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Review article

Hydrogen as an energy source: A review of production technologies and challenges of fuel cell vehicles

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ABSTRACT

The significant growth of both the global population and economy in recent years has led to a rise in global energy demand. Fossil fuels have a significant contribution to generating energy, which has raised concerns about sustainability and environmental impact. There are widespread efforts to find alternative sources in order to reduce dependence on fossil fuels and mitigate their environmental consequences. Among the alternative sources, hydrogen has emerged as a promising option due to its potential to be a clean and sustainable energy source. Hydrogen possesses several advantages, such as a high calorific value, a high reaction rate, various sources, and the ability to integrate with other renewable energy sources and existing systems. These attributes render hydrogen a stable and reliable energy resource, which can help reduce greenhouse gas emissions (GHG) and transition towards a sustainable future. In this review paper, distinct hydrogen production technologies, such as conventional, renewable, and nuclear energy, are investigated and compared. In addition, the challenges and limitations of the application of hydrogen fuel cells on vehicles and hydrogen circulation components are explored. Finally, the environmental impact of hydrogen vehicles, specifically their role in promoting sustainable development, is investigated.

1. Introduction

The desire for mobility is considered to be one of the fundamental aspects of human nature. The need for mobility is steadily increasing in correlation with the expanding global population and the globalizing nature of the economy (Mori and Hirose, 2009). The world has increasingly focused on environmental concerns over the past two decades (Kovač et al., 2021). It is crucial to address the adverse consequences of transportation, including traffic congestion, environmental pollution, and strain on infrastructure resulting from heightened mobility. Vehicles have a substantial impact on energy consumption by consuming vast amounts of fossil fuels, which has led to increasing environmental concerns (Aminudin et al., 2023). To tackle these issues associated with increased mobility, such as exhaust emissions and the phenomenon of global warming, it becomes imperative to adopt a renewable and environmentally friendly methodology. This can be achieved by reducing or eliminating dependence on fossil fuels through the development of existing processes or the utilization of renewable energy sources including biomass, wind energy, hydro, solar PV, and hydrogen (Dash et al., 2023; Olabi et al., 2021). For sustainable development, reliable, safe, and environmentally friendly energy supplies are fundamental. These green energies are of utmost importance in addressing concerns related to social, political, economic, and climate change issues. The Glasgow Climate Pact was introduced to combat global warming at the 26th United Nations Climate Change Conference (UNFCCC). This agreement reaffirms the goal of limiting the escalation of global warming to a threshold of 1.5 °C. The Glasgow Climate Pact also emphasizes the urgent need for nations to mitigate greenhouse gas (GHG) emissions promptly and shift towards renewable energy sources (Change, 2021). Hydrogen has a high potential for use in several sections as an energy carrier. Hydrogen possesses the capacity to facilitate decarbonization and is abundant in the universe, consisting of 90 % of all the atoms (Okonkwo et al., 2023; Liu et al., 2021a). Despite the abundant presence of hydrogen in the universe, its elemental form is not readily accessible. Hydrogen can be derived from both conventional fossil fuel resources as well as sustainable renewable energy sources. The elemental state of hydrogen is typically derived from compounds using various chemical and electrochemical procedures (Olabi et al., 2021). In Table 1, the characteristics of hydrogen are compared to other fuels (Stępień, 2021a; Ciniviz and Köse, 2012).

Hydrogen is regarded as an alternative fuel owing to its sustainable,

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Nomenclature

AC	Alternate current
AEM	Anion exchange membrane
ALK	alkaline
CCS	Carbon capture storage
CCU	Carbon capture utilization
CFRP	Carbo fiber reinforced plastic
CI	Compression ignition
CNTs	Carbon nanotubes
DC	Direct-current
DOE	Department of energy
EGR	Exhaust gas recirculation
FC	Fuel cell
FCEB	Fuel cell electric bus
FCEV	Fuel cell electrical vehicle
FCHEV	Fuel cell hybrid electrical vehicle
FCV	Fuel cell vehicle
GHG	Greenhouse gas
HHV	Higher heating value
ICEs	Internal combustion engines
LHV	Lower heating value
MOFs	Metal organic frameworks
NGR	Natural gas reforming
OTEC	Ocean thermal energy conversion
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
Pt	Platinum
PV	Photovoltaic
PwC	PricewaterhouseCoopers
SI	Spark-ignition
SMR	Steam methane reforming
STP	Standard temperature and pressure
WGS	Water gas shift

Table 1
Comparison of hydrogen properties with other fuels (Stępień, 2021a; Ciniviz and Köse, 2012).

Property	Hydrogen	Methane	Gasoline	Diesel
Molecular weight	2.016	16.043	~110	~170
Boiling point (K)	20.3	111	298–488	453–633
Carbon content (mass%)	0	75	84	86
HHV (MJ/kg)	141.9	55.5	47.3	44.8
LHV (MJ/kg)	119.9	50	44.5	42.5
Auto-ignition temperature (K)	853	813	~623	~523
Volumetric energy content (at 1 bar & 273 K; MJ/m3)	10.7	33	33×10^3	35×10^3
Adiabatic flame temperature (at 1 bar & 298 K at stoichiometry; K)	2480	2214	2580	~2300
Density (at 1 bar & 273 K; kg/m^3)	0.089	0.72	730–780	830
Stoichiometry air/fuel mass ratio	34.4	17.2	14.7	14.5

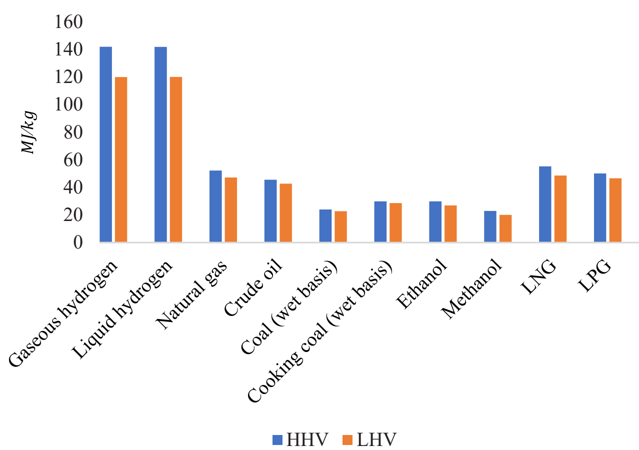

Fig. 1. Comparison of energy content of some fuel (Abe et al., 2019).

eco-friendly characteristics and non-toxic nature. Furthermore, hydrogen offers a considerably higher energy density in comparison to alternative fuel sources, such as crude oil and natural gas (Sharma et al., 2021). One of the key reasons hydrogen is utilized is its high energy density, which renders it an attractive option for energy storage and transporting applications. The problem of large-scale energy storage remains unresolved, which is constraining the broader adoption of renewable energy sources. Currently, batteries are the only approach for energy storage, which they are only effective for storing moderate amounts of energy for brief durations. However, other types of energy storage methods are often not available for commercialization and need testing for feasibility. At present, the sole alternative approach to following the green society development is utilizing green energy to produce hydrogen (Hassan et al., 2023a). Fig. 1 illustrates a comparison between the hydrogen energy content and other fuels (Abe et al., 2019).

Fuel cell vehicles have garnered significant interest owing to their potential to revolutionize transportation. Unlike traditional internal combustion engine vehicles, fuel cell vehicles produce zero emissions, offering a promising solution to combating air pollution and reducing GHG emissions (Harichandan et al., 2023). Hydrogen fuel cells are efficient devices utilized for the conversion of energy, operating through a chemical reaction involving hydrogen and oxygen. Fuel cell does not emit GHG during operation. Owing to the significant energy density of hydrogen, fuel cells can operate with less frequent refueling. However, another advantage of this engine is its fast and easy refueling (Wang et al., 2020). Also, the utilization of hydrogen for electricity production can be achieved by the conversion of kinetic and mechanical energy through its combustion in turbines or internal combustion engines (Yue et al., 2021). Automobiles are another use of fuel cells. For example, the Japanese government has raised the use of hydrogen in automobiles with a production capacity of 10,000 units of Toyota Mirai. Hydrogen's economic feasibility makes it a promising option for global prosperity (Luo et al., 2021). With advancements in fuel cell technology and infrastructure, these vehicles offer a compelling pathway towards a greener and more sustainable future for transportation (Oladosu et al., 2024).

The primary aim of this study is to present a thorough examination of the current hydrogen infrastructure in terms of production technologies and fuel cell vehicles. The study investigates different techniques for hydrogen generation, including conventional, renewable, and nuclear. In addition, this study examines the implementation of hydrogen fuel cells in automobiles as well as the importance of hydrogen recirculation components and obstacles of hydrogen fuel cell vehicles. Furthermore, the different storage options on fuel cell vehicles and their environmental impact are explored.

2. Hydrogen production

Currently, hydrogen is emerging as a reliable energy source in a peaceful manner. In 2022, approximately 88 Mt of hydrogen were produced globally. This quantity is 23 % higher than that produced in 2015 (Rasul et al., 2022). According to the global attention to hydrogen as an energy carrier for reducing global warming, PricewaterhouseCoopers (PwC) has conducted an analysis and projection of hydrogen demand until 2050 (Rasul et al., 2022; P. Coopers-PwC, 2017). Hydrogen production methods are categorized into three considerable categories: conventional (fossil fuels), renewable energy-based, and nuclear energy-based hydrogen production (Agyekum et al., 2022). Even though conventional methods are used for the high portion of hydrogen production today, there is a growing shift towards renewable electricity as the world becomes more focused on reducing GHG emissions. While there is a shift towards renewable electricity for hydrogen production, the high costs associated with using renewable energy sources remain a significant challenge for a green society (Ingaldi and Klimecka-Tatar, 2020). However, advancements in technology and decreasing costs of renewable energy sources are making it more feasible for global application.

2.1. Conventional technologies

Conventional hydrogen production methods account for a major fraction of the world's hydrogen demand (Dou et al., 2019). These methods, such as natural gas reforming and coal gasification, are not environmentally friendly and emit a large quantity of CO_2 and CO. However, there is a growing need to develop alternative and sustainable methods for hydrogen production (Hanley et al., 2018). The integration of conventional approaches with the carbon capture process is being employed to reduce the release of CO_2 emissions (Ishaq et al., 2022). Furthermore, research and development efforts are being focused on finding renewable sources for hydrogen production.

2.1.1. Natural gas reforming

The natural gas reforming (NGR) process accounts for a major portion of hydrogen production via fossil fuels, which comprise approximately 50 % of production of hydrogen in the world (Katebah and Linke, 2022). This approach is a feasible choice for rich countries with natural gas reserves, such as Russia and Iran. Currently, the most cost-effective approach is natural gas reforming, which has an efficiency range of 65–75 % (Liu et al., 2021a). NGR includes methane oxidation, steam reforming, and water gas shift reactions. After desulfurization of the natural gas, the steam methane reforming process is implemented at high temperatures to obtain syngas, which contains H_2 and CO. The subsequent step involves the utilization of a water-shift gas converter, wherein CO converts to H_2 and CO_2 with additional steam to increase efficiency and make extra H_2. The reactions that occur in natural gas reforming are as follows:

$$2H_2S + O_2 \rightarrow 2S + 2H_2O \tag{1}$$

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \tag{2}$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{3}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{4}$$

The process of natural gas reforming is effectively combined with carbon capture and storage/utilization (CCS/CCU) in order to capture and reduce the emission of CO_2 emissions into the environment (Dincer and Acar, 2015). This work decreases the environmental dimension of NGR and makes blue hydrogen rather than gray hydrogen. Also, novel processes entitled Electrified Steam Methane Reforming have been presented, which utilize electricity rather than combustion for reforming energy. This method has a higher thermal efficiency compared to the SMR process (Song et al., 2022). In addition, hydrogen could be generated from autothermal reforming (ATR), partial oxidation (POX), and pyrolysis of NG (Onwuemezie et al., 2024).

2.1.2. Coal gasification

Coal gasification is another commercial and fossil fuel-based method for the production of hydrogen that is widely adopted due to the wide availability of coal resources. Coal gasification involves the separation of oxygen from air, followed by the partial oxidation of coal at high temperatures (800–1300 °C) and pressures ranging from 30 to 70 bar. This process yields syngas, which is similar to the product obtained from natural gas reforming (Liu et al., 2021a). The syngas generated from coal gasification contains a mixture of CO, H_2, CO_2, and CH_4 at high temperatures. Subsequently, the syngas cooling unit recovers syngas heat that can be utilized in various applications. A shift reaction is then performed to increase the production of hydrogen. Coal gasification produces a large amount of CO_2, which is due to the high carbon base of coal. Coal gasification, analogous to the process of natural gas reforming, is integrated with CCS technology in order to decrease the release of CO_2 into the environment (Huang and Dincer, 2014). By integrating the coal gasification process with CCS, CO_2 emissions per H_2 produced are reduced, making blue hydrogen (Ghannadi and Dincer, 2024).

2.2. Water electrolysis

Electrolysis is one of the most common methods for manufacturing hydrogen. In this approach, electricity is used to separate water molecules into hydrogen and oxygen. Water electrolysis can be powered by renewable and non-renewable energy sources. In contrast to the other thermochemical processes, electrolysis does not produce any CO_2 during the cracking of water molecules into its components (Mergel et al., 2013). Proton exchange membrane (PEM) electrolyser, solid oxide (SO) electrolyser, and alkaline (ALK) electrolyser are the most significant types of water electrolysers (Nasser et al., 2022). These electrolysers vary in terms of their operating temperature, efficiency, and cost. The PEM electrolyser operates at low temperatures while the SO electrolyser operates at high temperatures. The PEM electrolyser offers many advantages compared to other technologies, namely: better efficiency, a higher hydrogen production rate, reacting quickly to fluctuations,

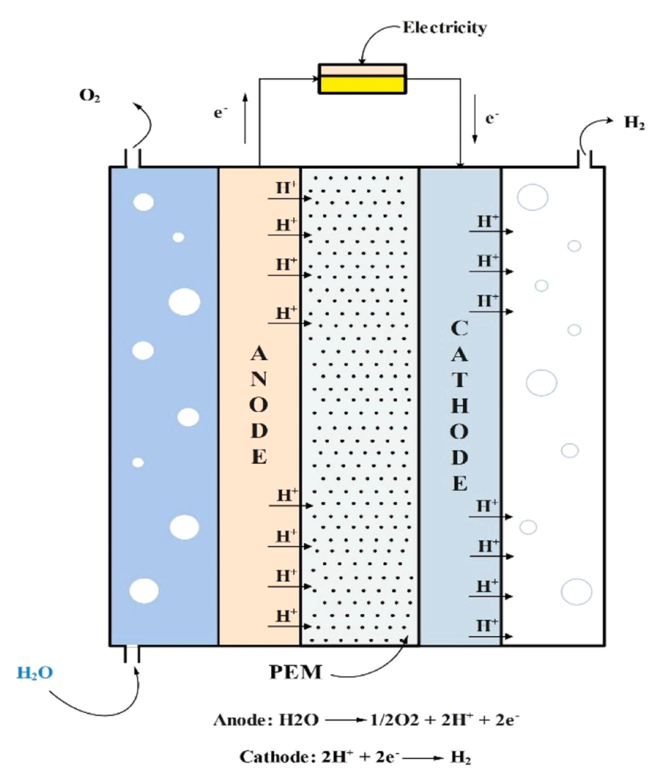

Fig. 2. Schematic diagram of a PEM electrolyser.

availability for employing in distributed systems, and compact design (Rashid et al., 2015). In Fig. 2, a schematic diagram of a PEM electrolyser is illustrated.

2.3. Renewable energy

2.3.1. Solar

Solar energy is widely acknowledged as a feasible and ecologically sustainable energy resource for the production of hydrogen. Even though manufacturing solar panels has negative environmental impacts, solar energy has been proven to have significantly lower GHG emissions compared to other traditional energy sources (Acar and Dincer, 2014). Additionally, advancements in technology will lead to the development of manufacturing processes. The solar energy source can be classified into three categories: photoelectrochemical, solar thermal, and solar photovoltaic (Joshi et al., 2011). Solar thermolysis, solar thermochemical cycles, solar cracking, solar reforming, and solar gasification are the types of solar thermal applications (Steinfeld, 2005). Although, due to the utilizing of fossil fuels in solar reforming, cracking, and gasification, they are not environmentally friendly. Hydrogen can be generated by solar energy, both directly and indirectly. The direct method for the production of hydrogen by solar energy contains photoelectrolysis, bio-photolysis, and other types that are shown in Fig. 3. Indirect production of hydrogen involves using solar energy to provide the required electricity for electrolyser and solar thermal processes like solar ammonia reforming (Ishaq et al., 2022). In accordance with the availability of solar energy in various regions, several studies have investigated the potential of producing hydrogen using solar energy in particular areas (Kalbasi et al., 2021; Zghaibeh et al., 2022; Ahshan, 2021; Touili et al., 2018). Abbas et al. (2023) investigated the potential of hydrogen production via solar PV in terms of techno-economic analysis. They utilized a 22 kWp PV system, an ALK electrolyser, an H2 compressor, and a hydrogen tank for a 9-year lifespan in some cities of Iraq. The findings indicate that the lowest quantity of H2 is 1713.92 kg, and the lowest quantity of O2 is 1199.74 kg. Conversely, the highest quantity of H2 and O2 is 1891.12 and 1323.78 kg, respectively. Also, the cost of hydrogen ranges from \$3.79/kg to \$4.19/kg (Abbas et al., 2023). Karayel and Dincer (2024a) analyzed the potential of hydrogen production in Canada using both onshore and offshore solar energy sources. The findings showed that the ALK, PEM, and anion exchange membrane (AEM) electrolyser can each produce 205.69 Mt, 201.12 Mt, and 211.17 Mt of hydrogen, respectively (Karayel and Dincer, 2024a). In Fig. 3, solar energy-based hydrogen production methods are presented.

2.3.2. Wind

Wind energy is a favored type of green energy source for manufacturing hydrogen. Wind energy is defined as the utilization of wind power by wind turbines to generate electricity. Wind turbines are devices that transform the kinetic energy of wind into mechanical energy, subsequently converting it into electrical energy through the utilization of a generator (Tan et al., 2022). Wind energy is a clear energy carrier and does not emit GHG. Wind turbine types can be categorized as onshore and offshore. Onshore wind farms are often situated on land, whereas offshore wind farms are typically situated on aqueous bodies, such as oceans or lakes. The electricity produced by wind turbines after conversion to DC is employed as a feed for an electrolyser to produce hydrogen (Sarker et al., 2023). Wind energy is a favorable, clean, and environmentally friendly source of power that is becoming increasingly popular around the world. Wind energy is not found everywhere and requires potential measurement but is efficient. Fig. 4 displays a schematic of hydrogen production through wind energy. Numerous studies

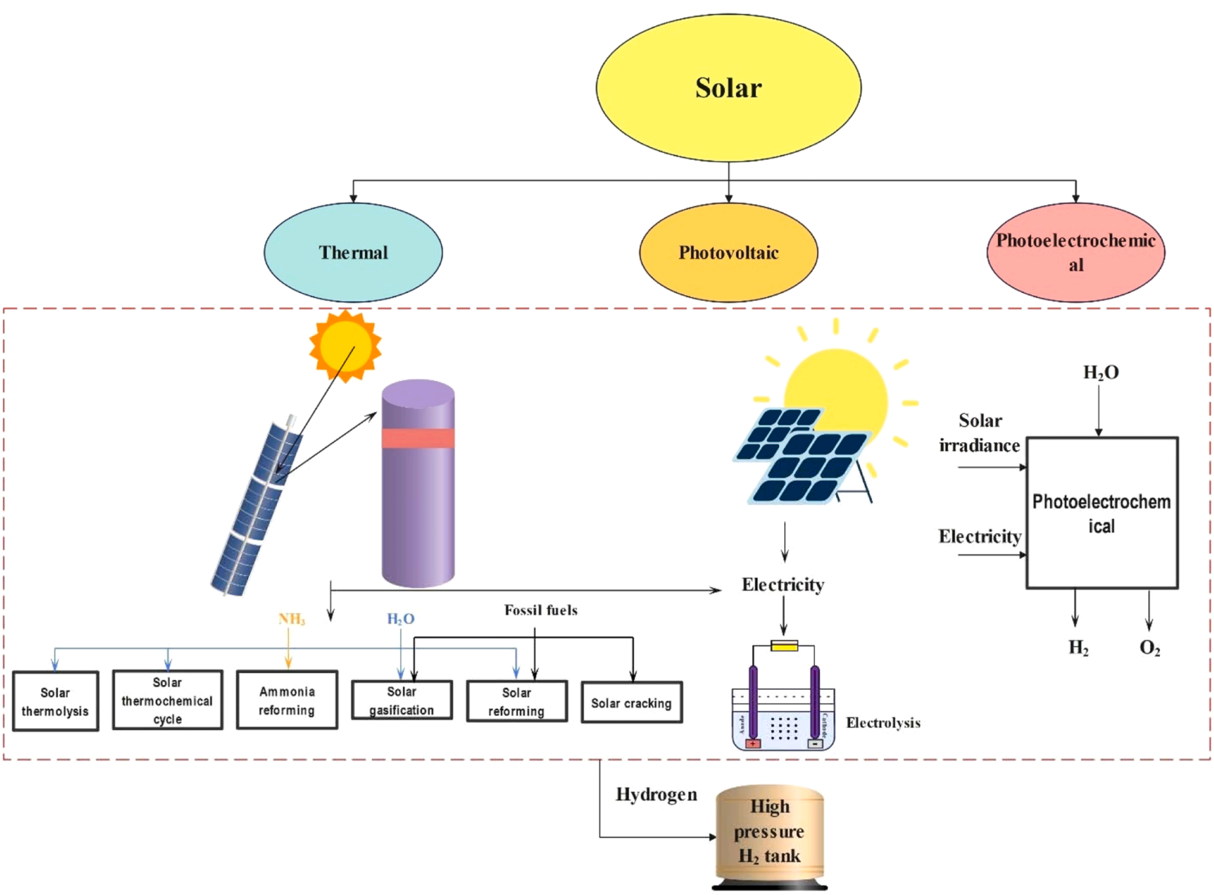

Fig. 3. Solar energy-based hydrogen production methods.

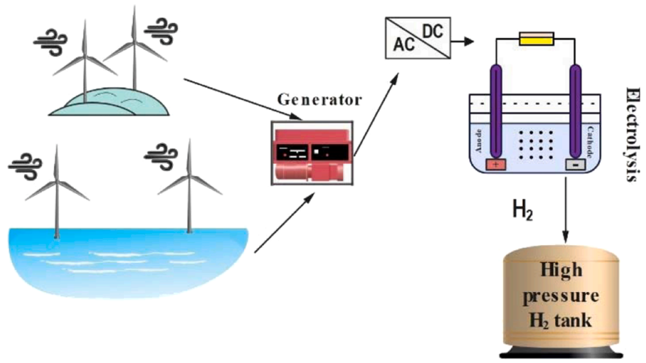

Fig. 4. Wind energy-based hydrogen production.

have examined the potential of hydrogen produced through the electrolysis of water powered by wind (Ayodele and Munda, 2019; Cheng and Hughes, 2023; Karayel et al., 2023a). Karayel and Dincer (2024b) have examined the potential of hydrogen production in Canada by employing a PEM electrolyser that is powered by wind energy. They analyzed each province of Canada and concluded that green hydrogen can be produced through onshore and offshore wind turbines at 402.63 and 37.29 Mt, respectively (Karayel and Dincer, 2024b). Jaszczur et al., (2023) examined the hydrogen production in the Middle East and Europe based on solar and wind energy (3 MWp). Based on the result, the Middle East is the better location for hydrogen production, with a cost of \$6.54/kg to \$12.66/kg compared to the Europe (\$9.88/kg to \$14.31/kg) (Jaszczur et al., 2023).

2.3.3. Geothermal

Geothermal energy offers a sustainable energy source that can be utilized in manufacturing hydrogen. Geothermal energy utilizes the heat from the Earth's subsurface to produce electricity, cooling, and heating (Ghazvini et al., 2019). The trend toward utilizing geothermal energy for electricity production is increasing due to its sustainability and low carbon footprint. Hydrogen production could be fulfilled through geothermal energy in various ways, such as through thermochemical processes or heat pump systems. In addition, geothermal energy can be utilized to supply the required electrolysis electricity, and enhances the electrolyser efficiency by heat water (Soltani et al., 2019; Mahmoud et al., 2021). Fig. 5 illustrates different methods of geothermal hydrogen production. Karayel et al. (2022) have examined the potential of green hydrogen via geothermal energy to help the government with future energy policies and sustainable development. They estimated that geothermal energy can produce 559.76 kilotons of hydrogen in Turkey (Karayel et al., 2022). Zuo et al. (2024) assessed the potential of geothermal energy for hydrogen production through an ALK electrolyser. Based on the results, 1.5–3 kg/h hydrogen can be produced based on 1 kg/s geothermal brines. The exergy efficiency of the plant and its total cost rate were 12.63 % and 10.42 \$/h, respectively, while after optimization, these parameters were 14.25 % and 11.97 \$/h (Zuo et al., 2024).

2.3.4. Hydropower

Hydropower denotes the flowing or falling of water to rotate turbines, which then convert the kinetic energy to electricity. Hydropower is accounted as the green energy due to the renewable cycle of water. The abundance of water sources around the world makes hydro a reliable energy source. Hydro meets a large portion of the world's electricity demand. Various types of hydropower, like tidal, dam water, and wave energy, have been developed to harness the power of water for electricity generation. Hydro-based electricity can be fed to a water electrolyser to crack water into its constituent elements (Lu et al., 2015). Fig. 6 presents a different type of hydropower energy source. In order to help policymakers, many studies have investigated the potential of green hydrogen production through hydropower (Recalde et al., 2024; Thapa et al., 2021; Karayel et al., 2023b). In a study, the potential of hydrogen production through wave, tidal, and undersea current sources has been analyzed with three electrolysers (PEM, ALK, and AEM). Based on the results, the potential of hydrogen production was 3.38 Mt for ALK, 3.55 Mt for PEM, and 3.75 Mt for the AEM electrolyser. In this study, wave and tidal energies comprise the 99 % of hydrogen production capacity (Karayel and Dincer, 2024c).

2.3.5. Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) is another green energy source that can produce hydrogen through electricity generation. OTEC is known as a marine renewable due to the electricity produced indirectly through solar energy (Herrera et al., 2021). OTEC operates by utilizing the temperature difference between deep colder water and warmer surface water, which is caused by the absorbed solar energy (Aresti et al., 2023). In a cycle, warm water is used for the vaporization of working fluid that have a low boiling point, like ammonia. Then, after producing electricity by turbine, colder water is utilized for the condensation of working fluid into vapor. The required electricity for the electrolyser can be provided through OTEC energy (Ishaq et al., 2022). Yilmaz et al. (2024) developed a tri-purpose system for power generation, hydrogen production (with compression), and water desalination based on OTEC. The energy and exergy efficiency of the purposed model were 12.20 % and 24.71 %, respectively. The system's net power generation was 150 kW, while its hydrogen and freshwater capacity were

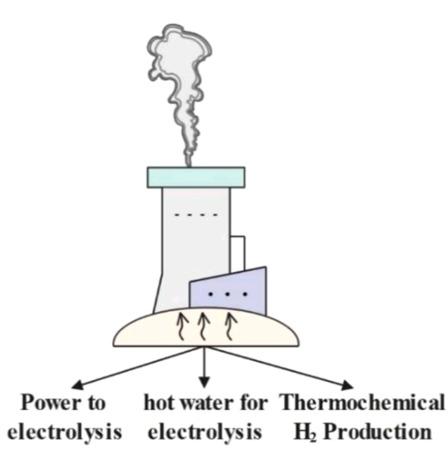

Fig. 5. Hydrogen production through geothermal energy.

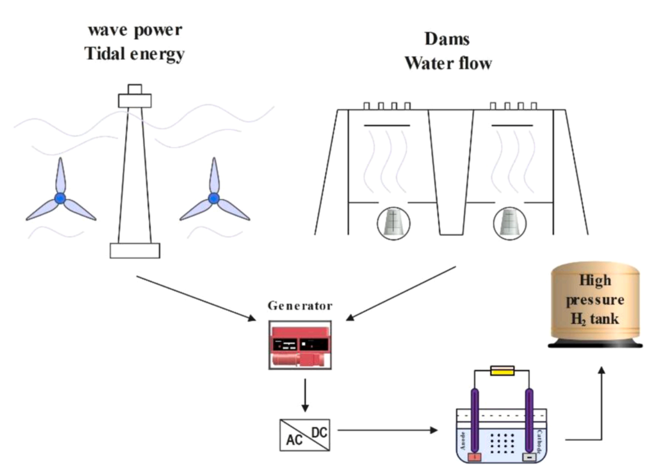

Fig. 6. Representation of hydropower technologies for hydrogen production.

0.0003011 and 4.755 kg/s, respectively (Yilmaz et al., 2024). In another study, three approaches of renewable energy sources consisting of wind, OTEC, and solar have been investigated for hydrogen production. The overall exergy and energy performance for OTEC based were 13.6 % and 5.61 %, respectively (Ishaq and Dincer, 2020). A schematic of the OTEC system is shown in Fig. 7.

2.3.6. Biomass

Biomass represents an alternative energy source with the potential to offer environmentally friendly energy options on a global scale. Biomass is abundant and can be achieved by different sectors such as hydrocarbon-based fuel, agriculture, forestry, and waste management. It has the potential to be employed for the generation of thermal energy, electrical power, and biofuels, diminishing reliance on fossil fuels and diminishing the release of GHG. There is a various pathway for production of hydrogen via biomass (Nguyen-Thi et al., 2023). Hydrogen can be generated by biomass pyrolysis, which is a thermal decomposition process of biomass in the absence of oxygen, resulting in the production of a gas mixture containing hydrogen (Aziz et al., 2021). Biomass gasification is another method that burns biomass with a limited amount of oxygen into a combustible gaseous mixture named syngas, or producer gas. Syngas contains hydrogen and carbon monoxide. In a supplementary stage of the Water Gas Shift (WGS) reaction, hydrogen is formed from carbon monoxide and water reaction (Nguyen-Thi et al., 2023; Pal et al., 2022).

As discussed, renewable energy has a high potential for producing green energy. Fig. 8 shows the different types of renewable-based technology for hydrogen production. As demonstrated in Fig. 12, the renewable hydrogen production technologies are not cost-competitive with conventional methods and need further research and development to become more economically viable. In addition, biohydrogen production through microbial fuel cells and microbial electrolysis cells should be considered. This emerging technology shows promising advantages such as efficiency, low energy demand, and waste conversion during hydrogen production. However, further development needs for widespread commercialization and implementation (Ferraren-De Cagalitan and Abundo, 2021; Saravanan et al., 2020).

2.4. Nuclear energy

The production of hydrogen by the utilization of nuclear energy is a sustainable method with no GHG emissions, which is typically called purple or pink hydrogen. Nuclear energy is produced through the fission of uranium isotopes. Nuclear fission generates heat that turns into steam, which generates electricity through turbines (Liu et al., 2023). Hydrogen can be produced through water splitting via thermochemical processes based on nuclear energy. Thermochemical processes have advantages compared to conventional methods (Pinsky et al., 2020). Nuclear energy is abundant, and this method does not require a separation membrane. Also, thermochemical processes based on nuclear energy have the potential for hydrogen production at a lower cost, with lower CO_2 emissions, and with higher efficiency. In this method, less temperature and electrical energy are required, and hydrogen can be produced from any kind of reactor (Liu et al., 2021a). However, the crucial factors in determining the most suitable type of reactor are the maximum temperature and its coolant efficiency (Venizelou and Poullikkas, 2024). Currently, several nations, are developing nuclear energy-based hydrogen production technology for future (Constantin, 2024).

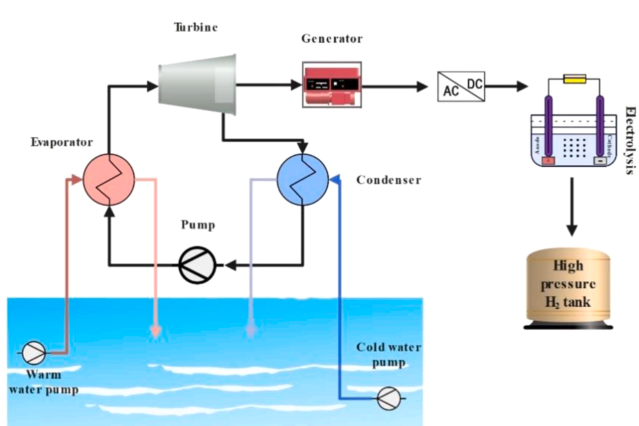

Fig. 7. The representation of the OTEC system.

2.5. Comparison between currently hydrogen production technologies

Various technologies for hydrogen production have been explored in the body of literature. Fig. 9 shows a schematic diagram of hydrogen production techniques.

The diagram illustrates that these technologies can be classified into three principal categories based on their resources, i.e., renewable, conventional (nonrenewable), and nuclear. Hydrogen production through steam reforming and coal gasification are the common methods related to nonrenewable energy sources, which are called gray and black hydrogen. However, by utilizing CCS/CCU technology, this process can become more environmentally friendly and this hydrogen is known as blue hydrogen (Salimi et al., 2022). Nowadays, renewable hydrogen production is considered due to low GHG emissions, sustainability, and environmentally friendly content. Solar, geothermal, wind, ocean thermal, hydropower, and biomass are the most common renewable energy sources. Currently, the cost of producing hydrogen using renewable energy sources like solar and wind electrolysis is not competitive with traditional methods (Ayub et al., 2024). However, technological developments are quickly narrowing the price difference. Between these types of energy, biomass is significantly considered for the future due to its low price and abundance (Olabi et al., 2021). Furthermore, the process of hydrogen production through water electrolysis using grid electricity is commonly referred to as yellow. The level of carbon emissions significantly depended on the sources electricity generation (Zainal et al., 2024). In Table 2, the merits and demerits of hydrogen production by different energy sources are demonstrated.

3. Fuel cell vehicles

Excessive utilization of fossil fuels leads to energy shortages and exacerbates global warming (Hamedani et al., 2024). Global initiatives have been launched to mitigate carbon dioxide emissions and advocate for the adoption of clean energy by the year 2050 (Lenox and Duff, 2021; Vieira et al., 2021). Hydrogen, as a renewable energy carrier poised to replace fossil fuels, holds promise for mitigating energy consumption and environmental challenges. Numerous nations have invested considerable resources in advancing hydrogen energy and fuel cells (Hosseini and Wahid, 2020). In fuel cells, hydrogen and oxygen are utilized to generate electrical power. There are various types of fuel cells with different methods of operation and performance. In Table 3, the operation conditions of various types of fuel cells are compared (Selmi et al., 2022).

Fuel cell vehicles or technologies stand out for their pollution-free nature and their rapid integration into different sectors, like transportation, power generation, residential applications, and other industries (Liu et al., 2021b). Among the diverse array of fuel cell types, Proton Exchange Membrane Fuel Cells (PEMFCs) have gained traction in industrial and residential settings due to their simplicity, portability, and quick activation (Fan et al., 2021). However, the widespread adoption of PEMFC faces significant obstacles related to durability and cost (İnci et al., 2021).

To tackle these hurdles, researchers are exploring diverse strategies,

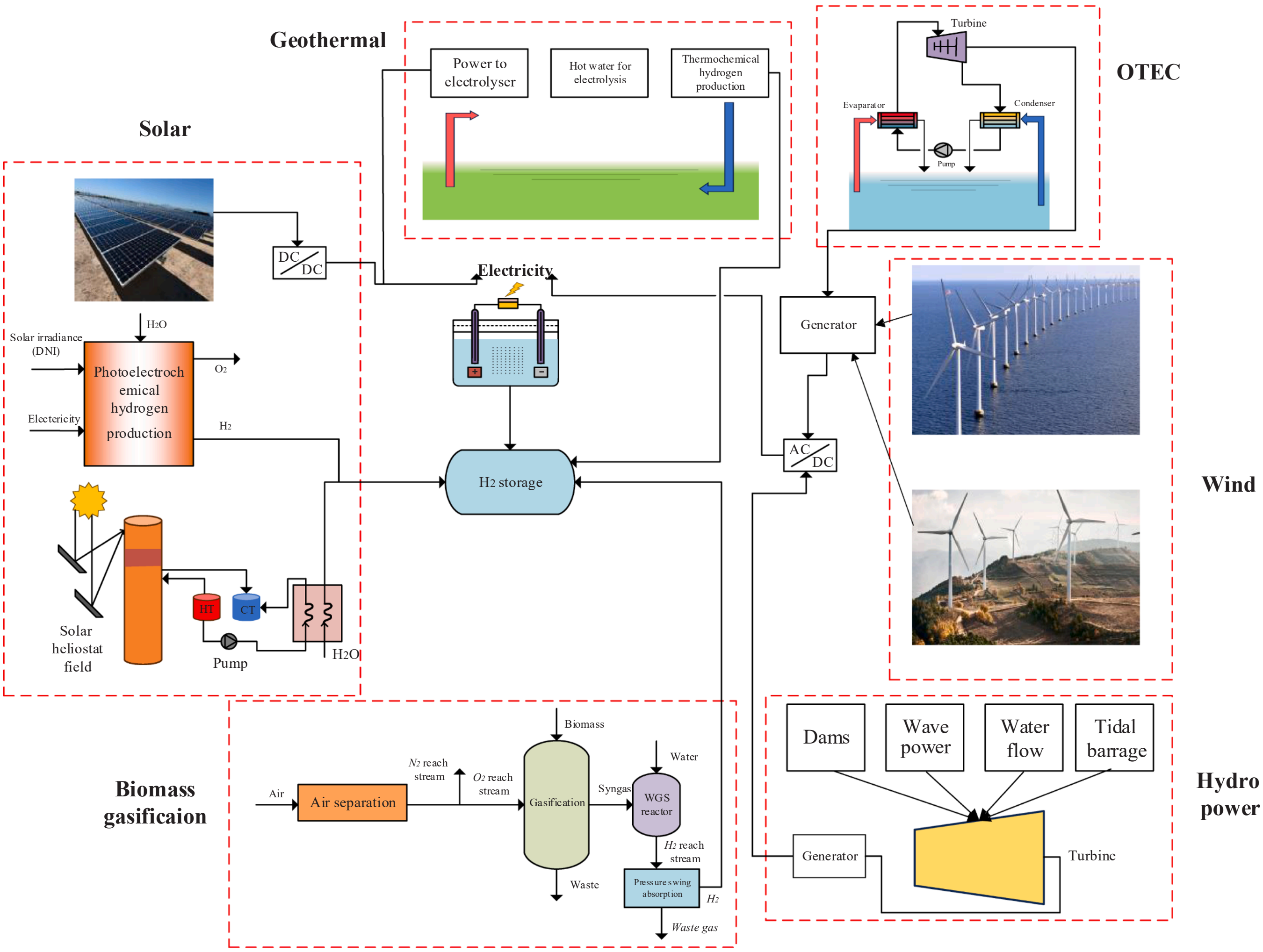

Fig. 8. Different renewable technologies for hydrogen production (modified from (Ishaq et al., 2022)).

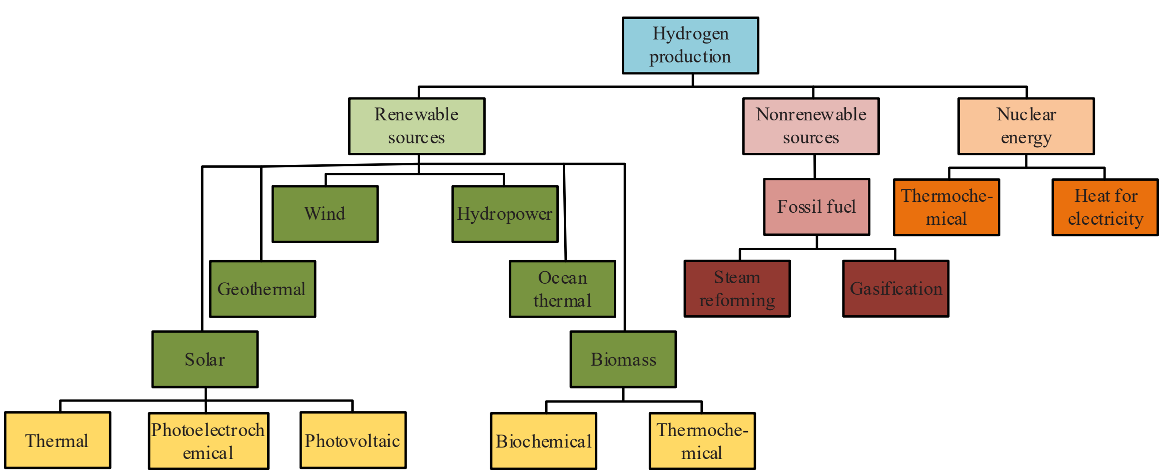

Fig. 9. Schematic diagram of hydrogen production technologies.

such as the development of economical electrode materials and the design of high-performance components (Zhao and Li, 2019). A PEMFC system comprises fuel cell stacks and several auxiliary subsystems, including the supply of hydrogen to the anode, air supply to the cathode, and cooling mechanisms (Wang et al., 2022). A graphical representation of a PEMFC system for fuel cell-based automobiles is depicted in Fig. 10.

The hydrogen supply subsystem is responsible for delivering fuel to the fuel cell stack, with the anode of the stack being secured from high-pressure hydrogen tanks. Before entering the fuel cell stack's anode, high-pressure hydrogen undergoes pressure reduction and regulation (Feng et al., 2023; Hu et al., 2021).

In Fig. 11, different mechanisms for anode hydrogen supply, such as

Table 2
Merits and demerits of various technologies of hydrogen production.

Hydrogen production technologies	Merits	Demerits
Steam reforming	• High yield of hydrogen • Economic benefit	o Need for refining o CO_2 emissions
Gasification	• Abundant sources • High efficiency	o Environmental pollutions
Solar thermal	• High efficiency • Clean	o High initial cost o Requires handling high temperature.
Solar PV	• Zero emissions • High efficiency	o Environmental impact related to manufacturing panels o Solar energy is not stable
Wind	• Very clean	o Wind energy is not available everywhere o Space requirement o Environmental impact related to manufacturing panels
Biomass	• Available and cheap • Waste reduction	o High energy requirement
Geothermal	• Low GHG emissions • Reliable and stable	o Requires handling high temperature.
Hydropower	• High efficiency • Reliable and stable	o High initial cost o Location-depended
OTEC	• Low GHG emissions • Stable and predictable	o High initial cost
Nuclear energy	• High efficiency • No GHG emissions	o Security concerns o Nuclear waste production

Table 3
Comparison of different FC technologies (Selmi et al., 2022).

Type of the FC	Operation temperature (°C)	Output power range (kW)	Efficiency (%)
Alkaline	Min: 90 Max: 100	From 10 up to 100	70
Phosphoric acid	Min: 150 Max: 200	From 50 up to 1000 W	42
Proton exchange membrane	Min: 50 Max: 100	Up to 250	60
Molten carbonate	Min: 600 Max: 700	Up to 1000	60
Solid oxide	Min: 650 Max: 1000	From 5 up to 3000	60

dead-end anode, hydrogen recirculation with a mechanical pump or ejector, and hybrid recirculation cycles, are demonstrated (Han et al., 2022). The dead-end anode subsystem, with fewer components, suits PEMFC stacks for smaller applications like fuel cell motorcycles (Chen et al., 2019). However, high-power fuel cell vehicles generally require excess hydrogen to prevent reactant shortages in the stack, necessitating hydrogen recycling (Nonobe, 2017). Hydrogen recirculation minimizes and ensures hydrogen waste stack and efficiency. In addition, it increases the gas flow rate in the anode flow channel and prevents anode flooding problems (Wang et al., 2022).

One of the key components of the hydrogen recirculation subsystem is the hydrogen circulation pump, which comes in two mechanical or ejector models. Mechanical pumps displace fluids by the movement of mechanical components and consume electrical energy (Barbir and Görgün, 2007). There are a different type of mechanical pumps like claw, scroll, roots, centrifugal, regenerative, and etc (Gao and Lin, 2023; Moradi et al., 2020). On the other hand, ejectors use high-speed fluid shear forces to introduce low-pressure fluid without the need for electricity consumption (Chouhan et al., 2020). Combining mechanical pumps and ejectors is also possible (Besagni et al., 2017). Another innovation in the field of hydrogen utilization is the electrochemical hydrogen pump. In this system, hydrogen is electrolytically split into protons and electrons at the anode through the use of DC voltage and then recombined at the cathode (Marciuš et al., 2022; Toghyani et al., 2019). Research indicates that electrochemical pumps can be more energy-efficient than mechanical pumps (Toghyani et al., 2018) or have comparable hydrogen losses in terms of electrical consumption (Wiebe et al., 2020). These devices are noiseless, stable, and easy to control, holding promise for hydrogen recirculation in the future (Durmus et al., 2021). However, electrochemical hydrogen pumps are currently expensive and not commercially available. Table 4 shows the technological properties of hydrogen recirculation systems (Liang et al., 2023; Zhang et al., 2023).

Compared to other technologies, ejectors and mechanical pumps are popular choices for manufacturers. Regardless of the pump type, as seen in Fig. 11 (b)–(d), the water and gas separator are one of the most crucial components (Han et al., 2021). The role of this separator is to remove liquid water from the anode effluent. Neglecting to do so may result in water inundation and disrupted mechanical pumps or ejectors, thereby endangering the fuel cell's durability and regular operation (Ijaodola et al., 2019).

3.1. Hydrogen-powered internal combustion engine vehicle (ICEs)

3.1.1. Spark-ignition engines

Research findings indicate that hydrogen-fueled spark-ignition (SI) and compression ignition (CI) engines exhibit reduced undesired emissions when compared to engines fueled by hydrocarbons (Shadidi et al., 2021). While nitrogen oxide (NO_x) emissions might be higher due to increased combustion temperatures, adjustments to the air-fuel ratio can mitigate this and lower the combustion temperature (Dimitriou and Tsujimura, 2017). Hydrogen-powered SI engines necessitate minimal modifications to operate with hydrogen and deliver enhanced combustion, increased efficiency, and virtually negligible emissions of hydrocarbons and CO (Rameez and Ibrahim, 2023). Lubricating oil evaporating and burning on engine cylinder walls produces a small amount of these pollutants (Rameez and Ibrahim, 2023; Luo and Sun, 2016). Notably, hydrogen engines outperform gasoline engines, particularly in part-load operation scenarios. Furthermore, spark-ignition engines can function under highly lean conditions due to the flammability-limits of hydrogen (Karagöz et al., 2019). However, applications demanding high torque at low engine speeds often favor engines with higher compression ratios, such as diesel engines (Fayaz et al., 2012; Stępień, 2021b).

3.1.2. Compression ignition engines

Hydrogen shows promise as an additive to traditional diesel fuel in CI internal combustion engines, supported by various factors. Incorporating little amounts of H_2 into CI engines enhances the uniformity of the diesel spraying, mostly because of hydrogen's exceptional diffusivity (Stępień, 2021b). The optimal blending of air and fuel results in a significant reduction in pollution emissions during combustion. Similar to SI engines, producing a trace amount of these pollutants can lead to incomplete lubricating oil burning (Rameez and Ibrahim, 2023; Antunes et al., 2009). It is crucial to acknowledge that CI engines cannot depend exclusively on hydrogen. As shown in Table 1, the auto ignition temperature of hydrogen is higher than other fuels, indicating that the compression temperature is not enough to start combustion (Chintala and Subramanian, 2017). Therefore, hydrogen could be utilized in a dual-fuel engine, where an ignition source like disel or bio disel initiates the combustion and hydrogen is injected into the engine (Thiyagarajan et al., 2022). Typically, the ignition fuel can make up 10–30 % of the

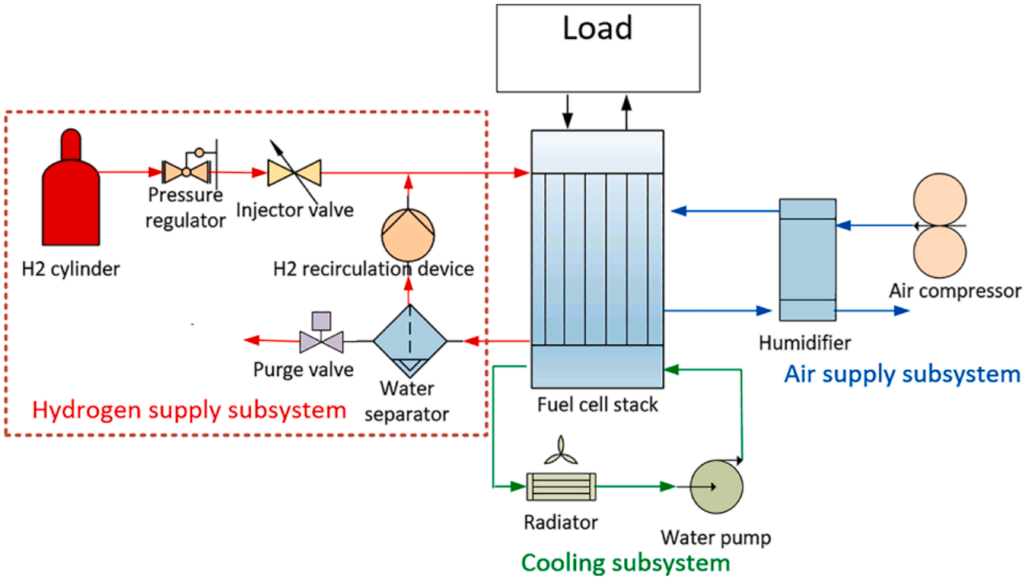

Fig. 10. PEMFC system schematic diagram for fuel cell vehicles (Han et al., 2022).

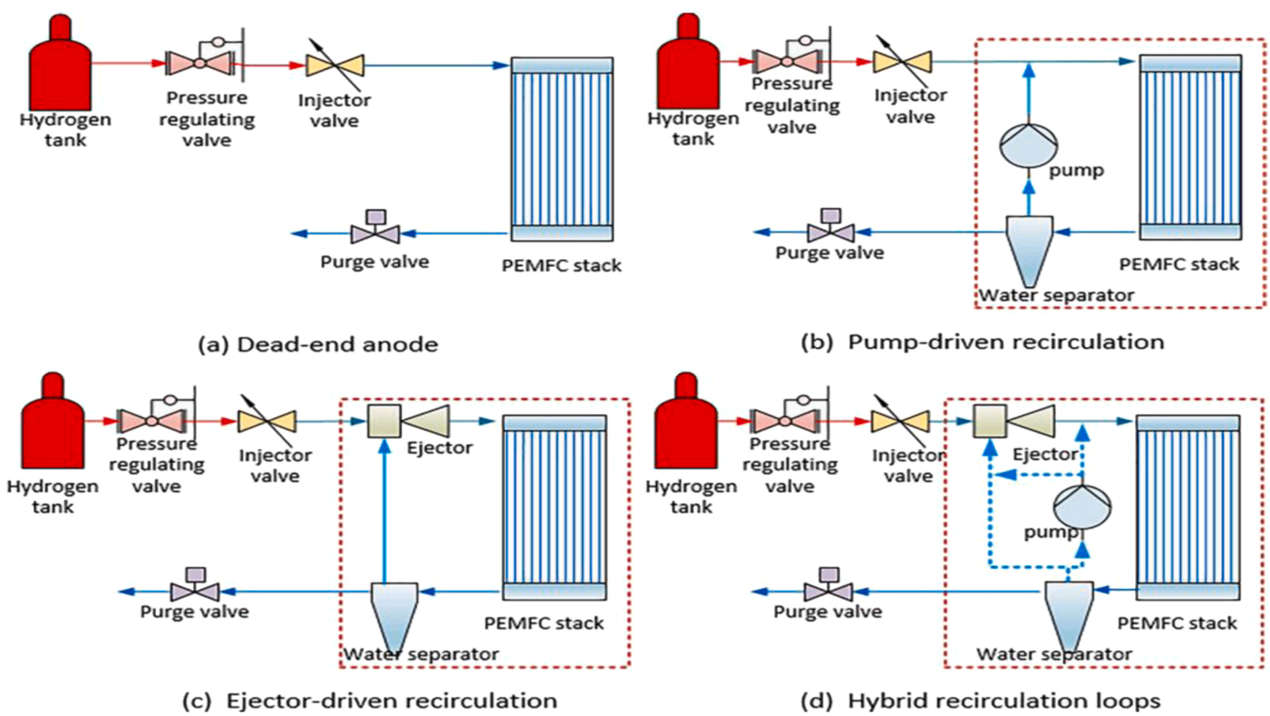

Fig. 11. Various mechanism of hydrogen supply in PEMFC (Han et al., 2022).

overall fuel, and hydrogen is used as the main source of energy (Stępień, 2021b).

One of the major concerns in hydrogen CI engines is the emission of NOx, which is similar to that of SI engines. One of the useful approaches to reducing NOx emissions is utilizing exhaust gas recirculation (EGR), which, due to its dilution effect, reduces the intake valve oxygen concentration (Rameez and Ibrahim, 2023; Stępień, 2021b). However, utilizing this approach has some disadvantages, like lower volumetric efficiency, higher particulate emissions, and a similar rate of smoke level with a conventional CI engine. It has been shown that the use of EGR results in a decrease in volumetric efficiency of around 15 % (Kumar et al., 2015). Another approach to mitigating NOx emissions and preventing knocking combustion and premature ignition is by introducing liquid water into the combustion chamber. However, this method leads to decreased engine volumetric efficiency when water is injected into the intake manifold (Korakianitis et al., 2010; Serrano et al., 2019).

3.2. Challenges of fuel cell electric vehicles (FCEVs)

The transportation sector has a substantial contribution to global CO_2 emissions. This sector accounts for around 25 % of CO_2 emissions (Zhu et al., 2024). Hydrogen fuel cell electric vehicles are a viable alternative among the several forms of sustainable vehicles. These

Table 4
Technological properties of mechanical pumps and ejector (Liang et al., 2023; Zhang et al., 2023).

Name	Properties
Claw pump	Good reliability, simple structure, built-in Compression, Leakage, abrasion
Scroll pump	Vast changeable flow range, good efficiency, low noise, low vibration, High production expense, abrasion
Roots pump	good reliability, Cost-effective, allowing reverse rotation, leakage, high noise, abrasion
Centrifugal pump	Compact structure, high efficiency, low noise, high noise (if run at undesign point) high speed, low life span, stall and surge
Regenerative pump	High head, compact structure, stable operation, low production cost, low efficiency
Ejector	Small size, reliability, cost effective

vehicles convert hydrogen and oxygen into electricity through a number of chemical reactions, resulting in the production of water and heat, and do not cause GHG emissions (Aminudin et al., 2023; Mendez et al., 2023). Table 5 presents several types of hydrogen cars together with their respective characteristics (Hassan et al., 2023b; Hyundai, 2024).

Currently, the extensive utilization of hydrogen cars encounters some obstacles. There is a need for extensive investment in hydrogen infrastructure, as well as the development of more efficient hydrogen production methods. The number of refueling stations should be increased, and the cost of green hydrogen should be decreased. Other obstacles, such as technological and safety challenges, need to be addressed, and developing sustainable and promising materials should be considered as well (Dou et al., 2023; Greene et al., 2020; Zhao et al., 2020). The subsequent sections delve into different barriers hindering the adoption of FCEVs.

3.2.1. Performance and durability

Performance of the fuel cell is a key factor for the development of hydrogen fuel cell vehicles in the future, which need to be competitive with battery electric vehicles (Aguilar and Groß, 2022). As mentioned, PEMFCs are considered the most suitable approach for FCEVs. While PEMFCs have achieved satisfactory energy density and precise performance targets like 4.4 kW/L, further advancements are necessary to fully meet the fundamental criteria for commercially viable systems (Wang et al., 2021). Furthermore, FCEVs require additional maintenance and repair in order to ensure durability and lifetime under various situations in comparison to battery electric vehicles (BEVs). However, due to the novelty of this technology, maintenance of this is not as widely available as for other types of vehicles (İnci et al., 2021). Addressing issues related to performance, durability, and reliability will be critical for the future of fuel cell systems.

3.2.2. Hydrogen supply and infrastructure

Green hydrogen plays a critical role in the zero emission feature of FCEVs. It is important that the contribution of green hydrogen should be developed again using conventional methods. Besides this matter, the supply chain of hydrogen including production, transportation, and large-scale storage should be further improved to ensure efficient distribution (Li et al., 2024). On the other hand, one of the major challenges of FCEVs in comparison to other types of vehicles is the lack of hydrogen refueling infrastructure. However, hydrogen vehicles have rapid refueling compared to electric vehicles, but the lack of infrastructure is a significant barrier. A substantial investment in the fields of construction, storage, and distribution is required to develop a widespread network of hydrogen infrastructure (Hassan et al., 2023b; Kountouris et al., 2024).

Table 5
Features of some hydrogen vehicles (Hassan et al., 2023b; Hyundai, 2024).

Characteristic	Toyota Mirai	Hyundai NEXO	Hyundai XCIENT	Honda Clarity	Mercedes-Benz GLC F-CELL
Vehicle type	Sedan	SUV	Truck	Sedan	SUV
Seating capacity	4	5	2	5	5
Range (approximate) (km)	805	612	400	579	500
Refueling time (compressed hydrogen) (min)	3–5	5	8–30	3–5	N/A
Power output (hp)	182	161	469	174	208

3.2.3. Cost barriers

Cost barriers are a significant challenge in expanding the adoption of hydrogen vehicles. Currently, hydrogen production costs via renewable energy are higher than conventional methods, which should be decreased by technology development (Oliveira et al., 2021). The comparison of hydrogen production costs based on technology is shown in Fig. 12 (International Energy Agency, 2023).

Presently, approximately, the cost of production for a range of 500,000 devices is 45 per kilowatt (Banham and Ye, 2017). The United States Department of Energy (DOE) has set specific goals for hydrogen transportation for the years 2020 and 2025. These goals are to achieve a cost of USD 30 per kilowatt for FCEVs and a cost of USD 600,000 for Fuel Cell Electric Buses (FCEBs) (Madheswaran et al., 2023). However, the average cost of FCEBs is around $1.8 million, which is 18 % lower than 2010 (Wang et al., 2020; Eudy, 2018). One of the other challenges in the cost aspect of hydrogen vehicles is platinum (pt). Pt is utilized in the catalyst layer, which in the scale of 500,000 fuel cell per year, comprises around 41 % of the budgets of the fuel cell stack elements (Thompson et al., 2018). The goal established by the U.S. DOE is to achieve a Pt loading of 0.1 mg/cm^2 by the year 2025. DOE is currently looking for a Pt loading of less than 0.2 mg/cm^2 and a durability of over 25,000 h for heavy-duty vehicles like trucks (Waseem et al., 2023).

3.2.4. Safety concerns

Various corporations oversee safety requirements for the global transportation system (Aikhuele, 2020; Khan et al., 2022). In the United States, the Society of Automotive Engineers (SAE) defines widely accepted automotive standards, encompassing guidelines for FCV design and testing systems, safety considerations, vehicle efficiency and performance, emissions, durability, vehicle terms, and fuel usage (Moretto and Quong, 2022; Barilo et al., 2017; Jayakumar et al., 2022). Additionally, other standards for testing and certification of fuel cells have been introduced worldwide. The CGA PS31 standard for the cleanliness of PEMFCs in the United States, the EC No.79/2009 standard by the European Commission for the approval of hydrogen vehicles, and the CNS 15499–1–2–3–4 series standards in China for the internal rechargeable energy storage system (RESS) have been established to ensure safety and prevent risks to the public (İnci et al., 2021). Adhering to these safety measures enables fuel cell hybrid electric vehicles (FCHEVs) to operate efficiently, leading to extended lifespans and enhanced performance. To ensure optimal operation, each FCHEV requires adequate protection and maintenance. Modern FCHEVs employ advanced power microelectronics to ensure efficient operation and secure functions of Energy Storage Systems (ESSs) (Zakeri and Syri, 2015; Khaligh and Li, 2010; Lukic et al., 2008).

3.2.5. Cold start

The presence of water in fuel cells necessitates careful consideration of cold start as a significant factor. When the temperature falls to zero degrees Celsius, the water in the fuel cell freezes and fills the aperture hole. Therefore, it is important that the fuel cell can be started and operated under freezing conditions without any issues (Liu and Xu, 2023; Mishler et al., 2012). However, it is possible to utilize hybrid battery systems to mitigate this issue, and water could be extracted

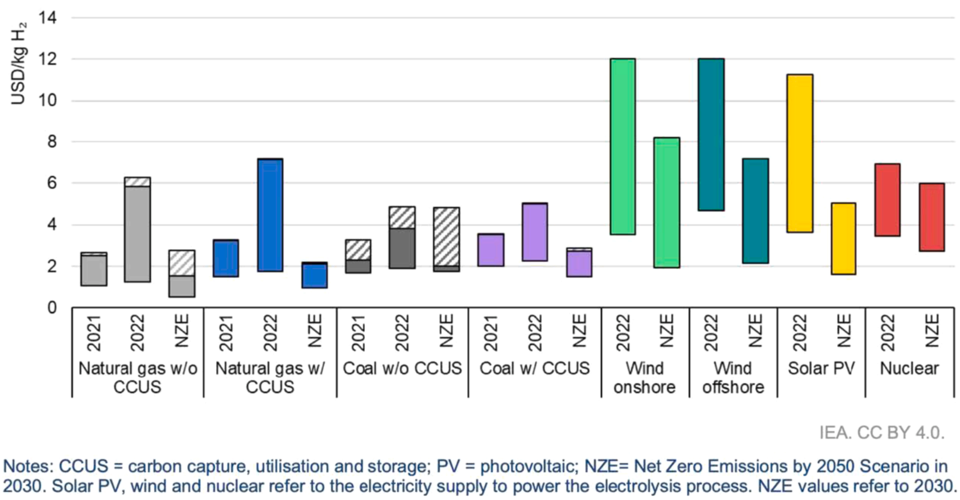

Fig. 12. Hydrogen production cost based on various technologies (International Energy Agency, 2023).

through liquid movement by capillary action (Wang et al., 2021). Therefore, it is essential to improve the performance of the fuel cell stack in terms of permeability and heat capacity to self startup. In addition, it is reported that some types of vehicles are purported to be capable of initiating operations at temperatures as low as −30 °C (Chen et al., 2021).

3.2.6. Hydrogen storage

In addition to grappling with challenges like onboard hydrogen storage and supply, ensuring vehicle safety, competing with alternative technologies such as EVs or hybrid electric vehicles (HEVs), and increasing community awareness, FCHEVs also confront significant hurdles. Given the highly volatile nature of hydrogen gas and the associated risks with onboard retention, securing hydrogen storage and ensuring vehicle safety are paramount (Whiston et al., 2020; Shen et al., 2023; Gómez and Santos, 2023). Moreover, enhancing public awareness is crucial for garnering support and acceptance for FCHEVs. Addressing concerns related to hydrogen storage can be increased by using storage tanks crafted from nanoporous polymer-based composite and nano-structure materials (Tian et al., 2019; Mondal et al., 2024). Also, hydrogen storage in vehicles is discussed in the next section.

3.3. Hydrogen storage for vehicles

Hydrogen storage represents a significant barrier in the advancement of hydrogen fuel cell cars. Hydrogen has a higher energy density per unit mass (120 MJ/kg) in comparison to conventional fuels like gasoline (44 MJ/kg). In contrast, hydrogen has a low energy density based on volume (0.01 MJ/L for hydrogen in STP vs. 132 MJ/L for gasoline) (Hwang and Varma, 2014). The U.S DOE has set a 2020 requirement of 4.5 wt% and 0.030 kg-H_2/L for gravimetric and volumetric capacities, respectively (Hassan et al., 2021). Various methods are being explored to address this issue, which are categorized into physical and chemical storage. In Fig. 13, different types of physical and chemical hydrogen storage are shown.

3.3.1. Physical methods

The utilization of compressed hydrogen is the main approach employed for the storage of hydrogen in cars. The hydrogen compression has high rates of filling and release and does not need energy to release (Durbin and Malardier-Jugroot, 2013). Compressing hydrogen to a high pressure level results in the utilization of around 13–18 % of the LHV of hydrogen, which influences the economical aspect of the process (Usman, 2022). Material composition is an important factor in choosing compressed hydrogen vessels. They must possess sufficient

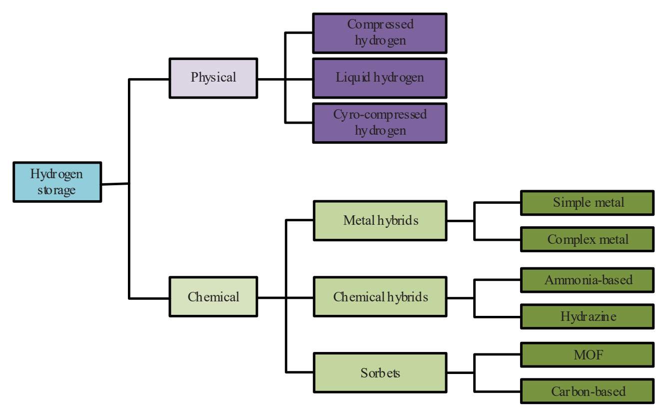

Fig. 13. Different type of hydrogen storage for vehicles.

strength to endure the high pressure and have high thermal conductivity to manage exothermic heat during filling hydrogen. Carbon fiber reinforced plastic (CFRP) and strengthened metals are the common materials used in compressed hydrogen vessels. However, CFRP has a relatively low thermal conductivity, which requires improvement (Hwang and Varma, 2014).

In contrast to compressed hydrogen, liquid hydrogen possesses a significantly greater volumetric energy density (70.9 kg-H_2/m3 at −253 C). This makes it a more efficient option for storage and transportation. Nevertheless, the process of hydrogen liquefaction consumes approximately 35 % of the hydrogen energy content, which is higher than compressed hydrogen (Usman, 2022). Also, adopting effective thermal insulation is necessary for liquid hydrogen tanks due to the low boiling point of hydrogen (20 k) (Hwang and Varma, 2014). The liquid hydrogen can be evaporated with high insulation. The rate of hydrogen vaporization is estimated to be approximately 1.5–3 % every day. Also, this boil-off occurs when the system is inactive and enhances the tank pressure, which raises safety concerns (Zhang et al., 2016). Fig. 14 illustrates a typical storage tank for liquid hydrogen (Rao et al., 2020).

Cyro-compressed hydrogen is the most considerable technology that combines the compression and liquefaction of hydrogen (Rivard et al., 2019). As noted above, compressed hydrogen has a low volumetric energy density, while the vaporization of liquid hydrogen causes hydrogen losses and raises safety concerns. Therefore, cryo-compressed hydrogen can address these issues by storing hydrogen in two phases at a lower temperature and higher pressure. This technology decreases the boil-off rate as well as safety problems. Ahluwalia et al. found a high efficiency

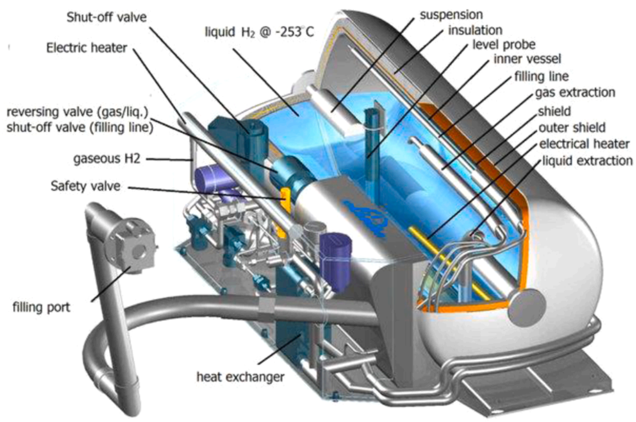

Fig. 14. Typical liquid hydrogen storage tank.
(source: Linde®) (Rao et al., 2020).

for a cyro-compressed tank while the vessel was filled to 85 % of its capacity. During the dormancy period of 7 days, the cyro-compressed system has not lost hydrogen (Ahluwalia et al., 2018). Apart from these advantages, the requirement of high insulation, a high rate of energy demand, and the availability of hydrogen infrastructure are the challenges of this technology (Hassan et al., 2021).

3.3.2. Chemical methods

Metal hybrids are one of the main categories of chemical storage technologies. Hydrogen can be absorbed by a number of metallic-based materials at low temperatures and moderate pressures to form metal hybrids (Satyapal et al., 2007). Metal-hybrid operation is based on reversible reactions of absorption and desorption of hydrogen on metal surfaces. These processes occur rapidly and possess a high volumetric energy density in comparison to alternative technologies (Tarasov et al., 2021). A simplified model of metal hybrid hydrogen storage is shown in Fig. 15 (Abe et al., 2019).

Metal hybrids can be classified into simple and complex hybrids. Complex metal hydrides refer to compounds that are created through the covalent bonding of hydrogen atoms to a central metal atom within a coordination complex. These compounds are typically stabilized by a cation (Jain et al., 2010).

Chemical hybrids are another type of chemical storage for hydrogen. Ammonia, ammonia borane, lithium amide, and hydrazine are some types of chemical hybrids. Chemical hybrids have higher gravimetric densities compared to metal hybrids due to their light elements. Also, the lower cost in comparison to liquid hydrogen makes chemical hybrids an attractive option (Hassan et al., 2021). However, irreversibility,

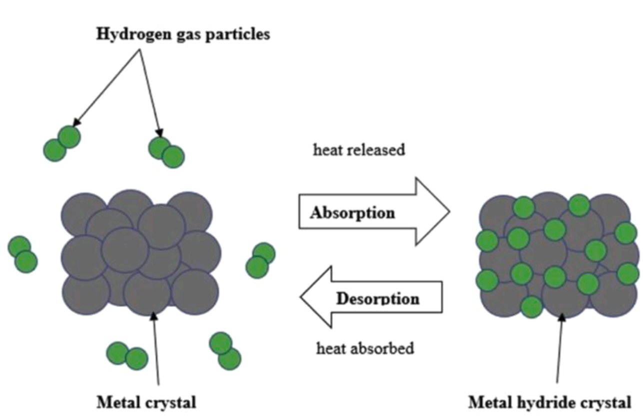

Fig. 15. A simplified model of metal hybrid hydrogen storage (Abe et al., 2019).

by-product utilization, and single-use application are disadvantages of them (Yang et al., 2010).

Sorbents are another category of chemical methods to storage hydrogen. Sorbents, such as carbon-based materials and metal-organic frameworks have attracted attention as potential hydrogen storage materials. These materials are very porous and have high surface areas, which can adsorb hydrogen molecules onto their surfaces (Vasiliev et al., 2007).

Metal Organic Frameworks (MOFs) belong to a group of crystalline materials made up of metal ions or clusters connected by molecular bridges. MOFs are considered for their high surface area and controllable structure features, which make them suitable for gas storage, including hydrogen. In addition, modifying MOFs with metal-supported catalysts can significantly enhance their hydrogen storage capacity through bridged hydrogen spillover. Nevertheless, the extremely porosity nature of these materials, results in a significant concern over their volumetric capacity (Zhao et al., 2022).

In the last few decades, carbon nanomaterials have been investigated due to their ability to adsorb hydrogen. Initial work related to carbon-based materials began in the late 1990s. Activated carbon and carbon nanotubes (CNTs) are the most common types of carbon-based materials for hydrogen storage. Although activated carbon has a lower capacity for H_2 adsorption compared to other carbon materials, it remains desirable due to its ease of production, abundance, and relatively well-understood chemistry. Also, CNTs possess a strong structure, high thermal conductivity, and a large surface area, making them ideal materials to storage hydrogen (Mohan et al., 2019).

4. Role of hydrogen in the transition towards a low-carbon society and the environment impact of hydrogen fuel cells vehicles

4.1. Potential role of hydrogen in the transition towards a low-carbon society

Hydrogen has a high potential for carbon emissions reduction on a worldwide scale. The versatility of this energy carrier and its ability to decarbonize multiple sectors position it as a essential components in the transition towards sustainable energy systems. Due to advancements in hydrogen production, storage, and utilization technologies, the appeal of integrating hydrogen into existing infrastructures and energy networks has increased. Hydrogen offers a significant solution for reducing GHG emissions and addressing the consequences of climate change, hence its growing adoption in industries such as transportation. The growing importance of hydrogen is being acknowledged by policy-makers, leading to increased efforts to expand production and create favorable regulatory frameworks. Adopting hydrogen as a clean energy solution offers significant potential for a more environmentally friendly and enduring future (Reigstad et al., 2022; Capurso et al., 2022; Khaligh et al., 2023). However, to achieve these goals, hydrogen challenges such as storage, production, and utilization technologies need to be addressed. Hydrogen is anticipated to supplant fossil fuels in the transport sector as the next step, requiring careful planning and appropriate infrastructure construction for refueling and charging zero-emission vehicles. Establishing and planning such infrastructure is both costly and time-consuming, emphasizing the importance of making investment decisions based on a thorough analysis of future hydrogen demand (Espegren et al., 2021; Turnheim and Nykvist, 2019).

4.2. Environment impact of hydrogen fuel cell vehicle

In contemporary times, the industrial revolution and the subsequent increase in energy consumption have led to an escalation in CO_2 emissions from fossil fuels. These emissions related to fossil fuels contributed 65 % of all GHG until 2019. Consequently, this phenomenon has a critical role in global warming (Diffenbaugh et al., 2017). A significant proportion of the global population is affected by pollution, which causes various issues in human life.

Hydrogen fuel cells are an interesting field for developing the environmental level of societies. Chi et al. have evaluated the environmental and economic performance of HFCVs to determine carbon reduction policies. Their study was conducted using the GREET model. The findings indicate that the utilization of renewable energies in the electrolytic water process for hydrogen production yields minimal air pollutants and GHG emissions. Conversely, conventional methods of hydrogen production exhibit better economic performance (Chi et al., 2023). Cascales et al. investigated the environmental effects of replacing internal combustion vehicles with hydrogen fuel cell vehicles. The study found that replacing 25 % of internal combustion vehicles with hydrogen fuel cells resulted in a reduction of 24,500 metric tons of CO_2 emissions annually in the autonomous region of Murcia (Cascales et al., 2015). Hienuki et al. analyzed the environmental life cycle of hydrogen fuel cell vehicles. According to the study, it was determined that hydrogen vehicles consume less energy than fossil fuels (1.8 MJ/km). Also, it was found that hydrogen fuel cells have lower GHG emissions when compared to gasoline (0.15 kg- CO_2 eq./km) (Hienuki et al., 2021).

In comparison to other types of vehicles, the life cycle of hydrogen vehicles has the lowest contribution to global warming. Bicer and Dincer (2018) presented and compared the life cycle environmental assessment of different fuel types used in automobiles in their study. Their analyses encompass the entire lifecycle of vehicles, from manufacturing to disposal, including vehicle operation. The result showed that hydrogen vehicles are the most environmentally friendly compared to other vehicles. Fig. 16 shows a comparison of the effects of various vehicle types' life cycles on global warming (Bicer and Dincer, 2018).

5. Future directions in field

Hydrogen, as a clean energy carrier, has the potential to play a significant role in society's future. It has an environmentally friendly concept and can be produced from network surplus electricity in unpickable conditions through an electrolyser. Hydrogen can be converted to ammonia and methane for easier transportation and storage, and these fuels can be converted to hydrogen again. This versatility makes hydrogen an appealing choice for decreasing GHG emissions and shifting to a more sustainable energy system (Schiebahn et al., 2015; Bagheri et al., 2024). In addition, due to the depletion of oil and gas reserves, offshore oil and gas platforms can be converted to renewable energy site production, which could be employed for hydrogen production (Leporini et al., 2019).

Hydrogen fuel cell electric vehicles will have a bright future, and the development of hydrogen fuel cells will create new job opportunities. These positions encompass roles such as director of research and development for FCEVs, consultant for hydrogen systems sales, hydrogen fuel cell power systems engineer, hydrogen production technicians, maintenance staff for hydrogen fuel cell power plants, hydrogen fueling station managers and installers of hydrogen energy systems (Bezdek, 2018). Nowadays, many countries that follow the carbon-neutral scenario are also pioneers in the development of hydrogen fuel cell vehicles in the transportation industry. These countries include Korea, the United States, Japan, Germany, China, and France. The Hydrogen Council predicts that by 2050, 400 million cars, 15–20 million trucks, and almost 5 million buses will have entered the market (İnci, 2022). In Fig. 17, the prediction of leading countries in the field of hydrogen fuel cell electric vehicles is illustrated (İnci, 2022).

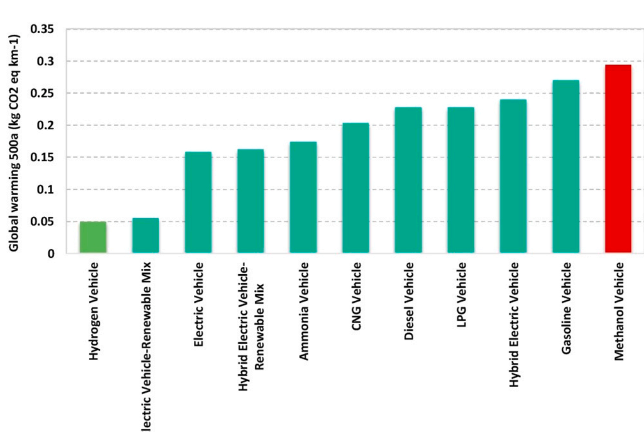

Fig. 16. Comparison of the life cycles of different vehicles in terms of their impact on global warming (Bicer and Dincer, 2018).

6. Conclusion

With the increase in global warming and the resulting environmental issues and climate changes, there is a need for sustainable solutions to transition to a carbon neutral future. Hydrogen is one of the green solutions to this problem that has a substantial potential to be used in several sectors to effectively mitigate GHG emissions and prevent climate change. In this review article, according to the importance of hydrogen in the energy transition, different aspects of hydrogen production and transportation are introduced and discussed. The findings obtained from this investigation are as follows:

- Hydrogen production technologies from conventional to renewable are introduced and discussed. Today, a large quantity of hydrogen is produced from fossil fuels due to their ecological feasibility. Environmental aspects of fossil fuels can be reduced by using CCU. However, water electrolysis powered by renewable energy is considered the most sustainable approach to hydrogen generation. Between renewable energy, solar and wind have significant potential for sustainable hydrogen production on a large scale. Also, the future potential of biomass is regarded, due to its low cost and abundant availability.
- Hydrogen is a promising energy carrier to utilize in the transportation sector. Hydrogen has the potential to be combined with IC engines like CI and SI, which is discussed. Also, hydrogen can supply the whole energy of the vehicle by using a fuel cell, which is a zero emission and sustainable approach. Among the various types of fuel cell vehicles, PEMFC is the most suitable for automotive applications. However, there are some limitations in large scale adoption.
- The hydrogen recirculation subsystem is one of the components in the PEMFC hydrogen vehicle that reduces the hydrogen waste and ensures the efficiency of the system.
- There are limitations for widespread adoption of hydrogen vehicles, like inadequate refueling infrastructure, high initial investment, hydrogen supply, safety concerns, etc. Also, the models of hydrogen fuel cell vehicles are limited and should be expanded.
- Hydrogen storage approaches like physical and chemical methods for hydrogen vehicles are introduced and discussed. In addition, environmental aspects of utilizing hydrogen vehicles are investigated and discussed.

In summary, this article review investigated the critical role of hydrogen energy in sustainable development. Various aspects of hydrogen energy, such as production technologies, hydrogen fuel cell vehicles, and environmental benefits, were discussed in detail. In addition, it suggested providing more research on emerging production technologies and modifying hydrogen fuel cell vehicle limitations for widespread adoption for future research. Also, research on cost reduction strategies and infrastructure development is recommended.

CRediT authorship contribution statement

Erfan Abbasian Hamedani: Writing – original draft, Visualization,

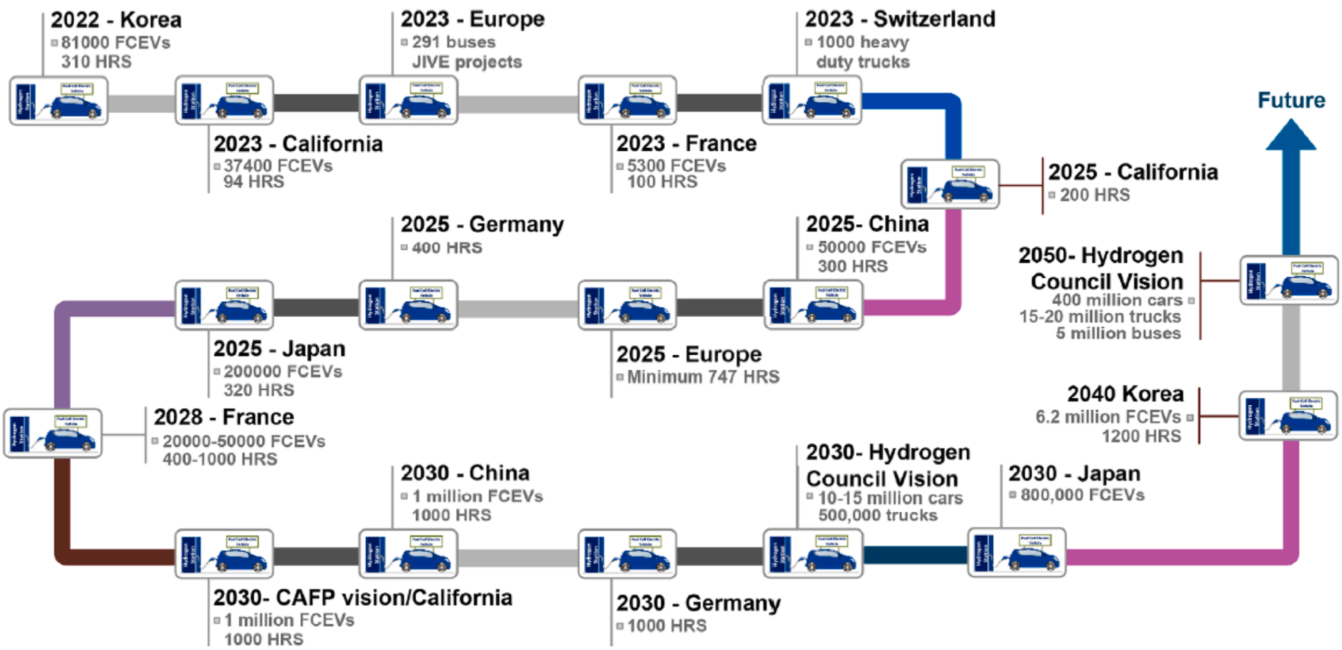

Fig. 17. Prediction and targets of countries in the field of hydrogen fuel cell electric vehicles (İnci, 2022).

Project administration, Methodology, Investigation, Data curation, Conceptualization, Writing – review & editing. **S. Talebi:** Writing – review & editing, Validation, Methodology, Supervision. **Seyed Ali Alenabi:** Writing – original draft, Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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