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Green energy from hydrogen

Năng lượng xanh từ hydro

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Abstract

Green energy is an important tool for reducing pollution on the planet and significantly contributing to the struggle against climate change. The paper focused on the following issues: the way to produce renewable energy, the method of transferring renewable energy into clean fuel such as hydrogen, how to increase the efficiency of this process, and the application of hydrogen and hydrogen fuel cell. On the other side, the disadvantages of the hydrogen engine are also analyzed along with the solution for the near future. Anyway the study aims to provide a holistic perspective on the potential role of Hydrogen Fuel Cell Vehicles (HFCVs) in achieving sustainable and efficient transportation systems in the future.

Keywords: green energy; pollution; climate change; efficiency; hydrogen.

Tóm tắt

Năng lượng xanh là một công cụ quan trọng để giảm ô nhiễm trên hành tinh và góp phần đáng kể vào cuộc chiến chống biến đổi khí hậu. Bài viết tập trung vào các vấn đề sau: cách thức sản xuất năng lượng tái tạo, phương pháp chuyển năng lượng tái tạo thành nhiên liệu sạch dưới dạng hydro, làm thế nào để tăng hiệu quả của quá trình này và ứng dụng của hydro và pin nhiên liệu hydro. Mặt khác, những nhược điểm của động cơ hydro cũng được phân tích cùng với giải pháp trong tương lai gần. Mặc dù vậy, nghiên cứu nhằm mục đích cung cấp một cái nhìn toàn diện về vai trò tiềm năng của xe pin nhiên liệu hydro (HFCV) trong việc đạt được các hệ thống giao thông bền vững và hiệu quả trong tương lai.

Từ khóa: năng lượng xanh; ô nhiễm; biến đổi khí hậu; hiệu quả; hydro.

1. Introduction

One of the biggest challenges the world is facing is to find suitable, sustainable and clean replacements for fossil fuels. Fossil fuels are ultimately unsustainable, and depending on them as the main power source leads to serious environmental issues such as pollution and climate change, along with economic and political issues related to the economy, security, and the political problems affecting the

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exporting countries. On the other hand, the use of renewable energy is already growing.

The results of the study found that there is a long-run relationship and there is a causality between these variables, indicating that renewable energy consumption, output, and export are related to CO_2 emissions. Specifically, from a long-term perspective, the results of co-integration and causality reveal that there is a two-way causal relationship between renewable energy consumption, output, export, and CO_2 emissions, supporting the feedback hypothesis; that is, output and export have an adverse impact on the environment, while renewable energy consumption has a favorable impact on the environment. In the short term, there is a direct or indirect one-way causal relationship between export, CO_2 emissions, and renewable energy consumption, which supports the growth hypothesis. The impulse response analysis validated the causality test results and supported the hypothesis. However, there is a substantial negative connection between industrial and agricultural exports and renewable energy consumption, implying that renewable energy will fail to supply peak industrial and agricultural export demand in the immediate term. In contrast, significant volumes of fossil fuels will be used to fulfill output and export demand. Therefore, on the road to social, economic, and environmental sustainability, it is vital to evaluate the influence of economic growth and energy use (both renewable and non-renewable energy).

Hydrogen is known to be the cleanest fuel due to its zero emission capability. It’s inherently immense energy content makes it the fuel for future but, it’s economical, safe and efficient usage for power generation remains a challenge.

Hydrogen energy is a flexible and clean energy source that has received a lot of attention as a possible answer to climate change and the transition to a more sustainable energy future [1]. It has the potential to transform a variety of industries, including transportation, energy generation, and manufacturing processes. Hydrogen is the most plentiful element in the universe, however it is mostly found in conjunction with other elements, such as oxygen in water (H_2O) and carbon in hydrocarbons [2]. To use hydrogen as an energy source, it must be harvested and transformed into useable form. There are several ways for producing hydrogen, including steam methane reforming, electrolysis of water, biomass gasification, and others [3]. Each approach has its benefits and considerations for efficiency, cost, and environmental effect. One of the primary benefits of hydrogen energy is its environmental impact; when used as a fuel, hydrogen only emits water vapor as a byproduct, making it a zero-emission energy source [4]. This is especially relevant in industries like transportation, where hydrogen fuel cells may be used to power electric vehicles with extensive driving ranges and quick refilling. Furthermore, hydrogen energy has the potential to help with renewable energy integration and energy storage [5]. Renewable energy sources like sun and wind are intermittent, and their output does not always match energy demand. Electrolysis of water can be used to make hydrogen during periods of surplus renewable energy output and store it for later use. It may be used to generate electricity when renewable energy supply is low, thus providing a reliable and dispatch able energy option. Hydrogen energy has emerged as a worldwide destination for a variety of industries owing to its ability to handle numerous energy concerns and contribute to a more sustainable future. Figure 1 depicts global hydrogen production (2010–2022).

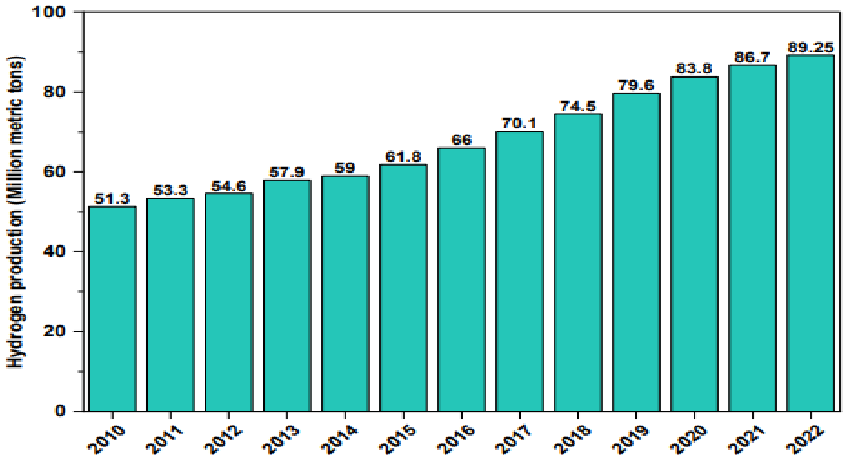

Figure 1. The global hydrogen production (2010–2022) [6,7]

The global demand for hydrogen energy is fueled by its adaptability, potential for decarbonization, and involvement in addressing a variety of energy issues. With increased expenditures, supporting regulations, and technical developments, hydrogen energy is gaining traction in a variety of industries throughout the world, contributing to a sustainable and low-carbon future.

2. Hydrogen types

Hydrogen energy may be classified into several forms based on its manufacturing techniques and applications. The following are the primary forms of hydrogen energy:

- Gray hydrogen is hydrogen created from fossil fuels like natural gas or coal using a method called steam methane reforming (SMR). It is the most popular way of producing hydrogen nowadays [8,9]. However, gray hydrogen generation emits carbon dioxide (CO_2), which contributes to climate change.

- Blue hydrogen is made from fossil fuels, much like gray hydrogen, but with an extra step called carbon capture and storage (CCS). The CCS process includes trapping and storing CO_2 generated during hydrogen synthesis underground, keeping it from exiting the atmosphere [10]. Blue hydrogen strives to lower the carbon impact of hydrogen generation.

- Green hydrogen is created by electrolysis of water, a method that uses renewable energy sources such as solar or wind power. Electrolysis is the process of employing an electric current to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) using an electric current [11,12]. Green hydrogen production has no direct carbon emissions because it is based on renewable energy, making it a clean and sustainable solution.

- Turquoise hydrogen, also known as low-carbon or decarbonized hydrogen, is made from natural gas but has carbon emissions offset by collecting and storing CO_2, similar to blue hydrogen. The difference is that turquoise hydrogen production often uses a different sort of methane reforming process known as methane pyrolysis, which can assist reduce the carbon intensity of hydrogen synthesis [13].

- Brown hydrogen is created from coal by gasification or other techniques. It is regarded as the most carbon-intensive technique of hydrogen generation because it entails extracting hydrogen from coal, a high-carbon fossil fuel [14, 15].

- Purple hydrogen is derived from nuclear energy sources, notably high-temperature electrolysis (HTE). This approach uses heat from nuclear reactors to drive the electrolysis process, allowing hydrogen to be produced with no direct carbon emissions [16].

Green hydrogen is considered the most ecologically beneficial and sustainable alternative among these sorts since it uses renewable energy sources. Blue and turquoise hydrogen, combined with carbon capture and storage, can assist minimize the carbon footprint of hydrogen generation. Figure 2 depicts global hydrogen production (2010–2022).

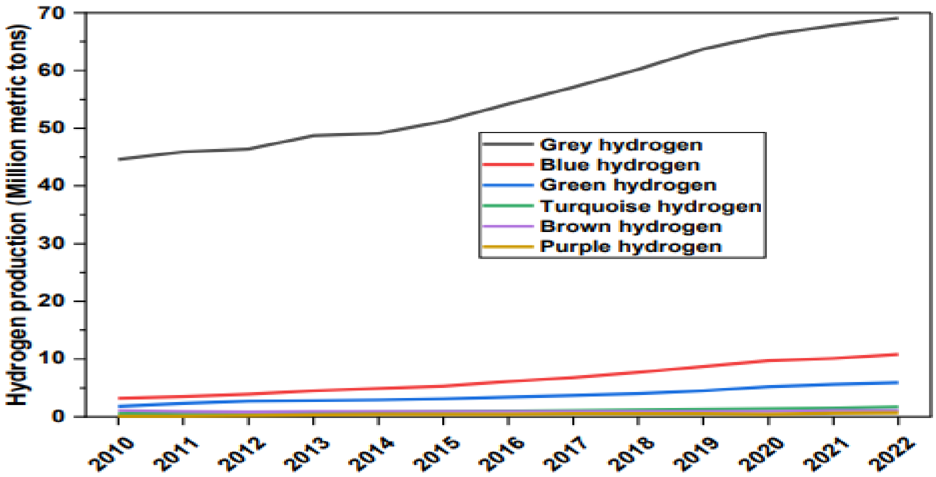

Figure 2. The global hydrogen production by type (2010–2022) [6,7]

3. Hydrogen production methods

Hydrogen generation is a critical component in developing a hydrogen economy. Currently, the bulk of hydrogen is created from fossil fuels, usually natural gas, using a process called SMR. SMR is a high-temperature reaction between methane (CH_4) and steam (H_2O) with a catalyst [17]. The process yields hydrogen gas (H_2) and CO_2.

$$CH_4 + H_2O \rightarrow CO_2 + 3H_2 \quad (1)$$

However, producing hydrogen from fossil fuels emits greenhouse gases, undermining hydrogen's environmental benefits as a clean energy source. Efforts are being undertaken to create and scale up low-carbon and renewable hydrogen manufacturing systems.

-The process of splitting water (H_2O) into hydrogen and oxygen using electricity is known as electrolysis. It takes an electric current to travel through water, which is normally accomplished using electrodes and an electrolyte [18]. The electrolysis reaction goes as follows:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (2)$$

Electrolysis is classified into two types: alkaline and proton exchange membrane (PEM). Alkaline electrolysis utilizes an alkaline electrolyte solution, whereas PEM electrolysis use a solid polymer membrane as the electrolyte [19]. Electrolysis may be driven by sustainable energy sources like solar or wind power, producing renewable hydrogen.

- Biomass gasification is the process of heating organic materials like wood chips or agricultural waste in a controlled atmosphere with little oxygen. The process generates a combination of gases, including hydrogen, carbon monoxide (CO), and methane (CH_4). Hydrogen may be isolated from the gas mixture using a variety of purification procedures [20].

$$C_xH_yO_z + Heat \rightarrow CO + H_2 + CH_4 + Other\ Gases \quad (3)$$

Biomass gasification has the benefit of using organic waste materials and can help to achieve a circular economy by decreasing waste and providing renewable hydrogen.

- Photoelectrochemical water splitting (PEC) is a technique that employs sunlight to divide water molecules into hydrogen and oxygen. A photoelectrochemical cell or photoelectrolysis system employs a semiconductor material as a photoelectrode. When sunlight contacts the photoelectrode, it creates an electric current, which powers the water splitting process [21,22].

$$2H_2O + \text{Energy (sunlight)} \rightarrow 2H_2 + O_2 \quad (4)$$

PEC water splitting has the potential to be a direct and efficient way of producing renewable hydrogen; nevertheless, it is still in research and faces hurdles like as enhancing photoelectrode efficiency and lowering production costs. In the context of HFCVs, PEC water splitting, or PEC hydrogen generation, is very important. This technology uses sunlight to break water molecules into hydrogen and oxygen, offering a clean and renewable method of producing hydrogen for HFCVs. The problem is to discover a suitable semiconductor material that can absorb a considerable amount of the solar spectrum, provide a sufficiently high photovoltage to drive the water splitting events, and stay stable under the operational circumstances.

Many researchers are presently working to develop efficient and cost-effective materials and designs for PEC cells. In terms of HFCVs, PEC hydrogen generation might provide a sustainable and carbon-neutral source of hydrogen fuel. To be feasible on a broad scale, PEC procedures must improve significantly in terms of efficiency and scalability. As stated in the article, technological developments in this area might help overcome one of the primary difficulties confronting HFCVs: the sustainability and environmental footprint of hydrogen generation.

- Thermochemical methods employ heat to create hydrogen through different chemical reactions. One example is the sulfur-iodine (S-I) thermochemical cycle, which involves a sequence of chemical processes that use sulfur and iodine molecules to create hydrogen [23]. These procedures are usually complicated, necessitating high temperatures and specific materials.

- Biological processes use microorganisms or enzymes to create hydrogen via biological reactions. For example, some microorganisms may produce hydrogen via fermentation or photosynthesis. Biological processes have the potential to generate sustainable hydrogen, but further study is needed to improve their efficiency and scalability [24].

4. Hydrogen fuel cell vehicles

The International Hydrogen Council predicts that the use of hydrogen energy will cut worldwide carbon dioxide emissions by roughly 6 billion tons by 2050. As a result, hydrogen energy is widely expected to become a critical node in the future energy system, contributing significantly to global energy transformation and boosting energy system flexibility. Hydrogen fuel cells provide several benefits, including great energy efficiency, minimal emissions, a wide range of energy sources, quick recharging, and exceptional low-temperature adaptation [25]. The hydrogen fuel cell, an electrochemical cell that generates electricity from the chemical energy of hydrogen, lies at the heart of much of this shift. In a hydrogen fuel cell, hydrogen molecules are separated into positively charged protons (blue) and negatively charged electrons (yellow). Protons move via an electrolyte membrane, but electrons must go through an external circuit to produce electricity. Ultimately, the protons, electrons, and oxygen molecules unite to form water.

Several nations throughout the world are actively pushing and implementing hydrogen fuel cell vehicles as part of their efforts to minimize greenhouse gas emissions and move to clean transportation. The following nations have been at the forefront of the use of hydrogen fuel cell cars:

Japan has been a pioneer in hydrogen fuel cell technology, with considerable expenditures in infrastructure and vehicle deployment. The nation has promoted HFCVs through a variety of programs and partnerships with automakers. Toyota Mirai, Honda Clarity Fuel Cell, and other vehicles are available in Japan, and the country is extending its hydrogen filling station network [26].

The Republic of Korea has actively promoted hydrogen as an alternative fuel for transportation. The government aims to have 6.2 million hydrogen vehicles on the road by 2040. Hyundai, a Republic of Korea carmaker, has been at the forefront of fuel cell vehicle development, notably the Hyundai NEXO. The government has invested in hydrogen infrastructure, such as refueling stations [27].

Germany has been attempting to promote HFCVs as part of its transition to sustainable energy and decrease reliance on fossil fuels. The German government has provided financial incentives to encourage the purchase of fuel-cell automobiles. Companies such as BMW and Audi have created hydrogen-powered concept automobiles, and efforts are underway to increase hydrogen refueling infrastructure [28,29].

The United States is making headway in the adoption of HFCVs. California, in particular, has been a leader in promoting HFCVs, with multiple hydrogen recharging stations located around the state. In some markets, automakers such as Toyota, Honda, and Hyundai sell fuel cell vehicles. The federal and state governments in the United States have offered incentives to encourage the use of fuel-cell cars [30].

China has invested considerably in hydrogen energy and fuel cell technologies. The government intends to become a worldwide hydrogen leader, with a goal of having over one million HFCVs on the road by 2030 [31,32]. Chinese manufacturers, like BYD and Geely, have been developing and producing HFCVs, while the government has encouraged the installation of hydrogen recharging stations [33,34].

Other nations, notably France, the United Kingdom, Canada, and Norway, have also expressed interest and made efforts to encourage the use of HFCVs, albeit the extent of deployment varies [35].

The development and use of hydrogen fuel cell vehicles (HFCVs) are part of a larger worldwide movement to shift to sustainable and low-carbon transportation options. Figure 3 depicts the percentage of used HFCVs among all cars in each nation in 2021.

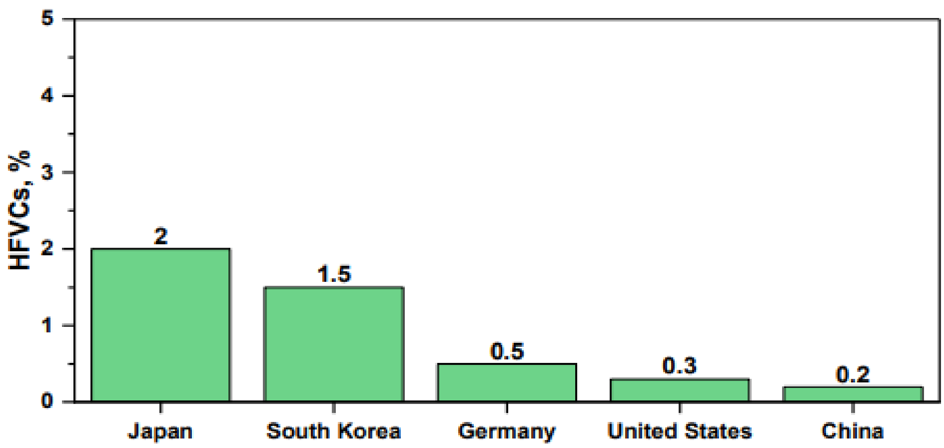

Figure 3. The percentage of used HFCVs to the total number of vehicles for the year 2021 [36,37]

Because the price is quite high and not suitable in the lack of supporting infrastructure, fuel cells are not widely used in Vietnam. However, researchers still believe that this is an inexhaustible, renewable energy source that plays a leading role in replacing fossil fuels, not polluting the environment. Many research topics on fuel cells from research institutes and universities initially had positive results. These include the research and development of proton exchange membrane fuel cells (PEMFC) using H_2 fuel of the Institute of Materials Science (Vietnam Academy of Science and Technology) or the research project "New nanostructured catalysts for efficient fuel cell production, cost savings and green H_2 energy production" by Assoc. Prof. Dr. Ho Thi Thanh Van (Head of Science Technology and External Relations Department, HCMC University of Natural Resources and Environment) HCM). Works by Assoc. Prof. Dr. Ho Thi Thanh Van is synthesizing Pt-Mo alloy nanocatalyst on Ti0, 8W0, 202 nanomaterials to improve CO toxicity and reduce costs for fuel cells using methanol directly. As is known, in conventional fuel cells, the composition includes H_2 gas, methanol, ethanol, oxidants, and two electrodes made of platinum (Pt) and graphite (Pb). Using platinum pushes up fuel cell costs, while graphite is less durable and toxic to the environment. Therefore, Assoc. Prof. Dr. Ho Thi Thanh Van and her colleagues have researched and developed new materials, both improving CO tolerance and replacing 25% of platinum for products. Practical testing shows that the new material improves the performance of the alloy compared to pure platinum, improving the activity and operation time of platinum electrochemical catalysis. The platinum replacement also reduces manufacturing costs, improves operability and increases fuel cell durability. Successful research into this new nanomaterial opens up opportunities and practical benefits in the widespread use of fuel cells, replacing fossil fuels and reducing global warming due to greenhouse gas emissions.

5. Hydrogen fuel cell application

The fuel cell, an energy conversion device capable of effectively capturing and using the power of hydrogen, is critical to making this happen.

- Stationary fuel cells can be used to provide backup power, power to remote places, distributed power generation, and cogeneration.

- Fuel cells can power practically any portable application that traditionally requires batteries, including hand-held electronics and portable generators.

- Fuel cells may also power passenger automobiles, trucks, buses, and marine vessels, as well as supplement existing transportation systems. Hydrogen can play a particularly major role in the future, replacing the imported petroleum presently used in our automobiles and trucks.

Fuel cells convert hydrogen's chemical energy straight to electricity, producing only clean water and possibly valuable heat as byproducts. Hydrogen-powered fuel cells produce no emissions and can be two to three times more efficient than standard combustion systems

- A normal combustion-based power plant generates electricity at 33 to 35 percent efficiency, but fuel cell systems may generate energy at up to 60 percent efficiency (and even higher with cogeneration).

- Under normal driving conditions, a conventional car's gasoline engine converts less than 20% of the chemical energy in gasoline into power that propels the vehicle. Hydrogen fuel cell cars, which employ electric motors, are far more energy efficient, using 40-60% of the fuel's energy, resulting in a more than 50% reduction in fuel usage when compared to a traditional vehicle with a gasoline internal combustion engine.

Furthermore, fuel cells work silently, have fewer moving parts, and are suitable for a wide range of applications.

In general, all fuel cells have the same fundamental structure: an electrolyte with two electrodes. However, there are several varieties of fuel cells, distinguished chiefly by the type of electrolyte utilized. The electrolyte dictates the type of chemical processes that occur in the fuel cell, the temperature ranges at which it can operate, and other criteria that define its most appropriate uses (see Table 1).

Table 1. Specification and application of different types of fuel cell

Fuel Cell Type	Operating Temperature	System Output	Efficiency	Applications
Alkaline (AFC)	90–100°C 194–212°F	10kW–100kW	60–70% electric	• Military • Space
Phosphoric Acid (PAFC)	150–200°C 302–392°F	50kW–1MW (250kW module typical)	80–85% overall with combined heat and power (CHP) (36–42% electric)	• Distributed generation
Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM)*	50–100°C 122–212°F	<250kW	50–60% electric	• Back-up power • Portable power • Small distributed generation • Transportation
Molten Carbonate (MCFC)	600–700°C 1112–1292°F	<1MW (250kW module typical)	85% overall with CHP (60% electric)	• Electric utility • Large distributed generation
Solid Oxide (SOFC)	650–1000°C 1202–1832°F	5kW–3 MW	85% overall with CHP (60% electric)	• Auxiliary power • Electric utility • Large distributed generation

Source: Argonne National Laboratory

Aside from the many benefits of hydrogen fuel cells, there are several limitations in their optimal use. The two most critical barriers to fuel cell commercialization are cost reduction and durability improvements. Fuel cell systems must be cost-competitive with existing power technologies while also performing as well as or better during their lifetime. Ongoing research aims to find and develop novel materials that will lower the cost and prolong the life of fuel cell stack components including as membranes, catalysts, bipolar plates, and membrane-electrode assemblies. Low-cost, high-volume manufacturing procedures will also contribute to making fuel cell systems cost competitive with older technologies.

A single fuel cell is made up of an electrolyte sandwiched between two electrodes: an anode and a cathode. Bipolar plates on either side of the cell help to disperse gasses and act as current collectors. In a Polymer Electrolyte Membrane (PEM) fuel cell, which is commonly regarded as the most promising for light-duty transportation, hydrogen gas travels via channels to the anode, where a catalyst splits the hydrogen molecules into protons and electrons. The membrane only permits protons to travel through it. While the protons are transmitted through the membrane to the other side of the cell, the stream of negatively charged electrons follows an external connection to the cathode.

This flow of electrons is electricity, which may be utilized to perform tasks such as powering a motor. On the other side of the cell, oxygen gas, usually obtained from the outside air, travels via channels to the cathode. When electrons return after accomplishing work, they combine with oxygen and hydrogen protons (which have passed through the membrane) at the cathode to generate water. This union is an exothermic reaction, which produces heat that may be used outside the fuel cell. A fuel cell's power output is determined by a number of criteria, including its kind, size, operating temperature, and gas supply pressure.

A single fuel cell (Fig. 4) generates around 1 volt or less of electricity, which is insufficient for even the simplest applications. To generate more power, separate fuel cells are connected in sequence to form a stack. (The phrase "fuel cell" is commonly used to refer to both the entire stack and the individual cell.) Depending on the application, a fuel cell stack might consist of a few or hundreds of individual cells placed together. This "scalability" makes fuel cells suitable for a broad range of applications, including laptop computers (50-100 Watts), residences (1-5kW), cars (50-125 kW), and central power generating (1-200 MW or more- see Table 1).

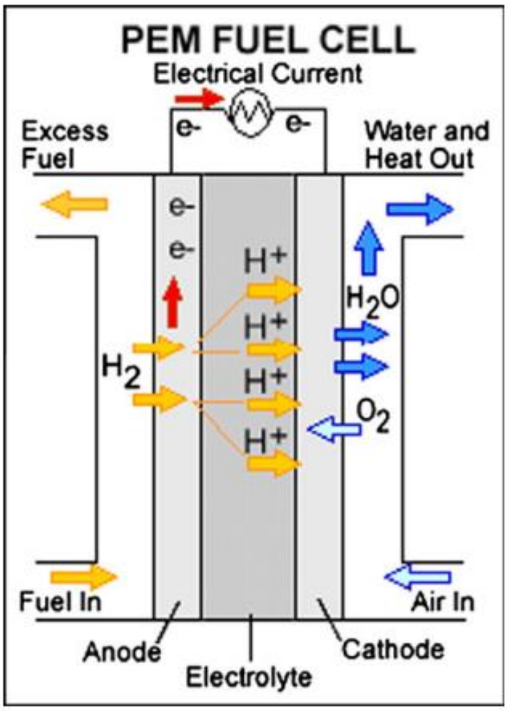

Figure 4. Schematic of a PEM fuel cell

6. Fuel cell/battery hybrid system

A pure fuel cell powertrain connects the fuel cell directly to an electric motor, which powers the vehicle's wheels. A hybrid fuel cell powertrain includes a fuel cell device and a battery or supercapacitor. The energy storage system provides additional power to the electric motor during periods of high demand, such as acceleration or hill climbing. When not in use, such as when cruising or braking, the fuel cell system replenishes the energy storage system. Both pure and hybrid fuel cell powertrains have advantages and disadvantages. Pure fuel cell powertrains are efficient and emissions-free, but they are expensive and have a limited operational range. Hybrid fuel cell powertrains provide better power and range, but are more sophisticated and may require more maintenance.

Fuel cell/battery hybrid systems have recently received a lot of interest due to their high energy density and low emissions. The online energy management system (EMS) is critical for these hybrid systems, since it controls energy flow and ensures optimal system performance, including fuel efficiency and fuel cell and battery deterioration. This study presents a unique energy management strategy for hybrid fuel cell/battery systems containing several fuel cell stacks.

Global emissions from maritime transport are now over 940 million tons of equivalent carbon dioxide (CO_2, eq), accounting for roughly 3% of total pollutant and greenhouse gas (GHG) emissions [38]. Recent forecasts indicate that global shipping emissions may grow by up to 45% by 2050 compared to 2018 levels [39]. Recently, the International Maritime Organization (IMO) and other national/international authorities imposed new and stricter limits on pollutant and GHG emissions from shipping, bringing significant technological and regulatory difficulties to the whole shipping sector.

7. Conclusion

The state-of-the-art assessment of current advancements in hydrogen fuel cell technology describes the kinds, construction, operating, and important operation factors that are critical to achieving maximum efficiency. The categorization of fuel cells based on reactants provides a diverse range of hydrogen gas sources for use in alternative power production. The role of electrolytes and charge carriers may be precisely defined based on the chemical processes of each kind of fuel cell. Because current fuel cell developments include the use of compressed hydrogen and oxygen gasses (made by energy expenditure) as reactants, they cannot be regarded a long-term answer to global power demands. The intermediary phases result in losses throughout each system, and the efficiency from energy in (when compressing the gasses) to energy out (in the form of electricity production), known as round-trip efficiency, decreases dramatically. Future advances in fuel cell research aim to build reversible cells that can function as both an electrolyser and a fuel cell, decreasing losses and therefore boosting total efficiency. Also, fuel cells have a long way to go in terms of contributing to sustainable development, and no one alternate power production method could meet the world's energy need. Renewable energy harnessing systems combined with fuel cell technology as a hybrid system might be envisioned as a viable solution to the problem. More study is needed in system integration of both renewable and fuel cell technologies in order to meet the stated objectives for energy production from alternative energy sources, which might make hydrogen fuel cell technology financially and technically viable for society.

The future of HFCVs is inextricably connected to the broader development of the hydrogen economy. As the globe shifts toward renewable and sustainable energy solutions, the hydrogen economy might play an important role in balancing energy needs, enabling energy storage, and lowering carbon emissions. Therefore, measures to promote HFCVs should be considered as part of a wider push toward a sustainable and low-carbon future.

While HFCVs bring both possibilities and problems, their potential contribution to a sustainable, low-carbon future makes them a worthwhile endeavor. Continued research and development, stakeholder engagement, supporting government regulations, and public acceptance are critical to realize the full potential of hydrogen fuel cell technology in the automobile industry. It is anticipated that with further efforts, the goal of a hydrogen society in which HFCVs are commonplace on our roadways will become a reality.

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