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REVIEW ARTICLE

Hydrogen fuel and fuel cell technology for cleaner future: a review

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Abstract
One of the main problems facing our planetary bodies is unexpected and sudden climate change due to continuously increasing global energy demand, which currently is being met by fossil fuels. Hydrogen is considered as one of the major energy solutions of the twenty-first century, capable of meeting future energy needs. Being 61a zero-emission fuel, it could reduce environmental impacts and craft novel energy opportunities. Hydrogen through fuel cells can be used in transport and distributed heating, as well as in energy storage systems. The transition from fossil-based fuels to hydrogen requires intensive research to overcome scientific and socio-economic barriers. The purpose of this paper is to reflect the current state, related issues, and projection of hydrogen and fuel elements within the conceptual framework of 61a future sustainable energy vision. An attempt has been made to compile in this paper the past hydrogen-related technologies, present challenges, and role of hydrogen in the future.

Keywords Hydrogen · Fuel-cell applications · Hydrogen storage · Environmental impacts · Energy

Introduction

In today's world, it is the need of the hour to reduce the dependency on fossil fuels. An increase in the global population and quality of life has led to 61a rapid increase in energy demand, and till date, fossil-based fuels are the major contributors towards meeting the global energy needs. The published data suggests that the energy demand is ever increasing since 1950 as shown in Fig. 1 (Ren et al. 2017). In addition, the non-renewable nature of fossil fuels suggests that these would inevitably be exhausted one day if human beings do not make efforts to conserve these resources (Shafiee and Erkan 2009). In the absence of fossil fuels, alternative fuels would be required to meet future energy needs, especially for the transportation sector, which consumes about 60% of global energy (Balat and Havva 2009). Among the available renewable energy resources, such as solar, wind, nuclear, marine, hydro, bio-fuels, and geothermal fuels, 61a high unit per mass (120 MJ/kg) is 61a critical factor to be considered without affecting the environment (Ren et al. 2016; Dunn 2002; Tour et al. 2010). The proposed "hydrogen economy" is powered by electricity, and hydrogen is 61a means of conserving electricity through chemical hydrogen bonds. In general, 6 kg of hydrogen can drive 61a light car at 61a distance of 500 km (Von Helmolt and Ulrich 2007; DOE 2015; Stetson 2012; Stroman et al. 2014).

Energy is 61a prerequisite for the development of 61a current state, and it is an important factor in sustainable development issues. Some of the available renewable sources of energy include solar radiation, wind, geothermal, and tides (Tollefson 2010). However, conversion of these renewable energy sources into useful forms of energy, such as hydrogen (bio-hydrogen), biogas, and biological alcohol, requires energy-consuming technologies (Dodds and Stephanie 2013). Recently, the importance of hydrogen fuel has been realized, and its use is becoming increasingly important. Widespread use of fossil fuels accelerates environmental degradation, as these fuels support the formation of carbon, nitrogen, sulfur, and other harmful oxides that may contribute to global warming (Dodds et al. 2015; Napp

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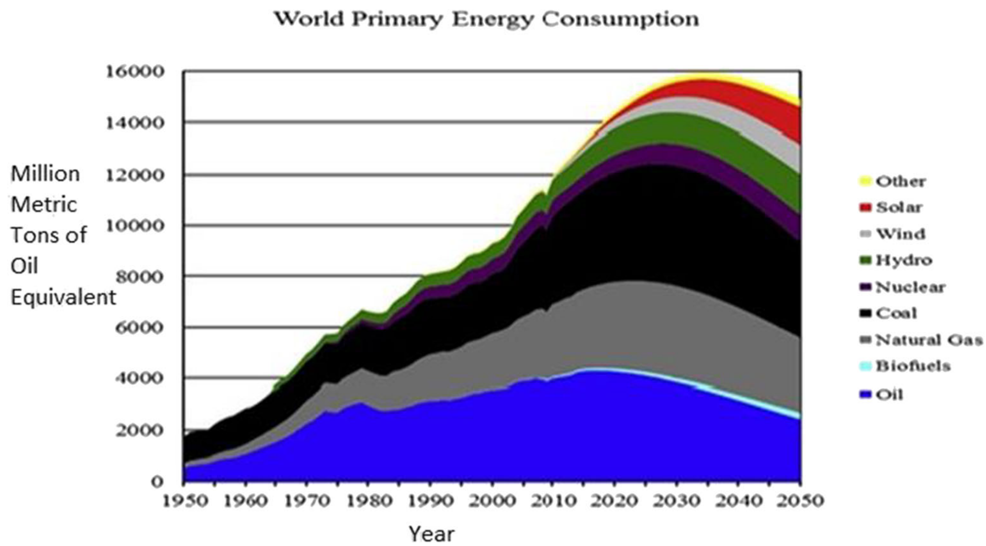


Fig. 1 Energy consumption (Ren et al. 2017)

et al. 2014). Hydrogen is 61a carbon-free energy element that could replace fossil fuels to meet global energy needs. It is considered as 61a clean and environmentally friendly energy source as it does not contain any traces of carbon (Ball and Marcel 2015; Samsatli et al. 2016). However, currently, the proportion of hydrogen produced from renewable resources is very low compared to hydrogen production driven from fossil fuels (REN21 2017; MacCarthy et al. 2015; Committee on Climate Change 2015; Explorer 2016; Kothari et al. 2010; Hübert et al. 2011; Ni et al. 2006).

Thirty years ago, hydrogen was recognized as “an essential element of 61a sustainable energy system” to provide safe, cost-effective, and environmentally friendly energy (US DOE 1995). Leading energy companies today consider hydrogen as the least dangerous and the least threatening to the global energy system (World Energy Council 2017; Energy 2003; Chamoun et al. 2015). “Hydrogen, as 61a viable alternative fuel, continues to promise much and deliver precious little” (Staffell et al. 2019). However, hydrogen may play an important role in the future with 61a low-carbon footprint (Martinez-Duart et al. 2015; Oener et al. 2017; Council 2017; Hart et al. 2016; Hanley et al. 2018) that offers 61a carbon-free energy. It also offers an efficient energy balance that can be easily transported and stored (Pudukudy et al. 2014; Abbasi and Abbasi 2011). A safer energy system allows less dependence on fossil fuels (Sheffield and Çigdem 2009; Dunn 2002) with the ability to work in the transport sectors (Coalition study 2010; Tollefson 2010), heat (Dodds and Stephanie 2013; Dodds et al. 2015), industry (Napp et al. 2014), and electricity (Ball and Marcel 2015; Samsatli et al. 2016). Together, they form two-thirds of global CO_2 emissions (REN21 2017; MacCarthy et al. 2015; Committee on Climate Change 2015) as shown in Fig. 2.

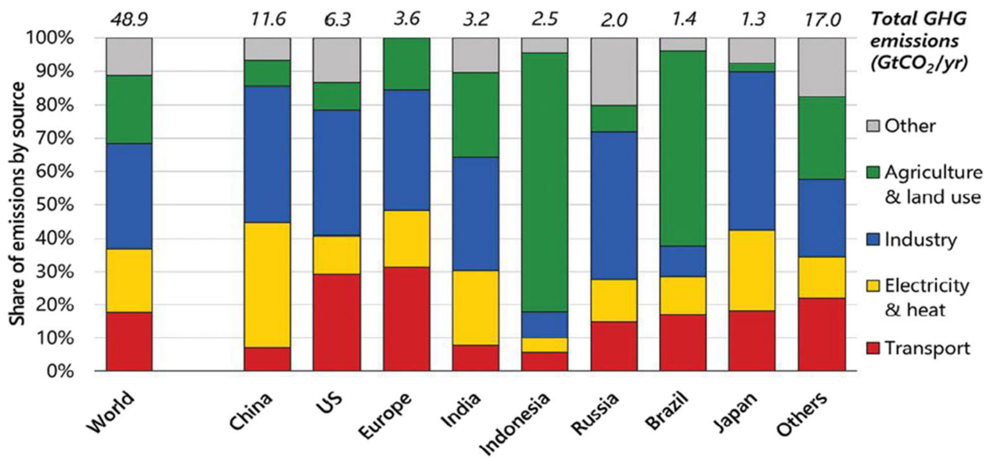
Hydrogen is considered as the future fuel because of its inherently immense energy content, low atomic mass, zero emission, and availability. It has higher mass energy than oil/petroleum that makes it suitable as an efficient energy source for many applications viz. automobiles, portable electronics, etc. (Ni et al. 2006). Usually, in high-temperature combustions, oxides of nitrogen are generated that results in atmospheric contamination, but utilization of hydrogen in fuel cells for power generation can completely eliminate this problem as it does not emit any harmful gases (Ahluwalia et al. 2005). Gahleitner (2013) has presented 61a critical study on power-to gas pilot plants for stationary power applications. The results of this study suggested that the amount of power produced in gas power stations using hydrogen was far more than what was produced in 61a renewable source–based power generation or gas distribution systems. Some European countries use power-to-gas technology to store energy in the form of hydrogen gas.

Hydrogen is foreseen as an appropriate alternative to conventional fuels that is eco-friendly and capable of replacing fossil-based fuels. The harmful effects of fossil-fuel combustion on the environment could be mitigated by using hydrogen as an energy source as well as energy carrier. Moreover, the immense energy content of hydrogen and low atomic weight make it 61a suitable candidate to reduce the burden on the global fossil-fuel reservoir, and environment by lowering the greenhouse gas (GHG) emissions. The published literature on hydrogen production, storage, and applications is quite vast and comprehensive. Therefore, the presented review is an attempt to consolidate the related information at one place that would help the scientific as well as non-scientific community to get 61a glimpse of the hydrogen and fuel cell technology.

Global scenario of hydrogen energy

Hydrogen is viable of the powerful alternative fuels for replacing the long-term fossil fuel (Dunn 2002). Numerous feasibility

Fig. 2 Worldwide greenhouse gas emissions (Explorer 2016)



studies have been carried out to investigate the feasibility of hydrogen as 61a potential replacement of the fossil fuels by European and Asian countries (Galli and Stefanoni 1997; Urbaniec and Robert 2009; Contreras et al. 2007). Leaver and Kenneth (2010) developed 61a multiregional model of an integrated energy system to assess the economic impact of hydrogen fuel cells and cell technology on the New Zealand economy (Dutton and Page 2007). The results show that hydrogen fuel fleets offer economic savings compared to conventional fleets. In countries like Norway (Contreras and Posso 2011), Brazil (Dutta 2014), Canada (De Souza 2000), and Venezuela (Momirlan and Veziroglu 2002), with high power density, HHES has the better potential to develop. In Latin America, the hydrogen energy field lacks exploration and development programs whereas Brazil is leading the research on generating H_2 energy from renewable resources (Durbin and Cecile 2013; De Lima et al. 2001; Da Silva et al. 2005).

An attempt has been made by various researchers to develop 61a mathematical structure (from 2000 to 20 years) that simulates the behavior of hydrogen generation, energy conversion efficiency, electricity costs, and electrolyzer cost based on the historical data and information provided by the manufacturer (Contreras et al. 2007). Europe, the USA, and Asian countries have made significant progress in the field of hydrogen energy (Ohta and Abe 1985). As part of the famous sunlight project, Japan in 1974 began investigating alternative energy sources such as hydrogen.

China has also reportedly taken the initiative to use H_2 as 61a power source (Ohta and Sastri 1979). Since 2000, the numbers of projects are running in collaboration with the National Natural Science Foundation that focuses on hydrogen storage, production, and fuel cell systems and sectors. The most important of these is 61a large electric vehicle development project backed by 880 million, in which half of the amount is to be used for the development of H_2 and fuel cells. The feasibility study of using renewable hydrogen as an alternative fuel has also been carried out in Bhutan (Yuan and Lin 2010; Young et al. 2007; Singh et al. 2007; Lee et al. 2008). These power systems have been shown to be located in remote and inaccessible places, which can lead to 61a large number of grid extensions resulting in energy development center. India Roadmap 2020 has proposed 61a Green Initiative Power with 61a capacity of 1000 MW (Lee et al. 2009). The roadmap provides milestones in hydrogen production reactors through biological and biomass methods that can be extended to the production of hydrogen in renewable space and the selection of technologies for commercial hydrogen production (Lee et al. 2009). Kim and Moon (2008) believed that the BTU tax, 61a government policy, would facilitate the transfer of hydrogen into oil by road transport. With the introduction of hydrogen as fuel in the road transport sector, the volume of conventional vehicles and CO_2 emissions would decrease and energy efficiency would improve in Korea.

Owing to the advantages offered by hydrogen, majority of global economies are eyeing the paradigm shift from conventional fuels to hydrogen for meeting their energy needs. The same is evident from the global hydrogen production capacity given in Fig. 3.

Why hydrogen?

Hydrogen is inherently 61a lightweight atom found in abundance on earth in the form of 61a chemical compound, like water, for example. It possesses immense energy content compared to conventional fossil fuels, as shown in Table 1. On the other hand, the bond energy required to break 61a reversible hydrocarbon bond is comparatively less, and hence, comparatively less energy is required to obtain hydrogen from its chemical compounds (refer to Table 1). Even conventional fossil fuels are complex compounds of hydrocarbons wherein hydrogen is deemed to be the primary powering source. It is the cleanest fuel ever discovered and can be obtained from water disassociation using electricity. Owing to its properties, hydrogen is considered as 61a viable alternative fuel capable of feeding the fuel cells on-board electric vehicles with no emissions. This would not only solve the problem of GHG

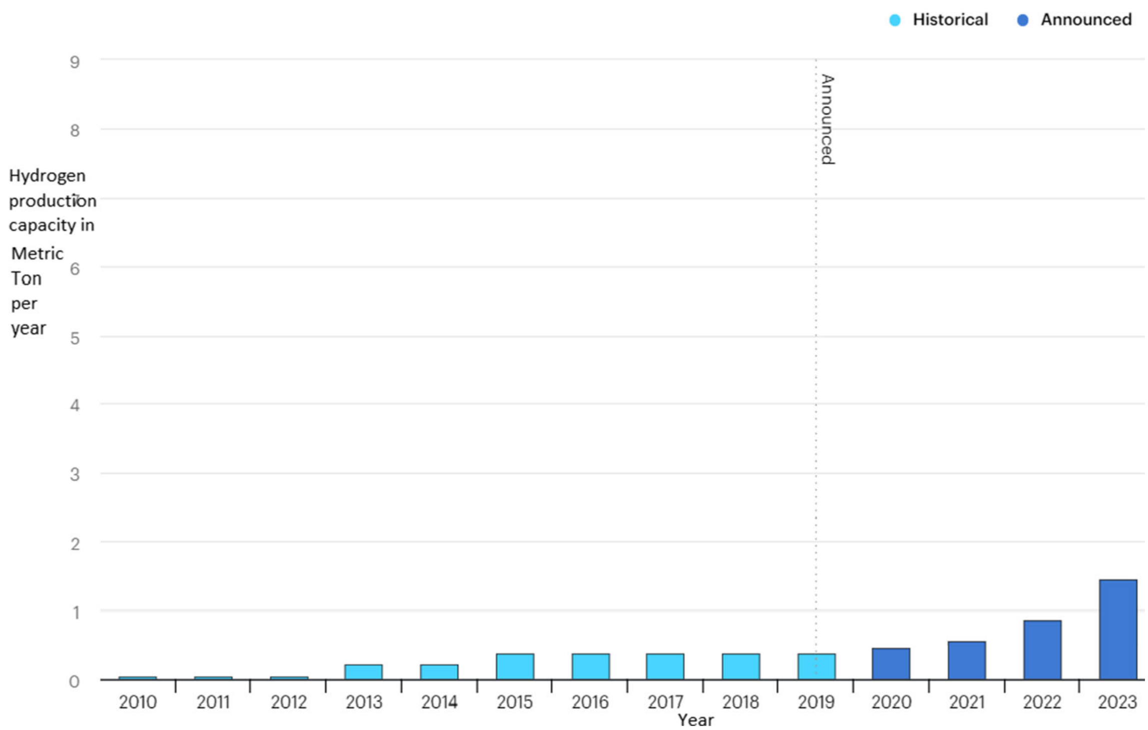


Fig. 3 Global hydrogen production capacity in metric ton per year (IEA 2014-2023)

emissions from vehicles but also resolve the issue of continuously depleting oil reserves. Besides, hydrogen fuel cells in combination with electric motors are 2–3 times more efficient than gasoline-powered internal combustion engines. However, its storage in an efficient and safe manner is yet to meet the benchmark. So, hydrogen is definitely the future fuel for meeting the energy needs of humankind, being 61a green source of energy with low GHG emissions and low-carbon footprint compared to the conventional energy sources.

Hydrogen production and energy storage

Sources of hydrogen

Talking about the physical appearance of hydrogen, it is the most common element of the universe (Jones 2015). Most of the hydrogen on earth is available in the form of chemical compounds viz. water, hydrocarbon in the dead, fossil fuels, and biomass (Utgikar and Thiesen 2005). On the other hand, the chemical bonds of compounds can be obtained by breaking down their bonds. Common methods include electrolysis from steam and hydrocarbons or carbon, metal acid reactions, ionic hydrides, and water (Hydrogen-energy 2020).

Availability of hydrogen

In general, fossil fuels and natural gas include hydrogen sources. Renewable sources such as wind, solar, geothermal, and biomass could also be used for hydrogen production. It is to be noted that hydrogen is not available in free form on planet earth. Instead, hydrogen is found as 61a chemical compound in the form of hydrocarbons. Hydrogen production

Table 1 Comparison of fuels in terms of bond energy and heating value

Fuel	Compound	Chemical formula	Bond energy (C–H)	Heating value (MJ/kg)
Wood	Cellulose	$(C_6H_{10}O_5)_n$	~ 600 kJ/mol	22
Coal (black)	Carbon	Mainly C + H_2O + S	~ 500 kJ/mol	33
Petrol	Octane	C_8H_{18}	~ 400 kJ/mol	47
Diesel	Cetane	$C_{12}H_{24}$	~ 400 kJ/mol	49
Natural gas	Methane	CH_4	~ 400 kJ/mol	54
Reversible hydrocarbons		$nCmH$	~ 30–50 kJ/mol needed	Hydrogen 142

could be summarized in the form of 61a flow chart shown in Fig. 4.

Hydrogen production

Cheap hydrogen production from 61a renewable source is an important element for real-life H_2energy. This tool enables the creation of actual process data–based theoretical stations, which can be used for laboratory-scale experiments. The process simulation results provide an opportunity to review different techniques and identify barriers and capabilities. A simulation is used to evaluate different melting and different techniques for hydrogen production (Miltner et al. 2010). This includes the modification of biogas as well as the modification of biomass by dark fermentation in which silica directly produces hydrogen from the biomass.

Production of hydrogen from water

Hydrogen can be produced from water in 61a variety of ways, such as heat, electrolysis, and chemical and photo-chemical reactions (Huang et al. 2011). Solar radiation is 61a reliable source of energy used to generate electricity in two different ways: PV and solar heat. Electricity from PV is widely used to run an electrolyzer meant to split water into hydrogen and oxygen. For the generation of photoelectric hydrogen, 61a storage system could operate under cloudy conditions and without sunlight (Markandya and Wilkinson 2007). The production of biological H_2 can be divided into three major groups, photo-fermentation, bio-photolysis, and dark fermentation (Oh et al. 2011; Kruse et al. 2005; Prince and Kheshgi 2005; Patriarca et al. 2012; Vijayaraghavan et al. 2009).

Production of hydrogen from glycerol

Glycerin can be obtained as 61a by-product while producing biodiesel from biomass and vegetable oil. About 1 kg of glycerin is produced against 9 kg of diesel fuel produced from biomass (Zheng et al. 2008). A base catalyzed reaction is generally employed to split the oil into glycerol and biodiesel.

Dave and Pant (2011) have shown how hydrogen production has increased with the improvement of glycerin vapor over nickel catalysts through zirconia, strongly supported by ceria. Bio-gasoline-ethanol compounds can be used as 61a raw material for the production of H_2 by catalytic vapors. Advances in the evaporation of biomolecules in nickel and platinum catalysts have led to the formation of H_2 in N_2 AI_2O_3, La_2O_3, and CO_2 AI_2O_3. A comparison of the activity of platinum and nickel catalysts shows that platinum catalysts are less effective than H_2 (Iriondo et al. 2012).

Production of hydrogen from biomass

An alternative of using biomass is to produce hydrogen by fermentation. Hydrogen is the title of 61a breach of the integrated budget yeast project under the EU's energy program. The project aims to design 61a complete hydrogen plant that will produce two phases of hydrogen. Marketing of hydrogen production technology was estimated after 2015 (Claassen et al. 2010; Boran et al. 2012). It is found that *Rhodobacter capsulatus* develops rapidly and 61a specific rate of growth is 0.025 h (Sasikala et al. 1993; Venetsaneas et al. 2009). It has been shown that the system can be used to produce acetic acid biosynthesis, growth, and hydrogen production even at low light intensity and low temperatures. The total hydrogen yield was 0.6 ml of H_2 per mole of acetic acid. This study shows that on 61a test scale, hydrogen can also be generated in 61a tube bioreactor in winter. An anaerobic hydrogen production system has been developed for biomass waste. Yang et al. (2011) reported that renewable lipid-extracted microalgal biomass residues (LMBR) are 61a source of hydrogen production. The process of manufacturing of LMBR biodiesel consists of biomass residues containing carbohydrates and proteins (Sialve et al. 2009; Zhang et al. 2011).

Production of hydrogen from other sources

Studies have shown that urea can be used as 61a raw material for H_2 preparation. Alkaline media is used in the process of producing hydrogen and other valuable products (nitrogen and freshwater) through the electrochemical oxidation of urea (King and Gerardine 2011). This urea oxidation with hydrogen has many advantages over the standard hydrogen preparation process. Pure hydrogen (100%) is manufactured for heat, pressure, and energy as well as other valuable products such as nitrogen (96.1%) and cheap freshwater (Boggs et al.

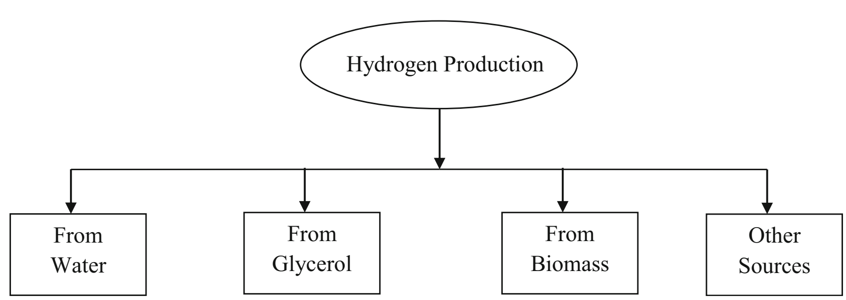


Fig. 4 Flow chart summarizing various sources for hydrogen production

2009). Cheap nickel is an alkaline medium that is found to be the most efficient driver for electrochemical oxidation of human urine (King 2010). Some researchers (Wrana et al. 2010) have found that electro-hydrogenation is an ideal way to produce hydrogen from organic matter. Electro-hydrogenation is 61a geochemical process in which microbial organic matter is oxidized to protons and electrons and produces hydrogen gas. Electrons can completely decompose the substrate, resulting in better performance of the H_2 cathode from previously calculated organic waste sources (Siso 1996; Stamatelatou et al. 2010; Castelló et al. 2009; Boggs 2010).

Energy storage methods

Energy storage methods in general can be broadly classified into five distinct categories (Yu and Chen 2011), namely:

(a) Mechanical energy storage
(b) Thermal energy storage
(c) Electrochemical energy storage
(d) Electromagnetic energy storage
(e) Chemical energy storage

(61a) Mechanical energy storage

The storage techniques for mechanical energy are mainly classified as compressed air storage, valve storage, and pump storage. The characteristic features of 61a compressed air storage system are long service life, high capacity, and so on. It converts compressed air into other alternative energy sources and thus has the capability of generating cold, heat, and electricity (Mei et al. 2015). However, some of the challenges that are experienced while operating this system are the complexity of the system, high tunnel storage conditions, and low efficiency. Valve storage also offers many advantages such as fast response, low efficiency and maintenance, high efficiency, long service life, good stability, no pollution, and short footprint, but the only drawback is it offers low energy density. One of the mature technologies is the pump storage system which features 61a long service life, low cost unit, and high capacity (Liangzhong et al. 2016). However, geographical conditions pose another challenge which limits the construction of pumping storage facilities. The overall investment is large and the time required for its construction is also long (Pati and Mishra 2020; Zhang et al. 2015).

(61b) Thermal energy storage

Sensible heat storage and latent heat storage are the broad division of thermal energy storage methods. By increasing the temperature of the heat storage material, sensible heat storage can be achieved. The commonly used heat storage device is water (Zahedi 2014). For example, in 61a photo-thermal system, the electricity or the required heating power can be supplied in the form of solar radiation by the heat storage system. Therefore, according to the desired grid, the electrical power of the heat storage system can be adjusted (García et al. 2011). The cost of an energy storage system is 1/30 that of the battery storage, and its efficiency ranges between 95 and 97% (Vick and Moss 2013).

The present research area for 61a concentrated solar thermal power (CSTP) plant is molten salt storage technology. It is marketed in various industrialized countries such as Spain and Italy, and other European and North American regions, due to its characterized features such as high heat capacity, low cost, and safety. However, its significant disadvantage is corrosion due to which there are issues regarding its practical use. Secondly, due to the high temperature of molten salt, the goods get damaged easily.

(c) Electrochemical energy storage

Lead acid batteries, lithium-ion batteries, and sodium sulfur batteries are included in technologies related to electrochemical energy storage. Traditional lead acid battery technology is well developed and offers low cost and easy maintenance (Wu et al. 2017). However, low life expectancy, pollution, low energy density, and so on are some of its disadvantages regardless of the low capacity for rapid, deep, and energetic discharges (Parasuraman et al. 2013). In recent years, some countries including the USA and Japan took 61a pledge to fabricate the highest lead acid batteries. They have been successful in manufacturing 61a wide variety of batteries which includes super batteries, lead carbon batteries, and many more.

Presently, the energy industry is using lithium-ion batteries in 61a wide range. These include lithium titanate, nickel-cobalt-manganese lithium batteries, and lithium iron-phosphate batteries. The cost of 61a lithium titanate battery is relatively high. The characteristic features of 61a lithium titanate battery are high safety, good charge/discharge, and long service life. These features make it an asset for further development of lithium ion batteries in the future. Nickel-cobalt-manganese lithium batteries have relatively high energy consumption. The mass production of these batteries is limited due to its high cost and limited resources of cobalt. The benefits offered by lithium iron-phosphate batteries are those of improved strength and stability along with 61a longer shelf/cycle life.

(d) Electromagnetic energy storage

The electromagnetic energy storage mainly consists of 61a super capacitor and super conducting magnetic energy storage. The main advantages of 61a super capacitor are fast response, high energy density, high efficiency, ambient temperature range, long service life, low maintenance, and so on (Zhang et al. 2016). However, it is suitable for use with other super capacitor energy storage technologies due to the low energy density (Béguin et al. 2014). A superconducting magnetic energy storage device's charge/discharge rate has fast response, high energy transfer efficiency, high power density, long life, etc. It also fulfills the requirement of high energy.

However, its disadvantages include low energy density, complex care, and high cost (Luo et al. 2015).

(e) Chemical energy storage

Another source of energy that uses synthetic gas (hydrogen gas), and thus hydrolyzes the electrolyte, is chemical energy storage. Carbon dioxide in natural gas (methane) can also be used to produce it. Due to this green technology, up to 100 GW of energy can be saved. It can also lead to widespread usage of energy storage as it eliminates environmental pollution. However, it suffers from low energy conversion efficiency problems and ranges from 40 to 50% with high cost and low security (Wang et al. 2016). Presently, in many countries, hydrogen storage technology has also been established as 61a vital method of using fuel cell hydrogen. A proton exchange membrane fuel cell is widely used in energy, heating, transportation, and other industries. It improves the use of renewable energy and acts as 61a backup energy source. As 61a large-scale energy system, the main motive of the present application is to improve efficiency, cost, and service life and thus utilize renewable energy and hydrogen in 61a better way.

Hydrogen storage

The storage of hydrogen is also very important due to its wide range of applications that range from stationary and portable energy to transportation. It also has the highest potential among high-range fuels (Das 1996). However, since the density of the ambient temperature is low, the energy per unit volume is low; therefore, it is necessary to develop an improved storage method that can increase energy density. Hydrogen can be physically stored as 61a gas or liquid (Dündar-Tekkaya and Yürüm 2016). Usually, 61a high-pressure tank is required to store hydrogen as gas (tank pressure 350–700 bar 5000–10,000 psi) (Zhu et al. 2015). Various hydrogen storage methods are shown diagrammatically in Fig. 5.

Compressed hydrogen storage A vehicle needs 61a high compression ratio to extract enough hydrogen to operate the vehicle for about 500 km. Due to the high pressure involved, the integrity of the tank is 61a problem. Tank material like high-strength steel is suitable for high efficiency, but due to hydrogen-bonding problems, the tank usually becomes overweight. Other material options are stainless-steel or composite cylinders. There are 3 or 4 types of commercial tanks available with light or metal cladding (Imamura et al. 2005). The commercially available pressure vessels contain 61a hydrogen mixture from 5000 to 10,000 psi. It needs to hold 5 kg of compressed hydrogen with 61a volume of 212 l (or 56 gal), which is much higher than normal (Zaluski et al. 1997; Zhu et al. 2006).

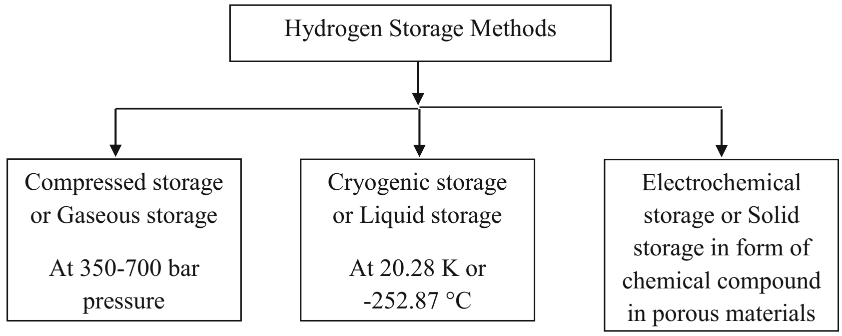
Liquid hydrogen storage The biggest problem with hydrogen storage in liquid form is maintaining cryogenic temperatures (Sakintuna et al. 2007; Xu and Song 2006; Polanski et al. 2008; Vijay et al. 2007). A major part of the energy expenditure is for maintaining the cryogenic temperature of 20.28 K or − 252.87 °C. Well-insulated containers are present, but over time, the liquid hydrogen gets trapped by the heat, turns into 61a gas, and must be released to avoid excessive pressure. An estimated 4.6 kg of tank capacity is estimated to be around 4% per day, but the disadvantages of large tanks are small (Gennari and Esquivel 2008).

Solid-state storage Hydrogen could be stored as 61a chemical compound generally referred to as solid-state storage. Various materials viz. complex metal hydrides, activated carbons, and other porous materials have been explored for solid-state hydrogen storage. However, materials like composites have problems in terms of material strength, tank safety, and ultimate tank weight, whereas problems associated with liquid hydrogen storage includes energy losses in terms of fluid leakage, etc. One solution for such problem is solid hydrogen storage, in which hydrogen is physically or chemically mixed with 61a particular hydrate substance, and hydrogen can be removed at any time by thermal catalysis (Kusadome et al. 2007; Shao et al. 2004). In the case of physically bound hydrogen, hydrogen gas is held to 61a level that has 61a large surface area when chemically combined with hydrogen substrate (such as metal hydrides and 61a compound hydride) and hydrogen. Hydrogen sorption and desorption properties of several materials, including chemotherapy exposed zeolites, organic metal framework, and carbon nano-tubes, were examined (Demircan et al. 2005; Muthukumar et al. 2005; Zaluski et al. 1995). The concentration has recently been converted to 61a complex, chemical hydride containing 61a large amount of hydrogen. This form (solid state) of hydrogen storage is considered as the safest among its counterparts because hydrogen ions get bound as 61a chemical compound instead of moving freely to react with oxygen. Generally, an integrated porous hydrogen storage electrode is incorporated within 61a modified unitized regenerative fuel cell (URFC) wherein hydrogen in ionic form gets adsorbed chemically as well as physically.

Hydrogen applications and fuel cell

Hydrogen can also be used for an electric power generation system, which includes fuel cells for vehicles and distributed production. Fuel cells use low-temperature electrochemical processes to convert hydrogen into fuel and directly oxidize it to electricity. Hydrogen fuel cells will be an important factor contributing to the future transition to 61a low-CO_2 sustainable energy system. To promote fuel cell and hydrogen

Fig. 5 A flow chart summarizing methods of hydrogen storage (Das 1996; Dündar-Tekkaya and Yürüm 2016; Zhu et al. 2015)



technology, many countries often create roadmaps with specific numerical targets.

There are currently three main technical barriers that must be overcome to move from 61a carbon energy system to 61a hydrogen economy. First, the cost of efficient and sustainable hydrogen production and delivery must be significantly reduced. Secondly, it is necessary to develop 61a new generation of hydrogen storage systems for vehicles and stationary applications. Finally, the cost of fuel cells and other hydrogen-based systems needs to be reduced. Hydrogen also has the advantage of storing volatile and renewable sources such as solar, wind, wave, and tidal energy (Priya and Das 2016). Therefore, it provides 61a solution to one of the main problems of sustainable energy. Hydrogen is produced from raw materials that do not contain fossil fuels, but are truly sustainable or renewable fuels.

In addition, it allows renewable energy to be brought into the local hydrogen transport sector, which has significant benefit in terms of energy and economic security. Hydrogen storage is 61a key component of energy storage, and creates 61a close relationship between sustainable energy technology and sustainable energy savings, commonly known as the “hydrogen economy.”

The protection of hydrogen is also important, because it involves not only scientific technology but also psychological issues. Despite its recognized credibility, the hydrogen industry has 61a unique record of safety for many years. However, hydrogen is different from modern gasoline because it can pass through smaller channels and has varied and combustion characteristics. This is also very different from carbon-based fuels. Hydrogen, like electricity, can be considered as 61a source of clean energy. Hydrogen can be produced from 61a variety of sources, including renewable and nuclear energy. Hydrogen as 61a fuel promises to be an alternative fuel for the transportation sector, production of electricity, heat and water for the end uses, and commercial applications including in telecom towers for providing back-up power. In the long run, hydrogen can simultaneously reduce reliance on foreign oil along with reducing harmful effects of greenhouse gas emissions (Priya and Das).

Hydrogen in fuel cells

Since 2018, most fossil fuels have been producing hydrogen through partial oxidation of methane and conversion of steam through coal gasification, biomass gasification, and electrolysis of water (Ogden 1999). In the periodic table, hydrogen is shown as the first period and the first group. Hydrogen gas is so light that it rises in the atmosphere and is rarely found in the pure form of H_2 (Altork 2010) as shown in Eq. 1.

$$2H_2\ (g) + O_2\ (g) \rightarrow 2H_2O\ (g) + \text{energy} \qquad (1)$$

When carried out in the atmosphere instead of pure oxygen, as usual, hydrogen combustion can produce 61a small amount of nitrogen oxides along with water vapors. Hydrogen is used as fuel due to the energy released, and electrochemical cells can use this energy with relatively high efficiency. When using heat only, standard thermal performance limits are applied (Pandev et al. 2017). Hydrogen is generally regarded as an energy carrier such as electricity (such as solar turbines or solar energy) because it must be generated from large sources of energy such as solar, biomass, and electricity (Slavova 2016; Open Research Online 2016).

Classification of fuel cells

In 1839, the first demonstration of 61a basic fuel cell is given by Sir William Grove (Grove 1839). “Fuel cell is an electrochemical device that produces electricity without combustion by combining hydrogen and oxygen to produce water and heat.” Marine ships, commercial vehicles and aircrafts, etc. are the wide applications of fuel cells. There are several types of fuel cell depending on the electrolyte base and operating temperature. Figure 6 shows the classification of fuel cells, and the different types of fuel cells are explained by Gautam and Ikram (2010) and Singla et al. (2019a, 2019b).

Phosphoric acid fuel cell

The evolution of this cell took place in 1965. As the name suggests, phosphoric acid with 100% concentration is used as an electrolyte in this type of cell. Its operating temperature is in the range of 150 to 220 °C. Reportedly, the electrocatalyst used is generally platinum, on both anode and cathode sides (Appleby and Foulkes 1993). The charge carrier in this fuel cell is H^+ ions (refer to Fig. 7). Since PAFC involves an external reforming of the fuel, it takes hours to start operating. The power density of this cell is 55%, and the performance of this cell is lower than that of the alkaline fuel cell. It is the first conventional fuel cell that got commercialized. The electrochemical reactions incurred in 61a PAFC are as below:

The chemical reaction of the anode is shown in Eq. 2:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (2)$$

The chemical reaction of the cathode is shown in Eq. 3:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (3)$$

The overall chemical reaction of this fuel cell in terms of Eq. 4:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (4)$$

Alkaline fuel cell

Generally, KOH is the electrolyte used in such type of cells. Usually, 85% concentration of KOH is used for high-temperature operations whereas 35 to 50% concentration is used for lower-temperature operations. A typical alkaline fuel cell could operate between the temperature ranges of 50 and 200 °C. However, its usual lower operating temperature is 50 °C, and its high operating temperature is 200 °C. In this type of fuel cell, OH^- ions are the charge carrier and platinum-based material acts as 61a catalyst (refer to Fig. 8). The electrolyte is the primary cell component, and H_2 is the primary fuel in 61a typical AFC. The average efficiency of the AFC is 50 to 60% of the combined cycle. In 1960, the first AFC was developed and was used for running the vehicle as well as the Apollo space vehicle (Koscher and Kordesch 2003; Carrett et al. 2001). While operating on O_2 and H_2, an AFC performs better than other fuel cells. The electrochemical reactions of this fuel cell are:

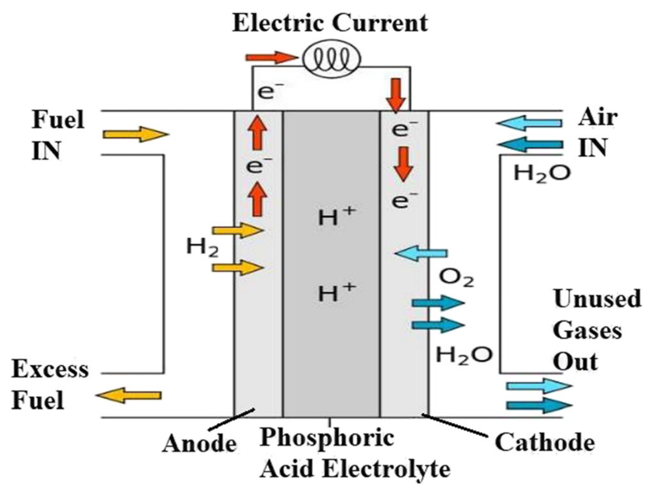


Fig. 7 Schematic of 61a phosphoric acid fuel cell (PAFC) modified from Coralli et al. (2019)

The chemical reaction of the anode is shown in Eq. 5:

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \quad (5)$$

The chemical reaction of the cathode is shown in Eq. 6:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (6)$$

The overall electrochemical reaction of this fuel cell in terms of Eq. 7:

$$2H_2 + O_2 \rightarrow 2H_2O \quad (7)$$

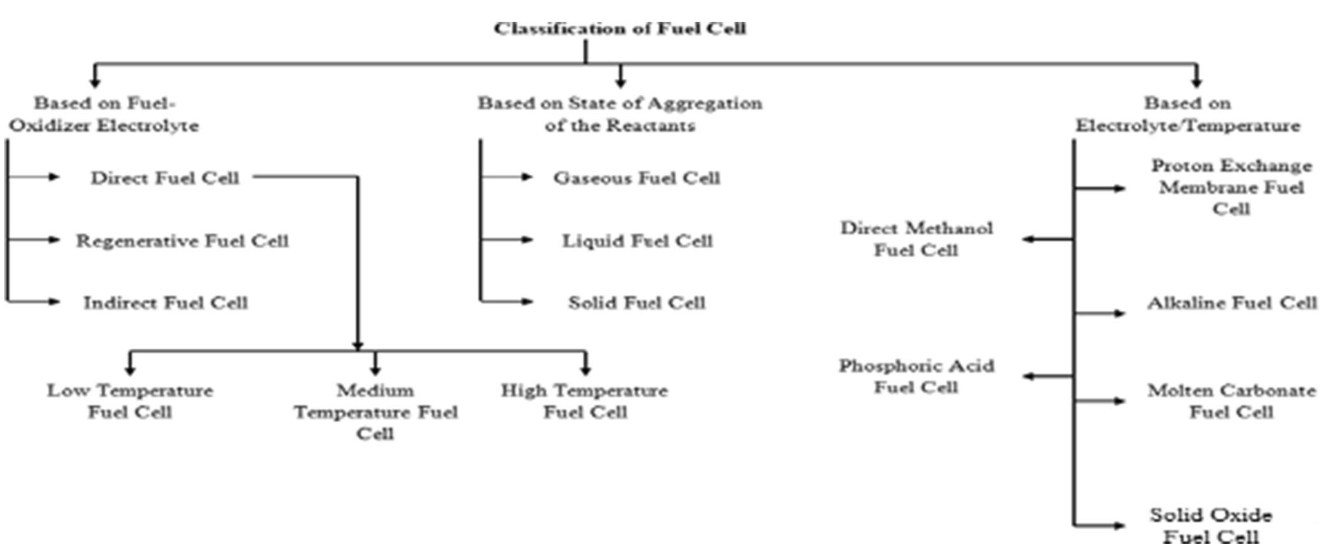


Fig. 6 Classifications of fuel cells (Singla et al. 2019a, 2019b)

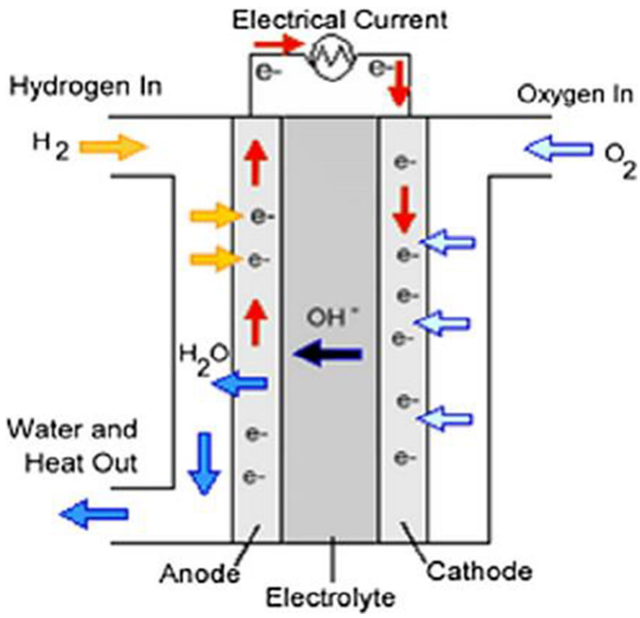


Fig. 8 Schematic of an alkaline fuel cell (AFC) (Vaghari et al. 2013)

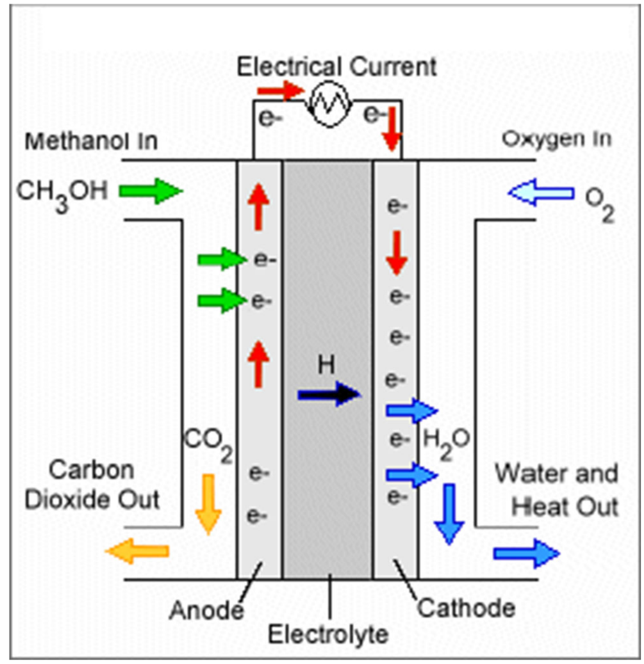


Fig. 9 Schematic of 61a direct methanol fuel cell (DMFC) (derekcarrsavvychemist 2020)

Direct methanol fuel cell

This fuel cell is also known as 61a direct methanol proton exchange fuel cell (DMPEFC). It is 61a special type of low-temperature fuel cell that operates on the principle of 61a PEMFC. Various components of 61a DMFC are two bipolar end plates that act as anode and cathode, catalysts, and an electrolyte membrane. In this type of fuel cell, H^+ ions are the charge carrier and platinum-based material acts as 61a catalyst (refer to Fig. 9). The primary fuel in 61a typical DMFC is methanol, and the average cell efficiency is up to 30 to 40%. From 1960 to the early 1980s, the trend of using conventional electrolytes got changed (Arico et al. 2009), and in the 1990s, polymer-based electrolytes were introduced in DMFC (Hacquard 2005). The chemical reaction of this cell is:

The chemical reaction of the anode is shown in Eq. 8:

$$\mathrm{CH_3OH} + H_2O \rightarrow \mathrm{CO_2} + 6H^+ + 6e^- \tag{8}$$

The chemical reaction of the cathode is shown in Eq. 9:

$$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \tag{9}$$

The overall electrochemical reaction of this cell in terms of Eq. 10:

$$\mathrm{CH_3OH} + \frac{3}{2}O_2 \rightarrow \mathrm{CO_2} + 2H_2O \tag{10}$$

It is revealed through research that when the ceramic-type electrolyte is used, then the operating temperature of the DMFC could reach between 450 and 500 °C (Giri 2016). The main disadvantage of this fuel cell is the slow startup. It takes more time to start compared to other fuel cells because of its high operating temperature.

Molten carbonate fuel cell

This cell got introduced in the 1960s. A combination of an alkali carbonate is generally used as an electrolyte in this cell and, hence, the name of the cell, MCFC. The operating temperature of this cell is between 600 and 700 °C. Carbonate ions ($CO_3^{=}$) are the charge carriers in the cell and nickel serves as 61a catalyst (refer to Fig. 10). End plates of this fuel cell are made from stainless steel to avoid corrosion, and the fuels used are CH_4, H_2, and CO_2. The efficiency of 61a MCFC ranges from 55 to 65% which is higher than that of other fuel cells. The MCFC is the second-generation fuel cell after PAFC because it is also used for commercial purposes (Ermete 2012). The electrochemical reaction of this cell is:

The chemical reaction of the anode is shown in Eq. 11:

$$H_2 + \mathrm{CO_3^{=}} \rightarrow H_2O + \mathrm{CO_2} + 2e^- \tag{11}$$

The chemical reaction of the cathode is shown in Eq. 12:

$$\frac{1}{2}O_2 + \mathrm{CO_2} + 2e^- \rightarrow \mathrm{CO_3^{=}} \tag{12}$$

The overall electrochemical reaction of this cell in terms of Eq. 13:

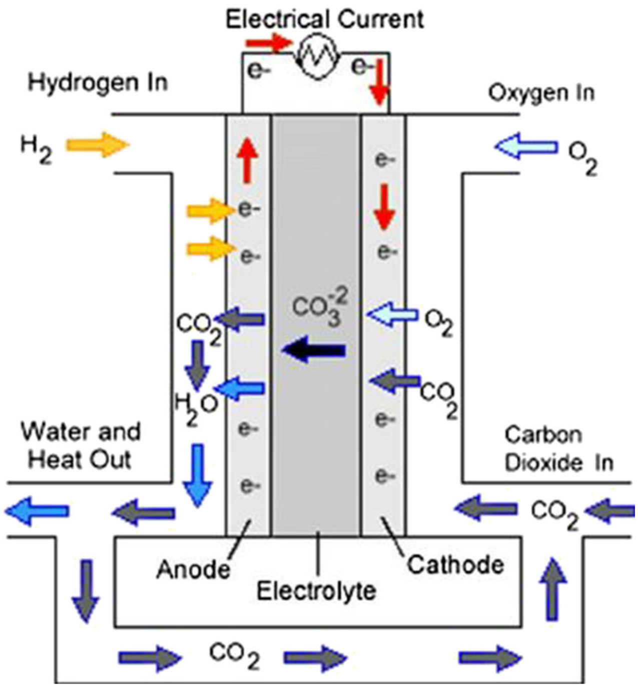


Fig. 10 Schematic of 61a molten carbonate fuel cell (MCFC) (Vaghari et al. 2013)

$$H_2 + \frac{1}{2}O_2 + CO_2 \rightarrow H_2O + CO_2 \quad (13)$$

Solid oxide fuel cell

The electrolyte used in this cell is solid, non-porous metal oxide. Its operating temperature is between 700 and 1000 °C. This cell has the highest operating temperature among all fuel cells. The $O^{=}$ ions are the charge carriers, and the catalysts used in this cell are made up of perovskite (refer to Fig. 11). The primary components of the cell are of ceramic. The efficiency of this cell is similar to that of 61a MCFC, and the power density of this cell is 1.5 to 2.6 (kW/m^3). Tabular and flat are the two different configurations of the solid oxide fuel cell (SOFC). SOFC was developed in the 1950s, but it was in the 2000s when its mechanical characteristics were improved (Bessette and Wepfer 1996; Patel et al. 2004). The electrochemical reaction of this fuel is:

The chemical reaction of the anode is shown in Eq. 14:

$$H_2 + O^{=} \rightarrow H_2O + 2e^{-} \quad (14)$$

The chemical reaction of the cathode is shown in Eq. 15:

$$\frac{1}{2}O_2 + 2e^{-} \rightarrow O^{=} \quad (15)$$

The overall electrochemical response of this cell in terms of Eq. 16:

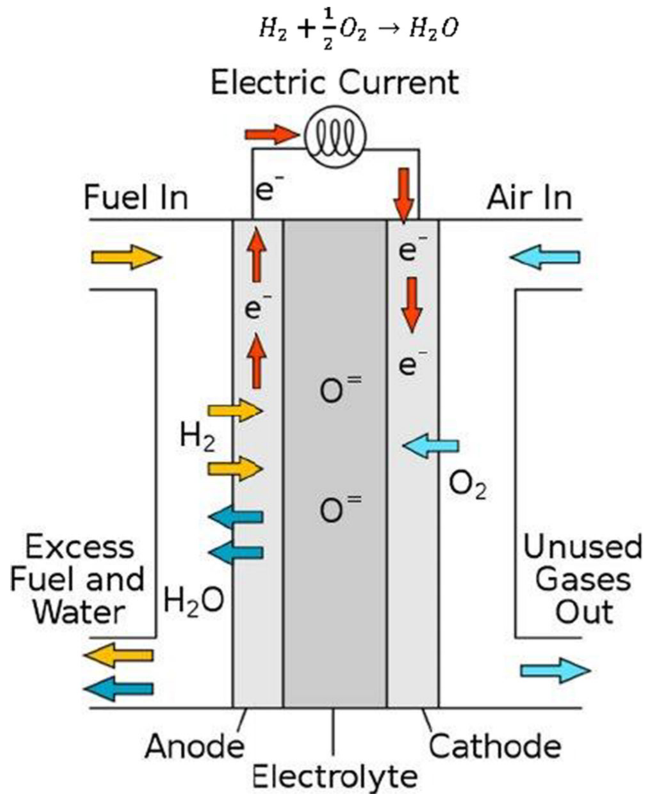


Fig. 11 Schematic of 61a solid oxide fuel cell (SOFC) (Vaghari et al. 2013)

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (16)$$

Polymer electrolyte membrane fuel cell

This cell is also known as 61a proton exchange membrane fuel cell (PEMFC). It consists of 61a membrane-type solid electrolyte made from 61a polymer called perfluorosulfonic acid (commercially known as Nafion). This membrane electrolyte serves as 61a proton exchange medium between the anode and cathode of 61a PEMFC as shown in Fig. 12. PEMFC is the most widely used fuel cell because of the quick starting time and shutdown time and simplicity. Its operating temperature ranges from 50 to 100 °C and the efficiency is between 40 and 60%. Based on temperature, this cell is divided into two categories, i.e., high temperature and low temperature. The operating range of 61a high-temperature fuel cell varies from 100 to 200 °C and low temperature varies from 50 to 100 °C (Feroldi and Basualdo 2012; Shamardina et al. 2010). The electrochemical reactions involved in the working of 61a typical PEM fuel are:

The chemical reaction of the anode is shown in Eq. 17:

$$H_2 \rightarrow 2H^{+} + 2e^{-} \quad (17)$$

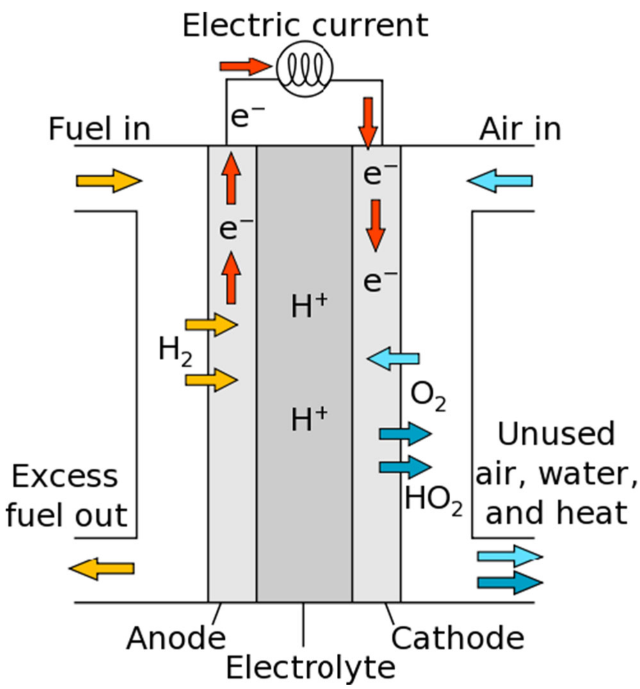


Fig. 12 Schematic of 61a polymer electrolyte membrane fuel cell (PEMFC) (Wikipedia 2020)

The chemical reaction of the cathode is shown in Eq. 18:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{18}$$

The overall chemical reaction of this fuel cell is shown in Eq. 19:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{19}$$

Practical advantages of hydrogen fuel cells

Battery-powered vehicles take nearly 45 min to recharge themselves whereas hydrogen vehicles are refueled in less than 10 min which is an additional benefit in terms of time (Thomas 2009). Moreover, hydrogen vehicles are much lighter in weight, in comparison with battery vehicles, which is 61a beneficiary element for heavy vehicles like trucks and buses. Not only limited to this, but hydrogen fuel cells also find applications in marine ships. The battery is composed of very hazardous materials like cobalt, lead, and lithium which are non-friendly to the environment as well as to human health. PEMFC mainly comprises polymers and graphite which are environmentally friendly and are easily available, except platinum. Due to its excellent catalyst properties at low temperature, its replacement is very difficult. Fears of 61a decline in platinum (Pt) reserves could be attributed to the widespread acceptance of proton exchange membrane fuel cells, but Heraeus says the expected demand for 2020 could be easily met (Rivard et al. 2019; BunesCansado 2018; Mir-Artigues et al. 2019; Chen et al. 2019). The hydrogen fuel cells are also suitable for stand-alone power supplies for remote location electrification, and as 61a portable power supply for meeting the energy needs of the defense troops at far-flung places and in war zones. Nowadays, these are being exploited to meet the power demand of miniature electronic devices. The hydrogen-based fuel cells definitely have all the potential to replace the lithium-based and acid-based batteries for 61a sustainable and better tomorrow.

Applications of fuel cells

Power

For the commercial, residential, backup power generation and industrial, the stationary fuel cells are used. In remote locations, fuel cells are very useful as power sources in weather stations, communication centers, military applications, etc. The fuel cell working on hydrogen is compact and lightweight, because in fuel cells, no moving part is involved. Stationary fuel cells have many different types, so that is why efficiency varies between 40 and 60% (Hart et al. 2014). Hydrogen as fuel also finds application in the fields of automotive, stand-alone power supplies, grid-connected renewable energy systems, and fuel cells.

Cogeneration

Cogeneration fuel cell systems including micro combined heat and power (MicroCHP) systems are used to generate energy and heat for factories and homes. The system generates continuous electrical energy, and at the same time, it generates residues of hot air and water. The efficiency of 61a cogeneration system reaches up to 85% (Mutombo 2017). A phosphoric acid fuel cell also uses 61a combined heat and power system, and its electrical efficiency reaches up to 90%. Solid oxide and molten carbonate fuel cells also use 61a combined heat and power system; due to this, their efficiency reaches around 60% of the system.

Hydrogen fuel cell electric vehicle

Hydrogen fuel cell electric vehicles (HFCEVs) produce electric energy from hydrogen and air which are powered by the fuel cell. The power produced from the fuel cell could be used to directly drive the electric vehicle and is also able to charge the battery, if it is needed. The latest fuel cell vehicle has 61a regenerative brake to capture energy and 61a battery pack that will help accelerate the fuel cell as shown in Fig. 13. The battery is 61a bit bulky, or has about the same area when used in 61a general hybrid electric vehicle (HEV). HFCEVs lead to 61a higher conversion efficiency and have 61a high growth cost than internal combustion engines (ICEVs) (Muradov and Veziroğlu 2008). HFCEV refueling is much faster than the battery charging. In the USA, the commercially sold model Toyota Mirai was introduced in 2015, and in Europe, the most sold model is ix35. Tucson is the model of Hyundai that was the first commercially produced hydrogen vehicle introduced in 2013 with 61a 24-kW battery capacity and 61a 100-kW fuel cell system.

FCVs have 61a driving range of over 300 miles and can be loaded in less than 10 min at 61a hydrogen station. This is comparable to traditional fossil fuel vehicles. Hydrogen has great potential as 61a future vehicle fuel. By 2030, it is estimated that fuel cell costs will compete with ICE based on advanced technologies and improved accessibility (Manoharan et al. 2019). An IC engine uses less than 20% of the fuel, and the fuel cell uses 60% of the fuel; that is why the efficiency of the fuel cell is better as compared to that of the IC engines.

Portable power systems

A fuel cell which generates power less than 5 kW and is quite lighter in weight, i.e., between 7 and 9 kg, can be referred to as 61a portable fuel cell (Choi et al. 2018). The market size of the portable fuel cell is quite large, around 40% of the whole market size of $10 billion. Therefore, very detailed research is being carried out by researchers in the field of portable power cell. First is the micro-fuel cell market, 61a small electronic device which provides power in the range of 1–50 W. Second is power generators in the range of 1–5 kW for applications like military outposts and remote oil fields

The micro-fuel cell is aiming to infiltrate the laptop and phone market. It can be 61a very effective and environmentally friendly alternative to lithium-ion batteries due to its advantage of higher energy density. The only drawback of the micro-fuel cell system is more elements in its system (the cell, the necessary fuel, and peripheral attachments) which lead to an increase in weight, nearly 530 Wh/kg, whereas the weight of lithium batteries is around 44 Wh/kg. Intense research on reducing the weight of the fuel cell system is carried out all over the world (Agnolucci 2007).

Hydrogen for mobility

Hydrogen storage methods in the transportation sector have 61a full potential to replace the existing battery technologies.

Overall efficiency

Efficiency decreases with each step involved in energy conversion. Production, utilization, and storage are the three main steps of hydrogen generation. Currently, the maximum efficiency achieved by the water electrolysis process is 86% including the heat recovery process (Marchenko and Solomin 2015; Muradov and Veziroğlu 2008). The overall efficiency of the process from compressing the hydrogen to 700 bars and then delivering it to the vehicle can vary between 5 and 20% (Durbin & Jugroot 2013). The proton exchange membrane fuel cell has an efficiency around 60% which is higher than that of 61a battery (Fuel Cell Technologies Office 2015). According to the report of the DOE, in terms of the electric vehicle energy conversion process, electrical energy to

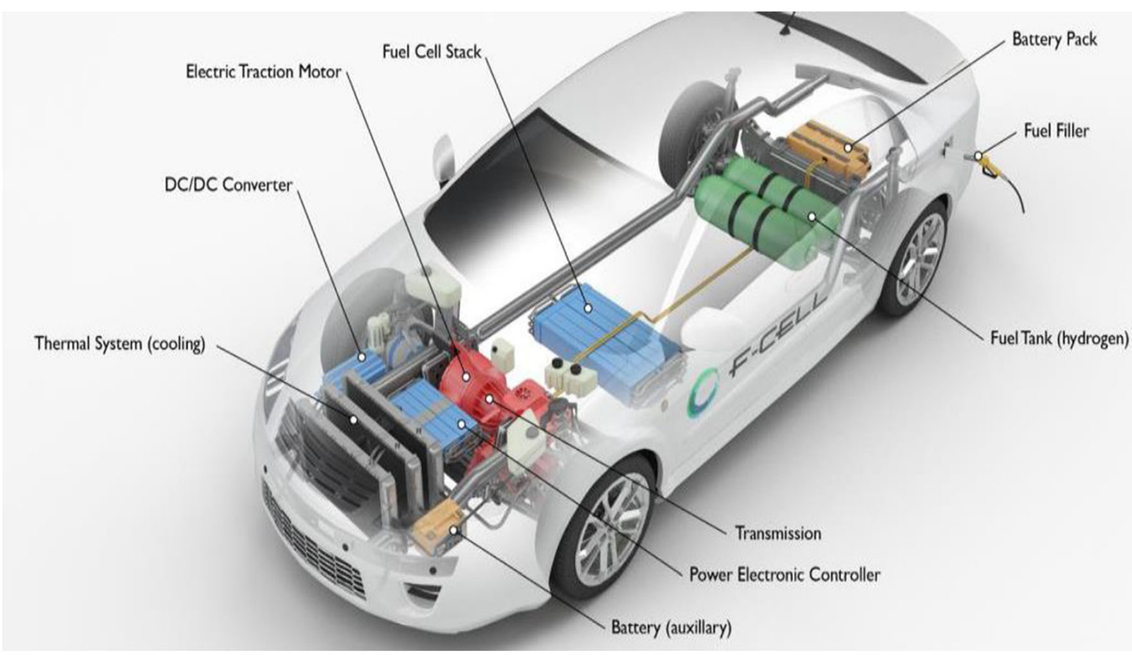


Fig. 13 Hybrid fuel cell electric vehicle (U.S. DOE 2020)

mechanical energy has an efficiency 59–62% approximately. Therefore, battery vehicles can be operated with better efficiency but the scale of increased efficiency is small.

Costs of battery vs. fuel cell

Although the battery and fuel cell systems are related to each other in many ways, comparison between the two is note negligible, especially when it comes from an economic point of view. There are various types of batteries along with the variation in price. The price of the lithium-ion battery can be fairly estimated around 270 \$/kWh, with an assumption that the battery charges and discharges at 61a rate of 1 C (Office of Energy Efficiency and Renewable Energy 2019; Philippot et al. 2019). At present, the cost of the compressed hydrogen tanks and fuel cell stacks is around 15 \$/kWh to 100 \$/kWh (ITM Power 2019). Therefore, 61a hydrogen-powered vehicle is more economical than 61a battery-powered vehicle. In many countries, the hydrogen price is subsidized by the government which further reduces the price of the hydrogen at the pump station to around 8 \$/kWh. The electricity production cost using hydrogen fuel cells is usually around 0.24 \$/kWh, which is cheaper than the electricity cost in many countries (Kaur and Pal 2019).

Hydrogen economy

The most important elements of the hydrogen economy are production, delivery, storage, conversion, and application. Hydrogen is difficult to store and transport, which is different from other fuels, such as electricity or batteries (Bossel 2006). Hydrogen storage requires special precautions because it is highly combustible and can be easily oxidized in containers and pipelines (Tajitsu and Shiraki 2018). Production of hydrogen through water electrolysis using 61a renewable energy source and its storage in ionic form (referred to as electrochemical hydrogen storage) is relatively safe to handle than its counter forms of storage (liquid or gaseous storage). Owing to the challenges associated with hydrogen energy, hybrid systems that include combinations of renewable sources and fuel cells are considered as 61a feasible way to meet the global energy need in the future.

Hazards and safety concerns of hydrogen

A detailed systematic evaluation is needed for proper assessment of negative impacts of technologies and products. Technology assessment is defined as "analyzing and evaluating the desirable and non-desirable consequences of technology" (Roes and Patel 2011). The aim of this type of assessment should be future oriented. Due to the high pressure and high combustion nature of compressed hydrogen, excessive precaution should be taken while refilling the hydrogen gas station. The "Risk assessment method" (Hübert et al. 2011) is 61a widely accepted safety assessment method. Every vehicle running by H_2 and H_2 fuel pump should be regulated by risk assessment. A detailed investigation of every incident is very necessary in the risk assessment method. Any incident related to H_2 is identified by the failure mode and effect analysis (FMEA) and hazard and operability studies (HAZOP) methods which are widely accepted as efficient ways of identifying the source of risk (Piètre-Cambacédès and Chaudet 2010; Kikukawa et al. 2009).

Safety program and awareness

The Canadian Transportation Fuel Cell Alliance (CTFCA) in Canada has been applied to the needs of Canada to promote the adoption of hydrogen as 61a hydrogen technology and fuel by Canadian stakeholders (MacIntyre et al. 2007). Ogden and Nicholas (2011) discussed 61a "clustering strategy" that would strengthen southern California infrastructure and introduce hydrogen over the next decade to meet California's zero-waste regulations. The analysis identifies the inclusion of hydrogen vehicles and fossil fuels in different areas, such as smaller cities (Santa Monica and Irwin) and larger cities (Los Angeles valley). Public awareness about hydrogen is an important factor in accepting hydrogen as 61a renewable energy source. Through an important analysis, conceptualization, and development of the results of Ricci et al. (2008), an important gap between secular recognition and knowledge about hydrogen uptake and questionable assumptions had been identified (Könnölä et al. 2007; Wegge and Zimmermann 2007; Crowl and Young 2007).

Technical challenges and future trends

Technical challenges

As the demand for energy is expected to increase threefold by 2050 globally, the oil/gas supply is doubtful to fulfill the increasing demand. For future energy systems in the transportation, industrial, and residential sectors, hydrogen and fuel cells have become an indispensable alternative for many countries. However, the conversion to 61a hydrogen economy will take decades due to the changes taking place in the energy sector (Edwards et al. 2008). Compared to current characteristics, cost, and reliability, the production, storage, and use of hydrogen need to be improved for it to make space in future energy systems. Some of the technical problems of the hydrogen economy are:

- Gasoline reduces hydrogen production costs to 61a level comparable to energy costs.

- Development of 61a CO_2-free route for mass production of sustainable hydrogen at 61a competitive cost.
- Development of practical hydrogen storage systems for vehicles and stationary applications.
- Development of 61a safe and efficient national infrastructure for hydrogen delivery and distribution.

Modern processes of maintenance/gasification, absorption of carbon dioxide, and development of new, efficient, and economical electrochemical processes are necessary during the period of transition. The latest power systems, batteries to cars and central or distributed power generation, can be replaced by fuel cells. The technology offered by fuel cells is of 61a very compelling form. This is so as presently, in the market, the efficiency of hydrocarbon fuels can be increased. This will be possible as hydrogen will become available in abundance in the future. The reduction in cost and increased durability of materials and components are the principal challenges with fuel cells.

Future trends

Hydrogen has been considered as the future fuel by the world's leading economies owing to its immense energy content and zero emission. However, its safe and efficient generation, storage, and usage are yet to meet the benchmark. The United States Department of Energy (U.S. DOE 2020) has set 61a target for hydrogen energy storage in terms of storage density which is yet to be met in order to completely replace fossil-based fuels—viz. gasoline, diesel, CNG, etc. on board vehicles. For the time being, the cost involved in hydrogen generation, storage, and usage in fuel cells is quite high compared to that of its fossil-based counterparts. Another challenge is to achieve the higher round-the-trip efficiency of 61a hydrogen-based power system which means that efficiency pertaining from electricity in to electricity out (round-the-trip). Many researchers across the globe are indulged in finding the optimum solutions to meet these challenges, but it would take way too long when all vehicles on roads would be seen running on hydrogen.

Another aspect for future automobile powering technology is that electric vehicles (EV) are dependent on lithium-based batteries for energy storage that limits their range of distance to cover in 61a single charge. Besides, lithium-based batteries are costly to recycle and end up in dumps after their lives are exhausted, which leads to the accumulation of toxic lithium on planet earth. Producing hydrogen from renewable energy sources, its storage in porous materials in ionic form, and later usage in fuel cells to generate electricity could be one of the solutions to the problem (Oberoi 2015). Future research will dwell on hybrid systems that could harness the advantages of both the hydrogen fuel cell technology and one or combined conventional renewable energy sources. A vehicle with 61a solar rooftop, 61a hydrogen storage–based battery, and 61a stack of fuel cells to power electricity-driven motors is 61a classic example of 61a future vehicle powering system. Such 61a system, unlike conventional fuels, would not emit any harmful gases and would have tremendous range compared to commercially available EVs. Another example is 61a vehicle installed with vertical-axis wind turbines on side panels to harness the wind draft of 61a moving vehicle, 61a hydrogen storage–based battery, and 61a fuel cell to power electricity-driven motors. Undoubtedly, these future technologies could save financial investment, worth millions, required to build up electricity- and hydrogen-charging stations across the countries.

Conclusion

The presented study in this manuscript clearly advocates the complete paradigm shift towards hydrogen as 61a viable fuel to meet the global energy needs. In the initial part of the article, the basics of the hydrogen atom are reported with 61a focus on the importance of hydrogen as an energy source. Its generation from different sources and ways of storage are discussed in detail in this article. The latter part of the manuscript consists of the advantages and numerous applications of hydrogen energy. Further, 61a part of the article throws light on hazard and safety measures required to deal with hydrogen. The last part of the article discusses about future technologies in context to hydrogen energy and powering automobile industry.

Hydrogen as 61a fuel promises to be an alternative for the transportation sector, stand-alone power supplies, grid-connected hybrid renewable energy systems, and energy storage. It is one of the novel alternatives to the fossil-based fuels in the sense that it is clean and green, and also has 61a higher energy density. Moreover, the electricity production cost using hydrogen fuel cells is quite less as compared to that of the electricity rates being charged by the electric utility companies in various parts of the world. The only critical factor that has to be taken care of is the control over the combustion rate of hydrogen gas. Public awareness about the usage of hydrogen is necessary due to the related safety issues. With the technological advancements in this field, now, the researchers have identified 61a way to store hydrogen as hydronium ions instead of gas. These ions are arrested in various porous materials through physisorption and chemisorption, and are used as fuel in hydrogen fuel cells to meet the electric power demand. The future automobile industry would be powered by hybrid systems instead of 61a single renewable energy source. Hybrid powering systems would be capable of utilizing the advantages of both renewable as well as fuel cell powering systems as 61a whole. Not only this, hydrogen as 61a fuel in hydrogen-based fuel cells is going to be the game changer in the field of portable power supplies for remote locations and war zones, power source for miniature electronic devices, and in marine ships. Thus, it can be safely concluded that hydrogen and hydrogen-based fuel cells would definitely contribute towards development of 61a sustainable society on the planet.

Authors' contributions To qualify as an author, one should (PN) have made substantial contributions to the conception and design; MKS have been involved in drafting the manuscript or revising it critically for important intellectual content, and ASO have given final approval of the version to be published. Each author should have participated sufficiently in the work to take public responsibility for appropriate portions of the content. Acquisition of funding, collection of data, or general supervision of the research group, alone, do not justify authorship.

Data availability There is no statement of availability of data and materials.

Declarations

Ethical approval The manuscript was not submitted in any other journal and it is not published in any previous paper.

Consent to participate For all research involving human subjects, freely given, informed consent to participate in the study must be obtained from participants (or their parent or legal guardian in the case of children under 16), and 61a statement to this effect should appear in the manuscript.

Consent to publish Individuals may consent to participate in 61a study, but object to having their data published in 61a journal article. Authors should make sure to also seek consent from individuals to publish their data prior to submitting their paper to 61a journal. This is in particular applicable to case studies.

Conflict of interest The authors declare that they have no competing interests.

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