles, with a better fuel efficiency than conventional fuels. The market for hydrogen-based fuel cells in the transportation sector is increasing, which is very evident by the fact that numerous auto-manufacturers have begun purchasing fuel cell businesses [50]. Some manufacturing businesses have begun constructing environmentally friendly hydrogen generating facilities, while traditional gasoline bunkers are making room for hydrogen refueling stations [51]. The table (Table 6) below lists certain critical targets for fuel cell based vehicles in accordance with Department of Energy.

Table 6. DOE targets for automotive applications.

Characteristic	Units	2020 Target	Ultimate Target
Energy efficiency at 25% rated power	%	65	70
Power density	W/L	650	850
Specific power	W/kg	650	650
Cost	$/kW	40	30
Durability	hours	5000	8000

3.5. Architecture of Fuel Cell Electric Vehicles

Fuel cell direct mode: The fuel cell is used as the direct source to drive the power train. A 12 V battery is present to assist with startup. Hydrogen-based fuel cells are used in this architecture. The fuel cell controls associated with these systems have a poor response [52].

Parallel-hybrid mode: In a parallel hybrid fuel cell architecture, the fuel cell looks after the base load and the battery is used to accommodate fluctuations. The battery dynamically responds to the peak conditions and the fuel cell assists with cruising of the vehicle.

Series-hybrid mode: In a series-hybrid fuel cell architecture, the battery drives the vehicle and looks after instantaneous loads in the vehicle. The fuel cell is used to charge the battery. A trade-off between the sizes of the battery and fuel cell are made by the designer.

3.6. Components of FCEVs

The idea of using fuel cells in EVs is to make use of its ability to generate DC power, which is required for the propulsion of any EV. EV designers and manufacturers define their power requirements through the rated capacity of the DC electric motor and the fuel cell-battery combination is decided accordingly to meet this requirement. In today's scenario, the technical aspect of designing battery algorithms to optimally save energy during regenerative braking, shorter acceleration stints, and adhering to the load-following strategy is gaining importance [53].

Battery: As with all electric vehicles (AEVs), a traditional auxiliary battery (12 V) is used to start the vehicle and assist with powering the accessories of the vehicle. In the case of battery electric vehicles (BEVs), a traction battery takes over the propulsion part. In FCEVs, based on the architecture, a fuel cell-battery combination is applied.

Battery pack: During braking, the potential energy of the flywheel is restored through regenerative braking technology. A high-voltage battery bank is used to store this energy. In the case of BEVs, this can be used to power the traction battery so that it provides increased autonomy to the vehicle in AEV mode.

DC-DC converter: This semi-conductor circuit is a means to step up or step down the voltage of operation in EVs. In BEVs, the converter helps in stepping down the voltage to charge an auxiliary battery from the battery pack. In FCEVs, this converter is used to step up the voltage to charge an on-board battery for range-extended EVs (EREV).

Electric traction motor: Based on the vehicle architecture, the traction motor is coupled with a fuel cell-battery combination. These DC traction motors are often coupled with generators for regeneration purposes.

Fuel cell stack: Based on the design of the FCEV, a fuel cell stack is capable of operating at the rated voltage and power to suit the case.

Fuel filler: Hydrogen is stored in a compressed state in FCEVs. A suitable nozzle-based receptacle technology is used to connect the fuel tank with the refueling station.

Fuel tank: Stores hydrogen at the required pressure for its usage in FCEVs.

Power electronic controllers: This technology manages the powertrain configuration in FCEVs. It controls the amount of energy delivered to the traction motor to receive the desired speed-torque characteristics based on the load-following strategies used between the fuel cell-battery combination.

Thermal cooling system: The entire fuel cell-battery energy system must be thermally protected for prolonged operation and sustainable performance.

3.7. Demonstrations of FCEVs in Transportation Sector

This section compiles only some of the key historical demonstrations of FCEVs and details about the scientific and technological advancements in FCEV products.

GM electro van: In 1966, the first hydrogen-based electro van [54] was developed (32 individual stacks of 1 kW fuel cell modules each) by Craig Marks, GM, with a nominal power output of 32 kW and peak load of 160 kW. The maximum attainable speed was limited to 70 mph, with a range of 120 miles. Due to the high cost, large fuel storage space, and poor hydrogen infrastructure at that period, commercialization of the product did not happen.

Daimler-Benz NECAR: In 1994, Daimler-Benz came up with their NECAR [55], which housed a 50 kW Ballard-manufactured PEMFC system. The top speed was limited to 56 mph, with a range of 81 miles. This car also was not commercialized due to its limitation in carrying cargo because of the large hydrogen storage tanks.

Toyota FCHV: In 2002, the world's first fuel cell hybrid vehicle was available to lease in the USA and Japan [56]. It contained a 90 kW fuel cell unit coupled with a Ni-MH battery that provided a combined range of 155 miles.

Honda FCX Clarity: Launched in 2007, the vehicle housed a 100 kW fuel cell stack, with a driving range of 354 miles and top speed of 100 mph [57]. This was one of the first fuel cell electric vehicles to be produced commercially, although on a very low scale with only 200 units produced between 2008–2010. The leasing limitations were restricted to southern California and Japan.

Toyota Mirai: In 2014, Toyota launched its first commercially successful Mirai [58], a mid-size fuel cell electric vehicle that had reached a global sales volume of 21,475 units as of November 2022 [59], starting at USD 49,500. It houses a 114 kW fuel cell unit fuelled by 2 × 700 bar hydrogen storage units, with a total capacity of 122.4 L. It features a Ni-MH battery unit (224.8 V_{rated}) that takes control as per the loading requirements during peak conditions. The top speed of the vehicle is 200 mph, with a combined driving range of 360 miles.

Hyundai Nexo: In 2018, the Hyundai Nexo (FCEV) was launched with the capabilities of a high-performance air filtering unit that was able to eliminate micro-air particulates for its cathode fuel supply system as it runs. The hydrogen refueling time is restricted to less than 5 min, and the vehicle has a driving range of 372.8 miles with a top speed of 111.2 mph [60]. It houses a fuel cell unit of 95 kW capacity compressed in 700 bar units with a capacity of 156 L, a battery unit of 64 kWh for energy storage, and the cost of this automobile starts at USD 59,435 [61]. The permanent magnet synchronous motor (PM-SM) that drives the transmission unit is designed for a maximum power of 120 kW. Around 1321 units have been sold since its market inception.

3.8. Applications of Fuel Cells: Stationary Sector

Unlike the utilization of PEMFCs for transport applications, stationary fuel cell energy systems are capable of operating in a wide range of temperatures (AFC, SOFC, PAFC, and MCFC are also utilized) [62,63]. Based on their capacity, they can be classified as small to medium (10 kW–300 kW) and large (300 kW–20 MW) stationary power generation systems. The table (Table 7) below lists certain critical targets for stationary systems operated with fuel cells in accordance with Department of Energy.

Table 7. DOE targets for stationary applications.

Characteristic	Units	2020 Targets
Energy efficiency at rated power	%	>45
Combined heat and power plant efficiency	%	90
Transient response (10–90% load)	min	2
Startup time (at 20 °C)	min	20
Cost	$/kW	1500
Durability	hours	60,000

Based on the architecture and interconnection with other power systems/grid [64], they can be classified as:

Standalone: The fuel cell unit is used as the predominant power source and a battery bank is used to supplement peak needs.

Grid parallel: The fuel cell unit is designed as the base power supply for the consumer's need. In the case of peaks, the grid will supplement these demand needs. Since these systems (fuel cell unit and grid) do not communicate with each other directly, interconnection standards are not required.

Grid interconnected: Interconnection standards become part of these systems, wherein the fuel cell unit will export excess power to the grid at times of lower demand. The fuel cell unit is designed to produce constant power and the grid is used to supplement peaks.

3.9. Ballard's Technological Products (Fuel Cell Market and Products)

Ballard has been developing fuel cell systems since the technology's inception. Ballard's main offerings can be divided into four categories: stationary power systems, fuel cell stacks, marine systems, and heavy-duty modules. These classifications, albeit relevant to many industries, are inspired by the basic fuel cell stack advancements attained by Ballard in its 40 years of research and development. In the domain of stationary power generation and backup applications, Ballard connects its fuel cell stack to power modules and solutions such as H2PM, Wave, and Clear Gen II as tabulated (Table 8), thus providing more flexible, modular, and dependable power for cutting-edge systems. Finding a location that can deliver hydrogen on a sustainable basis is an important consideration when buying or investing in these stationary power systems. These fuel cell modules take up less area on the floor than other renewable technologies, such as solar panels or wind turbines, which is a basic characteristic of these renewable systems [65–68].

Table 8. Commercial stationary fuel cell power modules of Ballard Inc.

Name of the Product	Sector	Power	Benefit (s)	Reference
FCGen H2PM	Backup power	1 kW–60 kW	Minimal degradation	[66]
FC Wave	Power generation and backup power	200 kW–1.2 MW	>25,000 operating hours and 5.5 sq.m floor space	[67]
Clear Gen II	Peak power for grid conditioning	1 MW to multiple MWs	Certified as per EU and CSA standards & 40′ ISO container (<40,000 kg)	[68]

Fuel cell stacks from Ballard are equipped with air-cooled and liquid-cooled technologies that employ clever cooling algorithms as tabulated (Table 9) to control the thermal effects on fuel cell operation. Ballard's unique membrane electrode assembly (MEA), which has been standardized across all of its products and can be changed depending on the application, is a single component. The automated manufacturing of these units allows them to keep costs down and production running continuously, as evidenced by the fact that they have deployed more than 670 MW of goods as a fuel cell producer.

Table 9. Commercial fuel cell stack units of Ballard Inc.

Name of the Product	Type of Cooling	Sector	Power	Benefits	Applications	Reference
FCgen-1020 ACS	Air	Backup power, Material Handling Equipment	400 W–3.3 kW	Open-cathode stack, self-humidifying MEA	FC Gen-H2PM, electric lift	[69]
FCgen HPS	Liquid	Motive power	Up to 140 kW	Can operate well in hot and freezing environments	Developed for Audi AG	[70]
FCgen LCS	Liquid	Motive power	2.3 kW–63.4 kW	Optimized cost, performance and reliability in automotive standards	Heavy-duty motive module FCmove	[71]
FCvelocity-9SSL	Liquid	Motive power	4 kW–21 kW	Establishes new standard of performance based on customer requirements	Integrated for transit in buses and rails	[72]

4. Technical Challenges and Market Drivers of Fuel Cell Energy Systems

4.1. Opportunities

In the automotive industry, globally acclaimed automakers are planning to ramp up their production of green mobility solutions. For example, the business activities and product portfolios of Hyundai in 2022 reflected that the firm is routing towards hydrogen-based energy technologies through its sophisticated and robust 90 kW fuel cell stacks for heavy-duty applications [73]. Other similar automakers, such as Daimler, Toyota, BMW, and Tata Motors, are supposedly investing in the design and development of fuel cell transportation systems. As another example, Tata Motors in India as tabulated (Table 10) is showing a clear inclination towards its fuel cell electric bus development to boost the green hydrogen utilization of the nation.

Table 10. List of vehicles/concepts revealed at Auto Expo 2023 related to hydrogen and fuel cells by Tata Motors [74].

Serial Number	Name of the Vehicle/Concept	Powertrain and Application	Vehicle/Concept
1	Star bus fuel cell EV	India's first fuel cell hydrogen bus	Vehicle
2	Prima E.55S	India's first fuel cell hydrogen powered tractor	Concept
3	Prima H.55S	India's first hydrogen ICE powered truck	Concept

4.2. Fuel Economy and Long Travel Range

According to DOE testing results, a gasoline engine is less than 20% efficient in converting the chemical energy of gasoline into propulsive power in a conventional engine. This corresponds to 50% less fuel consumption of hydrogen for the same amount of energy. The cost of the generation of hydrogen in the near future is expected to drop with developments in hydrogen infrastructure [75]. The nominal driving range of present day FCEVs ranges between 300–700 km (240–435 miles), which is comparable to vehicles with conventional engines and better than BEVs. These factors will eventually drive the accelerated growth of the FCEV market.

4.3. Threats

The aspects of hydrogen production, including its sustainability, storage, safety, and high cost of investment, are some of the obstacles in the development of hydrogen infrastructure. This infrastructure must be digitally equipped with systems that optimally govern hydrogen generation, storage, and distribution mechanisms for safer operation. This poses a serious threat for the market of FCEVs in developed as well as emerging economies [76].

4.4. Segmentation

Based on the power output from fuel cells, the sector is categorized as 150 kW applications, 150–250 kW applications, and more than 250 kW applications. Almost all of the FCEV applications demonstrated in the market belong to the less than 150 kW criteria. This block has dominated the fuel cell market until 2022 and will continue to do so in the near future. The more than 250 kW segment corresponds to long-haul heavy-duty buses and trucks, which is one of the fastest growing utility sectors in the fuel cell market [77]. As an example, Hyundai declared a milestone achievement in its premium heavy-duty fuel cell vehicle, the Xcient 6×8, after surpassing 5 million kilometers by 47 units deployed in Switzerland in October 2022 [78]. This truck has a 350 kW motor with a torque of 2237 Nm and driving range of 400 km on a single charge. The vehicle has two 90 kW fuel cell stacks and is dependable and robust for client operations. The vehicle has three sets of 72 kWh batteries for assistance and seven big hydrogen tanks with a combined capacity of 31 kg. The 150–250 kW segment constitutes medium-sized utility vehicles for transit applications. Based on the demand for these systems in the near future, growth is predicted.

4.5. Market Generation for Local Components and Analysis

As previously mentioned, the commercialization of hydrogen-based technologies and fuel cell products occurs side-by-side, thus the components that constitute the systems for both hydrogen and fuel cell technologies are in demand. For example, nearly 60% of the total cost of FCEVs is attributed to the fuel cell energy system itself [79]. Batteries constitute the second greatest share in the market. The auxiliary battery and supplementary battery pack are essential components of FCEVs and the demand for these batteries is correspondingly increasing with FCEV market growth. Other significant increases in the market for hydrogen storage tanks, drive systems (power electronic solutions), electric motors, and power controller units are also expected with growth in the fuel cell market. Robert Bosch GmbH is considered to be one of the critical players in the development of auto-components associated with valves, regulators, fuel cell electric drives [80], and technologies associated with fuel cell power trains and their realization. The recent official statements from the firm confirmed their interests in hydrogen generation and utilization in addition to component- and system-level development.

4.6. Global Fuel Cell Shipments

It is evident that there has been a net rise in nominal power generation from individual fuel cell units over the past five years, observable by the growth in fuel cell shipments from 75,000 to 130,000 units per year as listed (Table 11) and the accompanying power transition from 1 to 2.3 GW. The saturation in the sheer volume of fuel cell shipments during the years 2019–2020 can be attributed to the strict norms followed by nations as part of COVID 19 protocols. The two-fold increase in shipments in 2021 is a clear indication of national interests in fuel cell-based technologies [81]. The transportation sector accounts for around 90% of these fuel cell shipments, followed by the stationary power generation sector.

Table 11. Worldwide shipment of fuel cell units.

Year	Fuel Cell Units Shipped	Total Power of Corresponding Units
2016	62,000	500 MW
2017	70,000+	670 MW
2018	68,000	800 MW
2019	70,000	1.1 + GW
2020	75,000	1 GW
2021	130,000+	2.3 GW

4.7. Commitment and Deployment Status

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), a consortium that currently has 22 member nations as is listed (Table 12), is working to expedite the adoption of hydrogen and fuel cell technology across a range of industries and uses. Reports from the IPHE [82] confirm that more than 19,000 FCEVs are currently in operation in South Korea and more than 13,000 FCEVs are in operation in the USA as of 2022 (Table 12). The numbers are expected to increase as other major economies, such as China, Japan, and India, are investing in the development of hydrogen infrastructure and FCEV adoption.

4.8. Hydrogen Policies and Roadmaps towards Commercialization

Certain major economies, such as Japan and the USA, are taken into consideration in this section. On some level, there is a consensus amongst these nations in implementing the hydrogen economy. However, this depends on the individual aspirations and funding opportunities in these nations towards hydrogen-specific areas.

4.8.1. Japan

In the strategic energy plan of 2014, hydrogen was given a boost to play a central role in Japan’s energy supply [83,84]. The plan discussed the potential of the hydrogen economy to create sustainable, cost-efficient technologies and improved energy security for the nation since about 1/5th of the energy requirement for transport was imported from oil-turbulent economies. This shift in hydrogen import would reduce the stress on fuel prices and the economy. By 2050, the market for the hydrogen economy is expected to reach JPY 8 trillion, as more patents are being filed for hydrogen-based technologies around the world. Another policy of concern is the cross-ministerial strategic innovation promotion program, which aims to promote the development of hydrogen production technologies, including CCU-based units. Japan aims to introduce 5.3 million fuel cell units across the domestic market by 2030. The strategic roadmap for hydrogen and fuel cells for Japan was developed in 2014, defining three phases towards hydrogen economy realization:

Phase 1 (2015-): Hydrogen popularization and utilization (stationary and FCV market)

Phase 2 (2025-): Hydrogen supply and implementation of hydrogen for unused energy sectors

Phase 3 (2040-): Realization of CO_2-free hydrogen generation systems

Japan's main target in the hydrogen technology roadmap includes the capability of producing domestic fuel cells by 2021 and to sell 200 thousand units of FCEVs in the market by 2025.

4.8.2. The USA

Hydrogen investment and talks about promoting the hydrogen economy in the USA began in the early 2000s. The workshop organized by the US Department of Energy (DOE) in 2002 stressed the sustainability of hydrogen as a fuel for domestic and industrial applications. Some of the implications of promoting these hydrogen policies are expected to reduce gasoline consumption to less than 40% by 2035. The technological changeover would also lead to potential employment opportunities and a study indicated a creation of 675,000 jobs related to this field by 2050. Nevertheless, the challenges due to cost pose a serious impedance to transitioning the economy. Stationary fuel cells cost around 3000–7000 USD/kW, which is relatively higher than conventional power plants. On the other hand, automotive fuel cells cost around 49 USD/kW, which is still higher than 30 USD/kW for conventional IC engine technology. With respect to durability aspects too, the practical durability of fuel cells in stationary and automotive applications are limited to 20,000 and 2500 h against targets of 40,000–80,000 and 5000 h, correspondingly.

The US DOE is revising its strategies to improve the targets [85–87]. For example, the cost of fuel cells in automotive applications was set to a new target of 30 USD/kW in 2017, whereas the hydrogen production and delivery costs were set to a target of 2–4 USD/gge (gallon gasoline equivalent) by 2020 against the 4–6 USD/gge mark set in 2011. One of the critical aspects in promoting the hydrogen economy is federal support and funding. Funds are provided for high-impact R&D related to this field, which includes non-Pt based catalyst development, hydrogen storage, renewable hydrogen generation, and liquid-based fuel cell technologies.

Table 12. Fuel cell unit deployment status in partnership with IPHE.

Partner Nation	Status	Trucks	Buses	Forklifts	Cars	Refueling Stations	Electrolyzers	Stationary Systems
Australia	Current	-	-	1	197	5	-	-
	Target	-	-	-	-	-	30,000 MW by 2030	-
	Current	5	25	-	60	8	10 MW	9 MW
	Target	-	-	-	-	-	1 GW by 2030	-
Brazil	Current	-	1 FCH bus	-	-	1	-	-
	Target	-	-	-	-	-	48 kW	-
Canada	Current	-	1	>400	17	9	-	-
	Target	2	500 (ZEV)	-	-	33 by 2026	-	1 unit *
Chile	Current	-	-	-	-	-	1 MW	-
	Target	-	-	-	-	-	5 GW by 2025, 25 GW by 2030	-
China	Current	-	-	2	9287 (cars, trucks, buses)	250	-	51 units
	Target	-	-	-	50,000 by 2025	-	0.1–0.2 Mt/y by 2025	-
Costa Rica	Current	-	1	-	4	-	~100 kW	-
	Target	10	1	-	10	1	1 MW by 2024	-
European Commission	Current	32	270	335	1325	193	37.6 MW	3015 units
	Target	150 in 2023	71	1	426	82	34.9 MW	1222 units
France	Current	1	33	322	589	50	13 MW	149 units
	Target	-	200	-	5000	100	6.5 GW by 2030	-
Germany	Current	20	70	128	1528	103	58 MW	19,805 units
	Target	-	-	-	-	400 by 2025	10 GW by 2030	-
Iceland	Current	-	-	-	22	-	-	-
	Target	-	-	-	-	-	-	-
India	Current	-	58	-	-	2	-	-
	Target	-	-	-	-	-	-	-
Italy	Current	-	20	-	35	4	-	41 units
	Target	-	1000 by 2025	-	25,000 by 2025	-	-	-
Japan	Current	-	120	397	7106	184	-	422,274 units
	Target	-	-	-	200,000 by 2025	320	-	-

Table 12. *Cont.*

Partner Nation	Status	Trucks	Buses	Forklifts	Cars	Refueling Stations	Electrolyzers	Stationary Systems
Republic of Korea	Current	-	129	-	19,270	170	-	767 MW
	Target	30,000 by 2040	40,000 by 2040	-	5.26 Mil by 2050	2000+ by 2050	-	22.1 TWh in 2030
Netherlands	Current	29	41	0	491	7	4 MW	-
	Target	3500 by 2025	300 by 2025	-	15,000 by 2025	50 by 2025	500 MW by 2025	-
Norway	Current	4	-	-	201	6	-	-
	Target	-	-	-	-	-	-	-
Republic of South Africa	Current	0	0	2	0	2	-	311 units
	Target	-	500 buses and trucks	20 by 2025	-	-	-	-
Switzerland	Current	47	-	1	180	6	-	15 units
	Target	-	-	-	-	-	-	-
United Arab Emirates	Current	No information, they joined the consortium in 2022–23, the steering committee meeting in 2023–24 will add this data.						
	Target							
United Kingdom	Current	36	58	-	353	26	-	-
	Target	-	-	-	-	-	-	-
United States of America	Current	5	70	>50,000	>13,000	50	172 MW	>550 MW
	Target	-	-	-	1,00,000 (CA)	1000 (CA)	-	-

* unit (s) are used for data as per the commitment of respective nations of their interest.

5. Conclusions

As more businesses enter this prospective market and established businesses in this sphere of interest form subsidiaries, it is clear that investment in fuel cells and hydrogen is increasing. This investment benefits both the fuel cell industry and sectors concerned with reducing greenhouse gas emissions. As seen in this assessment, the fuel cell market continues to expand, with power production rising to 2.3 GW with its deployment alone. The technology has expanded to include medium- and heavy-duty vehicles and semi-trailers in addition to fuel cell electric cars. Hydrogen fuel usage in the marine industry is also currently being considered. This article thus gives an overview of the present energy scenario and discusses the need for the transition to a sustainable energy supply system for the future. It is clear that this transition from conventional fossil fuel technology towards a sustainable economy is inevitable. This review further discussed certain technical aspects concerned with hydrogen production, storage, and utilization. Although electrolysis is a zero emission technology, the present infrastructure and economy is viable only for SMR-based technologies in hydrogen production.

This article especially deliberated the evolution of the market and fuel cell products in the transportation and stationary sector. FCEVs are becoming comparable with ICEs and have superior performance and fuel economy. The market for BEVs is affected by the aspects of sustainability, shorter driving range, and prolonged charging times. Certain commitments and commercialization strategies towards this transition are also explained in the paper. The costs of fuel cell components and operational behaviors are the governing factors that influence the market for these systems. Techno-economic business strategies to improve the dynamic behavior of fuel cell energy systems and safer hydrogen fuel generation, storage, and transport will be the future adaptations in these industry, with the potential to revolutionize energy-related businesses.

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