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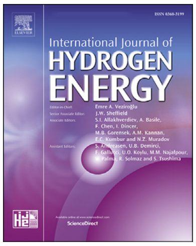

Review Article

Hydrogen electrolyser technologies and their modelling for sustainable energy production: A comprehensive review and suggestions

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HIGHLIGHTS

- This study examines hydrogen electrolysis, its modelling and a state-of-the-art review.
- Electrolysis offers a sustainable, high-purity method of producing hydrogen.
- Details of hydrogen electrolysis are presented, including challenges and prospects.
- Electrolysis technological issues and future suggested directions are outlined.
- Advancements in hydrogen electrolysis are necessary for a renewable energy future.

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ABSTRACT

The advancement of hydrogen technology is driven by factors such as climate change, population growth, and the depletion of fossil fuels. Rather than focusing on the controversy surrounding the environmental friendliness of hydrogen production, the primary goal of the hydrogen economy is to introduce hydrogen as an energy carrier alongside electricity. Water electrolysis is currently gaining popularity because of the rising demand for environmentally friendly hydrogen production. Water electrolysis provides a sustainable, eco-friendly, and high-purity technique to produce hydrogen. Hydrogen and oxygen produced by water electrolysis can be used directly for fuel cells and industrial purposes. The review is urgently needed to provide a comprehensive analysis of the current state of water electrolysis technology and its modelling using renewable energy sources. While individual methods have been well documented, there has not been a thorough investigation of these technologies. With the rising demand for environmentally friendly hydrogen production, the review will provide insights into the challenges and issues with electrolysis techniques, capital cost, water consumption, rare material utilization,

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electrolysis efficiency, environmental impact, and storage and security implications. The objective is to identify current control methods for efficiency improvement that can reduce costs, ensure demand, increase lifetime, and improve performance in a low-carbon energy system that can contribute to the provision of power, heat, industry, transportation, and energy storage. Issues and challenges with electrolysis techniques, capital cost, water consumption, rare material utilization, electrolysis efficiency, environmental impact, and storage and security implications have been discussed and analysed. The primary objective is to explicitly outline the present state of electrolysis technology and to provide a critical analysis of the modelling research that had been published in recent literatures. The outcome that emerges is one of qualified promise: hydrogen is well-established in particular areas, such as forklifts, and broader applications are imminent. This evaluation will bring more research improvements and a road map to aid in the commercialization of the water electrolyser for hydrogen production. All the insights revealed in this study will hopefully result in enhanced efforts in the direction of the development of advanced hydrogen electrolyser technologies towards clean, sustainable, and green energy.

Contents

Introduction

The current fossil-based energy and transportation systems are not sustainable, and the global energy demand is expected to rise due to population growth and industrialization in developing countries [1]. However, the increase in greenhouse gas (GHG) emissions from these systems have raised concerns about climate change and the need to prevent harmful human intervention in the climate system [2]. Utilising fossil fuels as the primary energy source has generated a significant rise in carbon dioxide (CO_2) and other GHG in our atmosphere [3], which causes global warming [4]. The impact extraction of natural resources can contaminate the water, air, and land with toxic byproducts of extraction when processing that has not been sufficiently treated [5]. Water quality can degrade gradually due to gradual changes in climate variables and environmental degradation. A recent study [6] discovered that

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consuming, cooking, and bathing with contaminated water potentially results in skin diseases, high blood pressure, kidney disease, diarrhea, acute respiratory infections, etc. To avoid similar effects in the future, business as usual must change, notwithstanding the tremendous efforts to improve performance made in recent research on the human health implications of water contamination by responsible enterprises and alert government [5]. The consequences also result in economic and political issues [7].

Supply security and climate change are two important concerns for the future of the energy sector, posing the issue of determining the most efficient approach to reduce emissions while also supplying the energy needed to sustain economies. Fossil fuels are finite; hence alternative energy sources are required [7]. Carbon pricing is one of the alternatives that has an important role in facilitating energy transitions, such as the transformation from high-carbon energy (coal and oil) to low-carbon energy (natural gas) and clean energy (renewable resources) [8]. The carbon market can minimise the cost of emission reduction in society, boost investment in green and low-carbon industries, and regulate capital flow by allocating carbon emission reduction resources optimally [8]. Future energy sources must meet the conditions of being carbon-free and renewable for the long-term treatment of climate change and reducing reliance on oil imports [9]. In terms of cost, electrolyzer production costs vary based on size, materials, and volume, and have been decreasing, but must decrease further to compete with other fuels; governments worldwide are promoting the use of electrolyzers as demand for hydrogen fuel in transportation and industrial processes increases [2].

Developing new energy systems based on renewable or sustainable resources is challenging [10]. Variable and intermittent renewable energy (RE) are the major challenges to 100% RE [11]. Location-dependent renewables are hard to store and transport [10]. The attractive concept of storing RE in a transferable, storable, and useable energy carrier such as hydrogen may provide the solution [12]. Hydrogen can be produced using fossil fuels and RE as feedstock, processes, and technology [13]. 96% of hydrogen is generated from natural gas, oil, and coal hydrocarbons. The presence of toxic carbon monoxide (CO) in hydrogen derived from hydrocarbon sources can significantly degrade the properties of fuel cells that convert the chemical energy of hydrogen to electrical energy [14]. A significant amount of the CO_2 emitted into the atmosphere contributes to climate change, destroying the ecosystem [15]. Producing hydrogen from non-renewable hydrocarbons is indeed not sustainable. Hydrogen must be produced using renewable sources and no CO_2 [16]. Currently, rising oil prices result in higher energy and production expenses, as well as an increase in interest rates [17]. Even though oil can influence the domestic and global economy, it is a non-renewable energy source [18]. A rise in oil prices induces industries to replace conventional energy products with sustainable energy alternatives [19].

Hydrogen is not naturally occurring like fossil fuels [9]. Hydrogen is an abundant renewable energy source [20]. Pure 100% hydrogen can be synthesized by water electrolysis to produce hydrogen and oxygen [13]. The electrolysis of water was first reported in 1789 [21], and industrial water electrolysis had been established for 100 years [22]. Water electrolysis comprises three adjacent components: the anode, electrolyte, and cathode. When hydrogen oxidises at the anode, cations move to the cathode through the electrolyte, and free electrons flow to the external circuit. At the cathode, cations and electrons reduce oxygen to water [23]. Water electrolysis has been mainly utilised for technical applications to generate hydrogen rather than oxygen [11]. Hydrogen produced by water electrolysis is the greatest energy carrier to balance renewable primary energy supply and end-use energy demand [24]. Hydrogen combustion produces water vapour. Thus, it is the cleanest, most efficient, and most sustainable fossil fuel alternative [16]. Hydrogen produced from renewable resources is also a) regarded as a viable solution to environmental issues, b) negligible greenhouse gas emissions, c) has high energy density, and d) works with fuel cells (FCs) [25]. Hydrogen is considered the most sustainable alternative to fossil fuels for ensuring energy sustainability [26]. The practicality and application of hydrogen necessitate the evaluation of factors such as storage capacity, energy density versatility, transportation, and environmental consequences [7]. Additionally, renewable energy sources such as solar, wind, and ocean energy are gaining popularity [27]. It might be an energy revolution. It inspires water electrolysis research [16]. When sources of power are intermittent and/or produce current densities that are much below these optimal levels for prolonged periods, conventional electrolysers can struggle to run efficiently and safely [28]. This is due to the gas production and membrane separator permeability issues. The high-efficiency gas diffusion electrodes and membrane electrode assembly can be promising industrial electrolytic devices [29]. Decoupling the oxygen and hydrogen evolution reactions of water splitting such that the two gases are not generated in the same cell at the same time may benefit with power supply intermittency and low current density operation [30]. Decoupled water electrolysis has recently become a major topic in water electrolysis, providing an ion-membrane-free electrolysis method for the production of high-quality hydrogen [31].

Electrolysers generate hydrogen and oxygen with little impurities. These can be extensively dispersed and suited to satisfy renewable energy systems' hydrogen and oxygen needs, fuelling stations for FC cars, and industrial uses. The most common types of electrolysers are alkaline and polymer electrolyte membrane (PEM) [32]. Alkaline electrolysis is an established and reliable technology that differentiates itself from other types of electrolysis in terms of cost and ease of use [33]. Modelling of water electrolyser is essential for simulating and predicting the behaviour of hydrogen generating systems. Realistic modelling of the full electrolyser (cell including balance-of-system components, including heat management and controls) is crucial when the electrolyser is coupled directly to a renewable source of electricity, as the irregular and variable power supply can be anticipated. In the previous ten years, electrolyser research has intensified, and increasingly sophisticated models have emerged [32]. As depicted in Fig. 1(a) (publications trend: data from the Scopus database), the increasing popularity of this research field is reflected by the volatility in the number of scientific publications published since 2004. This study focuses on hydrogen electrolyser papers that contain the terms "hydrogen

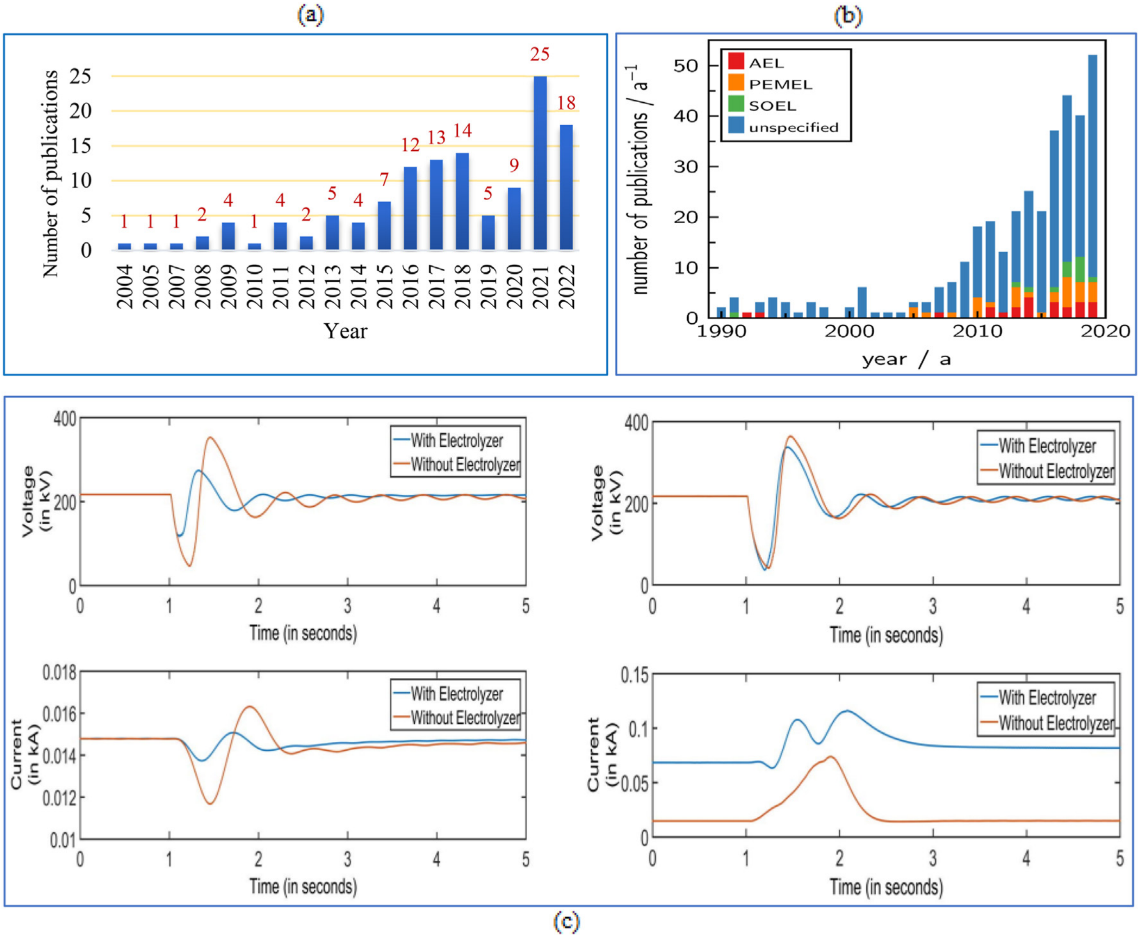

Fig. 1 – (a) Evaluation publications trend per year conducted in this study using Scopus including the terms ("hydrogen" AND electrolyser) AND ("control" AND "strategy") AND ("sustainable" AND "energy). The search was done for the fourth week of August 2022. (b) For different hydrogen electrolyser technologies, the number of publications per year from 1990 to 2019 containing the specified keywords Because of increased interest in the energy turnaround, the publication frequency rises in 2010. Despite the topic being frequently studied technology-independently, extra publications for technologies with low-temperature, such as proton exchange membrane electrolysis (PEMEL), and alkaline water electrolysis (AEL) have more publications than high-temperature technology like solid oxide electrolysis (SOEL) [19]. (c) Demonstration of the impacts of electrolyser on power system transient reduction of single-phase to ground fault and three-phase ground faults with and without electrolysers in the grid [20].

electrolyser," "control strategy," and "sustainable energy." The graphic reveals that hydrogen electrolysers with control strategies have been a popular research focus during the past decade. Simultaneously, research on hydrogen electrolyser is expanding; however, reviewing past literature for future development is necessary. Based on the study conducted by Ref. [19] For different hydrogen electrolyser technologies, the number of publications per year from 1990 to 2019 containing the specified keywords is shown in Fig. 1(b). Because of increased interest in the energy turnaround, the publication frequency rises in 2010. Despite the topic being frequently studied technology-independently, extra publications for technologies with low-temperature, such as proton exchange membrane electrolysis (PEMEL) and alkaline water electrolysis (AEL) have more publications than high-temperature technology like solid oxide electrolysis (SOEL). The hydrogen electrolyser has positive impact on the grid stability as shown in Fig. 1(c) [20]. It can be seen that the hydrogen electrolyser has decrease the transients state that are caused by faults in the grid as compared without electrolyser.

Numerous reviews published describe the use of hydrogen produced by water electrolysis. The review on water electrolysis technologies by Kumar et al. [21] supports the development of the PEM electrolyser as a practical method for producing hydrogen on a commercial scale. Carmo et al. [13] examine the current state of PEM electrolysis technology. Zeng et al. [25] examined water electrolysis technologies and compared water electrolysis using thermodynamic and kinetic parameters. Abdalla et al. [7] review hydrogen technologies that provide a comprehensive description and comparison of existing storage systems. Nikolaidis & Poulikkas [9] provide a comparative review of the most prominent hydrogen production methods. Tong et al. [22] highlight issues in electrolyser design and future techniques that may offer highly selective and active materials for water electrolysis in the existence of typical contaminants. Eriksson & Gray [23] review hydrogen

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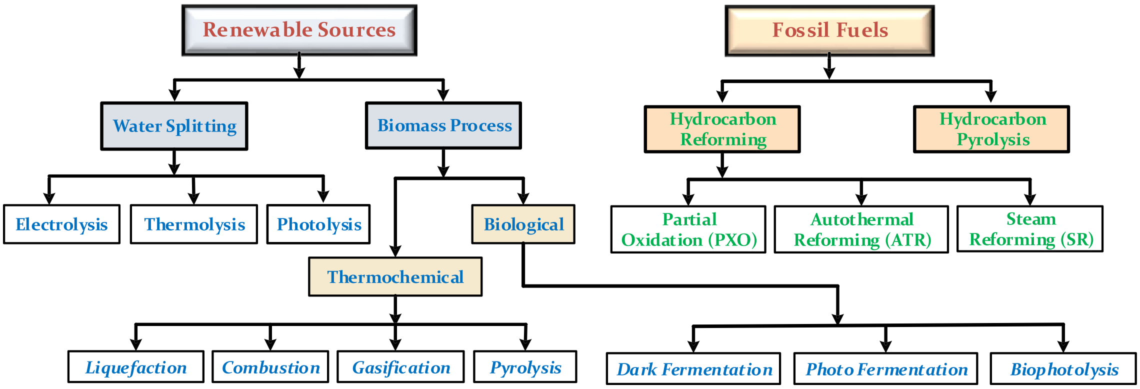

Fig. 2 — Methods of hydrogen production [6,21].

energy integration into hybrid energy systems, focusing on fuel cell power production. Dawood et al. [4] provide an overview of the hydrogen energy system and technology projects.

This paper provides an overview of hydrogen production from fossil fuels, and renewable sources discuss in section 2, as well as a description of water electrolysis as the most certain solution for eco-friendly hydrogen production, hydrogen as renewable energy storage, and a summary of project-based hydrogen storage. The evolution of hydrogen electrolysers is then discussed in Section 3. Section 4 covers hydrogen electrolyser models based on a literature review. Section 5 discusses the issues, difficulties, and solutions concerned with hydrogen electrolyser research. The conclusion in Section 6 reiterates the necessity to enhance research to realise the development of the hydrogen electrolyser. Our contribution in reviewing has three aspects: technologies with an emphasis on electrolysis production, models, and control strategies. In addition, limited literature describes the strategies used for controlling a hydrogen electrolyser. Reviewing the models and control strategies from different literatures can aid the researcher in comprehending how cell components affect electrolyser performance and recommend routes for future research to enhance electrolyser performance.

Hydrogen is among the most crucial energy carriers in existence today. Despite this, producing hydrogen from nonrenewable sources has many environmental implications. Producing hydrogen from sustainable sources is the best way for a hydrogen community to meet its energy needs. Sustainable development favours energy resources since they are affordable and have minimal to no negative impacts, with solar energy having the most potential. Thus, the widespread adoption of a light-based hydrogen energy system is vital for global sustainability. The hydrogen-based production, storage, utilization, and overview project based on hydrogen storage is intensively explored in this section 2.1. Contrary to other industrial operations (such as biological production and steam reformation), water electrolysis for hydrogen production is the focus of several works linked to energy implementations and RE technologies. Section 2.2 describes the primary technologies of water electrolysis: solid oxide electrolyser (SOE), polymer electrolyte membrane (PEM), and alkaline water electrolysis (AEL), as well as the electrolyser system structure, storage, and hydrogen renewable energy system for power generation. Section 2.3 provides an overview of hydrogen storage projects globally.

Hydrogen production overview

Hydrogen can be produced in a variety of ways. An initial split can be done according to the energy source employed in production. Presently, hydrogen is generated from natural gas (48%), heavy oils and naphtha (30%), and coal (18%) [24]. Indeed, 96% of hydrogen comes from fossil fuels, and the remaining 4% comes from water by utilising electrolyser, a RE source [36]. Hydrogen can be produced from two major categories using either fossil fuels and hydrocarbons or RE sources [37], as shown in Fig. 2. The first subcategory involves the processing of fossil fuels and comprises the hydrocarbon reforming and pyrolysis processes. The chemical techniques involved in the hydrocarbon reforming process are steam reforming, partial oxidation, and thermal steam reforming. The second subcategory involves technologies that produce hydrogen from renewable sources, such as biomass and water. The primary source of potential energy from biomass is heat production [38]. Biomass processes for hydrogen production can be categorized as either biological or thermochemical techniques, with examples of biological processes including bio photolysis, dark fermentation, and photo fermentation, while thermochemical processes include pyrolysis, gasification, combustion, and liquefaction; furthermore, water is also a highly desirable renewable resource for hydrogen production. Electrolysis is the primary synthesis mechanism in this context, although thermolysis and photo electrolysis are also gaining interest. Table 1 summarises various hydrogen production technologies, feedstock advantages, disadvantages, operating temperature, cost, and efficiency. The significant cost of hydrogen production technologies and their limited operational lifetimes necessitated the implementation of improvements. In developed nations, the costs of receiving such energy services have varied significantly in recent years [39]. Furthermore, the significance of energy efficiency as a policy goal is linked to economic interests, industrial competitiveness, and energy security, and is growing aligned to environmental benefits such as the reduction of carbon dioxide emissions and the customer's profitability/competitiveness [40].

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Table 1 – Summary of various hydrogen production technologies, advantages, disadvantages, operating temperature, efficiency and cost [21,28,29,30,31].

Technology	H_2 production method	Feedstock	Advantages	Disadvantages	Operating temperatures (°)	Efficiency (%)	Cost [$/kg]
Fossil Fuels	Steam Reforming (SR)	Hydrocarbons	Existing infrastructure and developed technology	CO and CO_2 produced an unstable supply.	700–1000	74–85	2.27
	Partial Oxidation (PXO)	Hydrocarbons	Revolutionary technology	Produced heavy oils and petroleum coke with H_2 Production.	800–1000	60–75	1.48
	Autothermal Reforming (ATR)	Hydrocarbons	Existing infrastructure and well-established technology	Utilising fossil fuels produces CO_2.	700–1000	60–75	1.48
RE-based biomass (biological)	Bio-photolysis	Biomass + Sunlight	Operated in mild conditions, consuming CO_2 and producing O_2.	Low H_2 yields, huge reactor necessary, O_2 sensitivity, high material price	Ambient	10–11	2.13
	Dark Fermentation	Biomass	A simple approach, no light, no limit O_2, CO_2-free, waste recycling	Removal of fatty acids, low H_2 rates, ineffectiveness, and the need for a large reactor volume	Ambient	60–80	2.57
	Photo Fermentation	Biomass + Sunlight	Recycled organic waste water is CO_2-neutral.	Low H_2 generation and efficiency, sunlight need, large reactor volume, O_2 sensitivity	Ambient	0.1	2.83
RE-based biomass (thermochemical)	Pyrolysis	Biomass	Cheap, plentiful, and CO_2-neutral	Tar creation, changing H_2 levels due to contaminants in the feedstock, and seasonal availability	300–800	35–50	1.59–1.70
	Gasification	Biomass	Cheap, plentiful, and CO_2-neutral	Changing H_2 rates due to feedstock contaminants, tar formation	800–1000	30–40	1.77–2.05
Water Splitting	Electrolysis	water	Existing infrastructure (O_2), zero-emission, and established technologies	Storage and transport constraints	700–1000	60–80	10.30
	Thermolysis	water	O_2-byproduct, abundant feedstock, clean and sustainable	High capital expenses, hazardous elements, and corrosion.	Above 2500	20–45	7.98–8.40
	Photolysis	Water + sunlight	No emissions, sufficient feedstock, and a by-product as O_2.	Inefficient photocatalytic substance, low efficiency, needs sunlight	Ambient	16	8–10

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Referring to Fig. 2, there are four primary production strategies/methods from a technology perspective: (i) hydrocarbon reforming, (ii) hydrocarbon pyrolysis, (iii) biomass processing, and (iv) water splitting [9]. Steam methane reforming (SMR) and pyrolysis are the most extensively utilised processes for hydrogen synthesis from fossil fuels [24]. These methods are the most developed and widely used technologies, supplying practically all hydrogen consumption. Hydrogen generated by the combustion of fossil fuels produces hazardous pollutants [32]. The unavailability of hydrogen gas in nature and the need for low-cost production technology are the key obstacles to using hydrogen gas as a fuel [33]. For instance, Parthasarathy and Narayanan [47] provide SMR and coal gasification as the cheapest solutions (0.75 US$kg^{-1} and 0.92 US$kg^{-1} of H_2 produced, these without CO_2 capture), whereas electrolysis costs between 2.56 US$kg^{-1} and 2.97 US$kg-1 by including the production of electricity with nuclear energy. Electrolysis is the most well-known water-splitting process. Additionally, the primary objective is to generate clean, efficient power when the reactor is coupled [28]. As a result, the primary focus is on water splitting, more particularly electrolysis. The emphasis is on hydrogen production by electrolysis technology; hence section 2.2 depicts an electrolysis process. Furthermore, for the production of hydrogen as shown in Table 1, diverse methods and sources are currently in use in transportation applications, stationary/domestic electric/heat generation, locally stored energy, balancing of renewable electricity production, and portable electronics [42].

Hydrogen production by water electrolysis

"Water is the coal of the future." declared Jules Verne in 1874's in his novel “Mysterious Island.” The first water electrolysis tests were done in 1789. The investigations used an electrostatic machine that discharged electricity onto gold electrodes submerged in water. Alessandro Volta devised the Voltaic pile in 1800 for electrolysis. They used copper electrodes and a voltaic pile to conduct electrolysis experiments. Finally, J. Ritter performed true water electrolysis, collecting both oxygen and hydrogen. However, due to engineering and technical issues, industrial electrolysis began in the late 1800s [35].

Water is plentiful and has endless foundation material. Hydrogen will be the purest type of energy that humanity may consume if the required energy consumption is met by renewable sources [6]. As seen in Fig. 2 and Table 1, hydrogen can be produced through electrolysis, thermolysis (or thermochemical water splitting), and photo-electrolysis (or photoelectrochemical water splitting (PEC) [28]. Water electrolysis is the process of separating water into its constituents by producing a potential difference between two electrodes in an electrolyte. Electrolysis is the reverse of the FC process, which utilises hydrogen and oxygen to produce electricity and water. Electrolysis requires a low-cost water and electricity supply [28]. Electrolysis is the ideal technique for splitting water. The process is endothermic; hence the input of energy needed is electricity. In electrolysis, hydrogen is produced at the cathode and oxygen at the anode through an equation (1) [49]. Equation (1) shows the half-reaction thermodynamic potentials at the anode and cathode are temperature and pressure dependent [50]. Electrons travel from the anode through an electrical circuit to the cathode, where they are consumed in the oxygen reduction process. When oxygen is present at the cathode, current can be generated, but the current generation is not spontaneous in the absence of oxygen. If the current generation is driven by introducing a voltage (>0.2 V in operation) between the anode and the cathode, protons are reduced to hydrogen gas at the cathode [51] (see equation (1)).

$$\text{Anode}: H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$$

$$\text{Cathode}: 2H^+ + 2e^- \rightarrow H_2$$

$$\text{Overall}: H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

Recently, the researcher found that nanoparticles efficiently transport electrons, affecting aerobic microbial energy metabolism for biohydrogen production. Nanoparticle surface and quantum size effects may promote biohydrogen production. For example nanomaterials such as Cu, Fe, Au, Ag, Pd, Ni, etc can be utilised to produce biohydrogen. Nanoparticle surface and quantum size effects may promote biohydrogen production. Nanoparticle size is proportional to electron transfer velocity among nanoparticles and enzyme stimulants like hydrogenase, which appears to catalyse the transformation of hydrogen to proton and vice versa, either as electron drains or even to produce reducing energy from oxidation [52]. The article [53] analyses the relationship between copper and zinc prices (mainly metals) from 2011 to 2021 and predicts their future pricing. This is utilised to balance the long-term models of commodity prices across multiple marketplaces.

Technologies of water electrolysis

Numerous hydrogen production technologies, including electrolysis, have been carefully analysed from economic, environmental, technological, and social perspectives [43,44]. Water electrolysis is now the most crucial industrial approach for practically pure hydrogen; therefore, its future importance [54]. Electrolysers are well-recognised as critical devices for converting energy to gas in P2G systems [46,48]. The P2G concept uses water electrolysis to convert RE (wind, solar, geothermal, hydro) into gas. Based on established technology, this attractive approach for hydrogen generation now accounts for only 4% of hydrogen production, but it is estimated to grow to 22% by 2050 [55].

In terms of electrolyte types, there are three primary types of electrolysers [56]: (i) solid oxide electrolyser (SOE) [57], (ii) polymer electrolyte membrane (PEM) electrolyser [58] and (ii) alkaline water electrolysis (AEL) [59]. Their varieties depend on the electrolyte, operating circumstances, and ionic agents (H^+, O^{2-}, OH) [60]. Nevertheless, the operational fundamentals are equivalent. These characterizations affect the electrolysis system's efficiency, energy prices, and capital expenditures, which affect electrolysed hydrogen prices [61]. Furthermore, liquid hydrogen has advantages such as high heating value per mass and huge cooling capacity as a consequence of its elevated specific heat [62]. Table 2 and Fig. 3 summarize the operation specifications of three types of electrolysers; solid

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Table 2 – Typical specifications of solid oxide electrolyser (SOE), polymer electrolyte membrane (PEM) and alkaline water electrolysis (AEL).

Electrolyser	SOE	PEM	AEL
Technology maturity	Demonstration	Commercial	Mature
Electrolyte	Ceramic (Solid)	Polymer (Solid)	KOH (Liquid)
Cell temperature, °C	500–1000	60–90	50–90
Operating Pressure (bar)	<30	15–30	2–10
Cell Voltage (V)	0.7–1.5	1.8–2.2	1.8–2.4
Current Density (A/cm^2)	0.3–1	0.6–2	0.2–0.4
Power density (W/cm^2)	–	Up to 4.4	Up to 1.0
Voltage Efficiency (%)	81–86	67–82	62–82
Charge carrier	O^{2-}	H^+	OH^-
Anode	LSM-YSZ	IrO_2, RuO_2	Ni, Ni–Co alloys
Cathode	Ni-YSZ	Pt, Pt–Pd	Ni, Ni–Mo alloys
System energy consumption, kWh/Nm^3	2.5–3.5	4.5–7.0	4.5–7.0
H_2 Capacity (Nm^3/h)	<40	<40	<760
H_2 purity	99.9	99.999	>99.8
Stack lifetime, hr	<40,000	<20,000	<90,000
System lifetime, yr	–	10–20	20–30
Cold start-up time, min	>60	<15	15
Advantages	Current density requires low energy, low capital loss, no catalyst, and high efficiency.	High current density, compact, high purity of hydrogen, simple design, quick response/start time	High stability, low cost, mature technology, no catalyst, longer lifetime
Disadvantages	Delamination of electrodes, safety problems, instability of electrodes, unsuitable sealing	Precious catalyst, lower durability, Expensive membrane, acidic medium	Gas permeation, lower density, corrosive electrolyte, dynamicity

LSM: Lanthanum strontium manganese, YSZ: Yttria stabilised Zirconia. References: [34,48,54].

oxide electrolysers (SOE) (a), polymer electrolyte membrane (PEM) (b), and (c) AEL. The polarisation curves and thermoneutral values of several different electrolyzer methods are presented in Fig. 3 (d) [63]. When compared to an electrolyzer that operates at a low temperature, SOE enables the achievement of larger thermoneutral current densities as well as relative power densities. Real-world systems typically function at temperatures higher than thermoneutral due to the accumulation of thermal losses, and the operative current densities are typically higher than the thermoneutral value [63]. Large-scale, sustainable hydrogen production is needed to reduce carbon dioxide emissions and boost industrial activities. Current commercial methods like low-temperature electrolysis will be expected to meet much of this demand during the upcoming 20 years [64]. Based on the study conducted by Ayers [64], collaboration among government, academic, and industry sectors will increase the hydrogen capacity during the next 25 years, as shown in Fig. 3(e). To show the high interest and importance of this technology towards green energy technology, different hydrogen electrolyzer projects are witness dramatic increase, according to the International Renewable Energy Agency (IRENA) [65]. It can be seen in Fig. 3(f) that the accelerated scalability of electrolyzers for the production of hydrogen.

According to Table 2, hydrogen production via AEL is currently an established technology with commercially viable megawatt (MW) scale facilities. PEM and SOE systems have also evolved to an enviable level of performance [45]. The most important criteria in Table 2 are voltage efficiency and current density. The efficiency of an electrolysis process is measured by comparing ideal and actual energy requirements [43]. Additionally, it was stated in a review [66] that comparing the energy usage and efficiency of different commercial electrolytic methods used in the United States, China, and Europe. A commercially accessible electrolyser has an efficiency range between 50 and 80% (73% and 64% for higher heating and lower heating values, respectively) when employing AEL or PEM electrolysers. Nonetheless, improvements are achievable and being pursued, as seen in Table 2. Currently, China has been the world's largest hydrogen producer for seven years, China has ranked number one in the world in hydrogen production. Cost considerations led to the production of 95% of this hydrogen from fossil fuels. The public is increasingly accepting of electricity-to-hydrogen conversion as a way of efficiently utilising abundant RE [60]. Worldwide, there are comparatively few demonstration projects integrating the electrolytic hydrogen production process with RE sources. This has been covered in Ref. [67].

Electrolyser system structure

The electrolyser stack comprises numerous separate cells connected in series to achieve a high voltage despite each cell's low potential (2 V). Also, high-current density electrolyser systems with parallel stacks can achieve multi-MW scalability at voltage levels (a several kV) [68]. Fig. 4 shows an electrolyser system introduced by Yue et al. [69]. The electrolyser is coupled to the gas–water separators and connected to the power source via an alternating current (AC)/direct current (DC) converter. The system requires a power supply unit (PSU) and a balanced plant (BOP). Gas separators separate the generated gases from the water before purifying and drying them to the desired level for separate clean

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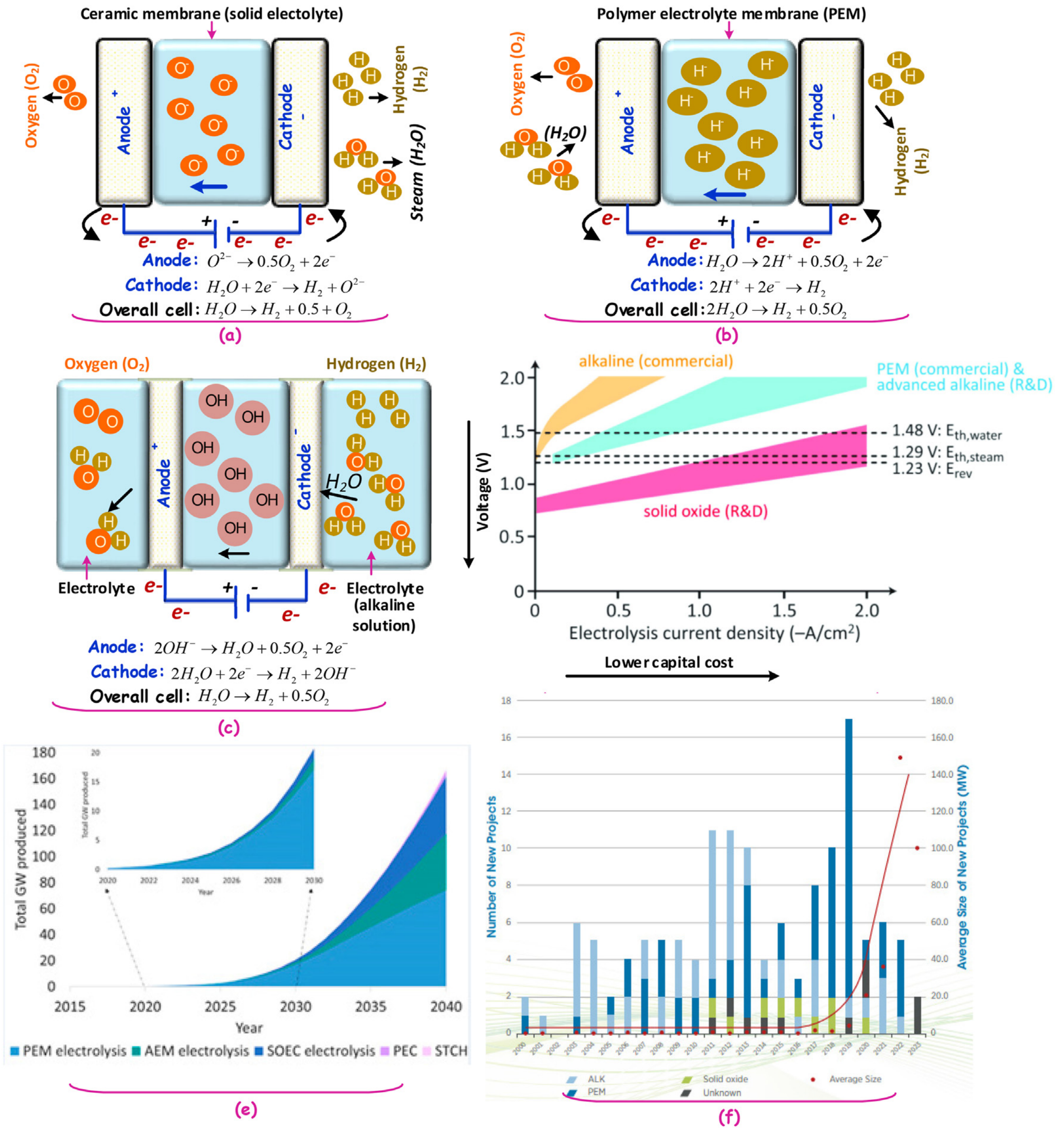

Fig. 3 – (a) Operation schematic of electrolysers (a) SOE, (b) PEM and (c) AEL [67]. (d) Voltage vs. current density comparison of the solid oxide, PEM, and alkaline electrolysers [63]. (e) Energy output (in the form of hydrogen) is expected from cutting-edge water-splitting technology in the next quarter-century [64]. (f) Project scale and electrolyser technology timetable for power-to-hydrogen projects across the globe based on International Renewable Energy Agency [65]. Accelerated scalability of electrolysers for the production of hydrogen.

hydrogen (H_2) and oxygen (O_2) gas. A heat exchanger heats the electrolyte as it flows through the electrolyser cells [70]. Electrolyser stacks can be connected in parallel in an attempt to increase the output current to a multi-megawatt level. Transformer and rectifier power the electrolyser stack.

Electrolyser system design

Energy storage (ES) is essential to assure the dependability of off-grid power supply from variable sources [66]. ES is utilised in power systems to improve energy supply (including improving the quality of voltage characteristics and lowering the influence of loads and unstable sources on these parameters) and manage energy flow [71]. By 2040, the IEA predicts that about a third of global electricity will come from unreliable renewable sources such as wind and solar [72]. This will necessitate large-scale, long-term electrical storage, with the generation and storage of hydrogen as a viable solution [73]. This large-scale hydrogen storage research seeks safe, reliable, lightweight, and expensive FC technologies. Hydrogen should be produced, delivered, kept, and transmitted. The key technological issue for a viable hydrogen economy is storage, which has proven to be an insurmountable obstacle. Making hydrogen more energy-dense is essential for transport. However, solutions to the hydrogen storage issue are rapidly emerging. Scientists are investigating novel methods of hydrogen storage. Hydrogen can be preserved in numerous

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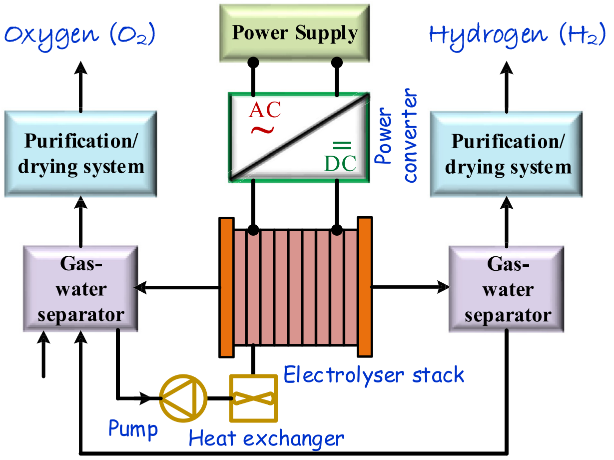

Fig. 4 – System structure of electrolyser [69].

ways for future use. Currently, compressed hydrogen, liquid hydrogen in cryogenic tanks, and storage material are available [74]. Hydrogen can be stored via physisorption, physical adsorption on a solid surface, or chemisorption using metal hydrides. Up to the present, the most popular method has been compressed gas [72]. Numerous reviews of various hydrogen storage systems are available [75,76] and are not covered in this study. Economical, environmentally friendly, and long-term mass storage are considered to be essential research goals.

Compressed hydrogen gas storage. A procedure for technically preserving hydrogen gas at high pressure is known as compressed hydrogen storage (up to 10,000 pounds per square inch). Toyota's Mirai FC uses 700-bar commercial hydrogen tanks [77]. Compressed hydrogen storage is simple and cheap. Compression uses 20% of hydrogen's energy [66]. The compressed technique is straightforward, but the procedure is inefficient in terms of volumetric and gravimetric efficiency [74]. The disadvantages are low system energy density compared to fossil fuel systems and high-pressure safety considerations [72].

Liquid hydrogen. Liquid hydrogen is referred slush hydrogen, generally highly resistant to corrosion and colourless at 20 K. Hydrogen is commonly stored as a liquid, which needs cryogenic storage. Despite compressed gas tanks (stored: 0.030 kg L^{-1}), liquid hydrogen containers have a storage capacity of 0.070 kg L^{-1} [74]. The storage tanks must be well insulated to keep the sub-zero temperature. When hydrogen is strongly bonded to certain other elements, liquefaction occurs. Current research focuses on developing stronger and lighter composite tank materials [74]. This procedure employs approximately 30%–40% of the hydrogen's energy output [78]. Even though the technique appears to be intriguing due to its gravimetric and volumetric efficiency, additional research is necessary to understand issues such as hydrogen uptake and release, a high hydrogen liquefaction rate causing energy loss, hydrogen braise, and storage cost [79]. The disadvantages of liquid hydrogen are high energy requirements, hydrogen boil-off, and high storage costs. Due to boil-off, it's not ideal for permanent ES [72]. In hydrogen storage, chemical bonding, molecule adsorption, and van der Waals attraction and dissociation all play roles in hydrogen transport. Electrochemical potential, temperature, and pressure can change molecular/ionic hydrogen's surface and bonding strength. The information may be found in this review [74], which does not discuss in this research.

Distributed hydrogen power system. Once hydrogen is produced, it can be utilised to store energy and convert it to heat or electricity or be used as an energy carrier [41]. FCs are the remedies for ES. FCs are ecologically friendly, silent, and have better energy efficiency [80]. FCs have positive and negative electrodes, connector plates, and current collectors. FC stacks can generate a few watts to multi-MW, rendering devices robust [41]. The electrolysis of water can function admirably on small sizes. It can be regarded as more sustainable due to the use of renewable energy. Water electrolysis may play a significant role in a decentralised power generation, transmission, preservation, and usage scheme serving isolated populations as shown in Fig. 5. It uses RE to produce hydrogen, which could be used as a fuel gas for heating and as a way to

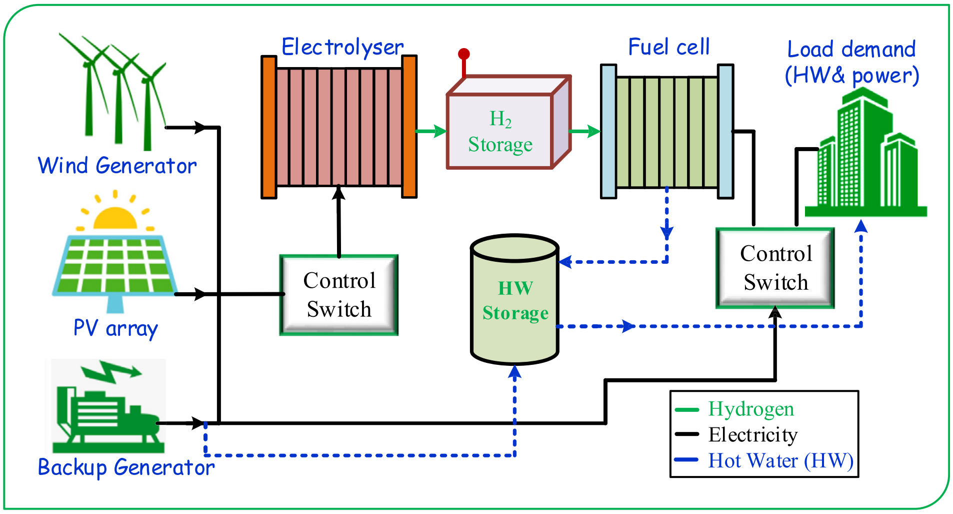

Fig. 5 – Hydrogen distributed power generation model [81].

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store energy. If RE sources are abundant, surplus energy can be kept as hydrogen by electrolyzing water. Hydrogen will then be utilised to generate energy in FCs or as fuel gas. The diagram also shows a diesel engine as a backup and a hot water storage tank for domestic use. This model for a distributed hydrogen RES was proposed by Badwal et al. [81].

Overview of project-based hydrogen storage

Numerous hydrogen ES projects have been undertaken worldwide, indicating hydrogen's viability as an ES medium for its widespread industrial usage. In 2011, Kippers et al. [82] introduced the Netherlands' Ameland project became the first to incorporate hydrogen into a natural gas network. The combination was delivered to 14 for domestic use. A PEM electrolyser produced 100% renewable hydrogen blended into natural gas at 5%–20%. Existing pipes, cooktops, and boilers were not evaluated for safety during the procedure.

In 2019, Pierson et al. [83] introduced the DATAZERO project to integrate RE into data centres by addressing the difficulties of sizing, optimising, and controlling RE in data centres in the software and hardware stages. It proposed a system based on PVs, WTs, hydrogen storage, batteries, and supercapacitors to improve IT infrastructure adaptability and manoeuvrability. Austrians store wind and PV underground with Underground Sun Storage. Because RE is not flexible and doesn't meet requirements, excess RE is converted to hydrogen for later use. The project discovered that Subterranean gas storage tanks could resist upwards of 10% hydrogen, helping to balance seasonal RE supplies [15]. In Europe, four demonstration facilities have been erected under the EU's Horizon 2020 initiative to show hydrogen and Li-ion batteries' technological and economic feasibility [3]. First-ever evaluation of metal hybrid storage in the UK can refer to Ref. [84]. HyDeploy is a hydrogen energy initiative to reduce CO_2 emissions and achieve net-zero emissions by 2050. HyDeploy is the first project in the United Kingdom to incorporate hydrogen into a natural gas pipeline. Furthermore, more diverse initiatives utilised RE sources to supply the electrolyser's electricity needs that may be discovered in reviews [48,69,78].

Hydrogen electrolyser models

Modelling has become an integral part of electrolysis technology development. An increasing number of research papers highlight the importance of conducting a comprehensive analysis of this subject to identify the advantages and limitations of scientific literature and to provide guidance for future research [85]. Numerous models for water electrolysis have been published in the literature, as it plays a critical role in hydrogen systems. Modelling of water electrolysis is crucial for simulating and predicting the performance of hydrogen-generating systems [32]. Most of these models are developed from the fundamental set of equations relating the applied potential to the current and hydrogen production in an electrolysis cell [86], and each is customized to its application or the background of its authors. Electrolysis cells are distinguished by their electrolyte composition [87]. Modelling is essential for quantifying efficiency, analysing dynamic behaviour, and developing effective control and monitoring systems [88]. For research and other purposes, modelling may reflect an energy system's behaviour, such as real-time prediction of the energy system's trajectory as its inputs and loads fluctuate [89].

Water electrolysis produces H_2 and O_2 (Equation (1)) in the two-stages electrochemical reaction. The reduction reaction is initiated at the negatively charged cathode, while at the positively charged anode, the oxidation reactions take place. The charge carrier can be O^{2}-, H+, or OH-, depending on the water electrolysis technology: SOE, PEM, and AEL. Numerous authors have used the approach to modelling water electrolysis. Under the influence of electrical energy, the entire operation of electrolysis demonstrates the separation of water molecules. The electro-motive force (emf) required to separate water into H_2 and O_2 is referred to as reversible voltage (U_{rev}), which is a function of temperature and pressure and can be computed using the Nernst equation [90] (see equation (2)):

$$U_{rev} = U^{0}_{rev,T,P} - \ln\left(\frac{R.T_{el}}{n.F}\right).\ln\left(\frac{a_{H_2O}}{a_{H_2}.a_{O_2^{0.5}}}\right) \tag{2}$$

Where $U^{0}_{rev,T,P}$ is the reversible cell voltage at standard temperature and pressure, R is the universal gas constant in J/(mol K), T_{el} is the operational cell temperature in K, $a_{H_2}, a_{O_2}^{1/2}$ and a_{H_2O} are the partial pressure of species (hydrogen, oxygen, and water activity), and F is Faraday's constant in C/mol. Ulleberg [91] proposed an empirical equation that incorporates temperature on overpotential to predict cell voltage (U_{cel}l) and electrolytic voltage.

$$U_{cell} = U_{rev} + \left(\frac{r_1 + r_2.T_{el}}{A}\right).I + \left(S_1 + S_2.T_{el} + S_3.T_{el}^2\right).\log\left[\left(\frac{t_1 + \frac{t_2}{T_{el}} + \frac{t3}{T_{el}^2}}{A}\right).I + 1\right] \tag{3}$$

where r_1, r_2 are the Ohmic parameters, A is the electrode's surface in m^2, I is current in A, S (include S_1, S_2, S_3), and t (include t_1, t_2, t_3) represents the anode and cathode overvoltage coefficients, respectively.

And

$$U_{el} = n_c.U_{cell} \tag{4}$$

where U_{el} is the electrolysis voltage in volts and n_c is the cell count [90].

Hydrogen production rate ($\dot{n}_{H2}$) depends on ion transport between electrodes and the electrolysis current.

$$\dot{n}_{H_2} = \eta_F.\left(\frac{n_c.I}{n.F}\right) \tag{5}$$

Where $\dot{\eta}_F$ is Faraday's efficiency that can be expressed between electrolytic hydrogen production and theory (can see in equation (6)):

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$$\eta_F = \left(\frac{\left(\frac{I}{A}\right)}{f_1 + \left(\frac{I}{A}\right)^2} \right) . f_2 \tag{6}$$

where f_1 and f_2 are the Faraday parameter in mA^4cm^{-4} that depends on temperature. The values for Faraday parameters can be seen in Ref. [92]. Khan & Iqbal [92] mentioned that hydrogen generation is proportionate to current flow and cell count, per Faraday's law.

In terms of thermal models, simple or complicated thermal models can be used to determine the electrolyte temperature of an electrolyser. According to the design model by Ulleberg [91], the thermal energy balance equals:

$$C_t \frac{dT}{dt} = \dot{Q}_{gen} - \dot{Q}_{loss} - \dot{Q}_{cool} - \dot{Q}_{sens} \tag{7}$$

where

$$\dot{Q}_{gen} = \eta_c (U_{cell} - U_{tn}) I \tag{8}$$

$$\dot{Q}_{loss} = \frac{1}{R_t} (T_{el} - T_a) \tag{9}$$

$$\dot{Q}_{cool} = C_{cw} . (T_{cw,in} - T_{cw,out}) \tag{10}$$

$$\dot{Q}_{sens} = \left(\dot{m}_{H_2} . c_{H_2} \right) . (T_{el} - T_a) + \left(\dot{m}_{O_2} . c_{O_2} \right) . (T_{el} - T_a) + \left(\dot{m}_{H_2O} . c_{H_2O} \right) . (T_{el} - T_{H_2Oi}) \tag{11}$$

where C_t is the overall thermal capacity of the electrolyser in J/°C, $\dot{Q}_{gen}$ is the generated heat in W, $\dot{Q}_{loss}$ is the heat loss transfer to the environment in W, $\dot{Q}_{cool}$ is the heat removed from the apparatus via the cooling system in W, $\dot{Q}_{sens}$ includes the enthalpy leaving the system with the H_2 and O_2-produced streams along with the heat transferred from the device to the incoming deionized water in W, R_t is the overall thermal resistance of the electrolyser in K/W, T_a is the ambient temperature in K, C_{cw} is the thermal capacity of the cooling water in J/K, $T_{cw,in}$ is the inlet temperature of cooling water, and $T_{cw,out}$ is the outlet temperature of the cooling water in K, $\dot{m}_{H2}$, $\dot{m}_{O2}$, and $\dot{m}_{H2O}$ are the mass flow rates of the hydrogen, oxygen, and inlet water respectively (in kg/s), c_{H2}, c_{O2}, c_w are the specific thermal capacities in J/(kg K) of the hydrogen, oxygen, and inlet water and T_{H2Oi} is the temperature of the entering water in K.

Polymer electrolyte membrane (PEM) electrolyser modelling

The PEM, also known as solid polymer electrolysis or sometimes referred to as proton exchange membrane electrolysis is a technology that is quite promising [86]. The PEM electrolyzer is composed of a polymer membrane, porous electrodes, and a polymeric proton exchange membrane (also known as polymer electrolyte membrane) that serves as a solid electrolyte [87]. The analysis identifies existing models using Scopus-obtained literatures as described in Fig. 1. In Refs. [85,87], several models of PEM electrolyzers have been proposed, such as the electrochemical, electrical, thermal, mass transfer, and fluidic models. Electrochemical models link input electricity to output hydrogen flow. Electrochemical models are central to modelling electrolysis [93]. The bulk of examined articles [94] relies on the mathematical formulation of the stack polarisation curve to determine stack efficiency (i.e. steady-state electrochemical models). A review of PEM FC models is available in Ref. [95]. The electrical model is based on the energy exchange between Gibbs energy and the electric source, while the heat transfer equation involves entropy, surrounding temperature, and chemical movement. The electrical model is determined by an algebraic relationship between the cell current (I) and voltage (V) at a particular temperature (T). In contrast, thermal, mass transport, and fluidic models are designed to describe dynamic behaviour [85]. The thermal model describes the dynamic temperature behaviour of the current I and voltage V, which can be referred to in Ref. [96]. Some of them incorporate a dynamic thermal model of the stack [97], and/or mass transfer descriptions [98] to account for the dynamic impact of temperature, pressures/concentrations on steady-state stack electrical response. Most commercial electrolysers are current-controlled to maintain consistent hydrogen generation. The electrical performance of an electrolyser is based on its polarisation curve, as demonstrated by Yue et al. [69]. To characterise the electrolyser's dynamic interactions, a mole-balancing model and voltage equation [99] for electrical model had been developed as shown in equation (12).

$$V = E + V_{act} + V_{trans} + V_{ohm} \tag{12}$$

Numerous authors have consistently utilised the same methodology for simulating the cell voltage or an electrolyser. When analysing a model for an electrolyser, the same equation (12) is utilised [96]. Upon applying the input voltage to the PEM cell, several voltages will be dropped. These drops are distinguished by their open-circuit voltage/reversible drop (E), activation drop (V_{act}), mass transfer losses (V_{trans}) and Ohmic losses (V_{ohm}) [96]. The circulation of current through the cell is dependent on these voltage drops, which are nonlinear functions of the current. The PEM electrolyser based on the electric scheme (V) depicted by equation (12) is the sum of open-circuit voltage/reversible drop (E), activation overvoltage (V_{act}), (V_{trans}) and (V_{ohm}).

In PEM, it is possible to optimise surface area and expose more active sites by decreasing particle size and producing ultrathin structures [100]. This catalyst displayed astonishing catalytic performance for acidic oxygen evolution reaction (OER) and outperformed the performance of commercial Iridium dioxide (IrO_2) catalysts. This was possible due to the ultrafine particle size and uniform dispersion. Xue and his colleagues [101] were successful in producing an ultrafine Iridium (Ir) nanocrystal catalyst that was supported by carbon nano bowls (Ir@HEDP/CNBs). The ultrafine size and homogeneous distribution of Ir nanocrystal have a low OER overpotential of 290 mV at 10 mA cm^{-2} and outstanding stability, as shown in Fig. 6(a–c). The short-range ordered Ir SA integrated into a Co oxide spinel structure. This Ir SA displayed a significantly greater acidic OER activity and outstanding stability, As can be seen in Fig. 6(d–f) [100,102]. The three-

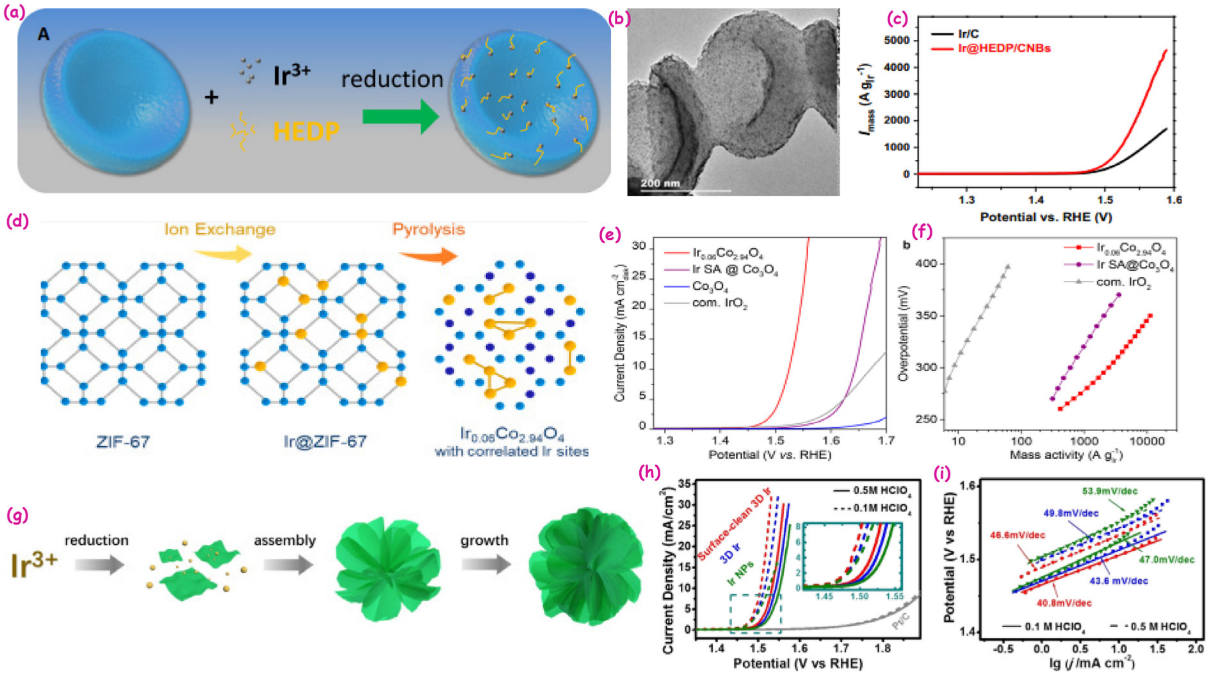

Fig. 6 – (a) Synthesis; (b) Transmission electron microscopes image of Ir@HEDP/CNBs; (c) oxygen evolution reaction concert of Ir/C in 0.1 M HClO4 and Ir@HEDP/CNBs [100]; (d) The synthesis of the Ir SA catalyst in detail; (e) Curves of Linear Sweep Voltammetry (LSV); (f) the collective action of many different catalysts [102]; (g) A diagrammatic representation of the 3D Or superstructure combination; (h) performance of oxygen evolution reaction; (i) slopes of Pt/C, 3D Ir superstructure, and Ir NPs, in HClO4 solution [100].

dimensional Ir catalyst had a surprisingly low overpotential of 240 mV and fascinating longevity with no voltage drop (Fig. 6(g–i)) [100].

Reversible voltage (E) is also known as open-circuit voltage. It is theoretical electrolyser voltage assuming losses are omitted [13]. This results from the chemical Redox reaction. This equation is derived from Gibb's free energy or the Nernst equation [96]. These two procedures are the same in theory, but distinct approaches exist in estimating the temperature-dependent open-circuit voltage (OCV). The formula details of the Nernst equation can be found in the articles presented by Awasthi et al. [98] and Lebbal & Lecoeuche [96]. A fundamental technique employing Gibb's Free Energy for OCV can be found in the articles [103]. The second term in equation (12) is the activation overvoltage (V_{act}). V_{act} is the voltage loss attributable to triggering the electrochemical reaction and is required to break molecular bonds. This occurs from proton transfer and chemical reaction velocity [96]. Temperature, catalyst material, usage, and loading affect this V_{act}. Material processing, temperature, active catalyst sites, usage, distribution, age, pressure, morphology, and many other difficult-to-quantify characteristics [104] all have a role. The activation overvoltage (V_{act}) for an electrolyser can be referred to in Ref. [104]. The V_{act} can be applied separately to the anode and cathode jointly, as in Awasthi et al. [98]. The values used to exchange current densities for the anode and cathode, tend to vary widely throughout the literature [105]. The third term in equation (12) is mass transfer losses, V_{trans}, are generated by flow restriction to the catalyst sites, such as the current collector and separator plate shape, as well as gas bubbles formed by the reaction products. The mass transfer losses, V_{trans} can be referred to in Ref. [13], accounting for the vastly different diffusion rates of hydrogen and oxygen that can be applied to both the cathode and the anode, respectively. The ohmic losses (V_{ohm}), are caused by electron flow resistance via current collectors and separator plates and proton conduction across the membrane. The use of Ohm's Law is the modelling approach used by practically all models for this type of loss [96] can be found in the article [13]. Yue et al. [69]depict the findings coincide with an equation the model in equation (12).

The PEM electrolyser's fundamental operating principle is depicted in Fig. 7(a). To start electrochemical reactions at both the cathode and anode electrodes, a minimal voltage of 1.23V is provided across the electrochemical cell. As water particles have good stability at room temperature, the dissociation of water into oxygen and hydrogen is quite high [93]. As can be seen in Fig. 7(b), a single PEMFC is made up of a membrane electrode assembly (MEA) that is positioned in the middle of gas diffusion levels and fluid flow plates that have been machined to include gas channels [106]. The final product water is moved parallel to the MEA as well as along the gas lines. In the PEM system, the rate of water consumed and hydrogen produced should be considered. In this context, Fig. 7(c) displays the rates of hydrogen production, water consumption at the anode, and water transport to the cathode due to electro-osmosis drag, diffusion, and hydraulic pressure difference. Dehumidification is therefore required to produce hydrogen at an acceptable purity [107]. In addition, the total mass of hydrogen that was produced as well as the corresponding energy is shown in Fig. 7(c), which is based on the

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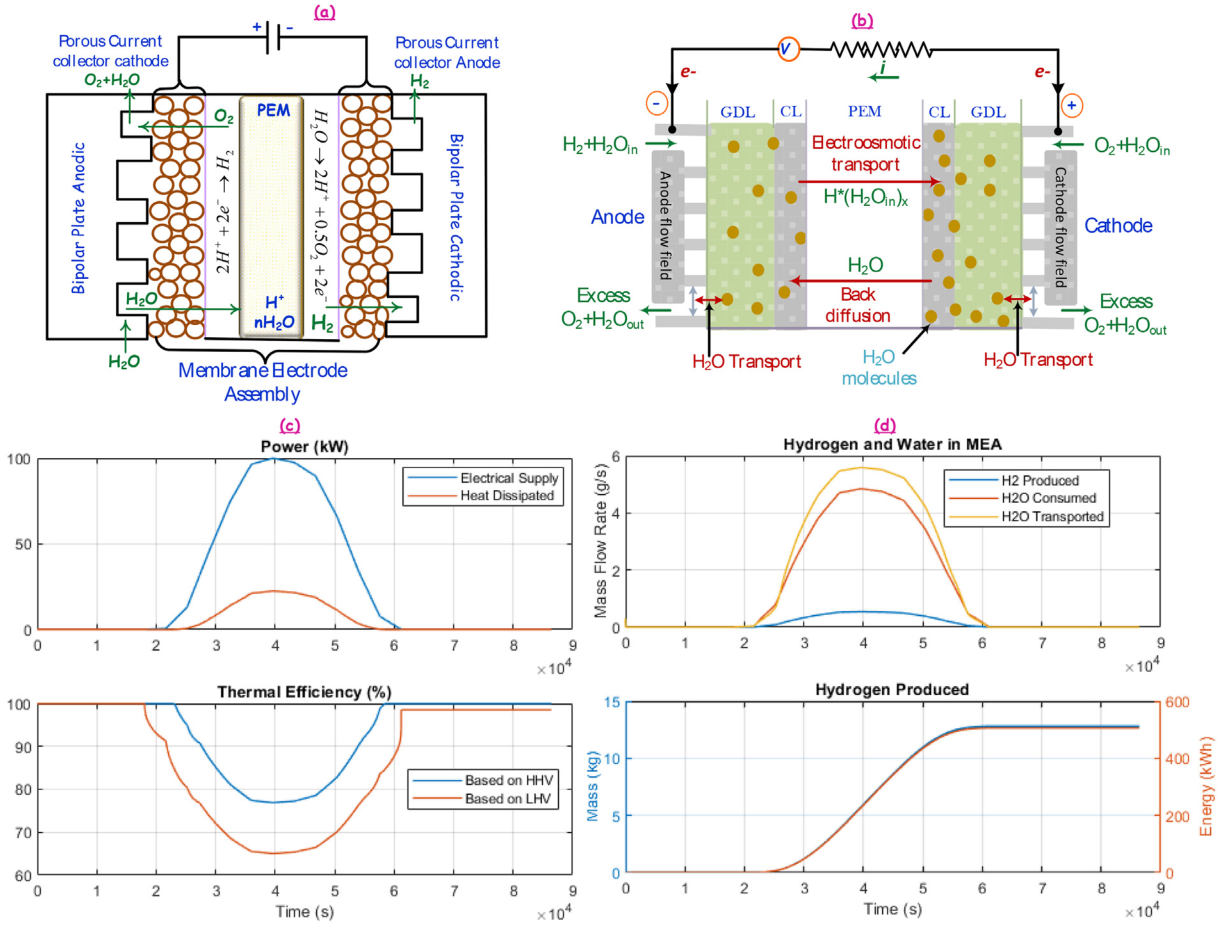

Fig. 7 — PEM Electrolysis System; (a) A simplified diagram of the PEM type of water electrolyzer cell [93]; (b) The internal water transfer process of Polymer electrolyte membrane fuel cells (PEMFCs) [106]; (c) The rate of hydrogen production, the rate of anode water consumption, and the rate of water transferred to the cathode [107]; and (d) the total amount of hydrogen that was generated as well as the energy that was equivalent to that amount due to its higher heating value [107].

higher heating value of hydrogen. This is an indication of the total quantity of energy that could be generated if a fuel cell were to be utilised to convert the hydrogen into electricity [107].

Recent research on PEM water electrolysis has been conducted using various methodologies and applications. Abdin et al. [32] presented an enhanced PEM electrolyser model based on interconnected modular mathematical models. The model is an effective resource for investigating control strategies. The suggested model can predict cellular response under a variety of steady-state situations. Aouali et al. [87] developed a novel (mathematical) graphical model design for the PEM-ELS for hydrogen production based on electrochemical, thermodynamical, and thermal equations. Using a lab-scale electrolyser, the model is experimentally validated. According to the findings, modelling results and lab-scale experimental data demonstrated adequate compatibility. Mohamed et al. [108] modelled PEM (dynamic model) with solar cells to identify variables that can influence the rate of hydrogen and oxygen production. Different physical equations, such as Nernst–Planck, and Nernst–Einstein, have been utilised to perform the simulation in MATLAB. This type of PEM is suitable for arid regions (Adrar) with high temperatures and solar radiation. Tijani & Rahim [109] modelled a PEM water electrolysis to examine the effects of temperature, pressure, and membrane thickness on cell efficiency. A sensitivity analysis using polarisation curves was performed at various operating pressures to evaluate the PEM electrolyser's characteristics and operating conditions. This study suggests the PEM electrolyser with 1 bar balancing pressure is the most efficient. Ruuskanen et al. [110] presented a Power-electronics-based power-hardware-in-loop (PHIL) simulator for a PEM water electrolyser system on an industrial scale. Comparing the current and estimated hydrogen generation of the PHIL simulator with the measured values of the commercial PEM electrolyser after measuring the solar PV system output power verifies the model.

A nominal current of 405 A is attained to examine the electrolyser as part of a smart grid and evaluate the electronic performance of various power suppliers. Guilbert & Vitale [111] provide a dynamic electrical model for PEM electrolysis. The model is based on an analogous dynamic electrical model that considers the PEM electrolyser's dynamic behaviour during abrupt input current changes. Experiments validate the model. Results accurately replicate the electrolyser's dynamic behaviour. Espinosa-Lopez [112] presents the

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modelling and experimental validation of the 46 kW PEM high-pressure water electrolyser deployed on the MYRTE platform, a real-scale demonstrator that studies the use of hydrogen to store intermittent RE. Particle Swarm Optimisation is utilised to discover electrochemical sub-model parameters, and a MATLAB-Simulink connected modular mathematical model is built for validation. Even in transitory operation periods, the stack voltage and temperature can be expected within 20–60 C and 15–35 bar. The model can predict a real-scale electrolyser's voltage and temperature evolution with the highest nominal power consumption documented in PEMWE modelling literature. The approach for identifying parameters can be applied to any PEM water electrolyser. Hernandez-Gomez [113] proposed and tested a static-dynamic model of a 400W PEM electrolyser. Each cell's mathematical model has adaptable parameters by running dynamic tests at varied input currents. The model's parameters are modified to the input current to replicate the electrolyser's actual performance better. This work can be used to construct a real-time PEM electrolyser emulator for hardware-in-the-loop testing of RES power electronics. Khelfaoui et al. [114] presented solar PV/PEM water electrolytes system performance in Algeria's Sahara. Modelling steps include parameter estimates and using those parameters to estimate solar PV module behaviour under varied temperatures and solar irradiation circumstances. The results indicated a high hydrogen generation of 284 L in one day for 8 h of running and an electrolyser power efficiency of 18–40%.

Alkaline water electrolysis (AEL) modelling

Alkaline water electrolysis (AEL) to produce hydrogen is now a mature, cost-effective, and long-lasting technique that has been widely employed in Chlor-alkali chemical industries for more than a hundred years [115]. AEL is considered a mature technology for any of these uses, and they are often directly connected to the grid to generate hydrogen within their nominal working range [116]. These low-temperature methods are mature relative to high-temperature electrolysis [117]. Traditional AEL uses aqueous solutions of water and 20–30 wt% potassium hydroxide (KOH) due to the excellent conductivity and corrosion resistance of stainless steel in this concentration range. NaOH, NaCl, and other electrolytes are also used. Liquid electrolyte conducts ions between electrodes. Literature has introduced alkaline technology dependent on an acidic electrolyte, emphasising the hydrogen evolution reaction performance to produce efficient, stable, and hydrogen evolution catalysts [118]. This technique has the benefit that the electrodes are composed of inexpensive catalysts such as cobalt, nickel, or iron. In addition, it has great gas purity and durability [119]. New commercial AEL operate at 100–400 mA cm^{-2} for current densities [117]. These devices can produce up to 99% pure hydrogen with an efficiency of 62–82% (refer to Table 2) [120]. Some technical information regarding AEL manufactured by Siemens, Hydrotechnik, McPhy Energy, ITM Power, and PERIC was reported in the commercial sector [121].

Recently, multiple review articles on PEM electrolysers have been published. On the other hand, there are a few reviews for AEL [122]. This work reviews AEL modelling from an electrical domain perspective. Since AEL performance is highly linked to electrolyte conductivity, their modelling according to temperature and KOH or NaOH mass fraction is also studied. It reveals the remaining modelling concerns. Electrolyser modelling is critical for simulating their performance in static and dynamic settings when connected to WTs, PV panels, and power grids. Electrolysers are managed by AC-DC and DC-DC converters (as seen in Fig. 8). Modelling electrolysers assists in creating fit, robust, efficient controllers to optimise energy efficiency. Finally, modelling helps design AEL to maximise energy efficiency [123].

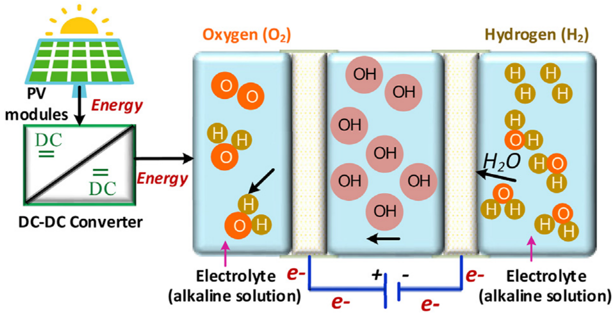

Fig. 8 – Schematic of solar-powered AEL. Solar radiation is converted to power through PV panels. Implementing a DC/DC power converter is necessary, as both direct and indirect coupling are conceivable [70].

According to Gambou et al. [122], less modelling research has been conducted on AEL than on PEM electrolysers. This discrepancy is due to the advantages of PEM electrolysers that have a higher current density, require less maintenance, and have a larger partial load range than AEL. The majority of research was on electrical domain modelling to build AEL modelling. AEL modelling can be divided into major categories: static modelling (including semi-empirical and empirical) and dynamic modelling. Multiple empirical mathematical equations have been utilised to construct a complicated model that can store the most excess RES energy [91].

Numerous semi-empirical formulae have been used to predict the electrolyser operation using the current-voltage curve for AEL [124]. Ulleberg [91] initially conceived one of the most prevalent semi-empirical models. The system incorporates kinetics, thermodynamics, and electrolyser resistance. Equation (5) refers to the equation form of the current-voltage curve. To improve the performance of the semi-empirical model of the AEL: temperature (t) [125], gas pressure P (bar) [70], the distance electrode-diaphragm d (mm) [126], and the electrolyte molarity concentration M (mol L^{-1}) [122] can be considered. According to Sanchez et al. [125], AEL performance is strongly temperature-dependent. Sanchez et al. [125] utilised a semi-empirical mathematical model for forecasting the electrochemical behaviour of an alkaline water electrolysis (AWE) system based on Faraday efficiency and polarisation curve as a function of current density under different operating temperatures and pressure. MATLAB was used to calculate the model's parameters based on non-linearly regressed experimental data from a 15-kW alkaline test system. In semi-empirical models based on the previous method, experimental results were compared to the model

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using a numerical regression method based on least square methods. Hence, the values of semi-empirical models differ from those previously published in the article [122].

For empirical formula, an electrical expression of the cell voltage, comprising the various voltages, is described by equation (13):

$$V_{cell} = E + (R_a + R_c + R_{ele} + R_{mem}).i_{el} + \eta_{act,a} + \eta_{act,c} \quad (13)$$

Where E is the reversible voltage, R_a and R_c are electrode ohmic resistances (anode and cathode), respectively, R_{ele} indicates ohmic electrolyte loss, R_{mem} is membrane ohmic resistance, $\eta_{act,a}$ and $\eta_{act,c}$ are the anode and cathode activation overvoltage. The Butler–Volmer equations (or Tafel's approximations) can be used to compute the anode and cathode activation overvoltage for water electrolysis [127]. This empirical model determines the configuration of the electrolyser during the experiment to give datasets by simply considering the operating temperature. During operation, the electrolyser's state varies. Variations in bubbling rate, electrolyte concentration, and pressure are not considered. The empirical model's accuracy depends on the number of measurements used to construct the analytical correlation [124].

Dynamic AEL modelling has received fewer studies than static modelling. Like static modelling, dynamic modelling requires experimental measurements to compute the parameters strongly influenced by gas pressure, temperature, and current [122]. As previously mentioned by Hernandez Gomez [113], electrolyser behaviour strongly depends on operational conditions. The model's parameters must be flexible to accurately recreate the electrolyser's behaviour under operating conditions. Different modelling methodologies, such as regression analysis, can be used to assess the model's parameters based on the equivalent electrical circuit and experimental data [128]. This methodology allows decent fitting, but genetic or Levenberg–Marquardt algorithms are also promising [122]. The essential benefit of dynamic modelling against static modelling is its ability to reliably reproduce the dynamic behaviour of AEL, whether powered by WTs or solar panels [113]. Taking into account current, temperature, and gas pressure increases modelling reliability. This modelling is a strong tool for developing efficient, resilient, and adequate controllers for dynamic operating circumstances [129].

Solid oxide electrolyser (SOE) modelling

SOEC is a promising candidate technology for achieving sustainable development [20]. SOE electrolysis provides remarkable efficiency, approaching 70–80%. SOE technology can boost the efficiency of water electrolysis by employing high operating temperatures, typically between 700 and 1000 °C. Consequently, SOE is steam electrolysis. In the late 1960s, pioneering work was conducted on SOE technology [67]. However, such high temperatures accelerate the deterioration of cell components, restricting SOE electrolysis in the research (demonstration) and development phase (see Table 2). Since the use of high-temperature heat minimises their electricity consumption, they have significant potential [67].

SO electrolysis technology has been the subject of study and development for more than four years, but there are few publications on the modelling of their functioning in both stationary and transient conditions [130]. Numerous research groups have researched the characterization and modelling of SOE, albeit not as many have studied AEL or PEM electrolysers, as this technology is still in the R&D phase [116]. Due to analogous mechanisms, such as gas diffusion and electrochemical behaviour, the majority of SOE numerical tools are based on SOFC mathematical approaches. In this section, an attempt is made to organise and review previous SOEC modelling work. The two most prominent forms of models, micro- and macro-level models, are described for the SOE model [20]. However, micro-level SOEC modelling is quite limited. It is reviewed work that is relevant to the SOFC effort [20]. Microscale modelling is recognised as an efficient method for elucidating the interaction mechanism between reactants and catalytic surfaces. It provides guidelines for creating and optimising the material configuration of catalysts [131]. Additionally, it is important to evaluate multiscale modelling research to fully grasp SOEC modelling by introducing diverse modelling methodologies [131].

Faraday's law, Butler-Volmer equation, Ohm's law, and gas transport equations are used in a macro-model simulation. According to Faraday's law, the applied current is proportional to the passage of oxygen ions through the electrolyte. The loss associated with the flow of oxygen ions in the electrodes on both sides of the electrolyte is described by Ohm's law (often with assumed electrolyte thickness). Most people assume electrodes have very low electrical resistance; therefore, Ohm's law only applies to the electrolyte phase. On each electrode, the Butler-Volmer equation represents the rise in potential (overpotential) required to trigger the reaction. The decline in performance is linked to concentration gradients across the electrode gas channel and the triple-phase border by the gas transport rule (often with an assumed electrode thickness). The dusty gas model has been proven to be the best appropriate model for modelling the gas diffusion process and is the most extensively used model. Fick's law and Maxwell-law Stefan's are two other commonly used models [20].

Most SOEC models describe limiting processes using overpotentials. This terminology comes from electrochemistry and represents entropy production in thermodynamic terms. It includes concentration overpotentials in both electrodes and activation overpotentials in both electrodes. All other overpotentials are operating-condition-dependent [20]. In this procedure, the actual cell voltage is influenced by several overpotentials. These overpotentials are ohmic, activation and concentration overpotentials can be found in Ref. [132]. Motylinski et al. [130] proposed methodology was validated and calibrated using experimental data, resulting in a prediction error of less than 5%. An article published by Daneshpour & Mehrpooya [133] presents the cell parameters calculation that utilises assumptions and the necessary data for cell voltage consumption. Additionally, Stempien et al. [134] evaluated the SOEC coupled with ex-situ methane synthesis reactor modelling by comparing the outcome to experimental data. A simple, single-pass system without heat recovery potentially achieves an overall energy efficiency of 60.87% (based on a lower heating value), an electrical energy efficiency of 81.08% (based on a lower heating value), and 1.52 $Nm^3h^{-1}m^{-2}$ of electrolyser methane production. The proposed technology can convert 100% of collected CO_2.

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Several reviews have explored the micro-level for SOE, which this section of the study will discuss. Chan et al. [135] modelled ion-conducting electrolytes for SOFC and SOEC. The model potentially relates to free electron and electron-hole concentrations. Temperature, oxygen partial pressure, and electrolyte thickness affect oxygen permeability. Later, permeability's effect on SOC was examined (Solid Oxide Cell). On one side of the electrolyte, gas combinations were tested. Grondin et al. [136] modelled the electrochemical process of SOEC's porous cathode utilising an artificial neural network (ANN). The expression takes microscale variables into account in the macroscale model with minimal calculation time. The ANN utilised three inputs of overpotential, water concentration, and hydrogen concentration to determine the cell's current density. Artificial intelligence (AI)-based optimisation method in SOE may enhance its capacity to process and analyse massive volumes of data rapidly and precisely. Utilising artificial intelligence-based optimisation may reduce pollution, boost energy efficiency, and optimise resource use for industries [137]. Shi et al. [138] studied CO_2 decrease in SOEC. They created a one-dimensional model that includes heterogeneous processes, electrochemical kinetics, electrode microstructure, mass transport, and charge transfer. Experimental data validated the model and showed good agreement. Carbon deposition at the electrode/electrolyte contact was also identified. Using simulations, they optimised electrode design. Another micro-modelling research related to SOFC is conducted by Ni et al. [139].

In numerous studies, SOC performance, the electrolyser model, and system-level analysis are discussed. Prior research in the field was studied to determine the operational envelope of SOE. Wang et al. [25] studied the functionality of micro-tubular SOE cells. A cell with a diameter of 1.8 mm and an active area of 1.74 cm^2 was tested at 650 °C with three concentrations of steam: 12, 36, and 60%. The maximum SOEC performance was 1.32 V at 0.57 A/cm^2. The efficiency of a 300 N m^3h^{-1} hydrogen generation system was determined using this cell's electrolytic properties. Due to the significant thermal energy recovery from the exhaust gas, the system efficiency reached 98%. Penchini et al. [140] report an experiment on hydrogen production utilising a 200 W SOE stack at 0–0.5 A/cm^2 current density. The tests were run at 700 °C, 750 °C, and 800 °C with steam inflow concentrations from 50% to 90% and water usage up to 70%. The greatest current density at 700 °C was 0.375 $A/cm^{2,}$ and the voltage was 1.49 V. Chen et al. [141] presented an impregnated electrode solid oxide electrolysis cell (SOEC). Four distinct temperature levels (650 °C, 700 °C, 750 °C, and 800 °C) and a 50:50H_2: H_2O mixture ratio were tested. At 750 °C, an electrolysis current of 1.7 A cm^2 and a hydrogen generation rate of 710.6 mL cm^2 h^1 were reached using an electrolysis voltage of 1.3 V and a steam content of 70%. Schefold [142] utilised an electrolyte-supported SOC of 45 cm^2 area that was operated in the steam-electrolysis mode for more than 23,000 h before the scheduled shutdown. The decrease of cell voltage was to be 7.4 mV/1000 h (0.57%/1000 h). Fang et al. [143] test a two-layer SOFC for 20,000 h. Long-term electrolysis operations were conducted at 700 °C, 750 °C, and 800 °C with a current density of 0.5 Acm^2 and a 50% steam conversion rate, with 50% humidified H_2. The analysis estimated voltage and ASR degradation over time. During the experiments, it was determined that voltage deterioration varies between 0 and 2% per 1000 h and that ASR degradation varies between 0.6 and 11.3% per 1000 h. Daneshpour et al. [133] present a solar-TPV device with a SOEC to produce hydrogen. Mathematical and electrochemical modelling of subsystems is performed, and system performance in different operating situations, such as current density, temperature, and SOEC steam mole fraction, is examined. The scaled-up STPV gadget obtained 17% efficiency. The suggested system can produce 7458 kg/h of hydrogen with 54% SOEC efficiency, according to sensitivity analysis. The proposed cumulative system efficiency is 34%.

Comparison between AEL and PEM modelling

As seen in Table 2, the commercialization of AWE, PEM electrolysis, and SOEC technologies are at various levels. As previously stated, the SOEC is currently being developed in the laboratory. AWE and PEM technologies, which are more developed, have already reached the commercialization stage [119]. As demonstrated in Table 2, PEM electrolysers produce more pure hydrogen and can attain higher current densities than AWE without sacrificing efficiency [144] due to the tightly-packed MEA and thinner membrane [145]. Their operating range is wider [119]. PEM has greater costs and lower stack and system lifetimes than AWE [25]. The pricey PEM has a short lifespan, requiring replacing. Membrane contamination or chemical self-degradation and anode deterioration cause PEM's limited lifespan. In AWE, non-noble metals like nickel (Ni) are acceptable electrocatalysts for hydrogen evaluation reaction (HER) and OER, but in PEM electrolysis, the acidic electrolyte requires valuable metals as electrocatalysts, which raises investment [146].

Several authors have compared both technologies; AWE and PEM. Felgenhauer et al. [121] compared 16 models developed by different manufacturers and examined AWE and PEM technologies for scalability, production capacity, and H_2 production costs. PEM electrolysers have a minor efficiency advantage over AW electrolysers (57–64% lower heating value) but degrade more quickly. They observed that system capacity increases cost efficiency, indicating scale economies. AWE systems are mature and cost-effective. Lower expenses offset PEM's considerably higher efficiency. Schalenbach et al. [147] compared an AWE electrolyser with Ni-based catalysts and a thinner separator to a PEM electrolyser with Iridium and Platinum-based catalysts and a Nafion membrane. The authors concluded that the AWE model with a thinner-than-usual separator could achieve higher efficiency than PEM electrolysis with a Nafion membrane. In addition, the authors examine the difficulties associated with both AWE and PEM. According to Gotz et al. [45], AEL electrolysers can be operated between 20% and 100% of design capacity, with overdrive up to 150%. This provides AEL with an excellent alternative for PtG equipment with an unpredictable power source. As per [45], an AEL predicted lifetime is 30 years (see Table 2), which is high compared to other types. AEL's efficiency and overall investment have improved in recent years. Concerning optimisation technology, it must not disregard (economic) realities [148]. For instance, in countries with developed economies and huge populations (such as Australia), it may take a considerable amount of time to promote and optimise the commercialization of the electrolysis project. Saudi Arabia is affluent economically but politically turbulent, hence this country will take longer to commercialize the electrolysis project. Thus, the government must raise investment to attain the desired outcome within an acceptable timeframe [149].

Hydrogen electrolyser control strategies, the technology of electrolyser, storage, and utilization

Hydrogen can be stored, transformed into methane, and regenerated into energy [150]. Hydrogen production, co-electrolysis, bioenergy hydrogenation, and other processes may produce transport fuel [151]. Researchers recently focused on blending fuels with biofuel in varying quantities to dramatically minimise emissions of greenhouse gases [152]. Hydrogen and electricity can enable the transport sector to become less oil-dependent by expanding its primary energy sources. Effective models of the complete electrolyser (cell plus stability elements, including thermal management and controls) are necessary when coupled directly to a renewable energy source, due to intermittent and variable supply [32]. A control system to manage energy is required to run, integrate, and interconnect components in a generation system, assuring safe operation and desired outcomes. An appropriate energy management (EMAN) strategy allows the system to supply demand, increase element lifetime, minimise operating costs, and maximise system performance, which is technically and economically feasible [153]. Various management strategies affect the behaviour of the system. Most scientific publications propose simulated techniques for hydrogen energy systems to maintain demand, including technical and economic optimisation criteria and many real-world concerns, such as hydrogen equipment degradation or energy vector management. Scopus-based literature searches using the terms "hydrogen electrolyser," "control strategy," and "sustainable energy" was performed to identify hydrogen system strategies. Here, we define important hydrogen system strategies.

AC microgrid control involves frequency and voltage. Efforts have been made concentrated on droop control [154–156] for parallel operation of converters since individual generators can be controlled simultaneously with one another and the grid without the need for direct communication [45]. It is utilised in distributed control systems for power-sharing [154]. Various control strategies can be layered together to obtain optimal system performance. For example, Sun et al. [154] introduced the frequency-based PV/battery/FC-electrolyser hybrid system as voltage sources with modified droop control. The battery inverter adjusts the droop coefficient based on droop control to balance SOC while charging and discharging. The FC-electrolyser supplies inadequate system energy or absorbs redundant system energy for safe and steady operation. Veerakumar et al. [155] implemented a combined droop and derivative-based fast active power regulation controller on a 300 MW PEM electrolyser. This results in a safer and more rapid adjustment of the active power utilised by the megawatt-scale PEM electrolyser, so aiding quickly and efficiently in limiting the dynamic frequency response during the first few seconds following the emergence of an active power imbalance. As presented by Quan et al. [156], the V–A characteristics of both FC and electrolyser can be considered as an offset voltage in series with a voltage droop. The increase will be advantageous for the following control design.

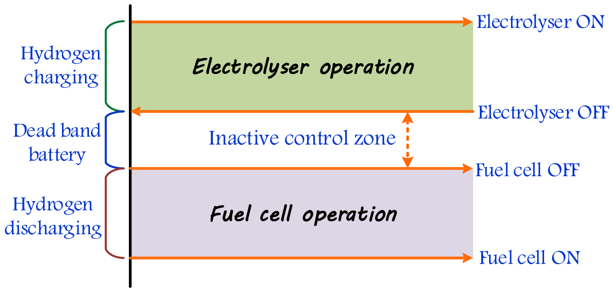

Fig. 9 – A schematic representation of the hysteresis band [157,159].

The "hysteresis band control" is the simplest and most effective delivery method for the energy management of power to power; The electrolyser is triggered if RE production is larger than electricity consumption, and the FC system distributes power if electricity demand exceeds RE supply [45]. The hysteresis band control method can be adapted for each purpose by utilising several operational parameters. For PtP systems, the FC and electrolyser can operate at fixed or variable power to match demand. Modifying the hysteresis band for PtG and hydrogen refuelling maximises hydrogen generation [157]. This prevents the battery from being entirely depleted or overworked. Batteries can support stationary FC systems' steady or rated power modes. The FC can function at peak efficiency with battery backup, minimising hydrogen use [158]. As demonstrated by Valverde et al. [157] and Uleberg [159], Fig. 9 displays a schematic representation of the hysteresis band. Literature [160–162] utilises hysteresis operation mode governed by battery SOC. The hysteresis bandwidth is fixed and depicted by a simple flow chart, despite being an improvement in degradation. Storage system utilization can be improved.

Table 3 summarises the main controller strategy based on the control algorithm based on evaluation publications using Scopus. The main distinction between the different solutions presented in Table 3 is based on design control, optimisation objectives, electrolyser technology, and storage configuration to resolve the challenge with the hydrogen ES system. Optimal control overcomes concerns found after years of operating hydrogen energy systems [45]. In general, the papers cover methods and systems such as MILP model [163–166], MPC [167–169], PSO [170,171], PI [172,173], GA [174,175], HOMER [176–178] and FLC [179–181].

Mixed integer linear programming (MILP) is frequently used for hydrogen electrolyser networks. Samsatli et al. [163] use MILP to optimise wind-hydrogen-electricity networks. The model determines the appropriate number, size, location, whether to transfer energy as electricity or hydrogen, transmission network structure, hourly operation of each technology, etc. Hydrogen-electric networks can cover all of Britain's transport needs by the on-shore wind. Maroufmashat

Table 3 – Summary of the controller algorithm strategy based on optimisation objectives, the technology of electrolyser, and storage configuration of the hydrogen-based-energy system for evaluation articles using Scopus.

Reference	Control algorithm	Optimisation objectives	Technology of electrolyser	Storage configuration
[163–166]	MILP	• Cost reduction [163–166] • Ensure demand [163–165] • Increase lifetime [165,166] • Improve performance [166]	• CAPEX [163] • AEL [164,166]	• H_2 [163–166] • Battery: H_2 [166]
[167–169]	MPC	• Cost reduction [167] • Ensure demand [167–169] • Increase lifetime [168] • Improve performance [167,168]	• PEM electrolyser [167–169]	• H_2 [167–169]Battery: H_2 [168]
[170,171]	PSO	• Cost reduction [170,171] • Increase lifetime [171] • Improve performance [170,171]	• PV-EL [170] • Alkaline and PEM electrolyser [171]	• H_2 [170] • Battery: H_2 [171]
[172,173]	PI	• Cost reduction [173] • Ensure demand [173] • Improve performance [172,173]	• HAE electrolyser [172] • PEM [173]	• H_2 [173] • Battery: H_2 [172]
[174,175]	GA	• Cost reduction [174] • Improve performance [174,175]	• AEL [174,175]	• H_2 [174,175]
[176–178]	HOMER	• Cost reduction [176–178] • Ensure demand [176,177] • Increase lifetime [177,178] • Improve performance [177,178]	• Alkaline and PEM electrolyser [176] • PEM electrolyser [177,178]	• H_2 [177] • Battery:H_2 [176,178]
[179–181]	FLC	• Cost reduction [179] • Ensure demand [180,181] • Increase lifetime [180] • Improve performance [179–181]	• PEM [179,181]	• H_2 [179,181] • Battery: H_2 [180]

et al. [164] use MILP to demonstrate a distributed hydrogen energy generation system in an innovative urban energy system. The aim function optimises network operations and maintenance costs and hydrogen refuelling station capital costs. Their evaluation shows that distributed hydrogen generation is environmentally and economically preferable to H_2 delivery. Mukherjee et al. [165] employ MILP to size and operate microgrid renewable energy sources, hydrogen storage and production (electrolysers), and fuel cell systems. MILP subject requires a 2000 kW renewable energy system (400 kW solar PV and 1600 kW WT), in which the backup fuel cell system size rises to 4000 kW if vehicle-to-grid services are not used in the MG. The study highlights the environmental emission offsets and economic benefits of using FCs in an MG with microturbines and PV as RE sources. Gillessen et al. [166] utilised MILP to minimise total system expenses. A case study for a hybrid ELS/battery system directly coupled with a big PV power plant without a grid connection.

Particle swarm optimisation (PSO) was used in Refs. [170,171] to optimise the electrolyser system. PSO is one of the most often used techniques for determining the optimal design of renewable power plants due to its high performance and durability [171]. According to Sayedin et al. [170], the PSO approach for water electrolyser offers more flexibility, but higher prices and complexity. PSO is a swarm-based optimisation approach [170]. This paper [170] explains how the PSO algorithm optimises the ELS system to reduce energy loss. For the given location and PV module, the PV/ELS system may reach 97.83% energy transfer efficiency and less than 7.67 kWh yearly energy loss. In Ref. [171], PSO was utilised to discover component sizes that minimised the Levelized cost of energy (LCOE) while retaining off-grid energy. Hydrogen can prevent oversizing battery and PV systems, reducing the P2P system's final cost.

Proportional Integral (PI) and the Proportional Integral plus (PI+) controllers are conceived and implemented in the Hydrogen generative Aqua Electrolyser (HAE) power system [172]. PI + simulation findings show a better transient and steady-state response for interconnected power systems [172]. In Ref. [173], the PI controller reacts to frequency deviation and gives the current controller's reference signal. PI controller shows that the PEM electrolyser's quick dynamics allow significant flexibility. A genetic algorithm (GA) is a simple, efficient optimisation method based on evolution. Several works indicate that PSO is as efficient as GA but converges faster. A micro-GA that determines the global least total annualised system cost for optimal storage [174]. They designed and optimised a net CPV-Hydrogen system for standalone operation. The study proposed in Ref. [159] has used GA for photovoltaic-AEL to demonstrate the best approach for a 10 kW electrolyser.

The hybrid Optimisation Model for Electric Renewables (HOMER) is one of the most useful optimisation tools used to optimise RES–hydrogen energy system structure [176,177] and to acquire feasible MG configurations and the net present cost of each feasible system [178]. Research [176] uses the HOMER model for optimisation tools in off-grid and grid-connected hybrid renewable energy systems (HRES). The simulation in Ref. [177] showed that the phase change material (PCM)-based thermal management technology presented can store heat produced during charging and dissipate it during hydrogen discharge. A numerical model in HOMER [178] was used to identify novel, technically feasible MG configurations for the hut.

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The major components of FLC have been divided into three parts. Initially, input membership functions are used to fuzzify the inputs. Then, outputs are generated based on inference rules. Finally, the defuzzified fuzzy outputs are applied to the primary control system. FLC has several benefits: simplicity, adaptability to any problem, and the capacity to solve problems without data or information [182]. FLC controls the water entering the electrolyser to improve hybrid PV-PEM ELS system efficiency [179]. The overall system efficiency was significantly enhanced in the case of proper temperature control via the proposed FLC approach [179]. FLC-based power management was used in Ref. [180] to achieve persistent off-grid electrical energy independence. Fuzzy-based power management system [181] assures the intended performance based on the unpredictability of the future load and control strategy.

According to Parra et al. [12], among optimum control systems, MPC has lately acquired popularity due to its capacity to accommodate technical restrictions (e.g. power limits, ramp-ups, etc.). This is significant for preserving sensitive equipment (e.g., electrolyser and/or FC systems) while minimising system costs for storage and increasing overall revenue [167]. Also, Fischer et al. [167] demonstrated that MPC boosts electrolyser profitability and performance. According to Fischer et al. [169], operating an electrolyser and feed-in plant based on rapidly changing set values necessitates a highly dynamic MPC-controlled system. It was proved that MPC is well-suited for operating such plants in the context of energy network limits and changing boundary circumstances, such as time-varying electricity prices. Serna et al. [183] developed another MPC. This study aimed to ensure wind and wave turbine hydrogen generation and electrolyser functionality. They created a Mixed Integer Quadratic Programming solution for MPC with naive predictions to accomplish the objective. Torreglosa et al. [184] used predictive control to increase the performance of a RES with hydrogen storage. MPC enhanced FC and electrolyser efficiency by determining optimal operating points. All of these publications [167,169,183,184] indicate model predictive control's practicality for RES with hydrogen storage.

Table 3 also displays the objectives related to cost reduction, ensuring demand, increasing the lifetime, and enhancing the system performance. It shows that cost reduction and system performance improvement are the major goals of the optimisation strategy for the evaluation papers. According to Ref. [173], the electrolyser and fuel cell system has a 10-year lifespan and must be replaced after 10 years. The costs involved in hydrogen electrolyser technologies include the replacement cost for FC and ELS modules, annual operating and maintenance costs, total capital investment costs, etc [165]. Hence, It is crucial to analyse how the network configurations affect performance and costs [147]. In summary, the discussion on cost reduction and objectives based on the optimisation of hydrogen electrolyser technologies finds the following points in the literature shown in Table 4.

The controller performance has been reviewed in the water electrolyser system (see Table 3) reference [167,168,170,171,174,177]. The controller performance to be utilised in a power-to-gas (P2G) plant, for example, includes full load hours, hydrogen feed-in, self-consumption, and relative control error [167]. Nguyen et al. [177] employ HOMER to assess ESS performance, including load profiles, technical performance and component characteristics, climate data in solar radiation and economic performance. Study [168] achieves a superior performance objective using model predictive control and can be used to improve MG sizing. Their simulations reveal a 76% drop in the station's default time and a better fill rate for the hydrogen tank and batteries, chemical and electrical losses are reduced by 38% and 11%, respectively, while battery deterioration is reduced by 1%. Article [170] illustrates system performance depends on the design and operating parameters utilised by the PSO algorithm to minimise the energy loss of the PV/EL system. The optimisation process starts at $E_{loss} = 8.46$ kWh/yr and continues until $E_{loss} = 7.67$ kWh/yr. The study's performance data on

Table 4 — The objectives in cost reduction based on the optimisation of hydrogen electrolyser technologies.

Reference & years	Control algorithm	Objectives for cost reductions	Outcome
Samsatli et al. (2015) [147]	MILP	Efficiency and unit costs of each technology (capital, operating, and maintenance costs).	• Using existing wind turbines reduces the network's total cost by 7%, despite the turbines' 22% lower cost.
Maroufmashat et al. (2016) [148]	MILP	To optimise network operations, maintenance, and hydrogen refuelling station capital costs	• The average daily strike price of grid-purchased power for electrolyser = \$0.036 per kWh. • Levelized cost of hydrogen produced through the hydrogen fueling station = \$6.74 per kg.
Mukherjee et al. (2017) [149]	MILP	Incorporating FCs into an MG to save on annual operation expenses	• The fair system cost in Canada (\$41.2 Million) due to the population size.
Gillessen et al. (2017) [150]	MILP	to minimise hybrid electrolyser/ battery costs	• Average costs of hydrogen for a 3000 kWel electrolyser system (0.057−0.308 €$_{2015}$/kWhH$_2$)
Marocco et al. (2021) [151]	PSO	Minimising the final cost of electricity generated through the P2P system	• The LCOE hybrid storage configuration with Li-ion batteries and alkaline electrolysers costs 0.51 €/kWh.
Samani et al. (2020) [157]	PI	Capital costs and operational costs were analysed in the large-scale electrolyser	• The economic approach earns 770 k€/year (main reserve) and 970 k€/year (hydrogen sale).
Burhan et al. (2016) [158]	GA	To minimise the total annual cost of the system.	• Finds the global minimal annualised system cost. The cost data represents in Ref. [174].

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hydrogen production in an electrolyser employing a micro-GA can be useful for long-term component design because it shows how system performance varies during various weather situations [174]. Other studies relating to the performance characteristics of the hydrogen storage system are referenced in these articles [178–181].

As shown in Table 3, the majority of systems use PEM electrolysers for their electrolysers. This is due to the PEM electrolyser operating at a greater current density (hydrogen output per unit of the active region), resulting in a more compacted stack than alkaline [171]. However, AEL is considered a hydrogen production technology. The AEL technology is more mature than other technologies, and the majority of large-scale systems that have been implemented are based on this technology. The benefits of AEL technology are its availability for huge plant capacities, low costs, and long lifetime. Moreover, research-based electrochemical models for electrolyser (alkaline and PEM) and PEM fuel cell devices have been constructed [171] to accurately describe their normally nonlinear behaviour.

In terms of storage, Table 3 reveals that the majority of reported systems store hydrogen. Hydrogen is a versatile ES medium that may be utilised for short- and long-term storage and converted to power, heat, and transport fuel [164]. There are three major properties of storage technologies [163]: maximum available capacity, injectability (the highest rate at which gas can be pumped into storage), and deliverability (the maximum rate at which gas can be extracted from storage). The studies [163–181] concluded that integrating electrolysers with hydrogen storage devices yields beneficial outcomes in a high-efficiency energy route, hydrogen production and storage is possible with low-cost power.

In grid-connected topologies, the grid is an active component that maintains the balance of power by absorbing or delivering energy when the hydrogen stock exceeds its working limits [137]. In these topologies, such as those analysed in Ref. [185], the surplus or deficiency of energy is adjusted by injecting energy from the grid or purchasing energy from the grid. These topologies increase the strategy's adaptability and ensure demand regardless of the energetic environment. Also, the described model [176] demonstrated that RE integrated into the model as inputs having priority to the grid. Furthermore, P2G can supply services to the power grid and operate as an alternative to grid expansion for electric networks with significant wind and PV penetration [169]. Fischer et al. [167] optimised grid operating to reduce load. The power-to-gas plant was optimised using model predictive and rule-based control. It can be stated that hydrogen produced electrolytically can aid in balancing the electric grid (storage) and provide an energy carrier for usage in other industries.

Fig. 10 depicts the development steps for hydrogen across many applications. Hydrogen can be utilised in fuel cells, stoves, turbines, internal combustion engines, gas boilers, and the chemical and petroleum industries [9]. The real value of hydrogen electrolyser and FC technologies are realised when they are implemented on a large scale and in numerous applications. This can also provide opportunities and directions for the future development of technology. Overall, hydrogen is important for balancing the electric grid, decarbonizing the transportation industry and essential for various industrial processes [37].

In term of price, low-carbon solutions become more competitive when fossil fuel prices rise [187]. However, since 2013, some countries reported the RES-electricity output exceeding national demands and negative price were recorded (103 times in Germany in 2017) [188]. Today, RES-electricity production considerably influences the kWh price on the

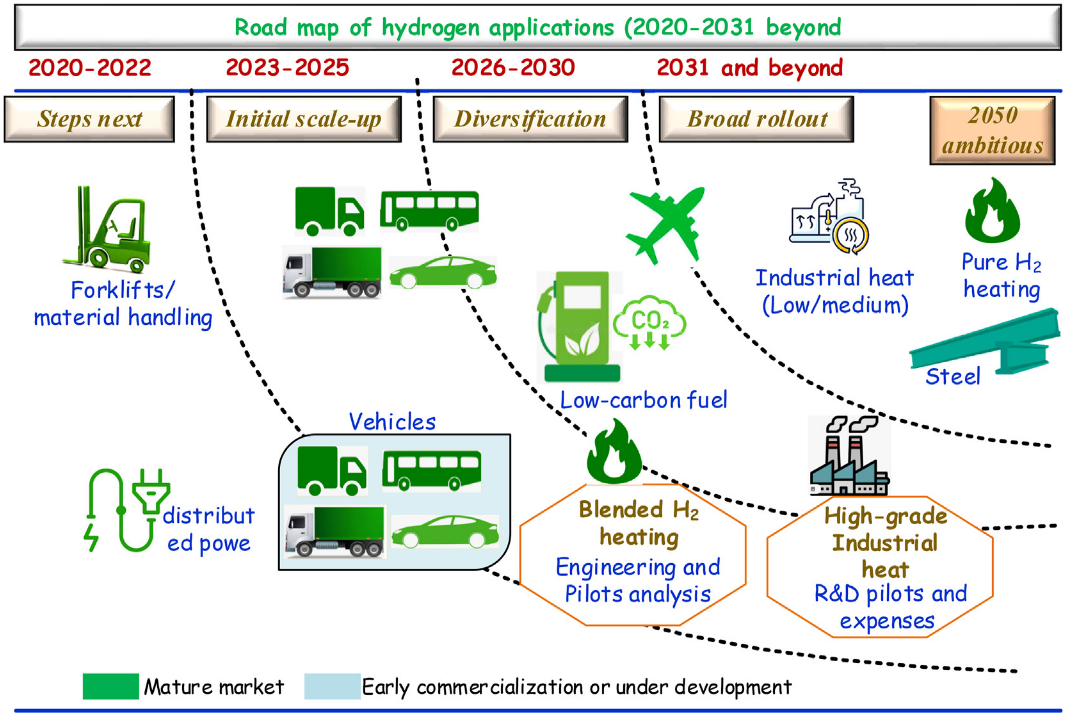

Fig. 10 – Hydrogen applications roadmap (2020–2031 beyond) [186].

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market [188]. According to Ref. [189], hydrogen mobility (7 €/100 km) is cheaper than fossil fuels (15.6 €/100 km). In many other countries, the breaking point is approaching that can make hydrogen production even cheaper (5.4 €/100 km). It is interesting to notice that fuel prices will rise, including for natural gas, and it will be better to utilise hydrogen electrolyser rather than fuel for other uses because they have a higher added value (can be provided at refuelling stations as a clean fuel for fuel cell electric vehicles or utilised as a chemical feedstock). Additionally, the Hydrogen Council [188] estimates that through 2030, $280 billion must be invested in the hydrogen value chain, spanning production to delivery to retail, as well as the industries that supply end-use equipment. Long-term storage demand will rise by 60–70% in the coming years. In Germany, 15% of electricity is used to produce hydrogen to develop an energy system with 80–90% renewable electricity. Experts predict that supporting the renewable energy system utilising hydrogen may demand capital investments of $20 billion in the distribution network, including liquefaction plants and vessels, and $30 billion in storage capacity until 2030.

Issue, challenges, and solution

Hydrogen offers tremendous efficiency, can be produced from a wide range of domestically accessible resources and emits no pollutants or greenhouse gases. Developing hydrogen as a major energy carrier will necessitate the resolution of numerous logistical, technological, and economic difficulties [190]. These difficulties may motivate a research team to consider fresh lines of inquiry or potential applications for hydrogen electrolyser technology. This section summarises the main issues, challenges, and solutions of hydrogen-powered energy systems which considered the electrolysis methodologies, capital cost, water utilization, rare materials, electrolysis efficiency, environmental impact, storage and security considerations.

Electrolysis methodologies

Most electrolysis technology is alkaline-based; however, PEM and SOEC have been developed [48]. Raising operating temperatures in electrolyzer is not a simple process. High temperatures in acidic PEM electrolysers exacerbate corrosion and membrane stability difficulties, making high-temperature PEM electrolysis inappropriate. Alkaline anion exchange membranes are promising PEM alternatives [191]. Cross-permeation poses a formidable obstacle for AEL to achieve reliable gas purity at high pressure [86]. SOEC electrolysers are the most effective in electrical efficiency but the least developed. SOEC has significant challenges that hinder the SOEC technology: i) functionality under pressure is difficult because vitreous cell gaskets cannot withstand raised pressures, ii) material stability [86], and iii) and hot, pure oxygen generated at the anode is corrosive (cause complexity and heat exchange problem). This must be dissolved to safeguard metallic components [192]. SOEC prototypes promise high efficiency and localized heat production [1].

Capital cost

Capital costs are initial system investments. According to Clerici & Furfari [193], the levelized cost of hydrogen (LCOH) for today, 2030, and 2050 includes the efficiency and costs of the electrolysers, the cost of the feeding RES, and their capacity factor. The current hydrogen production system employing AELs costs 1000 to 1500 EUR/kW, including installation, while PEMELs cost 2000 to 3000 EUR/kW [69]. AWE is well-developed, although production is minimal. AWE electrolyser manufacturers make small-volume electrolysers for specific markets, increasing BoP costs. AEL reduction in cost relies on more price production, whereas PEM price reduction requires technological advances. However, installation technologies and economies of scale may lower capital costs in the future. Generating hydrogen in a cost-competitive method is regarded as the greatest constraint for water electrolysis to promote clean hydrogen as an energy vector [1]. By 2030, there is an expectation of a significant reduction in the capital costs of both electrolyser and fuel cell (FC) systems, particularly the stack cost. One approach to reducing costs and maintaining efficiency is by increasing the active area of the stack, which will reduce the number of cells needed to produce a specific amount of hydrogen, as outlined in Ref. [194]. Moreover, the increasing political interest in green hydrogen can accelerate the reduction in costs. National and international goals can have a direct impact on the economy and industry. The support of public and private investments can promote the development of cutting-edge technologies, optimise manufacturing, construction, and installation processes, and mature the industry [195].

Utilization of water

Electrolysis of water, or splitting it into hydrogen and oxygen, began commercial use in 1890. According to Ref. [196], a PEM requires 18 L of H_2O and 54 kW-hours of power to produce 1 kg of H_2. Water is required for the electrolysis-based production of hydrogen [69]. If all of today's devoted producing hydrogen, 70 Mt, was supplied by water electrolysis, water use would account for 1.3% of the worldwide energy sector's water usage. For desalination of salt water, reverse osmosis is an alternate solution and has little impact on the entire cost of producing H_2. Currently, the integration of seawater into the water electrolysis process must be facilitated [197].

Furthermore, the use of water in electrolysis can cause environmental problems, if the water source is not properly evaluated and managed [198]. The electrolysis procedure requires freshwater free of contaminants such as salts and minerals. It is anticipated that there are 1.4 M km^3 of water on Earth, of which just 2.5% is freshwater. 69% of freshwater is snow or ice, 31% is groundwater, and 0.2% is useable to humans [199]. If the water used for electrolysis is not properly treated and filtered, it can result in the discharge of contaminated effluent, which can be detrimental to aquatic ecosystems and have potential health consequences for humans. Electrolysis water and energy sources must be properly examined for decreased environmental consequences. Solar and wind power can minimise electrolysis' environmental impact. Different filtrations (graphene nanotubes and

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nanolayers, carbon dots, activated bentonite, various nanoparticles, etc.) and coagulation technologies (enhanced by electricity, various nanomaterials, etc.) [199] can exhibit good water purification capabilities. Electrolytic cell effluent can be purified and reused, saving water.

Utilization of rare material

Electrolyser systems utilise rare materials for electrode catalysts, electrolyte additives, etc [69]. Every metal has a particular level of activity, corrosion resistance, electrical resistance, and durability. Nickel, Raney nickel, and cobalt are commonly employed as electrode materials in alkaline solution electrolytic baths because of their corrosion resistance and satisfactory cost [200]. Corrosion resistance applies not only to the utilised catalysts but also to the counter electrode and separate plates. Noble catalysts (Pt, Ir, and Ru), titanium current collectors, and separator plates are costly, and resources concentrated enough for profitable mining are scarce [201]. PEM electrodes need to use distinct materials for strong corrosion resistance and catalytic activity. Significant market penetration of PEM electrolysis is expected to affect the requirement for iridium and its pricing [13]. Catalyst cost reduction is a priority to lower stack costs. Advanced support structures, mixed metal oxides, and nanocatalysts offer solutions [69]. Researchers have continued using platinum nanoparticles supported on carbon black (Pt/C) as standard PEM electrolysis catalysts [13]. Fuel cell use in Europe in 2030 will demand 7% of the world's platinum supply [69]. In addition, unique synthesis techniques for producing new support materials, catalysts, and electrode systems are required [13]. A roadmap should be developed for the development of electrocatalysts and components over the years. This should include plans and guidance for enhancing technology, durability, and cost-effectiveness, as well as future insights [13].

Electrolysis efficiency

Electrolyser efficiency refers to the electrolyser's converting electricity into hydrogen. Present electrolyser system efficiency and durability are not sufficient, holding back the commercial release of hydrogen energy systems. The limitation in efficiency due to the parameters affects the overall electrical resistance of the system. Nowadays, water electrolysis system efficiency is near its optimum. A PEM system's efficiency is 60%, which is predicted to rise to 67%–74%. The aim for AEL systems is 70%–80% electrical efficiency [69]. Ionic liquids have been used to enhance electrolytic solution conductivity, stability and make them a promising alternative. Souza et al. [202] used an ionic liquid sample of 1-butyl-3-methylimidazolium-tetrafluoroborate in water as an electrolyte solution at ambient temperature with certain cheap electrode materials such as nickel, carbon steel, nickel–molybdenum alloy, and molybdenum. All electrocatalysts had system efficiency between 97.0% and 99.2% [202]. The efficiency recorded was higher than commercial and industrial electrolysers. Nonetheless, it ought to have taken into account that most such electrolysers operate at current densities significantly higher than the experimental value [202]. As demonstrated by Asghari et al. [197], a holey nanostructure and good electrical conductivity of electrocatalysts are required to improve electrolysis electrode efficiency. Additionally, significant control and the capability to operate the energy system efficiently can increase the efficiency of these electrolysers [203]. The proposed project must optimise the design characteristics of each subsystem to increase efficiency. A deeper analysis can also construct an experimental setup (eg: the polarisation curves of PVs and electrolysers ought to be precisely matched) for additional inquiry into the real efficiency and verification of the theoretical results [204]. To date, there is no benchmark to measure the efficiency process of hydrogen electrolyser by including heat. The European Commission supports defining criteria for NAT water electrolysis [1].

Impact on the environment

Global warming is regarded as a significant environmental issue caused by the uncontrolled use of fossil fuels such as oil, coal, and natural gas since it contributes to disastrous events such as floods and droughts. Hydrogen can decarbonize energy systems, making its adoption crucial. Under this scenario, numerous countries have launched significant attempts to address this issue. Canada pledged to reduce GHG emissions by 30% below 2005 levels by 2030 [205]. South Korea launched its "2nd Climate Change Response Master Plan" to lower greenhouse gas emissions from 709.1 million tonnes in 2017 to 536 million tonnes in 2030 for a sustainable and low-carbon greener society [206]. However, hydrogen might be considered an indirect greenhouse gas [69]. Hydrogen technologies can replace fossil fuels that directly produce man-made greenhouse gas, but production, compression, storage, and transportation emissions can lead to indirect greenhouse gas concentrations that could affect atmospheric chemistry [207]. According to Rujiven et al. [207] global molecular hydrogen emissions could range from 0.2 to 10% in an energy system. However, before the widespread use of hydrogen, it is necessary to investigate the uncertainties surrounding its effects as a greenhouse gas in energy systems. Policymakers must consider the potential negative impacts of hydrogen use in the energy system and implement specific regulations on molecular hydrogen emissions and air pollutants, as well as policies promoting the use of hydrogen energy technologies.

Storage and security considerations

Hydrogen electrolysis technologies need to address storage and safety concerns as these are crucial aspects in the design of energy systems and plants. Ensuring safety is essential not only for the well-being of operators and personnel but also for the surrounding public and the region [165]. The incident involving hydrogen technologies was reported. Hydrogen has been associated with danger since the Hindenburg disaster, which resulted in the explosion or burning of hundreds of hydrogen-powered airships [208]. It results in the deaths of many victims. Fig. 11 depicts several instances in the Hindenburg accident involving hydrogen-inflated airships. Furthermore, Sakamoto et al. [209] also present the accident database for hydrogen and hydrogen fuelling stations in Japan and the USA.

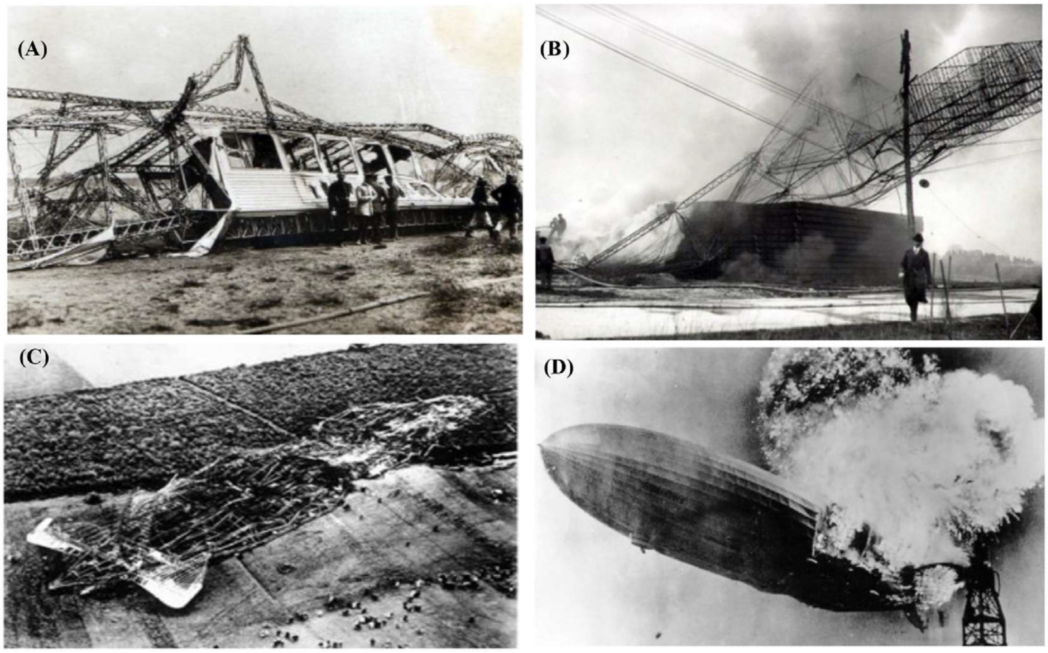

Fig. 11 – Hydrogen technology incidents [211]: A) Fire destroyed airship Schwaben in Dusseldorf, B) USA Army airship Roma perished after it collided with high-tension electrical wires near Langley Field, C) British R101 lost altitude and crashed near Beauvais, France, D) Hydrogen fire at Lakehurst Naval Air Station destroyed Hindenburg.

Hydrogen, like all fuels, is dangerous. Thus, the safe use of any fuel focuses on preventing situations with combustion, oxidant, and fuel [210]. Some of the hydrogen's characteristics require additional engineering controls to ensure its safe use [203]. Investigating the safety and reliability of hydrogen distribution to users is essential. It is important to understand the characteristics of hydrogen, implement safety measures into hydrogen systems, and provide training in safe hydrogen storage and handling. Although the limitations and challenges of water electrolysis have been summarized in a literature review, there are still many issues that need to be addressed. With the growing demand for green energy, water electrolysis has gained significant interest, and it is essential to collect and review past research and development for future studies.

Conclusion

The demand for hydrogen as an energy carrier is rising, driven by concerns such as climate change, population growth, and the depletion of fossil fuels. Climate change is one of the most pressing issues of our time. To address this issue, reducing CO_2 emissions from the power sector, transportation, industry, and heating is essential. Hydrogen has the potential to play a significant role in solving this problem, as green hydrogen can aid in decarbonizing various industries, such as manufacturing, transportation, and electricity production. Efforts have been made to expedite this transformation process and make it a reality. To contribute to this effort, the primary objective of this review is to provide an overview of academic research trends and identify the characteristics and development of hydrogen electrolyser technologies and their modelling for sustainable and green energy production. The review examines the fundamental concepts of numerous hydrogen production methods and their benefits and drawbacks. Additionally, it focuses on recent advancements in water electrolysis technology, including water electrolysis technologies, electrolyser, hydrogen as sustainable energy storage, and project-based hydrogen storage. The review also highlights recent research on electrolyser modelling, control techniques, technology, and utilization. Based on the review, several challenges and open issues that need to be addressed to enhance the effective improvement of hydrogen electrolyser technologies have been highlighted. The outcomes of this study show that an energy management control system is necessary to operate, integrate, and interconnect components in a generation system, thereby ensuring safe operation and desired outcomes. The majority of scientific publications suggest that simulating the control algorithm for hydrogen energy systems can increase performance and reduce costs. The challenge of hydrogen electrolyser is evaluated in detail in section 5, where suggestions for future research are provided. Addressing these challenges will boost the applications of hydrogen electrolyser. According to a review of the literature, many improvements are needed in the near future. To advance this technology, several recommendations should be considered. Firstly, the control strategy should be updated and improved to enhance the safe operation, capacity, security, lifetime expansion, functions, and efficiency of the electrolyser. Additionally, cost reduction should be a priority without compromising the system's performance and durability. Secondly, novel techniques to boost grid stability should be investigated, such as energy storage technology implementation in simulated systems, such as backup electrolyser facilities. Thirdly, further research is needed to commercialize water electrolysis-based systems that use renewable energy

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to produce hydrogen and develop infrastructure, economically viable technologies, and a sustainable hydrogen economy. Fourthly, future research may explore the techno-economic implications of utility company and station management modelling to predict the trade of fluctuating renewable energy output, the distributed power functioning of electrolysers, and the complexities of hydrogen production, storage, and demand. Finally, policymakers should encourage the development of hydrogen-integrated energy systems to facilitate hydrogen's integration into today's energy markets.

In conclusion, this study highlights the need for advancements in hydrogen electrolysis research and progress to establish the hydrogen vector as a reliable, cost-effective alternative to resolve renewable energy-related issues. By improving the performance of electrolysis, the integration of hydrogen into the global electricity system can be accelerated.

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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