Hydrogen energy systems: A critical review of technologies, applications, trends and challenges

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Hydrogen energy systems: A critical review of technologies, applications, trends and challenges

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A R T I C L E I N F O

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A B S T R A C T

The global energy transition towards a carbon neutral society requires a profound transformation of electricity generation and consumption, as well as of electric power systems. Hydrogen has an important potential to accelerate the process of scaling up clean and renewable energy, however its integration in power systems remains little studied. This paper reviews the current progress and outlook of hydrogen technologies and their application in power systems for hydrogen production, re-electrification and storage. The characteristics of electrolysers and fuel cells are demonstrated with experimental data and the deployments of hydrogen for energy storage, power-to-gas, co- and tri-generation and transportation are investigated using examples from worldwide projects. The current techno-economic status of these technologies and applications is presented, in which cost, efficiency and durability are identified as the main critical aspects. This is also confirmed by the results of a statistical analysis of the literature. Finally, conclusions show that continuous efforts on performance improvements, scale ramp-up, technical prospects and political support are required to enable a cost-competitive hydrogen economy.

1. Introduction

Although a considerable part of the global energy demand is currently served by fossil fuels, the harmful impacts of the combustion of fossil fuels are unignorable: greenhouse gas, acid rain, etc., which are devastating to the environment and human beings. To this end, global energy transformation is gaining momentum, which is accelerated by the rapid development of using renewable energy. To enhance this momentum and to mitigate emissions, hydrogen has been explored as a substitute energy carrier, while generating electricity from hydrogen using a fuel cell causes no local pollution because the only byproduct is pure water. Another advantage of hydrogen lies in its high specific energy density. It can provide three times more energy than gasoline combustion per unit mass [1]. Also, hydrogen can be locally produced, which reduces countries' dependence on external energy suppliers. Besides, hydrogen can be extracted from an extensive range of substances, such as water, oil, gas, biofuels, sewage sludge, etc. [2]. In particular, the abundance of water on earth assures the production of hydrogen in a rather sustainable way. Splitting water by electrolysis offers promising opportunities for synergy with the renewable energy. The hydrogen can be produced before it is used due to the intermittent nature of some renewable energy resources so that it is suitable for distributed production and centralised production connected directly to the remote renewable resources. The hydrogen produced from an electrolyser is perfect for use with fuel cells. Stationary fuel cell technologies also facilitate the development of distributed power backup, stand-alone power plants and co-generation. It provides a substituted option of the traditional power grid because combined with a fuel cell, the electricity can be produced when and where it is needed so that the hydrogen does not necessarily to be stored.

Advances of integrating hydrogen in power systems have been gradually made in recent years ranging from production and storage to re-electrification and safety issues. Extensive descriptions of the existing progress can be found elsewhere and a number of studies are seeking to characterise the current progress in hydrogen system integration by novel methods [3]. A wide consensus has been reached that producing hydrogen from renewable energy sources (solar, wind, etc.) shows great promise for the world's sustainable development [4]. Chi et al. have pointed out that changing the hydrogen production by using renewable electricity can enhance the interconversion of electricity and hydrogen and expand the hydrogen application [5].

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Nomenclature

Abbreviations

°C	Degrees Celsius
AEL	Alkaline electrolyser
AFC	Alkaline fuel cell
BOP	Balance of plant
CAPEX	Capital expense
CCHP	Combined cold heat and power
CCP	Combined cold and power
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
EUR	Euro
H_2	Hydrogen
H_2O	Water
HHV	High heating value
IRENA	International Renewable Energy Agency
km	Kilometre
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life cycle assessment
LPG	Liquefied petroleum gas
MCFC	Molten carbonate fuel cell
Mt	Megatonne
MW	Megawatt
MWh	Megawatt-hour
O_2	Oxygen
ORC	Organic ranking cycle
PAFC	Phosphoric acid fuel cell
PEM	Proton exchange membrane
PEMEL	Proton exchange membrane electrolyser
PEMFC	Proton exchange membrane fuel cell
PV	Photovoltaics
SOEL	Solid oxide electrolyser
SOFC	Solid oxide fuel cell
USD	United States dollar
VCC	Vapour compression cooling

Physics symbols

α	Charge transfer coefficient
ΔG_f	Free enthalpy (water)
Δh_f	Free enthalpy (hydrogen)
η	Efficiency
F	Faraday constant
i_0	Exchange current density at the electrodes
i_{loss}	Hydrogen crossover current
$i_{max,c}$	Limiting current at the cathode
I_{stack}	Stack current
n_{cell}	Number of cells
P	Pressure
R	Gas constant
R_{eq}	Equivalent resistance
T	Temperature
V_0	Reversible voltage
V_m	Molar volume
V_{cell}	Cell voltage
V_{stack}	Stack voltage

Numerous researches on renewable hydrogen production technologies were launched and have generated great interest [6]. Producing hydrogen from renewables using photocatalysis have been reviewed in [7] and [8], in which the solar energy is used for water-splitting. Wang et al. have focused on the intensification technologies on the component level to save the energy consumption in the hydrogen production [9]. On the system level, several advanced cutting-edge power-to-gas projects have been reviewed and investigated in [10,11]. Electrolysis and methanation status in terms of the cost and the capacity have been reviewed in [12] for power-to-gas applications, while the effects of hydrogen injection on the gas infrastructure and gas quality have been studied in [13]. As most power-to-gas plants are located next to remote renewable energy sources, it requires the produced hydrogen to be stored and then fed to the gas distribution system, therefore, researches have been launched to improve the hydrogen storage capability [14]. Abe et al. pointed out that the current hydrogen storage technologies had not fully satisfied the techno-economic feasibility and further investigations on solid hydrogen storage are demanding [15]. The security issue of hydrogen storage and delivery were studied in [16], as well as the reliability of the presently available technologies. A detailed review of utilising hydrides for hydrogen storage in stationary and transportation applications is found in [17].

It is noticed that recent reviews have stated the importance of integrating hydrogen in power systems, however, they tend to focus on specific hydrogen technologies. Some reviews have acknowledged the undertaking of hydrogen in various power systems. For example, Mazloomi et al. [18] have discussed the prospects and challenges of hydrogen as an energy carrier while explaining current hydrogen production technologies and cost potentials, while discussions on the system level are lacking. Hanley et al. [19] have analysed the role of hydrogen in the future economy based on eight existing hydrogen powered system models. The prospects of hydrogen penetration and decarbonisation are stated, however, key hydrogen technologies and the current progress of developing hydrogen technologies have not been fully addressed. Parra et al. [20] have analysed the current progress of hydrogen energy system from the points-of-view of cost, products, applications and control strategies, but lack detailed insights into the current development status of the hydrogen technologies and their evolution. Besides, challenges in terms of technological and social aspects are not discussed, while integrating hydrogen in power systems requires significant investment and intensive coordination in both research and social aspects.

This paper is devoted to treating hydrogen powered energy systems as a whole and analysing the role of hydrogen in the energy systems. As hydrogen has become an important intermediary for the energy transition and it can be produced from renewable energy sources, re-electrified to provide electricity and heat, as well as stored for future use, key technologies including water electrolysis, fuel cells, hydrogen storage and their system structures are introduced in this paper, in which the characteristics are described by the corresponding models and experimental results. It provides general explanations for readers who are not or partly engaged in different hydrogen technology fields. Moreover, four principle hydrogen integrated applications including energy storage, power-to-gas applications, co- and tri-generation and transportation are introduced and interpreted by remarkable projects. Current status on hydrogen applications is analysed statistically in terms of cost, consumption, efficiency and durability, which justifies the need of further progress in the related technologies. The current status is also illustrated by the level of research based on the literature survey across the time. Last but not least, this paper critically discusses the perspectives of developing hydrogen integrated energy systems in

Table 1
Comparison of different types of electrolysers in their operation temperature, stack voltage efficiency and pros and cons [21].

Type	Operating temperature	Stack voltage efficiency	Pros and cons
Alkaline electrolyser (AEL)	<80 °C	62%–82%	Pros: good durability and maturity. Cons: low partial load range, low current density.
Proton exchange membrane electrolyser (PEMEL)	<80 °C	67%–82%	Pros: good compactness and efficiency, fast response. Cons: more expensive and lower durability.
Solid oxide electrolyser (SOEL)	>700 °C	Around 100%	Pros: high efficiency and operation pressure, reusable heat. Cons: low maturity, not widely commercialised.

terms of performance, ramping-up scales, technical perspectives and social and political implications.

Following sections of this paper are arranged as follows: Section 2 presents the dominant technologies in hydrogen production, re-electrification and storage and their principles. Section 3 introduces the four major applications of hydrogen-integrated power systems. The current status in terms of cost, consumption, efficiency and durability are analysed in Section 4. A detailed publication survey is described in Section 5 and Section 6 presents the insights and prospects of developing hydrogen power system technologies before concluding.

2. Hydrogen technologies

Some hydrogen technologies that are typically used in hydrogen power systems are introduced in this section. They include electrolytic hydrogen production, hydrogen re-electrification using fuel cell, hydrogen storage and converter technologies. The characteristics of these technologies are presented and demonstrated by some experimental results.

2.1. Electrolytic hydrogen production

Hydrogen production methods like steam reforming, coal gasification and electrolysis of water are majorly used today for industrial hydrogen production. Other hydrogen production methods like reforming ethanol and sugars, water biophotolysis, photochemical water splitting and high-temperature water splitting are still in the stage of development and are rarely industrially deployed. Today, with the declining cost for renewable electricity, there is a growing interest in water electrolytic hydrogen production, which consumes electricity to extract hydrogen from water while causing no carbon byproducts like CO_2.

2.1.1. Water electrolysis principle

In a water electrolysis cell, two electrodes are put in the electrolyte solution and are connected to the power supply to conduct current, as shown in Fig. 1. When a sufficiently high voltage is applied between the electrodes, water is decomposed to produce hydrogen on the cathode and oxygen on the anode. The addition of an electrolyte raises the conductivity of the water, which facilitates the continuous flow of electricity. Acids and solid polymer electrolytes are commonly used in water electrolysis, and use different ions as charge carriers: H^+, OH^-, O^{2-}, etc. The reactions of water electrolysis at the electrodes with different charge carriers may be different, but the overall reaction is always the same:

$$2H_2O + \text{electricity} + \text{heat} \rightarrow 2H_2 + O_2 \tag{1}$$

2.1.2. Water electrolysis technologies

Three principal types of electrolysers and their characteristics are summarised in Table 1. AELs have the dominant place in today's electrolyser market and have been developing for many years. SOELs can split water at very high temperatures and they do not need as much electricity as that of other types of electrolysers. The efficiency of SOELs is, therefore, high. PEMELs are quickly gaining momentum in recent years and large PEMELs are now being commercialised. They can benefit from their low gas permeability, high proton conductivity, thin proton exchange membranes, and good compactness. Moreover, PEMELs can be operated with high efficiency at high power density, fast response, relatively low operating temperature, small footprint and balance of plant (BOP) simplicity [22].

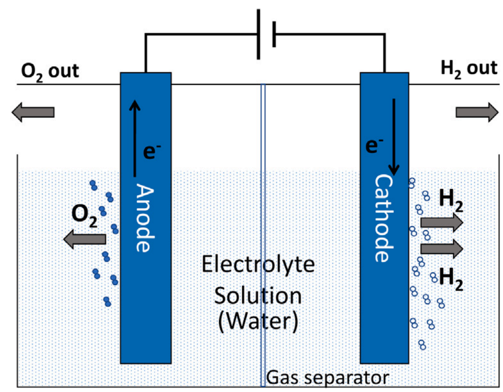

Fig. 1. Water electrolysis principle: Two electrodes are placed in the electrolyte solution, which are connected to the power supply to conduct current. Water is decomposed into pure hydrogen and oxygen gas, appearing at the cathode and the anode, respectively.

2.1.3. Electrolyser system structure

The electrolyser stack consists of several individual cells, which are connected in series so that it can reach a rather high voltage even if each individual cell has a low voltage (approximately 2 V). Moreover, electrolyser systems with stacks connected in parallel are able to reach a multi-MW scale with relatively low voltage (up to a few kV) given a high current density [23]. To make the system operational, a power supply unit and the BOP are also necessary, as shown in Fig. 2. The produced gases enter into gas separators where they are separated from water and then being purified and dried. A pump is used to pump the electrolyte through the electrolyser cells and the heat exchanger is used to reach the operating temperature [24]. A transformer and a rectifier in the power supply unit are used to feed direct power into the electrolyser stack.

2.1.4. Electrolyser electrical characteristics

Most commercial electrolysers are current-controlled so that their hydrogen production rate can be fixed at a set current value [25]. The performance of an electrolyser can be illustrated by its polarisation curve, as shown in Fig. 3. The measurements come from a 33-cell 5 kW PEMEL with an active area of 700 cm^2, which is operated under constant pressure and temperature. The experiment was realised at UBFC's FCLAB and FEMTO-ST laboratories in Belfort, France. To quantify the dynamic interactions of the electrolyser, one can model it based on mole balance on the electrodes and derive the voltage equation [26]. Eq. (2) shows a commonly used electrolyser model, which is the sum of open circuit voltage $V_{0,el}$, activation overpotential $V_{act,el}$, ohmic overpotential $V_{ohmic,el}$ and concentration overpotential $V_{conc,el}$.

$$V_{cell,el} = V_{0,el} + V_{act,el} + V_{ohmic,el} + V_{conc,el} \tag{2}$$

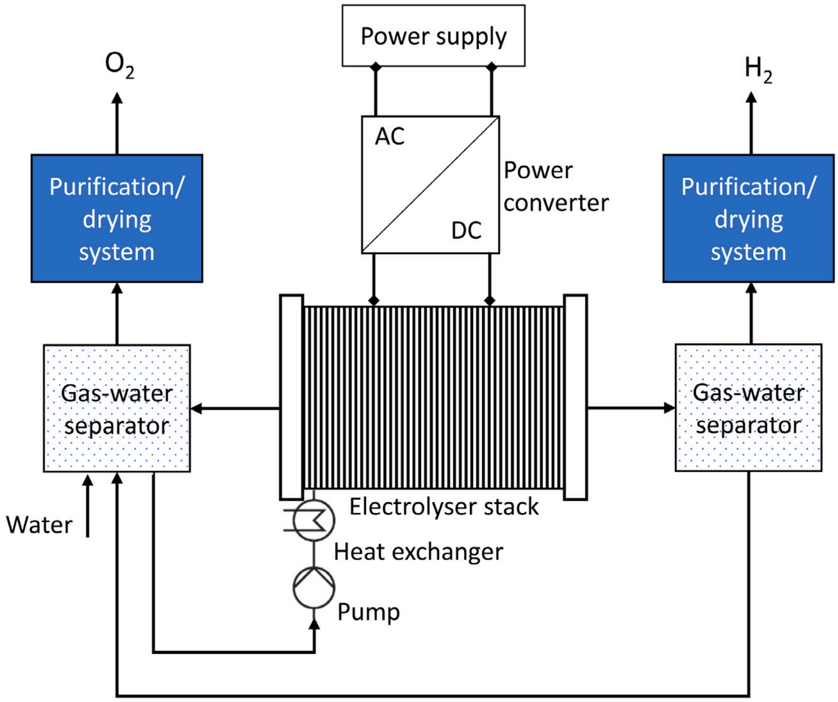

Fig. 2. Electrolyser system structure: The electrolyser is connected to the power supply through an AC/DC power converter and are connected to the gas–water separators and purification/drying systems to separate out pure hydrogen and oxygen gas. The supplied water is stored in the gas–water separator and is pumped into the electrolyser.

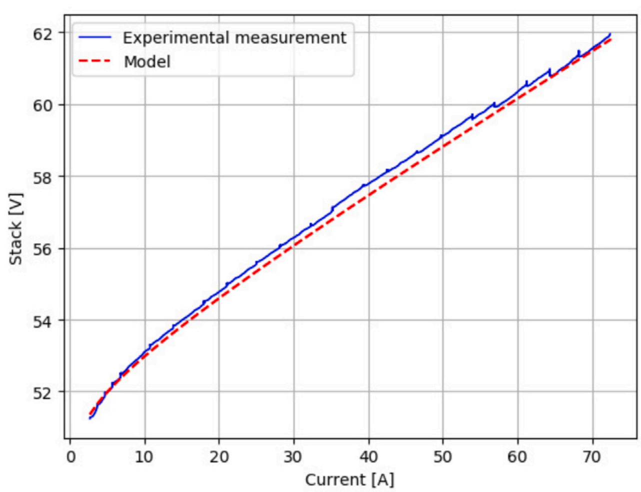

Fig. 3. Polarisation curve of a 33-cell 5 kW PEMEL with an active area of 700 cm^2, comparing with the model identification result of (2) and (3).

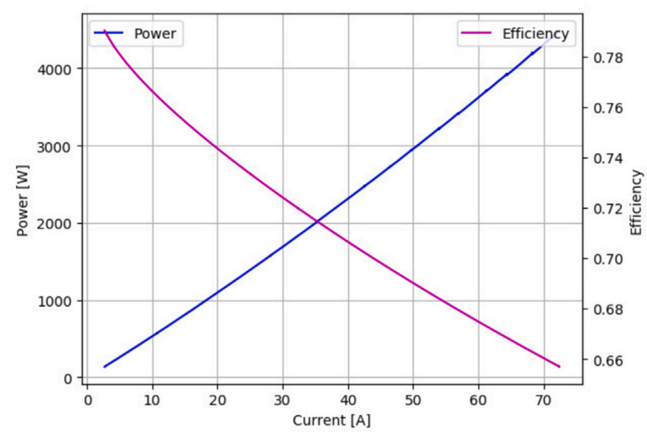

Fig. 4. Power and efficiency curves of a 33-cell 5 kW PEMEL with an active area of 700 cm^2: Increasing the current will raise the supplied power, however, it will sacrifice the efficiency.

The three overpotential losses caused by electrochemical reaction, ohmic loss and mass transport, respectively, can be modelled using the following model [27]:

$$V_{cell,el} = V_{0,el} + \frac{RT}{2F}\ln\left(\frac{P_{H_2}P_{O_2}^{0.5}}{a_{H_2O}}\right) + \left(R_{eq}+R_m\right) i + \frac{RT}{\alpha_a 2F}\ln\left(\frac{i}{i_0}\right) + \frac{RT}{\alpha_c 2F}\ln\left(1+\frac{i}{i_{lim}}\right) \tag{3}$$

where index a denotes anode and c denotes cathode, R is the gas constant, T is the operating temperature, F is the Faraday constant, i is the current density, i_0 is the exchange current density, α_a and α_c are the charge transfer coefficients, R_{eq} is the equivalent resistance of the electrodes and the interface, R_m is the resistance of the membrane, P_{O_2} and P_{H_2} are the oxygen and hydrogen pressure and a_{H_2O} is the water activity (1 if water is liquid). The determination of the parameters is discussed in [28]. The model validation results in Fig. 3 show that measurements are in good agreement with the model.

Fig. 4 shows the power and efficiency curves versus the applied current. The stack voltage efficiency can be calculated using (4), which is the ratio between its reversible voltage and operation voltage:

$$\eta_{EL} = \frac{E_{rev}}{n_{cell}\cdot V_{cell}} \tag{4}$$

with

$$E_{rev} = -\Delta G_f/2F \tag{5}$$

where n_{cell} is the number of cells, ΔG_f is the free enthalpy during the course of the formation of a mole of water at standard pressure,

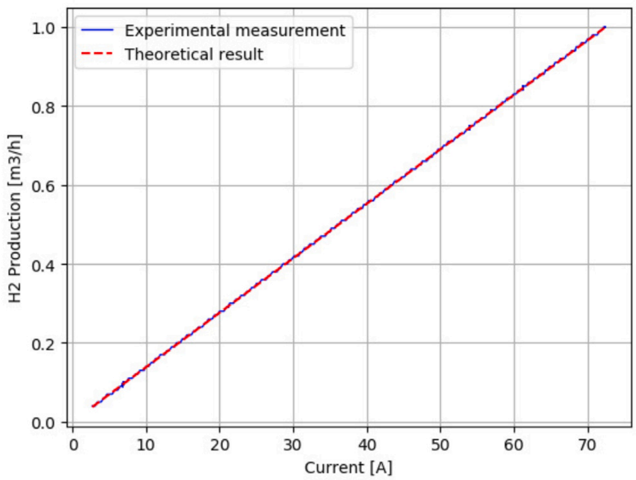

Fig. 5. Hydrogen production rate of a 33-cell 5 kW PEMEL with an active area of 700 cm^2: A higher current defines a higher hydrogen production rate according to (6). The experimental result is well adapted to the theoretical calculation.

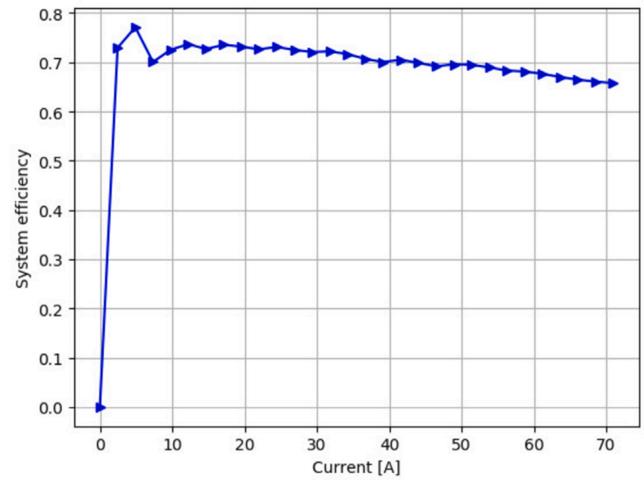

Fig. 6. System efficiency of a 5 kW PEMEL system considering ancillary losses.

which equals 285.83 kJ/mol. It does not mean that it should operate the electrolyser at low current density to increase the efficiency because the provided power is low at low current density, leading to the high specific cost. As shown in Fig. 5, the higher the current, the higher the hydrogen production rate. The theoretical calculation is based on the following equation:

$$\text{Production rate}_{H_2} = \frac{n_{cell} \cdot I \cdot V_m \cdot 3600}{2 \cdot F} \tag{6}$$

where I is the current and V_m is the molar volume of hydrogen, which equals to 0.022414 m^3 mol^{-1}. Therefore, correct current density should be selected with the objective of finding the optimum between minimising the specific electrolyser cost and ensuring the high efficiency.

The system efficiency of hydrogen power system concerns, on one hand, the stack voltage efficiency of the hydrogen devices, as discussed above and on the other hand, the system efficiency when considering the consumption of all auxiliaries. The efficiency of a water electrolysis system can be represented by the ratio of the high heating value (HHV) of the fuel produced over the electricity used, written as:

$$\eta_{EL} = \frac{\text{HHV}\left(\frac{\text{kWh}}{\text{kg}}\right) \times \text{produced hydrogen (kg)}}{\left(\frac{\text{Stack input energy (kWh)}}{\text{Power supply efficiency}}\right) + \text{ Ancillary losses (kWh)}} \tag{7}$$

Fig. 6 shows the system electrical efficiency of a 5 kW PEMEL system described above. The efficiency of the PEMEL system decreases with increasing current density.

2.2. Hydrogen re-electrification

Hydrogen re-electrification refers to the generation of electricity from hydrogen. Hydrogen can first be re-electrified through combustion. Similar to internal combustion engines running on gasoline, some combustion engines or turbines can also run directly on hydrogen. However, hydrogen combustion engines are less efficient than gasoline combustion engines, with a thermodynamic efficiency of around 20%–25% [29]. This is due to the fact that hydrogen has relatively a low volumetric energy density. Besides, when combusting hydrogen, nitrogen oxides are emitted even though no CO_2 is released [30]. Compared to hydrogen combustion engines, using fuel cell is a preferable way to maximise the potential benefits of hydrogen as fuel cells convert the chemical energy of hydrogen into electrical energy directly so that their efficiency can reach 60%–80%, with only water as a byproduct [31]. Fuel cells are now commercially applied in a variety of stationary and transportation applications.

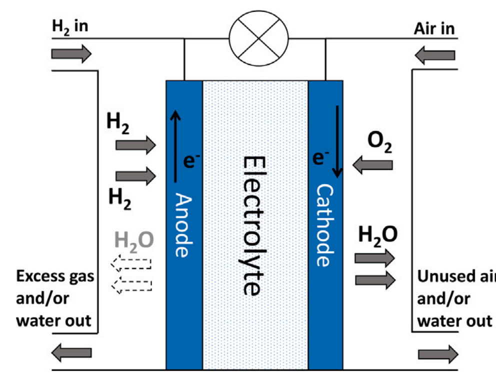

Fig. 7. Fuel cell operation principle: Hydrogen and oxygen are passed through the anode and the cathode, respectively, and water molecules are produced by combining protons, electrons and oxygen at the cathode.

2.2.1. Fuel cell operation principle

The fuel cell is supplied with hydrogen at the anode where ionisation occurs to release electrons and H$^+$ ions and it is supplied with air on the cathode where negative ions are produced, as shown in Fig. 7. Similar to electrolysers, different fuel cell types differs in their charge transfer directions and charge carriers in the electrolyte so that the water may be produced on both sides. The process is facilitated by using catalyst, which is usually carbon materials coated with platinum. Although different charge carries lead to different reactions on the electrodes, the overall reaction is always the same:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{electricity} + \text{heat} \tag{8}$$

2.2.2. Fuel cell technologies

Different types of fuel cell work with different types of electrolytes. Their characteristics are summarised in Table 2. The following focuses on the PEMFC as it can be operated with a rather low temperature and it has gained a lot of interests in both transport and stationary applications.

2.2.3. Fuel cell system structure

A fuel cell system consists of a stack and its auxiliaries including a hydrogen tank, pumps, an air compressor, power electronics, a thermal management system, etc., as shown in Fig. 8. A fuel cell can generate 0.6 V to 0.8 V nominal voltage at nominal load [32], while the stack voltage can be upgraded by increasing the number of cells. Similar to

Table 2
Comparison of different types of fuel cells in their operation temperature, stack voltage efficiency and pros and cons [31].

Types	Operating temperature	Stack voltage efficiency	Pros and cons
Proton exchange membrane fuel cell (PEMFC)	80 °C–100 °C (low temp.) or 200 °C (high temp.)	50%–60%	Pros: fast start-up, widely used in transport and stationary applications. Cons: expensive catalyst.
Solid oxide fuel cell (SOFC)	800 °C–1000 °C	60%–80%	Pros: solid electrolyte, reusable heat and lower cost. Cons: issues with metal corrosion.
Alkaline fuel cell (AFC)	Around 70 °C	Around 60%	Pros: good current response. Cons: used mostly for space applications.
Molten carbonate fuel cell (MCFC)	Around 650 °C	60%–80%	Pros: good conductivity and high current density. Cons: only used in large-scale stationary applications due to slow start-up.
Phosphoric acid fuel cell (PAFC)	Around 180 °C	Over 80%	Pros: high efficiency with heat co-generation. Cons: low current density and high catalysts cost.

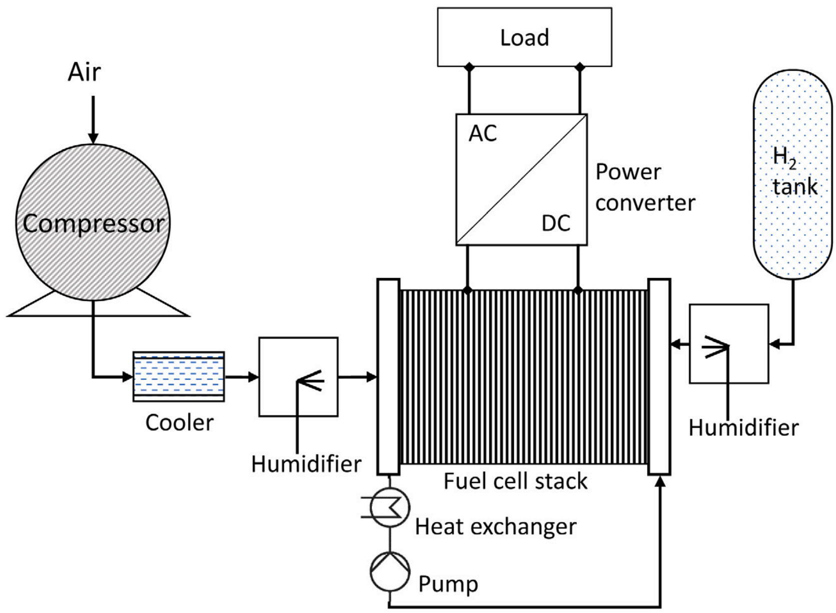

Fig. 8. Fuel cell system structure: Hydrogen and air are compressed and humidified into the fuel cell stack and the produced power is supplied to the load through an AC/DC power converter.

electrolysers, fuel cell stacks can be connected in parallel to increase the output current so as to reach multi-MW scales. Besides, the current can also be raised by increasing the active area of cells. The fuel cell system also has some auxiliaries, for example, the air is supplied by a compressor powered by a motor and the hydrogen is supplied using a pressurised tank where the flow and the pressure of the hydrogen are controlled. In addition, a cooler is used to cool off the compressed air and a humidifier is used to prevent the membrane dehydration [33]. The generated DC power can be then inverted to AC power and distributed to the grid.

2.2.4. Fuel cell electrical characteristics

Fuel cells can be characterised by the polarisation curve, which shows the voltage–current characteristics. The polarisation curve of a 5-cell 300 W PEMFC stack with an active area of 100 cm^2 is shown in Fig. 9, measured at UBFC's FCLAB and FEMTO-ST laboratories in Belfort, France. The polarisation curve is modelled as (9). Contrary to the model of electrolyser stack, fuel cell stack voltage is modelled as the reversible voltage $V_{0,fc}$ subtracting activation losses $V_{act,fc}$, ohmic losses $V_{ohmic,fc}$, concentration losses and crossover losses $V_{cross+conc,fc}$.

$$V_{cell,fc} = V_{0,fc} - V_{act,fc} - V_{ohmic,fc} - V_{cross+conc,fc} \tag{9}$$

A more detailed model may also be used [34]:

$$\begin{aligned} V_{cell,fc}(i) = {} & V_0 - \frac{RT}{2\alpha_a F}\ln\left(\frac{i_{loss}+i}{i_{0,a}}\right) - \frac{RT}{4\alpha_c F}\ln\left(\frac{i_{loss}+i}{i_{0,c}}\right) \\ & - iR_{eq} - B_c \ln\left(1-\frac{i}{i_{max,c}}\right) \end{aligned} \tag{10}$$

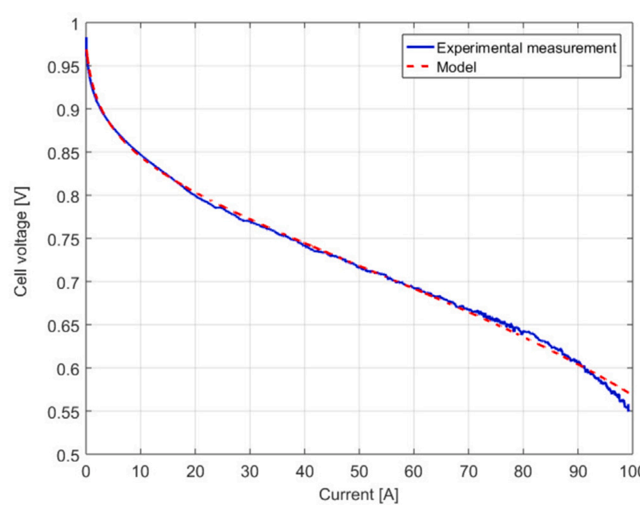

Fig. 9. Polarisation curve of a 5-cell 300 W PEMFC stack with an active area of 100 cm^2, comparing with the model identification result of (9) and (10).

where i_{loss} is the hydrogen crossover current, $i_{0,a}$ and $i_{0,c}$ are the exchange current at the electrodes, R_{eq} is the equivalent ohmic resistance, B_c is an empirical parameter considering the water and gas accumulation effects and $i_{max,c}$ is the limiting current at the cathode [34]. The model validation is fitted with the measurements, as shown in Fig. 9.

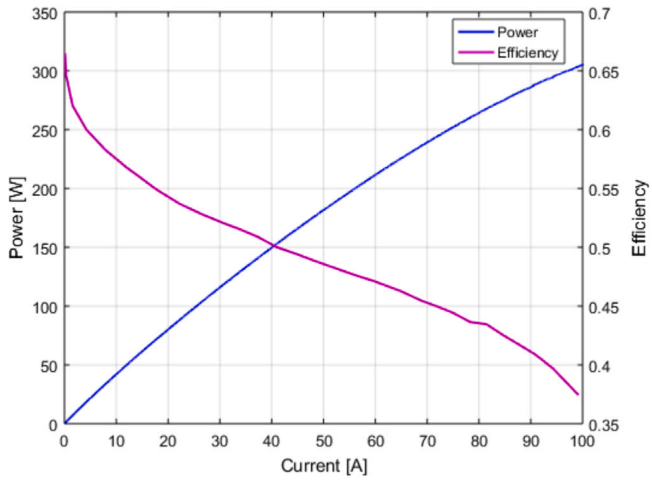

Fig. 10. Power and efficiency curves of a 5-cell 300 W PEMFC stack with an active area of 100 cm^2: Increasing the current will raise the delivered power by the fuel cell, however, it will sacrifice the efficiency.

The stack voltage efficiency of the fuel cell is presented by the ratio of its output power over the energy flux contained in the reactants, calculated by [35]:

$$\eta_{FC} = \frac{V_{stack} \cdot I_{stack}}{\dot{n}H_2 \cdot \Delta h_f} \tag{11}$$

with

$$\dot{n}H_2 = \frac{n_{cell} \cdot I_{stack}}{2 \cdot F} \tag{12}$$

where Δh_f is the free enthalpy during the complete combustion of a mole of hydrogen, which equals to 285.83 kJ/mol. Fig. 10 shows the power and efficiency curves versus the applied current of the above described PEMFC stack.

In fact, the maximum efficiency of the fuel cell is found to be achieved at partial load. Decreasing the current density below its maximum power density value helps to decrease the cell voltage loss and therefore, to increase its efficiency [36]. Efforts have been made on the system level to make the fuel cell operated in its maximum efficiency region through system control and strategy design [37,38].

Besides, the net efficiency of the fuel cell system is calculated based on the following equation, which is the ratio of produced electricity over the HHV of the consumed hydrogen:

$$\eta_{FC} = \frac{\left(\frac{\text{Stack output energy (kWh)}}{\text{Power output efficiency}}\right) - \text{ Ancillary consumption (kWh)}}{\text{HHV }\left(\frac{\text{kWh}}{\text{kg}}\right) \times \text{consumed hydrogen (kg)}} \tag{13}$$

2.3. Hydrogen storage

The high mass-based energy density of hydrogen makes it one of the most promising future fuels. Hydrogen contains 33.33 kWh energy per kilo, compared to 12 kWh of petrol and diesel [39]. However, storing the same amount of hydrogen requires a larger volume. The development of hydrogen storage technologies is, therefore, a fundamental premise for hydrogen powered energy systems. Conventional technologies store the hydrogen as compressed gas and cryogenic liquid, while for large-scale applications, underground storage turns out to be a preferable method. In recent years, solid-state hydrogen storage has seen rapid development and is believed to be the safest hydrogen storage mode. Different technologies of hydrogen storage have been summarised in Fig. 11.

2.3.1. Compressed gas

To store more hydrogen a smaller volume, being compressed to high pressure is one of the options. The most common way of storing hydrogen is to compress it into steel gas cylinders under a pressure of up to 700 bar [40]. Fig. 12 shows the evolution of hydrogen density as a function of pressure. By compressing the hydrogen gas under 700 bar, it reaches a volumetric density of 36 kg/m^3 [41]. It can be realised in the state-of-the-art lightweight composite steel high-pressure gas cylinders [42,43]. Compressed hydrogen storage is widely used when transporting hydrogen through hydrogen pipeline and hydrogen tube trailer, however, the capability of transport is largely limited by the weight of the gas cylinder. Lighter materials that can be used to compress hydrogen at high pressures are under development [44]. Another technological issue to be solved may be the heat transfer process during compressing. As the temperature rises inside the tank, composite degradation may take place and cause a severe consequence. Researches on high thermal conductivity materials and structural design have been deployed to improve the heat transfer behaviour [45,46].

2.3.2. Underground hydrogen storage

Various solutions have been proposed for large-scale hydrogen storage. Except for the buried tanks compressing hydrogen in gas and liquid, hydrogen underground storage solutions, such as aquifers, depleted deposits of natural gas and oil and salt caverns are the principal choices for large-scale hydrogen storage in medium and long term. The first two types are of porous structure and their capacity may be influenced by the geological conditions. Most underground hydrogen storage of the world is in depleted deposits, approximately 75% [47]. In recent years, salt caverns have seen great interests in storing hydrogen gas owing to their stability and imperviousness of their walls of salt caverns. The volume of a salt cavern can range from 100,000 to 1000,000

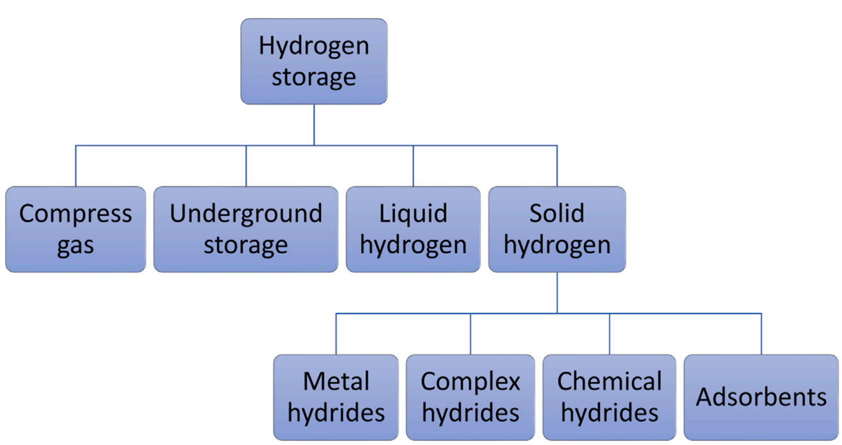

Fig. 11. Different technologies of hydrogen storage.

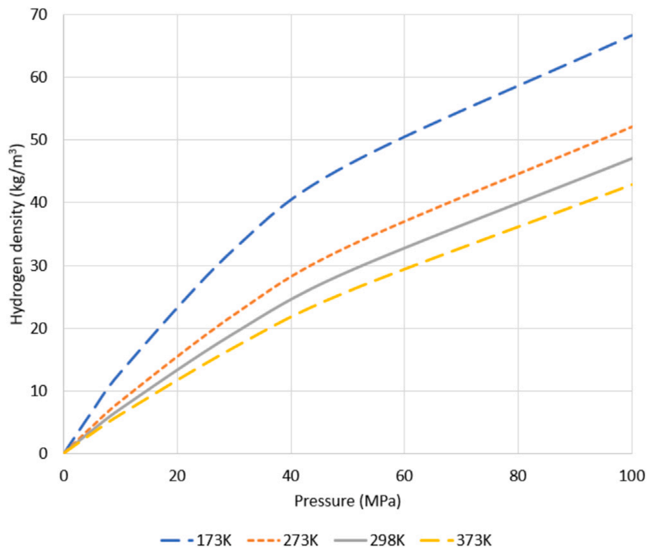

Fig. 12. Hydrogen density evolution at different temperatures and pressures.
Source: Data from [41].

m^3 working at a maximum pressure of 200 bar [48]. However, the development of salt cavern hydrogen storage is limited by some technical aspects where the tightness of the boreholes and the transfer capacity of the surface installation are of significant importance. Besides, environmental limitations and sustainable development should also be taken into consideration when making location plans [47].

2.3.3. Liquid hydrogen

As hydrogen can be converted into its liquid form at a low temperature (20–21 K) and ambient pressure, liquid hydrogen is another way to store hydrogen in a small volume and the realised volumetric density can reach 70.8 kg/m^3, which is even a little bit higher than that of solid hydrogen, i.e. 70.6 kg/m^3 [43]. However, it is time and energy-consuming to liquefy the hydrogen while about 40% energy is lost during the liquefaction process. At the moment, liquid hydrogen is reserved for special high-tech applications, e.g. space travel, and has not yet been largely commercialised [49].

2.3.4. Solid storage

Despite the above-mentioned physical-based hydrogen storage technologies, solid hydrogen is another option that is realised by combining hydrogen with solid materials through absorption and adsorption. Absorption stores the hydrogen directly into the bulk of the material to formulate chemical compounds. Among them, metal hydrides have aroused more and more interest owing to their high hydrogen storage capacity. Palladium, for example, can absorb 900 times its own volume of hydrogen at room temperature and atmospheric pressure. A detailed review of using various metal hydrides materials can be found in [50] and mathematical studies of sorption/desorption process modelling in metal-hydride systems are detailed in [51]. The dynamic system simulation models have been investigated in [52] and [53], which simulate the high-pressure metal hydride bed and the heat exchange in vehicles. For large-scale development of metal hydrides, efforts have been made towards lowering the cost, optimising the operation temperature and enhancing the thermal management of the system [16].

Besides, there are also complex hydrides (Mg_2NiH_4, $LiAlH_4$, $NaBH_4$, etc.) and chemical hydrides (LiH, NaH, CaH_2, etc.) that store the hydrogen by absorption, however, the lack of reversibility and the complex reactions to extract hydrogen are the main challenges of these methods. Another choice of storing hydrogen is by adsorption, which physically adsorbs hydrogen using porous materials, such as metal–organic frameworks and carbon materials. The advantage of this option is that they can avoid thermal management in the charging and discharging process [16]. However, the physical adsorption hydrogen storage is still far away from large commercialisation as the filling time is still under satisfaction when considering the storage capacity [36].

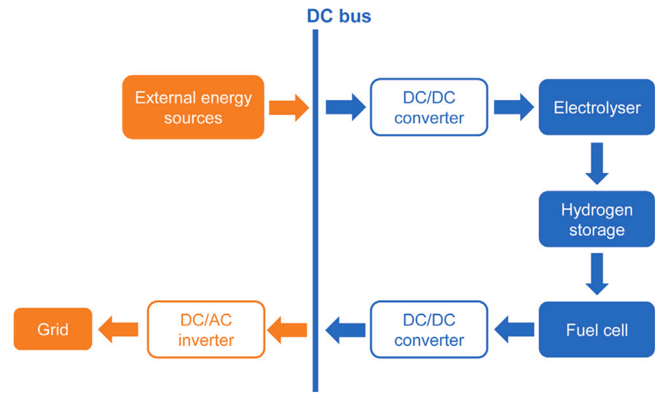

Fig. 13. Hydrogen powered energy system connected by power electronic converters, in which the DC/DC converters are used to lower down the high DC voltage output to meet the requirement of low DC voltage input of the electrolyser and to boost the low variable voltage from the fuel cells to regulate the voltage for grid-connection proposes. The DC–AC converters are used for grid integration.

2.4. Converters

In hydrogen powered energy systems, it is the power electronic converters that link the different parts in terms of hydrogen production and utilisation. For example, DC/DC converters are applied to step down the external delivered voltage to the level of the supply voltage of the electrolyser, and to level up the DC voltage of the fuel cell with high voltage gain. In addition, DC/AC rectifiers and inverters are applied when the electrolyser and the fuel cell are connected to the grid [54,55]. A typical structure of a distributed hydrogen powered energy system with power conversion is shown in Fig. 13.

To ensure the proper operation of hydrogen power systems, the converters must be featured with flexible voltage ratio, high conversion efficiency and low current ripples [56]. Different topologies of converters have been investigated in stationary power applications [57,58] and vehicle applications [59]. For example, soft switching techniques for fuel cell applications have been proposed in [60]. It has achieved 95% boost converter efficiency at full fuel cell load. A comparative study in [61] has found out that other converter topology, such as interleaved half-bridge DC/DC buck converters, can effectively improve the converter performance in electrolyser applications in terms of cost, efficiency and reliability. Studies also found that compared with conventional single-phase converters, multi-phase interleaved converters can reduce the switching losses and mitigate the current ripples as they can share the current between different legs of the converter [62]. Besides, isolated topology is believed to be a favourable way to maximise efficiency and reduce the cost, whereas the input of the converter is electrically insulated to the output. The voltage can be easily stepped up and down through an optimally sized transformer without losing energy efficiency [61]. However, further efforts in fault-tolerant conversion should be made to eliminate the power switch failures, i.e. open-circuit failures, short-circuit failures, etc. while at the same time, enhance the voltage ratio and ensure the reliability of the system.

3. Applications in power systems

As hydrogen plays an important role in various applications to store and transfer energy, in this section, four typical applications of integrating hydrogen into power systems are introduced and demonstrated with example projects: energy storage, power-to-gas system, fuel cell co- and tri-generation and vehicular applications.

3.1. Energy storage

Considering the high storage capacity of hydrogen, hydrogen-based energy storage has been gaining momentum in recent years. It can satisfy energy storage needs in a large time-scale range varying from short-term system frequency control to medium and long-term (seasonal) energy supply and demand balance [20].

3.1.1. Medium to long-term energy storage

The recent years have seen rapid growth in renewable energy generation. However, the intermittent nature of some renewable energy resources makes them time and season-dependent. Therefore, the generated renewable energy needs to be stored in a reliable form, which should be tolerant to the fluctuation and randomness of those renewable energy sources. There are several existing energy storage options, e.g., pumped hydro energy storage, compressed air energy storage, batteries, etc. [63]. Compared with them, hydrogen has its advantages of high energy storage capacity, long storing period and flexibility. It can smooth out the energy volatility and uncertainty and absorb, especially, the excess renewable energy generation [64]. It can be applied to deal with:

- Energy time shift: Hydrogen is used to equilibrate the demand and supply by storing the excess of the energy generated by renewables when the supply is larger than demand and when it is needed, the hydrogen can be used for power generation or grid injection through, for example, stationary fuel cells. In particular, the energy generated during low demand and low electricity price period tends to be stored in hydrogen to lower the energy cost and in contrary, the hydrogen is used to produce electricity during high demand and high electricity price period, gaining the most benefit. Besides, the storage duration of hydrogen is much longer than batteries, up to weeks or months, compared to hourly or weekly storage of batteries [65].
- Seasonal variation: Hydrogen can also be used to shift the renewable resources across the seasons due to the seasonal difference in energy production. Moreover, hydrogen storage capacity can reach up to MWh, even TWh, owing to its high energy density, while batteries tend to be used in kWh to MWh applications, i.e. one needs to expand the size of the instrument to reach a greater storage capacity [63,66].

Numerous hydrogen energy storage projects have been launched all around the world demonstrating the potential of its large industrial use. For example, DATAZERO (https://www.irit.fr/datazero/index.php/en/) is a project aiming at integrating renewable energy in data centres, solving the sizing, optimisation and control problems on both software and hardware levels [67]. It has proposed an all green solution to supply the electrical loads by photovoltaics (PVs) and wind turbines and using hydrogen storage, batteries and supercapacitors to handle the limited flexibility and controllability of the IT infrastructure. As shown in Fig. 14, batteries and supercapacitors are used to meet the short-term and fast response requirements, while the hydrogen storage system is responsible for long-term energy storage and takes the seasonal variations into consideration.

Underground Sun Storage (https://www.underground-sun-storage.at/) is an Austrian project that stores the energy from wind and solar power below ground. As the energy from renewable sources lacks flexibility and cannot be controlled to meet the demand, excess energy generated from renewables is reproduced into hydrogen through water electrolysis and stored for further use. The outcome of the project has found out that the underground gas storage tanks can tolerate hydrogen (up to 10% in gas), which has the capacity of balancing out the seasonal supplies of renewable energy [68]. There are also other projects that use hydrogen as the energy carrier to solve the mismatching problem between system demand and load. For example,

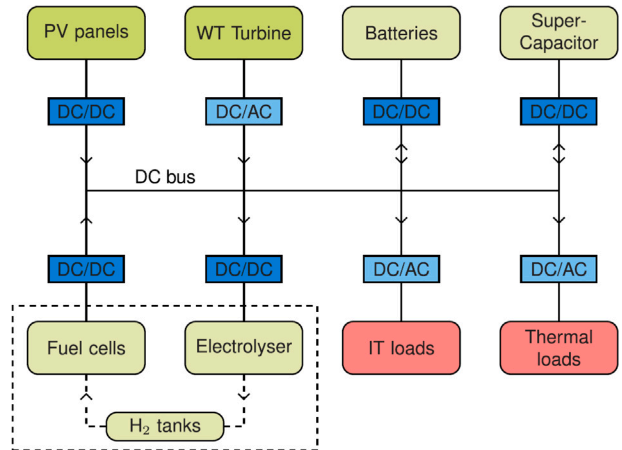

Fig. 14. Power supply infrastructure of data centres (project DATAZERO: https://www.irit.fr/datazero/index.php/en/) [67].

Orsted (https://us.orsted.com/Wind-projects) in Denmark has planned to use the excess wind energy of wind farms to power the electrolysers and produce hydrogen during the wind farms' oversupplying period. SoCalGas (https://www.socalgas.com/) in the United States has launched a project to produce hydrogen by an on-campus solar electric system and the produced hydrogen is converted into methane directly through a bioreactor.

3.1.2. Ancillary services

Fuel cells and electrolysers can also play a role in providing ancillary services to the grid. These services mainly come in the form of flexibility, which is the main requirement to integrate renewable energy sources. Examples of ancillary services include congestion mitigation, reducing negative price occurrences, frequency regulation, voltage support and black start.

Like other types of energy storage, hydrogen can first be used to mitigate transmission and distribution line congestion which can result from an insufficient line capacity [69]. This may, for example, arise due to renewable generation exceeding export line capacity, as in the HAEOLUS project (http://www.haeolus.eu) where excess wind generation feeds an electrolyser to produce hydrogen. Congestion tends to increase market prices, as well as renewables curtailment [70,71]. Redispatching costs are also incurred when such congestion occurs. Similarly, such installations can help delay investments in new and expensive transmission and distribution capacity.

The second type of service is to help reduce the number of occurrences of negative prices on markets. Such negative prices mostly occur due to inflexibility in the generation, either renewable (e.g., none or little dispatchable) or conventional (e.g., due to minimum power output or uptime). Increasing electrolysers consumption can, for example, provide a fast and efficient solution to increase demand, i.e., by providing a form of negative generation [72]. A similar result can be achieved by decreasing fuel cell power output or shutting them down.

Frequency regulation aims to maintain the grid frequency close to its reference value (50 or 60 Hz) by injecting or absorbing power coordinately to ensure the balance between supply and demand. Several types of such regulation reserves are distinguished in European networks. Frequency containment reserve (FCR), or primary reserve, provides constant containment of frequency when it deviates from the nominal value in a very short term. For frequency deviations longer than 30 s, the restoration of frequency is handled by frequency restoration reserve (FRR), with a much larger capacity. Both FCR and FRR services can be achieved by fuel cells and electrolysers, by increasing or decreasing their power setpoint following a frequency signal [73]. In case of a frequency drop, e.g., due to a generator failure, a fuel

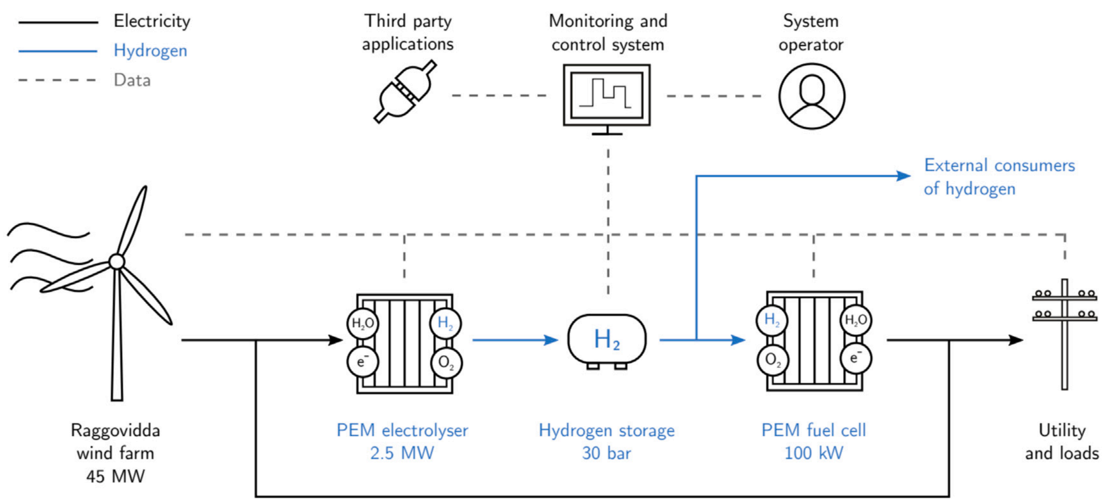

Fig. 15. Integration of a 2.5 MW electrolyser in a state-of-the-art wind farm (project HAEOLUS: http://www.haeolus.eu/).

cell can increase its power output and an electrolyser decrease its consumption, which makes it a form of demand response asset. Compared to conventional turbine-based generators, fuel cells and electrolysers are much more flexible with very high ramp-up and ramp-down rates, short response times (with setpoint changes in less than a second) as well as low minimum up times [74]. On the other hand, operating equipment in such a way for a long duration may significantly reduce their lifetime.

Another service which can be achieved by hydrogen equipment is voltage support [73]. As other devices connected to the grid through power electronics-based converters, the power factor of fuel cells and electrolysers can be adapted based on the local needs for voltage support. This is in turn achieved by supplying or absorbing reactive power through inverter or rectifier control. Black start is another possibility, in the case of a blackout [75]. A conventional generator, such as a diesel genset, is typically used to bring a power station back into operation. A fuel cell can also achieve this, without any emission or noise.

While most of these services may also be provided by other types of energy storage, hydrogen benefits from its high energy storage capacity while also being able to respond to setpoint changes within a second. This high flexibility level enables hydrogen technologies to potentially benefit from increased revenue from providing such services [76], for example on the reserves or capacity markets, while reducing the payback time of the installations. In most studies, providing a series of different services and selling hydrogen for other applications does indeed seem required to enable the profitability of hydrogen installations [70,76].

3.2. Power-to-gas

Power-to-gas is an application which usually uses electric power to produce a combustible gas. As hydrogen is believed to be a combustible gas with rather high energy density, power-to-hydrogen applications are gaining momentum. The hydrogen produced by an electrolyser can then be methanated into methane and injected to the natural gas grid, or stored, providing a balancing service to the energy market.

Various pilot and demonstration projects have been launched or are about to be launched around the world [10,11,13]. According to the statistical research in [12], around 85% of the state-of-the-art power-to-gas projects are located in Europe, while a few are located in the USA and Japan. Germany holds the highest installed power share with around 40 MW and a 100 MW power-to-gas pilot plant is being built for industrial use, which will be connected to the grid from 2022 [77]. Besides, numerous power-to-gas infrastructures are being constructed in areas with abundant wind and solar resources. Due to the relatively low demand and a constrained transmission network connecting them to other areas, hydrogen finds its place in both securing stable power supply and increasing value-creation of these areas. Benefiting from storage facilities, it is possible to smooth out the variations on wind power production to secure that the loads in these areas are satisfied at all times.

Project HAEOLUS (http://www.haeolus.eu/) proposes the integration of an MW-scale electrolyser in a remote wind farm in the north of Norway. It aims to demonstrate that the combined operation of both systems can enhance the flexibility and grid integration of the remote wind farm and increase its economical profitability. A 2.5 MW PEMEL is used for converting collected wind power into hydrogen and a 100 kW PEMFC is used to distribute the hydrogen for multiple uses. As shown in Fig. 15, a monitoring and control system is developed to remotely control the combined system. Project HyCAUNAIS (https://www.europe-bfc.eu/beneficiaire/hycaunais-storengy/) intends to demonstrate also the feasibility of operating a flexible power-to-gas system with the methanation process. It is equipped with a nominal 1 MW electrolysis unit, which is optimised for very flexible operation (up to +/−1 MW up/down) to meet the needs of the network and also to be controllable according to wind production. The produced hydrogen is methanated and injected to the natural gas grid. Furthermore, it is coupled with a bio-methane production unit from landfill biogas.

Besides, power-to-gas produced hydrogen can be injected into the existing gas grid. It offers an efficient storage solution using existing infrastructure and saving construction cost. For example, Jupiter1000 (https://www.jupiter1000.eu/) is a power-to-gas industrial demonstrator project, which aims to transform renewable electricity into gas in order to store it. The produced hydrogen and methane are being injected into the gas grid around France. Based on studies, a volumetric level of around 15%–20% blended hydrogen should be the allowable proportion when being injected into the gas grid for eliminating hydrogen embrittlement problem. This value should be further lowered in high-pressure gas transmission grids as high pressure can add to the effects of hydrogen embrittlement [78]. The additional cost of hydrogen injection is calculated as 0.39 EUR/kg assuming that the cost of hydrogen production is 5.21 EUR/kg using a 5 MW PEMEL with an average electricity cost of 30 EUR/MWh [79]. The injected hydrogen can provide the subsequent use in a range of different applications including power generation, heat provision, transport applications such as gas-fuelled urban buses or passenger cars.

Most power-to-gas projects today, with or without methanation process, tend to be pilot projects that last for 1 to 3 years, while large industrial plants are planned around the world and need more social and political supports [77]. The potential improvements lie in the aspects of hydrogen and methanation producing efficiency, as well as the utilisation of the by-products, like oxygen and heat.

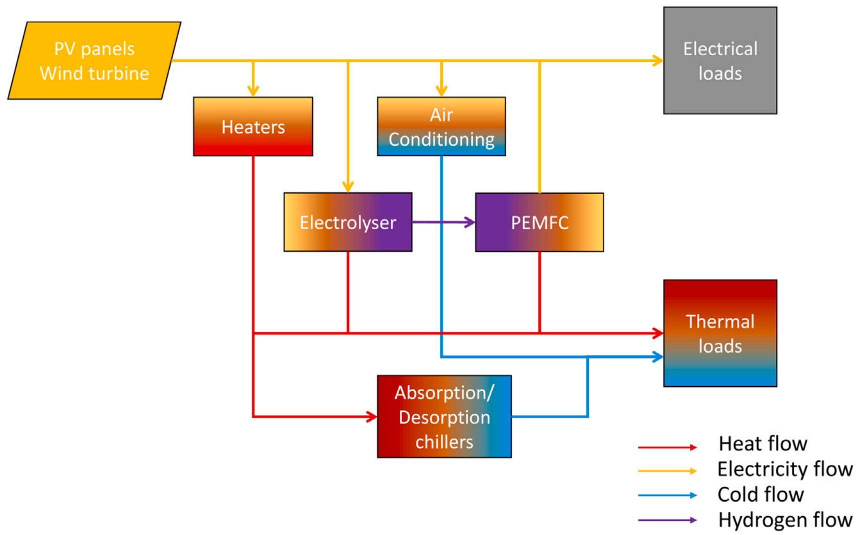

Fig. 16. Demonstration of the working principle of tri-generation.

3.3. Co- and tri-generation

To improve the efficiency and to reduce the cost, fuel cells can be used as prime movers for combined heat and power (CHP) generation or combined cold and power (CCP) generation, known as co-generation, or to be used for combined cold heat and power (CCHP) generation, known as tri-generation. The mechanism of running a tri-generation system to produce electricity and heat from renewable energy sources through electrolysers and PEMFCs is shown in Fig. 16.

3.3.1. Co-generation

The process of using fuel cells as prime movers to produce both electricity and heat concurrently is called co-generation, in which the electricity is used to provide the electrical needs, while the released heat is used for heating applications so that the total efficiency can reach up to 95%. A typical fuel cell co-generation system is made up of a stack, a fuel processor (a reformer or an electrolyser), power electronics, heat recovery systems, thermal energy storage systems (typically a hot water storage system), electrochemical energy storage systems (accumulators or supercapacitors), control equipment and additional equipment (fans, pumps, communication devices, etc.).

Nowadays, a great number of commercial projects are launched to develop fuel cell co-generation applications. Japan is a leader country on small-scale co-generation installations driven by the ENE-FARM project (about 300,000 units in 2018), which provides electricity and heat for home use by deploying PEMFCs from 0.3 to 1 kW. As homes are supplied with liquefied petroleum gas (LPG), a reformer is used to convert the LPG into hydrogen and the residual heat can be used to heat up water. Then the PEMFC stack combine hydrogen with ambient oxygen into water and at the same time, produce electricity and heat to meet the electrical needs and to heat water for kitchen, bathroom, room heating, etc.

In Europe, micro-co-generation for residential applications is currently in commercial development. The first European project for micro-co-generation using fuel cells is the ene.field project (http://enefield.eu/). From 2012 to 2017, over 1000 residential micro-CHP fuel cells were installed across 10 European countries. Project PACE (http://www.pace-energy.eu/) follows up the work of ene.field project. This project started in 2016 and ends in 2021, in which 2800 micro-CHP fuel cells over 10 European countries are being installed. In the ene.field project, an environmental life cycle assessment of micro-CHP fuel cell has been carried out. It concludes that in all the scenarios investigated, fuel cell co-generation produced less greenhouse gas compared to gas boilers and heat pumps. For these two projects, they have reached an electrical efficiency and overall efficiency of 60% and 95%, respectively.

3.3.2. Tri-generation

Tri-generation is an extended application of co-generation, which couples a prime mover to thermally driven equipment to produce cooling. Typically, a heat pump is used to produce cold from a thermal sink, which contains two reactors, a condenser and an evaporator. The two reactors consist of an absorption/adsorption reactor and a desorption reactor. The vapour or gas extracted from the absorbent passes through the condenser where it transforms into a liquid by rejecting heat, then the refrigerant liquid passes through the evaporator at low pressure, where it absorbs heat to evaporate.

Compared to the traditional distributed cold, heat and electricity, fuel cell tri-generation can lower the carbon emissions and increase energy efficiency. In [80], using a 593 kW SOFC and absorption chillers, total carbon emissions were divided by two and the overall efficiency of the system reached 75%. For large scale applications, [81] has run a simulation for a 339 kW SOFC, coupled with a combustor and a heat steam recovery, which could recover 267 kW of heat for an overall efficiency of 84%. They also studied a system of 339 kW with an absorption chiller for cold production, which could generate 303.6 kW of cold and increase overall efficiency to 89%.

In isolated applications, making full use of the fuel cell rejected heat can reduce electrical power consumed by the compressor and allows to store cold when there is no cold demand [82]. This improves the autonomy and the efficiency of the system. A combined organic rankine cycle (ORC) and a vapour compression cooling (VCC) have been used in [83] to produce hot water and cold effect, where the fuel cell provides 8 kW electrical power. Meanwhile, the released heat can be used to run the ORC and/or to be stored for domestic hot water supply. Then, the ORC produces mechanical power for the compressor of the VCC. Thermal solar panels are used in addition to power the ORC. They are able to recover 70 kW of heat and 16 kW of cold, while the overall efficiency can reach 85%.

3.4. Application of hydrogen in transportation

Hydrogen-fuelled electric powertrains provide a solution for long-distance driving with clean energy, while battery-powered vehicles suffer from range limitations. 3% of global vehicle sales in 2030 are expected to be hydrogen-fuelled, and this percentage could reach 36% in 2050 [84]. Several companies are developing fuel cell powertrains in terms of their quality, reliability and dependableness to accelerate their commercialisation in the vehicle market. For example, Mirai fuel cell vehicles developed by Toyota have used mass-production PEMFCs with a 3.1 km/L volume power density and a 144 kW (155 DIN hp) maximum power output, where a 1.6 kWh nickel-metal hydride battery is connected in parallel to deal with the regenerative braking and also assist during high-power demands when accelerating. The current hydrogen storage systems in most commercial hydrogen fuel cell vehicles are high-pressure compressed hydrogen fuel tanks. For example, Honda's Clarity fuel cell vehicle, Hyundai's NEXO fuel cell vehicle use such tanks, while BMW's Hydrogen 7 has used a liquid hydrogen fuel tank.

Other than fuel cell vehicles, fuel cell ships have been in development in recent years. The high pollution caused by ships, counting for around 2.5% of total global greenhouse gas emissions makes the shipping sector to shift to more sustainable sources of energy, i.e. hydrogen. Fuel cells are capable of powering ships sailing relatively long distances compared with those powered by batteries and meeting the auxiliary energy needs of larger ships. The same is true for fuel cell trains. Hydrogen-fuelled regional multi-unit trains have been put into operation in Europe and are expected to have even higher market share in the future, which may take place of 30% of the currently used diesel fleets [85].

Moreover, instead of injecting the hydrogen into the grid, hydrogen integrated with on-board systems gives a chance for the hydrogen producer to resell the hydrogen at a higher price. NREL has revealed that the potential price of hydrogen is about 3 to 10 USD/kg, while the most common price of hydrogen fuel is 13.99 USD/kg [86]. Besides, developing on-board hydrogen applications can also help to reduce the need to increase the capacity of grid infrastructure for vehicle charging. As the hydrogen refuelling infrastructure can be considered in the light of the existing gasoline and diesel stations, the recharging stations for alternative electric vehicles equipped with batteries can be less demanded.

4. Current status

This section summarises the current status of hydrogen powered energy systems, in which current progress is considered in the points-of-view of capital costs, hydrogen production cost, water and rare material consumption, system efficiency and durability.

4.1. Capital cost

Capital cost is about capital investments at the beginning of the system installation. Current capital costs of electrolysers, compressed tanks and fuel cells have been summarised in [20] and several cost-effectiveness analysis has been conducted in recent projects and researches [87–91].

The capital cost of the current hydrogen production system using AELs ranges from 1000 to 1500 EUR/kW including installation and that of PEMELs is twice these numbers, i.e., 2000 to 3000 EUR/kW [92]. Although alkaline water electrolysis has been well developed, the production volume is rather low. This is because the electrolyser providers tend to fabricate small-volume electrolysers for niche market, which increases at the same time the cost of BoPs. Therefore, potential cost reduction for AELs depends on more cost-efficient production, while for further reduction in the cost of PEMEL, breakthroughs in technological developments are required.

Different dimensions of stationary fuel cell systems are deployed to meet various demands from serving residential buildings to industrial applications. Fuel cell micro-CHPs for family homes and small buildings with an installed capacity of 0.3–5 kW now cost around 10,000 EUR/kW. Some mid-sized installation for larger buildings of 5–400 kW now cost 4500 EUR/kW to 7500 EUR/kW and large scale installations of 0.4–30 MW costs 2000 to 3000 EUR/kW for specific industrial applications [93]. The capital costs have the potential to be largely reduced in the coming future owing to more mature installation technologies and economies of scale. Target capital expense (CAPEX) values for 2030 are expected to reach 3500 EUR/kW, 1500–4000 EUR/kW and 1200–1750 EUR/kW for micro-CHP, mid-size and large scale applications, respectively [93,94].

With the gradual maturity of technologies, the capital costs of both electrolyser systems and fuel cell systems are expected to decrease significantly by 2030, especially the stack cost. Technological advances in increasing the active area of the stack are required, which can reduce the number of cells for producing a certain amount of hydrogen, and therefore, decrease the cost.

4.2. Hydrogen production cost

The cost of steam reforming hydrogen is mainly shaped by the gas prices, which currently ranges from 1.4 to 1.8 EUR/kg with CO_2 capture [95]. However, driven by the exhaustion of fossil fuels and the decreasing cost of renewable electricity, electrolytic hydrogen becomes competitive and is about to see continuous increasing deployments shortly. The current hydrogen production cost of AEL is 3.2–5.2 EUR/kg, while using PEMEL, the cost is 4.1–6 EUR/kg [92]. Regarding hydrogen's compressing, storing and dispensing, the pipeline scenario cost is 1.8–2.6 EUR/kg and the distributed scenario cost is 2.1–3 EUR/kg. This cost is expected to be reduced to 1.6 EUR/kg as the ultimate goal [96].

Although producing hydrogen through water electrolysis is a promising solution, the consumption of electricity should be considered. If the hydrogen is produced through water electrolysis with an assumed efficiency of 60%, all today's dedicated hydrogen demand requires 3600 TWh of electricity consumption, which exceeds the total annual electricity generation in Europe [97]. One promising solution for lowering down the electricity price is to generate electricity from renewables or nuclear power. As renewable energy sources, e.g. solar and wind, have been explored with declining costs, renewable electricity becomes less expensive. Although the hydrogen produced using renewable energy may suffer from high transmission and distribution cost as the locations could be remote, the final profit is considerable. A cost–benefit analysis of an integrated wind–hydrogen system in Corvo island has been conducted in, which found that the local renewable energy can cover 80% of the electricity demand of the island [98]. Projects for installing electrolysers at the locations with excellent solar and wind resources have been launched all over the world and future large-scale industrial deployments are about to be undertaken.

4.3. Consumption of water

Except for electricity, water is another necessary element for hydrogen production via electrolysis. Theoretically speaking, 0.81 L of water is consumed to produce 1 N m^3 of hydrogen but at least 25% more water is consumed in a practical manner, i.e. 1 litre of water is required in reality [99]. According to the literature, to produce 1 kg of hydrogen using a PEMEL needs 18 litres of water and 54 kWh of electricity [100]. Supposing all of today's dedicated hydrogen production, i.e. 70 Mt was produced by water electrolysis, water consumption would represent 1.3% of the water consumption of the global energy sector [101]. One alternative solution to is to use reverse osmosis for seawater desalination. The electricity cost for desalinating 1 m^3 of water is 0.7–2.5 USD, which is believed to have little influence on the total hydrogen production cost [102]. Efforts on how to easily integrating seawater into water electrolysis process are required for the moment.

4.4. Consumption of rare materials

Rare materials can play different roles in fuel cell and electrolyser systems. For example, they could be used as catalysts and co-catalysts of electrodes, electrolytes additives, etc. [103]. The consumption of rare materials has generated a wide concern on their high cost, concentrated supply and resource shortage [104].

Rather than using Nickel-based electrocatalysts for the alkaline hydrogen oxidation reaction in alkaline technologies, PEM fuel cells and electrolysers need more expensive rare materials to formulate their bipolar plates and the catalysts of anode and cathode to achieve competitive efficiency. The commonly used bipolar plates are of titanium, which makes up 50% of the cost of the PEMEL stack [105]. Catalysts for the anode and the cathodes make up 10% or less the total stack cost [92]. The electrodes of PEMFCs and PEMELs also need expensive metal elements to provide high corrosion resistance and catalytic activity. The anode normally uses iridium and ruthenium-based catalysts and the cathode uses palladium and platinum-based catalysts [92]. A study has shown that 7% of the world's platinum supply will be required for the fuel cell use in the Europe in 2030 [106].

To reduce the stack cost, catalyst-related cost reduction is regarded as a priority. Solutions exist in developing advanced support structures, mixed metal oxides and nano-scale catalysts. For example, carbon nanotube supported platinum catalyst has been developed to reduce the use of platinum [107]. It is expected to reduce the iridium and ruthenium used on the anode and the platinum used on the cathode to 0.4 mg/W and 0.1 mg/W, respectively, in 2030 [93].

4.5. Environmental impact

The environmental impact of hydrogen depends, most of all, on how it is produced. Current hydrogen supply relies on coal gasification and steam reforming of natural gas, rather than being generated through renewable energy because the costs of steam reforming are relatively low [108]. This kind of hydrogen is called "grey hydrogen", which is massively used in the industry nowadays. However, the process generates hydrogen, as well as CO and CO_2 gases. The produced CO are burned to be turned into CO_2, which is the major contributor to the greenhouse gas. "Grey hydrogen" production emits at least 10 kg CO_2 per kilo hydrogen production [109]. Due to the increasing carbon tax, the price of the "grey hydrogen" has become no longer attracted. Besides, the climate change due to emissions causes problem in human health and may also generate costs on the population displacement, which may be hardly quantified but add to the hydrogen cost. As the hydrogen is playing an important role in the energy transition, it is not only necessary to make the hydrogen economy economically feasible but also needed to maximise its decarbonisation potential. Alternative pathways to reduce emissions in the medium term is to produce "blue hydrogen" and "yellow hydrogen". "Blue hydrogen" is reformed from the natural gas or coal-derived gas with carbon capture and sequestration (CCS) and a 90% carbon capture rate is possible with less than 1.5 kg CO_2 emitted per kilo hydrogen production [109]. However, "blue hydrogen" production depends on the fossil fuel supply chain and CCS storage facilities. It reduces emissions and saves costs in the short to medium term, but it will be more expensive in the long term. The hydrogen produced electrolytically by nuclear energy is called "yellow hydrogen", which is zero-carbon. LucidCatalyst has reported in 2020 that the cost of hydrogen from nuclear power is 2 USD/kg, which is competitive to "grey hydrogen", 0.7–1.6 USD/kg without costing CO_2 emissions [110]. In the long run, producing "green hydrogen" using renewable electricity (e.g., solar, wind) should be promising owing to the cost reductions for electrolyser CAPEX and the increasing capacity of the renewable energy.

On the other hand, hydrogen itself can be regarded as an indirect greenhouse gas [111]. The proportion of the hydrogen emitted from a hydrogen energy system during production, transport or at the point of use may range from 0.2 up to 10% [112]. Although hydrogen technologies have the potential to replace fossil fuels that generate directly man-made greenhouse gas, the inevitable emissions through the hydrogen production, compression, storage and transportation process can lead to the indirect concentration of the greenhouse gas [113]. This is because the hydrogen can react with hydroxyl radicals and reduce their concentration, which perturbs the oxidation reactions of hydroxyl radicals and other greenhouse gases, e.g. CH_4 and CO, and increases the greenhouse effects [112]. The oxidation of hydrogen also increases the water content in the stratosphere and cools down the lower stratosphere. The low temperature may create more polar stratospheric clouds and impede the breaking-up of the polar vortex, causing larger and deeper ozone hole [114]. However, as few studies have been conducted to consider the impacts of hydrogen as a greenhouse gas in energy systems, the uncertainties should be investigated before the large-scale hydrogen deployment.

Life cycle assessment (LCA) is an efficient tool to evaluate the potential environmental impacts of hydrogen energy systems. The EU has published the International Reference Life Cycle Data System (ILCD) Handbook, in which several impacts are considered: climate change, ozone layer depletion, photochemical oxidation, acidification potential, eutrophication potential and resource and fossil fuels depletion, etc. These environmental impacts can then be translated into damage impacts on the human health, ecosystem quality and resource scarcity. For example, Mehmeti et al. have conducted midpoint and endpoint LCA, corresponding to 17 problems on the ecological level and 3 problems oriented on the damage, to evaluate different hydrogen production methods and pointed out that the electrolysis using renewable energy showed the most benefits [100]. If hydrogen is going to play an important role in future energy systems, life cycle criteria must be assessed to know how it might perform better and also to convince the stakeholders. As the methodological choices of LCA studies vary in goal and scope definition, life cycle invention and assessment, the results and their interpretation can be affected, therefore, a methodological framework that can facilitate the decision-making in the hydrogen sector should be defined from a generalised perspective [115].

4.6. Efficiency and durability

The current achievements on efficiency and durability of fuel cell and electrolyser systems are still not satisfactory and remain as challenges that hold behind the successful market introduction of many hydrogen energy systems. In fact, the efficiency of water electrolysis system is very close to the ultimate target today. The electrical efficiency of AEL systems is around 63%–73%, while the ultimate goal is 70%–80% [93]. A PEMEL system has a lower efficiency of around 60%, which is expected to be improved to 67%–74% in the future [92]. However, in real systems, the operating efficiency can be even higher as the electrolyser can work at higher efficiency with partial loads rather than full loads. Developing optimisation and control strategies to aid electrolysers working at their optimal load may help to improve the operating efficiency. For fuel cell stationary applications, the thermal efficiency should be considered as well. The current achieved electrical efficiency and thermal efficiency of micro-CHP applications is around 36% and 52%, respectively [93]. For mid-size applications, the electrical efficiency and thermal efficiency are 50% and 37%, respectively and for large-scale applications, they are 55% and 32%, respectively [93].

Another challenge is due to the fact that the components of fuel cells and electrolysers may suffer from various degrees of degradation. The degradation may come from electrical, mechanical and thermal deformation, which lead to performance loss. In practice, the operating voltage of an electrolyser stack in a hydrogen production system decrease by about 0.4–5 μV per operation hour and the current electrolyser system durability is around 40,000 h, which implies un efficiency up to 10% lower compared to the initial state [21]. The same is applied to stationary fuel cell systems. The system life is designed to be around ten years for micro-CHP, however, the replacement of the stack must take place twice due to the stack voltage degradation in limited operation time of 40,000 h [93]. A system lifetime of 15 years without stack replacement is expected in the industry. For mid-size and large-scale applications, the system lifetime is around 10 years with one stack replacement and is expected to reach 20 years in the near future. Besides, unsatisfied durability and reliability of the

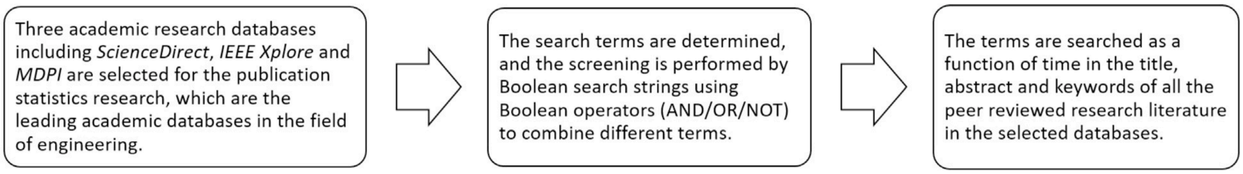

Fig. 17. Review procedure and criteria for screening.

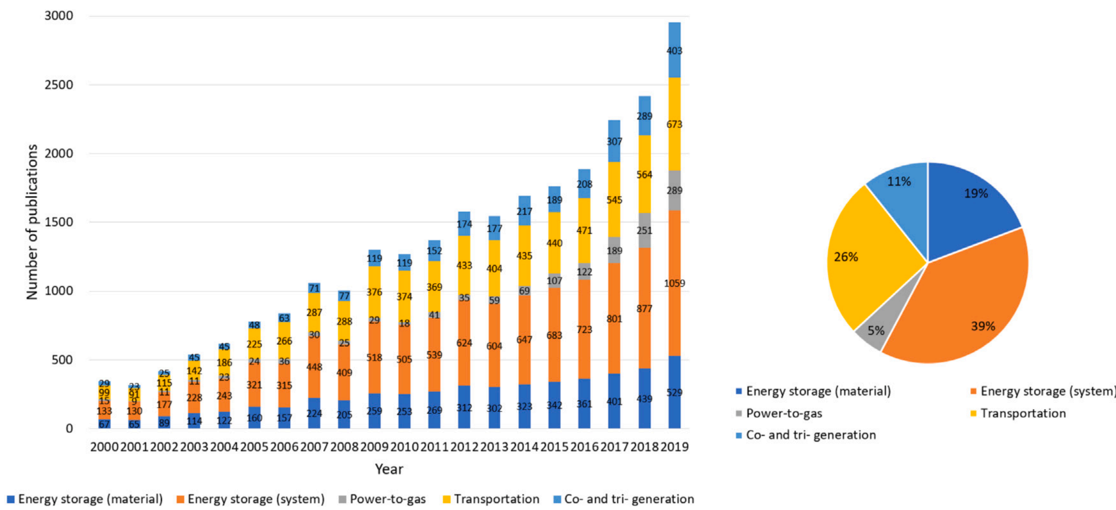

Fig. 18. Yearly evolution and percentage distribution of publications from 2000 to date containing terms "hydrogen" AND "storage" AND "material", "hydrogen" AND "energy storage system" NOT "tank", "hydrogen" AND "power-to-gas", "hydrogen" AND "transportation", "hydrogen" AND ("co-generation" OR "tri-generation"). The search was made on the 2th June 2020.

current hydrogen integration systems are usually associated with a high maintenance cost, while non-optimised operation conditions could be a critical reason leading to the unexpected shutdowns and degradation of the components [116,117]. Efforts on developing system health control and management may be one solution to reduce this part of the cost.

5. Publication statistics

The statistical status of research publications regarding hydrogen powered energy systems is investigated in this section, which has illustrated the increasing importance of hydrogen in today's power systems. The review procedure and the criteria for screening are shown in Fig. 17.

Based on the above review procedure, the yearly evolution of publications investigating different hydrogen power system applications from 2000 to date and the percentage distribution is shown in Fig. 18. It is noted that the researches on hydrogen-based energy storage consist of researches on storage materials and tanks, as well as researches on the system level. The two aspects are considered separately. It is found that all these applications have seen an increasing trend in research efforts. The number of researches on hydrogen-based energy storage systems has taken first place, followed by that of transportation, which has seen a rapid increase. Research on hydrogen storage materials has also aroused great interest owing to the rapid development of material engineering. Publications on the applications of power-to-gas and co- and tri-generation have shared a relatively small part, however, they are getting a rapid increase since 2010 and may continue as the research hot-spots in the coming future.

Fig. 19 shows the yearly evolution of research works regarding the different performance of hydrogen powered systems and the percentage distribution. The searched terms include cost, efficiency and durability, which concern mostly the feasibility and effectiveness of developing hydrogen powered energy systems. Researches regarding hydrogen system efficiency have attracted the most interest, followed by cost and durability, while each of them has seen a yearly increase. Researches on system durability and lifetime share the smallest part, 14% compared to 30% of cost and 56% of efficiency, and have got more emphases only after 2010. As the current durability of hydrogen powered systems and components is still on the way to reach the satisfied level, researches on diagnostic, prognostics and fault tolerant control should be further encouraged.

6. Discussion

This section summarises the projected performance evolution of different aspects of hydrogen power systems on the basis of current status and a trend of increasing system scale is disclosed by reviewing current power system projects. Prospects on technical perspectives and political implications are discussed based on previous analysis.

6.1. Projected performance evolution

Recent years projected cost and performance evolution of fuel cell stationary applications are shown in Fig. 20. It could be seen that continuous efforts should be made to lower down the capital costs of systems in different dimensions, while the maintenance cost should be largely reduced and tends to touch the goal of 2030 target soon. The lifetime and the electrical efficiency of micro-CHP are still on the way of improvement, while the thermal efficiency goal has already been achieved. For mid-size applications, thermal efficiency is under development and has hardly been improved during years. The lifetime of mid-size applications is expected to be doubled for 2030. Efforts on improving the electrical efficiency of both mid-size and large-scale applications should be made in the coming years, whereas the lifetime and thermal efficiency of large-scale applications are about to reach a satisfying level.

Fig. 21 shows the performance evolution of producing hydrogen from renewable electricity using AEL and PEMEL. The technologies of

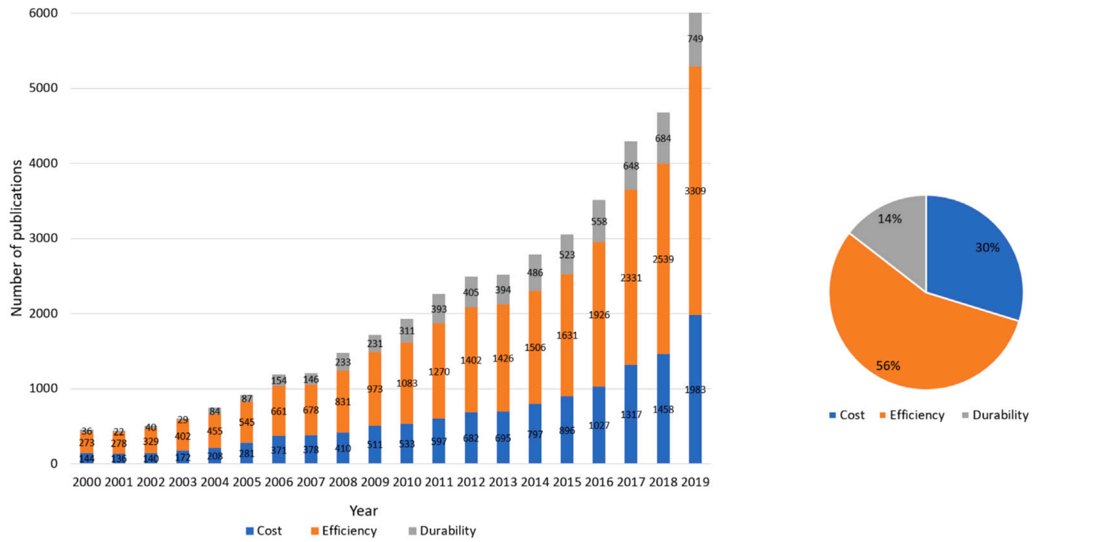

Fig. 19. Yearly evolution and percentage distribution of publications from 2000 to date containing terms "hydrogen" AND ("cost" OR "economy"), "hydrogen" AND "efficiency", "hydrogen" AND ("durability" OR "lifetime" OR "degradation"). The search was made on the 2th June 2020.

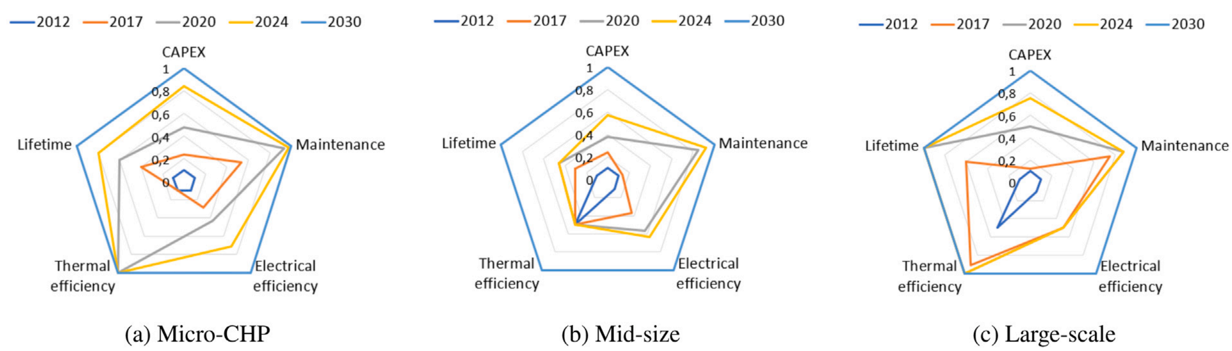

Fig. 20. Performance evolution of different scales of fuel cell applications (indicated by normalised medium values).
Source: Data from [93,94].

Fig. 21. Alkaline electrolyser.

deploying AEL are more mature than deploying PEMEL systems. Efforts on reducing costs and enhancing the system durability and reliability for PEMEL systems are demanding in future work. Besides, for the two electrolyser systems, the use of rare materials on the electrode catalysts is expected to be further reduced, possibly through nano-structure development.

6.2. Scale ramp-up

The collected data from past decades shows that AEL systems tend to reach MW system size rather than PEMEL systems owing to the rather mature technologies [92]. From now on, PEMEL systems are likely to catch up as most manufacturers start to use multi-stack PEM systems rather than single-size ones. By 2030, 2–4 MWe electrolyser stacks and 7 MWe systems are expected to be the common hydrogen production scale over the world [93]. With the rapid development of renewable resources, large-scale systems can easily reach system response requirements. Fig. 22 shows the trend of the increasing scale of the installed power-to-gas plants from 2000 to date around the world.

By 2030, the European Clean Hydrogen Alliance aims to install at least 40 GWe renewable hydrogen electrolysers in Europe, which

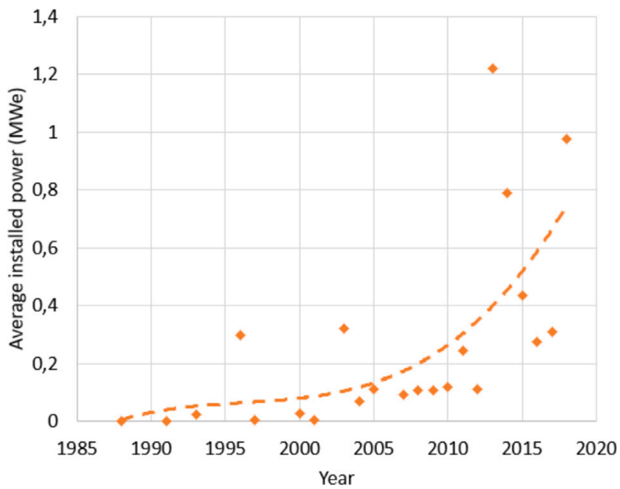

Fig. 22. Increasing installed scale of the worldwide power-to-gas projects (from 2000 to date).
Source: Data from [119].

is a huge leap over the current 250 MWe electrolysers installed in place [118]. Some countries have also started to install large-scale hydrogen projects, for example, the Fukushima project in Japan with an installed capacity of 10 MWe will be put into operation in 2020 and the projects installed in Crystal Brook Energy Park and Eyre Peninsula of Australia are planned to reach capacities of 50 MWe and 15 MWe, respectively. Even larger systems have been under construction or will be constructed around the world in the near future.

6.3. Technical perspective

The development of hydrogen powered energy systems has been industrially mature to some extent, however, room for its technology improvement is still significant. The summarised performance evolution in Section 6.1 shows that enhancements on the cost, efficiency and durability are demanding to different degrees and achieving them concurrently is also important.

Research and development of approaches to reduce cost while improving system efficiency and durability should be undertaken. Studies have been carried out for developing models and designing control and optimisation strategies ranging from supply chain to system structure, e.g., cost minimisation [120,121], scheduling design [122,123], system sizing [124,125] and response optimisation [126,127]. The topology of hybrid hydrogen power systems and techno-economic solutions have been reviewed in [128]. The analysis has pointed out that current strategies for operating a hybrid hydrogen power system are mainly designed to satisfy the power supply, while the strategies devoted to solving the techno-economic optimisation criteria are demanding and should be further developed, especially for the increasing widespread distributed systems. A model predictive control method has been proposed in [129] for a hydrogen-based microgrid in order to meet the energy demand of an office. The proposed event-based control method can successfully track the power load using the renewable energy and the stored energy and at the same time, minimising the power purchase from the local grid. An optimised stochastic design has been proposed in [130] for a PV-battery–hydrogen system, which has proved that the integrated system can sustain an affordable electricity cost over the system's lifetime owing to the energy storage components. Similarly, a multi-optimisation problem has been solved in [131] for an integrated solar and wind energy system, which assessed the exergoeconomic performance and derived the optimal operation conditions of the system. A modelling process has been introduced in [132] for a self-sufficient renewable-based microgrid, in which the system is used to supply electricity and hydrogen to a resident and a car fleet. The fuel cell and electrolyser modes have been realised through an reversible solid oxide cell system and a constrained optimisation strategy has been developed for sizing of the plant components. A two-level multi-objective strategy consisting of the long-term planning of the system capacities and the short-term operation optimisation for an integrated renewable system in microgrid has been developed in [133].

Besides, adequate system and component modelling should be another prerequisite for successful system control and optimisation and ultimately, for hydrogen cost reduction. Li et al. have proposed a 2D model for the hydrogen-based microgrid system and to cooperate between different storage systems, a two-layer structure has been built to solve the allocating-and-dispatching problem, while minimising the operation cost [134]. A mathematical model has been proposed in [135] for a PV–hydrogen-based power system, which facilitate the study on the energy, economy and environment. Direct techno-economic models are also favourable for evaluating the hydrogen production cost, as proposed in [136]. Moreover, when the hydrogen system is integrated with renewable energy resources, the complexity of the system augments and the uncertainties in the power load and supplies increases. Therefore, the configuration of this kind of system should be delicately designed to deal with the nonlinear characteristics and additional variables [116]. Ren et al. have modelled the PV reactor using a 3D multiphysical coupling mathematical modelling method and further used it for studying the dynamic behaviour of an integrated system and determining the decision variables [137]. Planning models that integrate renewable energy in the system have been reviewed in [138], which has justified the uncertainty analysis is necessary, especially for those systems that with different penetration degrees of renewable resources. An optimisation strategy for a renewable energy microgrid with a stochastic module and Monte Carlo simulation has been proposed in [139], in which the uncertainties of renewable sources are taken into consideration. Yang et al. have proposed a robust optimisation method for a microgrid, which have considered both uncertainties in renewables and loads [140]. Other investigations on integrating the renewable energy into microgrids have been reviewed in [141,142].

The publication statistics in Section 5 have also indicated that there is a short of hydrogen system durability improvement in the current research interest and the current achievements on durability issues are still far away from the 2030 target (see Figs. 20 and 21). To meet the industrial needs and to improve hydrogen system durability and reliability, more studies on monitoring the operation and the ageing process of the system are necessary. Diagnostics and prognostics are the methods for identifying the state-of-health, locating the faulty components and predicting the residual lifetime of the system and its components under actual operating conditions. Works on fuel cell diagnostics and prognostics have gained in popularity in the past decade [143,144], while those of electrolysers have remained as a nascent field [145]. For example, Jouin et al. have reviewed the prognostics and health management activities in the PEMFC applications [146], while Lin et al. have analysed the prognostics methods used for different scenarios, i.e. health monitoring, fault diagnosis, prolonging life span, etc. [147]. A review of electrochemical diagnostic methods of PEMFCs have been conducted in [148], which has pointed out that the diagnostic methods existing in the literature cannot be simply applied to the online applications, while an optimised EIS multi-frequency analysis could be a possible solution on-board. As the operation principle of fuel cells and electrolysers are rather similar, the same techniques could be developed for both of them. The key point here is to integrate the diagnostics and prognostics to the control module and to deploy sequence corrective actions or predictive maintenance schedules according to the monitoring results. In this way, the risk of faulty operations could be reduced by detecting and mitigating degradation phenomena, and therefore, it can improve the overall durability of the system. Besides, adaptable maintenance schedule, i.e. predictive maintenance, could be conducted based on predicted system performance so that to save operational and maintenance cost, especially in the remote area.

6.4. Social and political implications

6.4.1. Over Europe

Europe has been in the leading place of developing hydrogen powered energy systems. It has also a large market potential for further profitable business. More than 300 companies in the EU have been engaged in fuel cell and hydrogen sectors, while more in related supply chains [149]. A great deal of techno-economic analysis on operating hydrogen-fuelled facilities have certified the economic feasibility of hydrogen power systems by taking into consideration all direct and indirect costs. Chiefly, marketizing hydrogen-based fuel has a two-fold impact, i.e. integrating renewable energy in current fuel infrastructure and eliminating greenhouse gas emissions. To enable a more favourable environment, some measures could be undertaken.

- A first concern is the electricity price. Taxes take a major share of the electric bill in Europe's power-to-hydrogen applications, leading to difficulties for shrinking down the cost. Exemptions on taxes and levies must be considered, at least with some regulations, for example, avoiding electricity consumption during peak period.
- Gas pipeline systems should be put into practice for hydrogen transport in the near future. Studies have shown the viability of transmitting and distributing hydrogen with the existing natural gas grid, however, the injection of hydrogen is, for the moment, largely limited by national permitting rules. Legal pathways should be considered by the authorities to support gas pipeline development, therefore, give more opportunities to the development of power-to-gas applications.
- Curtailed renewable energy source electricity production has been observed in European countries. As the development of renewable energy source is even faster than the ability to inject them into the local grid, the congestion in the grid leads to the curtailment of the renewable energy sources. A preferable solution could be undertaking regulations for putting in place the priority of connection and dispatch of the renewables and in case of curtailment, compensations should be considered by the policymakers adequately.

6.4.2. Around the world

Hydrogen, as a pollution-free energy carrier, tends to be an essential choice for potential power system developments in all countries around the world. For the moment, reducing its cost and pursuing wide applications are the two main priorities. Following recommendations are suggested in both social and political sectors:

- Large-scale applications should be encouraged. As the technologies are ready to a major extent, large-scale applications are believed to be an economised way providing the minimal infrastructure investments compared to the high operation capacity, especially for areas with abundant renewable energy. Hundred megawatts to gigawatts applications are expected with proper policy supports.
- New hydrogen markets should be developed in the coming decades. Hydrogen as a promising energy transition solution must be considered in all aspects that have suffered from resource exhaustion and pollution: industry, trucking, aviation, shipping, chemical sectors, etc.
- Governments hold the leadership in accelerating the hydrogen economy. Absence of specific regulations will hinder the industrial operations in various ways (impacts on time, cost, etc.). Therefore, coordination, regulation and standardisation should be supported by the governments to help allow the market entry of hydrogen powered energy system.

7. Conclusion

Hydrogen is playing an important role in supporting the decarbonisation of various sectors, e.g. industry, transport, power generation, etc. Efforts have been made to accelerate the process of transforming this potential into reality. This paper has reviewed the key technologies that facilitate the hydrogen integration into energy sectors in terms of production, re-electrification and storage. The applications on the system level for the stationary background are highlighted and the potential of hydrogen to store and transfer energy is recognised. The improvement of the technology readiness level makes it possible to achieve major installations of the renewable hydrogen electrolysers in the coming years.

This paper has also pointed out that the current status on the system capital cost and hydrogen production cost are still not competitive for the hydrogen's wide introduction to the industrial deployments and the consumption of water and rare materials have limited the development from the aspect of sustainability. Moreover, the efficiency and durability of electrolyser systems and fuel cell systems are not satisfied, which lead to the high operation and maintenance cost. Based on the literature survey across the time, a variety of progress is demanded in the near future. Research and development of approaches to reduce cost while improving the system efficiency and durability should be undertaken. Furthermore, policy-makers should enhance the measures that can bring hydrogen to today's markets and promote the development of hydrogen integrated energy systems.

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.

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