

Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production

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ABSTRACT

The global shift toward sustainable energy solutions emphasises the urgent need to harness renewable sources for green hydrogen production, presenting a critical opportunity in the transition to a low-carbon economy. Despite its potential, integrating renewable energy with electrolysis to produce green hydrogen faces significant technological and economic challenges, particularly in achieving high efficiency and cost-effectiveness at scale. This review systematically examines the latest advancements in electrolysis technologies—alkaline, proton exchange membrane electrolysis cell (PEMEC), and solid oxide—and explores innovative grid integration and energy storage solutions that enhance the viability of green hydrogen. The study reveals enhanced performance metrics in electrolysis processes and identifies critical factors that influence the operational efficiency and sustainability of green hydrogen production. Key findings demonstrate the potential for substantial reductions in the cost and energy requirements of hydrogen production by optimising electrolyser design and operation. The insights from this research provide a foundational strategy for scaling up green hydrogen as a sustainable energy carrier, contributing to global efforts to reduce greenhouse gas emissions and advance toward carbon neutrality. The integration of these technologies could revolutionise energy systems worldwide, aligning with policy frameworks and market dynamics to foster broader adoption of green hydrogen.

Abbreviations

CCS	Carbon dioxide Capture and Storage
AEM	Anion Exchange Membrane
ALK	Alkaline Electrolysis
BOP	Balance of Plant
CCU	Carbon dioxide Capture and Utilisation
CFD	Computational Fluid Dynamics
DC	Direct Current
EPEX	European Power Exchange
F-ADP	Fossil abiotic depletion potentials
FCVEs	Fuel cell electric vehicles
GHG	Greenhouse Gas
LCOH	Levelized cost of hydrogen
LCA	Life Cycle Assessment
LHV	Low Heating Value
SMR	Steam Methane Reformer

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HRES	Hybrid renewable energy systems
HER	Hydrogen evolution reaction
RES	Renewable Energy Sources
PEC	Photo-electrocatalysis
PV	photovoltaic
P2G	Power-to-Gas
PEMEC	Proton Exchange Membrane Electrolysis Cell
PMS	power management system
NG	Natural Gas
MT	Metric Tonnes
MPP	Maximum power point
STH	Solar-to-hydrogen
SOE	Solid Oxide Electrolysis
OER	Oxygen Evolution Reaction
WI	Western Interconnection
WT	Wind turbine

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1. Introduction

The global quest for sustainable energy solutions has become necessary to minimise climate change and reduce reliance on fossil fuels. Hydrogen, as a clean energy carrier, is uniquely capable of storing and transporting renewable energy, thus playing a pivotal role in the global energy transition [1]. Particularly, the production of green hydrogen—generated through water electrolysis using electricity sourced from renewable energies—offers a compelling solution to reduce reliance on fossil fuels and significantly cut greenhouse gas emissions [1,2]. Therefore, developing and optimising efficient technologies for green hydrogen production is crucial for achieving global carbon reduction targets and advancing the commercialisation of clean energy technologies. Integrating renewable energy sources with modern technology has become a powerful path towards a cleaner and more resilient energy future in this paradigm shift. Among several technological constraints, the harmonious integration of renewable energy sources with electrolysis technology has received increasing attention. This study begins a detailed analysis of the evolving environment around integrating renewable energy sources, notably in the context of green hydrogen generation with electrolysis.

This article highlights the path to unlocking the potential of green hydrogen as the foundation of a sustainable energy ecosystem by thoroughly examining technological breakthroughs, obstacles, and possibilities. Hydrogen can serve as a significant energy carrier in the process of decarbonisation. It has the potential to be used in several areas, such as transportation, heating in buildings, industrial processes, and power generation. Several factors can either facilitate or hinder the speed at which technology is learned, and infrastructure is developed to ensure a dependable and affordable energy supply [3]. This is particularly relevant for the production of green hydrogen in regions with abundant solar resources, such as the Middle East and North Africa (MENA) [4,5]. From a global standpoint, green hydrogen is anticipated to be traded worldwide in neutral energy systems regarding greenhouse gas emissions. However, this will only be possible if a thorough assessment of the entire process chain is crucial for developing effective global policies [6]. Additionally, in the United States [7], green hydrogen is considered a viable and environmentally friendly method for attaining carbon neutrality. Despite its substantial benefits, the production and handling of hydrogen, particularly green hydrogen, present several critical challenges. These include the high costs of electrolysis equipment, the technical complexities associated with integrating fluctuating renewable energy sources, and the substantial energy requirements for hydrogen compression, storage, and transportation. Handling hydrogen also introduces safety risks due to its highly flammable nature and low ignition energy, necessitating advanced safety protocols and systems.

Green hydrogen is produced through water electrolysis using electricity derived from renewable energy sources, offering unprecedented potential as a clean and adaptable energy source. Unlike its traditional competitors, the generation of green hydrogen emits much less greenhouse gas emissions, making it a potent weapon for combating climate change across industries. Applications range from powering automobiles and businesses to acting as a storage medium for emerging renewable energy sources. Hydrogen production technologies involve four critical stages: production, storage, transportation, and use. Serious attention and significant improvements are needed in those stages to revolutionise hydrogen production. The transportation of hydrogen from the production site to the consuming site is a crucial operation in the hydrogen manufacturing economy since it can lead to higher production costs, hence affecting its affordability. The storage of hydrogen is regarded as a pressing and challenging task as it facilitates the advancement of secure, dependable, efficient, and sufficient storage

systems [8]. The proportion of hydrogen produced from sustainable sources is very low compared to fossil fuels hydrogen-driven production due to the exorbitant cost associated with water analysis, hydrogen storage, and huge infrastructural investment. Also, Fuel cells utilised for converting hydrogen into electricity exhibit lower efficiency compared to alternative energy conversion processes. Consequently, more significant quantities of hydrogen must be consumed to produce equivalent energy [9–11]. Despite these challenges, it is anticipated that the advancement in technology through integrating renewable energy sources with the production and utilisation of green energy will address the highlighted issues and opportunities associated with expanding the production, storage, and distribution infrastructure. However, realising this potential necessitates a full knowledge of the integration of renewable energy and electricity generation, which is the primary goal of this research.

Review articles on various topics have already been published on the subject of hydrogen systems of energy. While some focus on integrated green hydrogen production with a single energy source, others emphasise hybrid renewable energy systems [12–21], Vidas and Castro [12] focused on integrated hydrogen value chain and water splitting by green electrolysis. The authors fail to explore grid integration and green energy storage. Recently, Kojima et al. [13] provided information about the current fluctuating power and generation status in the water electrolyser configuration. The author fails to address the impact of Hybrid renewable energy integrated green hydrogen production.

Mazloomi and Gomes [22] considered the manufacture and storage techniques in addition to the risks and safety concerns associated with the technology, hydrogen is a very viable option both as a fuel for future automobiles and as a form of energy storage in massive power systems. Thema et al. [23] studied power-to-gas initiatives that create hydrogen or renewable gas to replace natural gas, including a cost-development estimate for electrolysis and carbon dioxide methanation. Dutta [24] examined hydrogen generation and storage techniques while also paying attention to risk and security concerns. In their study of hydrogen as a potential primary energy carrier, Abe et al. [25] put particular emphasis on how hydrogen is stored in metal hydrides. Gahleitner [26] studied power-to-gas pilot plants that utilised renewable electricity to electrolyse water to create hydrogen. Eveloy and Gebreegziabher [27] analysis of anticipated power-to-gas scenarios revealed the need for significant advancements in fields like effectiveness, affordability, and reliability if widespread adoption of these kinds of systems eventually becomes feasible. The possibilities for storing and delivering hydrogen were explored, and risk and security concerns were examined by Ref. [28]. Hanley et al. [29] reviewed the use of hydrogen in energy networks and examined potential factors and regulations that would make hydrogen more advantageous than other low-emission energy sources. They discovered that the case with the greatest likelihood is one in which hydrogen technologies are mostly used after 2030. With an emphasis on mass manufacturing, standardisation, and supportive policies, Parra et al. [30] present a techno-economic analysis of hydrogen energy systems and emphasise policies that they believe may hasten the widespread use of hydrogen technology. By providing a synopsis of actual projects, Bailera et al. [31] evaluated the various processes utilised to transform renewable energy sources into methane in power-to-gas projects. Power-to-gas initiatives in Europe were taken into account by Ref. [32], those who hypothesised that power-to-gas plants will be crucial for refineries in the coming years to lower the emissions associated with their products.

Badreldin et al. [33] critically examine various oxidation processes. The analysis covers reactions that use sacrificial reagents, such as wastewater pollutants, as targets. Processes that source biomass and then partially reform it to produce hydrogen and beneficial byproducts were also looked at. The analysis presented here provides an understandable overview of the existing difficulties and barriers associated with using alternate oxidation processes as a strategy to address industrial hydrogen generation demands. Important technical insights were

also offered to further the use of alternate oxidation processes. The review by Chatterjee et al. [34] presents the current PV-PEC technological integration for green hydrogen. They start by discussing the basics of PV and water splitting techniques (photocatalysis, electrolysis, photo electrocatalysis (PEC), and electrocatalysis (EC), in addition to the reasons and how independently solar water splitting equipment evolved from PV with external electrolyzers (PV-EC) to the incorporation of PV with EC (IPV-EC) and PEC (PV-PEC). The authors then go over the principal difficulties in PV-PEC incorporation and give an overview of the key developments in conception and material science for high solar-to-hydrogen (STH) efficiency and extended device lifetimes. Cu-oxide is emphasised as a developing material, along with the significance of material choice and metal-oxide semiconductor nanostructures for PV-PEC integration. Other sources of renewable energy integrated with green hydrogen were not considered. Rumayor et al. [35] used super-green hydrogen, commonly known as photo-hydrogen, to demonstrate a potential performance scenario that may be a viable alternative for electro-hydrogen. The research has produced future possibilities by calculating the values of operational factors such as the energy required to generate the cell, solar-to-hydrogen efficiency (STH), and lifespan through a series of sensitivity assessments. These factors were examined using two effect categories: fossil abiotic depletion potentials (FADP) and global warming potentials (GWP). For benchmarking, proven water electrolysis was used to explain the desired performance where the PEC technology might be effectively deployed on a large scale. A close look at the previously published review articles revealed the absence of detailed and updated studies on integrating renewable energy sources, such as solar, wind, and hydropower, for clean hydrogen production, energy storage solutions, and grid stability. This review article aims to provide a clear and up-to-date understanding of the current state of the art in renewable energy-integrated green hydrogen production. The novelty of this article lies in its comprehensive and critical review of integrating renewable energy sources with electrolysis for green hydrogen production, addressing the technological, economic, and grid-related aspects of this emerging field.

This research aims to systematically analyse and enhance the integration of renewable energy sources with advanced electrolysis technologies, significantly improving the production of green hydrogen and thereby contributing to a sustainable energy future. This review is distinguished by its comprehensive approach that explores the complexities of integrating renewable energy with electrolysis technologies and showcases cutting-edge technological advancements and practical applications. It provides a detailed analysis of how system integration, particularly photovoltaic and electrochemical water-splitting technologies (PV-PEC), can boost solar-to-hydrogen conversion efficiency (STH) and prolong equipment longevity. The paper bridges various research gaps by proposing an integrated framework, facilitating a deep understanding of multiple aspects of the integration process. Furthermore, the review delves into technological progress and innovations in proton exchange membrane electrolysis, alkaline electrolysis, and solid oxide electrolysis systems, emphasising their strengths, limitations, and combined potential to accelerate the green hydrogen revolution.

The contributions of this review can be summarised as follows. This review conducts a comprehensive and critical analysis of the latest research findings and practical cases, offering deep insights into how to effectively integrate renewable energy sources and electrolysis technologies to facilitate the production of green hydrogen. The article reveals multiple approaches to addressing efficiency and cost-effectiveness through technological innovation. It underscores the importance of policy support, standardisation, and market acceptance in promoting the widespread adoption of green hydrogen technologies. The thoroughness and innovativeness of this study provide a robust foundation for research and practice in green hydrogen as a future clean energy solution, heralding its significant potential to combat climate change across various industrial sectors.

The structure of this review article is organised as follows: Section 2

discusses various green hydrogen generation methods, including water electrolysis, biomass gasification, and thermochemical processes, outlining their advantages, disadvantages, and industry status. Section 3 delves into different electrolysis systems, such as solid oxide, proton exchange membrane electrolysis cell (PEMEC), and alkaline electrolysis, exploring key technical challenges and recent advancements. Section 4 focuses on integrating these electrolysis systems with renewable energy sources like wind, solar, and hydropower, emphasising grid integration and energy storage solutions. Section 5 assesses the market potential and cost competitiveness of green hydrogen alongside regulatory frameworks that support its adoption. Finally, Section 6 summarises the research, highlights the role of green hydrogen as a sustainable energy carrier, discusses emerging challenges, and offers recommendations for future research directions.

2. Green hydrogen production technologies

2.1. Electrolysis: process overview

A water electrolysis cell is made up of a cathode and an anode that are separated by a membrane and submerged in an electrolyte. Electricity travels via the electrolyte when it is linked to a direct current power source, causing the water to separate into oxygen and hydrogen [36]. Every single electrolyser structure comprises a series of electrolysis units, a dryer and purifier for gas, and a device to remove heat. In accordance with the necessary product specifications, both oxygen and hydrogen gas products are required to be purified, cooled, and dried before being stored or delivered to the market. A secure atmosphere-facing venting system must be used for the oxygen gas. It is also possible to sell this oxygen as a by-product, pending the existence of suitable markets. Electrolysers are presumptively designed with a 3 MPa outlet pressure in this emissions-determining system. An electrolysis mechanism might need to be compressed to reach 3 MPa pressure or dried, depending on how the electrolyser is built. The energy required to accomplish this, as well as the resulting emissions, must then be determined and taken into account [37]. Fig. 1 presents the electrolysis process flow diagram.

2.1.1. Proton exchange membrane electrolysis cell (PEMEC) electrolysis

Grubb developed the first Proton Exchange Membrane Electrolysis Cell (PEMEC) water electrolysis in the early 1950s, and GE created alkaline water electrolysis in 1966 to address its shortcomings. PEMEC fuel cells use solid polysulfonated membranes (fumapem®, Nafion®) as an electrolyte (proton conductor), and PEMEC water electrolysis technology uses solid polysulfonated membranes as a working medium. These PEMEC have many benefits, including reduced gas permeability, high proton conductivity (0.1 ± 0.02 S/cm), reduced thickness (≤ 20 to $300 \mu\text{m}$), and high-pressure operations [38].

PEMEC water electrolysis is one of the preferred methods for converting renewable energy to highly pure H_2 from an environmentally friendly and sustainable perspective. An additional promising PEMEC water electrolysis method has excellent benefits like an ergonomic layout, a significant density of current (greater than 2 A cm^{-2}), excellent efficiency, rapid response, a modest footprint, and the ability to operate at reduced temperatures ($20\text{--}80^\circ\text{C}$) [39]. It also produces ultrapure O_2 and H_2 as a byproduct. PEMEC electrolysis plants can also be easily balanced, making them more appealing in various industries. The most advanced electrocatalysts for PEMEC electrolysis are highly active noble metals, like Iridium (IV) oxide (IrO_2)/Ruthenium (IV) oxide (RuO_2), which are used in the O_2 evolution reaction (OER) at the anode and the Pt/Pd hydrogen evolution reaction (HER) at the cathode. Consequently, this renders PEMEC electrolysis a bit more costly than alkaline water electrolysis. In PEMEC water electrolysis, lowering production costs while maintaining high efficiency is, therefore, a major challenge. Since then, considerable effort has been put into enhancing the PEMEC water electrolysis components, and as a consequence, this

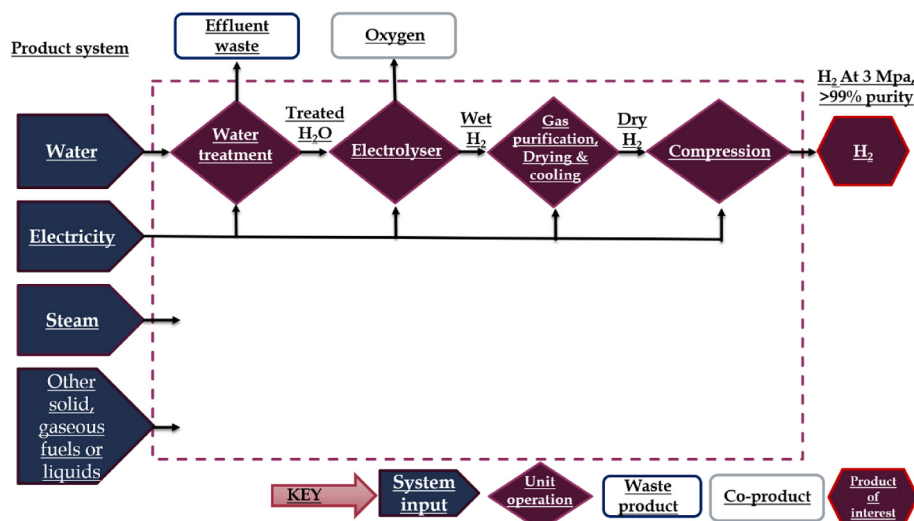


Fig. 1. The electrolysis process flow diagram.

technology is getting close to commercialisation [40]. The PEMEC electrolysis is shown in Fig. 2.

The system of PEMEC electrolysis is scalable and modular (see Fig. 3). It could be created based on the final application and the quantity of hydrogen needed. The systems in question operate at temperatures between 50 °C and 80 °C and have an elevated current density (roughly 2 A/cm²).

One of the primary benefits of PEMEC electrolysis technologies is the ability to generate high-purity (greater than 99.99%) and high-pressure hydrogen in a single facility. PEMEC electrolysis technology exhibits a quick start-up when dealing with variable power sources (like renewable energy), allowing it to operate in all of the nominal working ranges (0%–100%). Using a solid electrolyte also eliminates the need to manage a liquid electrolyte, which is required by an alkaline system.

Because of the application of precious metals as catalysts (such as Pt, Ru, and Ir), these configurations are expensive and expose materials to extremely acidic media. While the proton exchange membrane in PEMEC electrolysis interacts with an acidic environment, it is essential to clarify that the solution is not extremely acidic as the primary challenge stems not from the acidity but the high voltage across the electrode

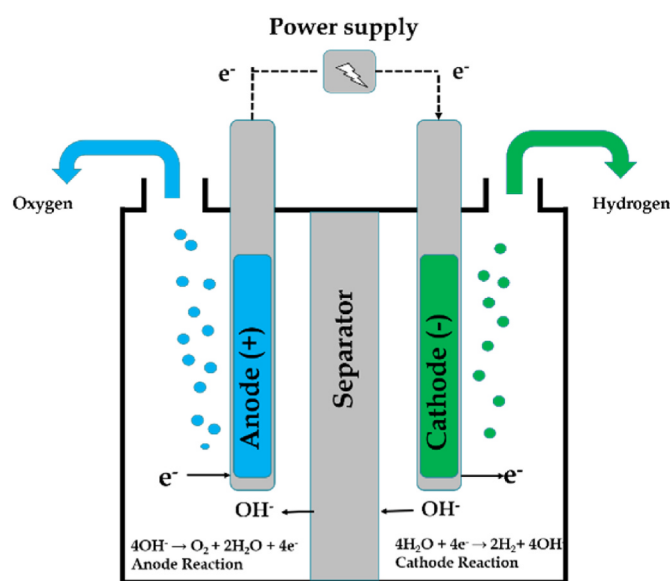


Fig. 3. Alkaline electrolysis.

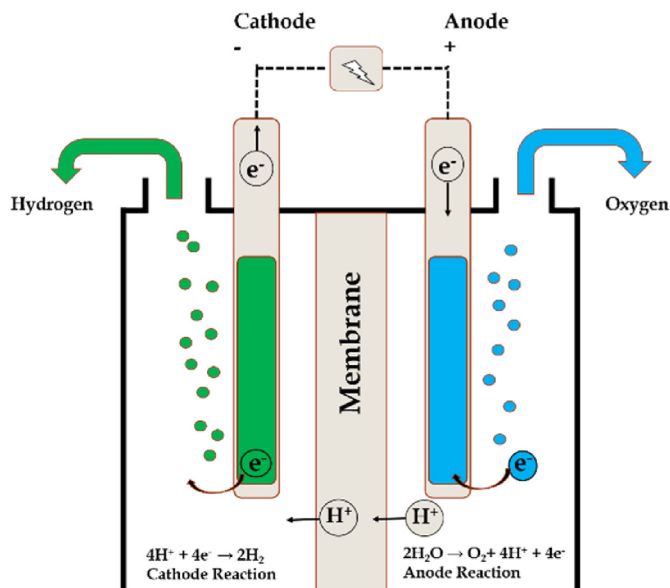


Fig. 2. Simplified Illustration of a PEMEC electrolysis system.

plates. Consequently, in order to advance PEMEC electrolysis, it is essential to achieve the maximum efficiency of the stack at the lowest possible cost. The usage of power (kWh/kg) for PEMEC electrolysis systems has been on the decline since 2010, indicating that the production of hydrogen efficiency has been steadily increasing. According to projections for the year 2030, operating at 1000 mA/cm² will enable power usage to reach approximately 45 kWh/kg of hydrogen [41].

Even so, voltage degradation—more specifically, the overpotential that must be employed in an electrolysis cell in order to keep the production of hydrogen constant—also has an impact on the effectiveness of a PEMEC electrolyser. Various PEMEC electrolyser producers have provided robustness data that ranges from 50,000 to 75,000 h of operation with a maximum degradation rate of 4–8 μV/h [42].

2.1.2. Alkaline electrolysis

Potassium hydroxide serves as the liquid electrolyte used by AEL. Metal makes up the electrodes. A hydrogen- and oxygen-impermeable diaphragm is situated between the two electrodes [37].

AEL currently operates at about 70% efficiency, with long-term expectations of 80% efficiency. It is the most well-established process

because it has been used extensively since 1927, has fewer investment expenses than the other two methods, and can currently produce the greatest nominal outputs (>100 MW) without using essential raw materials. It also has a longer lifespan than the other two techniques.

In contrast to PEMEC electrolyzers (see Table 1), AELs are less durable. Due to the fact that the gases dispersed in the electrolyte are still present in the cycle, they are particularly susceptible to contaminants in the product gas. The cold start time of AEL is of a lengthy 50-min duration as well [43].

Modern commercial use of alkaline electrolysis demonstrates the maturity of the technology. High-capacity hydrogen production systems in the MW range are available for commercial use [42].

The main benefits of this technology over competing ones include its advanced state, accessibility, and affordability (these are applications that do not depend on components that include noble metals). It has also been demonstrated to be durable. Moderate current densities and applying an extremely corrosive liquid electrolyte are the primary negative aspects.

Overall, commercial systems operate at temperatures ranging from 65 °C to 90 °C, with standard pressures ranging from 10 to 30 bar. Since the gases produced in both the cathode and anode can easily diffuse by means of the porous diaphragm employed as a separator, the quality of the generated hydrogen is approximately 99.5%–99.9% (vol.). As a result, a purification phase dependent on de-oxo reactors capable of removing oxygen traces and enhancing purity to a level >99.999% is required in the event that higher purity hydrogen is required. Inasmuch as the operation occurs in nominal conditions within 0.25–0.45 A/cm², the total efficiencies of these types of systems range from 51% to 60% with regard to the minimal heating value of the hydrogen. In operation, the production of H₂ is restricted to a power range of 20%–100% of the nominal capacity to avoid the buildup of flammable mixtures caused by gas diffusion via the diaphragm, which occurs mainly at reduced current densities (0.1 A/cm²) [42].

Regarding the robustness of these technologies, current industrial equipment provides approximately 95,000 h of operation with a standard degrading ratio of 1–3 μV/h, which sufficiently meets industrial standards (25 operating years). Operating with variable charges, however, clearly impacts these systems. Operating in an environment of dynamic charges and turning them off and on again regularly decreases their lifespan, which lowers the purity of the gas produced and results in less efficient operation.

The present advancements in research and development in this field are primarily focused on finding solutions to the two biggest drawbacks of this type of electrolysis: the low current density and the issues associated with operating in dynamic environments. As a result, the future challenges are as follows [41,44–46].

Table 1
Techno-economic features of PEMEC and ALK electrolyzers between 2017 and 2025.

Methods	PEMEC		ALK	
	2017	2025	2017	2025
Efficiency (kWh electricity per kg of hydrogen)	58	52	51	49
Lifespan stack (working hours)	40,000	50,000	80,000	90,000
Low Heating Value Efficiency (%)	57	64	65	68
OPEX (Initial CAPEX % per yr)	2	2	2	2
CAPEX -overall cost of the system (both costs of installation/power supply) in EUR per kW	1200	700	750	480
Lifespan of the system (yrs)	20 years		20 years	
Output pressure (Bar)	30	60	atmospheric	15
CAPEX –replacement of stack (EUR per kW)	420	210	340	215

- Produce novel materials to enhance the catalytic function of the electrodes, thereby lowering the high voltages for both the reaction at the cathode and the anode reaction.
- Improve the distance within the electrodes to minimise ohmic losses and enable operation at elevated current densities. Today, the electrode spacing is typically less than 1 mm. Additionally, as the electrodes are in close proximity to the diaphragm in many designs, a zero-gap design for cells is employed to conserve space. However, because there is little room between the electrodes in these designs, the discharge of the produced gases may be constrained. As a result, improved designs that enable better flow distribution are required.
- The creation of AEMs as separators in electrolysis cells would eliminate the need for a liquid electrolyte. This type of membrane will enable higher current densities, decreased diffusion within the cathode and anode regions, and decreased ohmic excessive potential connected with the distinguishing medium currently employed (diaphragms).
- Creating alkaline electrolyzers with operating temperatures of up to 150 °C would speed up electrochemical reactions by increasing the conductivity of the electrolyte. The primary disadvantage is that the components in the cell corrode at such temperatures.

Table 1 gives a broad summary of the techno-economic features of PEMEC and ALK electrolyzers at present and their anticipated advancements in the future. Modern PEMEC electrolyzers can function more adaptable and quickly than ALK systems now in use. The greater working range and quicker response time of PEMEC technology present a substantial benefit in enabling adaptable operations to generate income from various electrical markets.

2.1.3. Solid oxide electrolysis

Dönitz and Erdle [47] are credited with developing solid oxide electrolysis (SOE), which was first used in the 1980s. Due to the conversion of electrical energy into chemical energy and the increased efficiency of processes in producing ultra-pure hydrogen, SOE has garnered an enormous amount of interest. Steam is produced from water during SOE, which operates at high pressures and temperatures (500–850 °C). As depicted in Fig. 4, the SOE’s mechanism of operation employs O₂ conductors that are typically made of yttria or nickel-stabilized zirconia.

Solid oxide fuel cells have recently been used to create and study several ceramic proton-conducting components. Nevertheless, ceramic

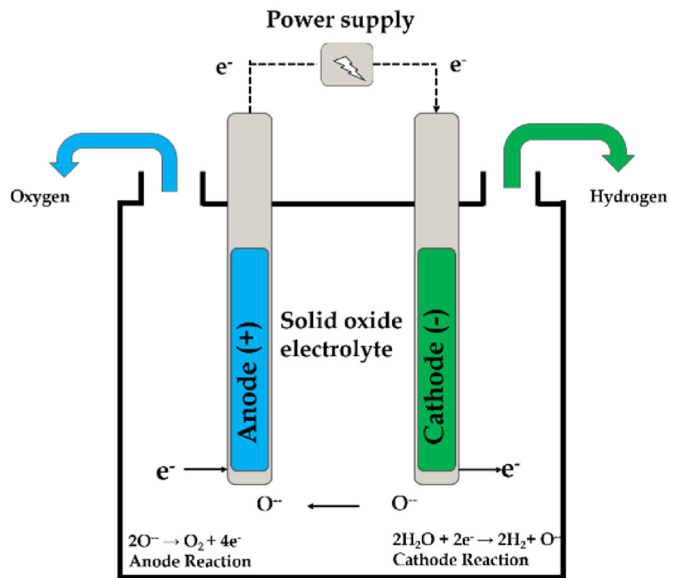


Fig. 4. Simplified illustration of a solid oxide electrolysis.

proton-conducting materials are receiving greater recognition for the SOE electrolysis process as a result of their more effective ionic conductivity and high efficiency when compared to O^{2-} conductors at temperatures ranging from 500 to 700 °C [48]. The primary benefit of SOE technologies over lower-temperature electrolysis is their higher operational temperature. However, there are some challenges with the degradation and lack of stability of SOE that must be resolved before it can be commercialised widely [49]. The SOE is still in the early stages of development. Compared to PEMEC and AEL, it has the lowest nominal throughput (150 kW) and the most elevated capital expenditure. Additionally, cold starts can take longer and are extremely lengthy.

As opposed to PEMEC electrolyzers, which run at temperatures between 70 and 90° Celsius, and commercial alkaline electrolyzers, which usually run at temperatures below 100° Celsius, solid oxide electrolyzers are required to operate at temperatures sufficiently elevated for the solid oxide membranes to work effectively (roughly 700–800° Celsius). The possibility of lowering the temperature at which they operate to 500°–600 °C is being explored by modern lab-scale solid oxide electrolyzers that employ proton-conducting ceramic electrolytes. The solid oxide electrolyzers can efficiently use the heat produced at these high temperatures (from a variety of sources, such as nuclear energy), thereby requiring less electrical energy to generate H_2 from H_2O .

Despite being the least advanced electrolysis technology, SOE electrolyzers are the most electrically effective electrolyzers due to their high operating temperatures. They employ a solid electrolyte, and because they operate at temperatures well above the boiling point, they do not exhibit the same distribution of gas and liquid issues that electrolysis at lower temperatures does. Due to the operating circumstances under which SOECs function, they are also free of the need for precious metal catalysts [50].

These systems can achieve current densities comparable to PEMEC electrolysis systems, but because of the elevated degradation at such temperatures, they typically operate below 1 A/cm². The associated cell voltages are approximately 1.3 V, resulting in a power usage that is significantly lower than that of the competing technologies (3.2 kWh/Nm³ H_2). By accounting for both the electrical system and the thermal usage, efficiencies can rise above 90%.

High temperatures of operation, though, necessitate the use of expensive components and more intricate manufacturing processes. The internal resistance of a cell can rise because distinct parts of the cell exhibit different rates of thermal expansion, making the start and stop cycles harmful to the interfacial contact between the electrolyte and electrodes. This results in a breakdown of the various layers. Along with gradual accumulation and reoxidation during electrolysis, part degradation also causes the electrodes on the cathode side to become inactive as a result of Ni hardening. The cell assembly is extremely delicate and intricate because the various parts must be made of very thin materials in order to improve the conductivity properties. Because of these reasons, a lot more research will be necessary before this method of operation can be used commercially to optimise the system, materials, and components [51].

However, by utilising the energy produced from various thermal sources, which include nuclear reactors, solar concentration power plants, and geothermal energy, this method possesses immense value for producing hydrogen. Further, given that a solid oxide cell is basically a solid oxide fuel cell operating in reverse, the use of reversible devices that can function as a fuel cell or electrolyser is an option.

On a final note, it should be mentioned that co-electrolysis methods, which use steam and carbon dioxide to produce synthesis gas (hydrogen + CO), can increase the total efficacy of SOE technology. This is intriguing from a commercial perspective in relation to the production of various synthetic fuels. Because of its superior efficiency and conversion rate, which offer a few possibilities to lessen carbon dioxide emissions, slow global warming, and store renewable energy, this process has garnered a lot of attention. However, because of the elevated temperature at which it operates and the challenge of activating the

double bond C=O of carbon dioxide, more specialised cathodes are needed for SOE. As a result, research is being done to create materials that are suitable for this purpose and have a high degree of catalytic activity and superb durability for the electro-reduction of H_2/CO_2 [52]. Degradation ratios for SOE processes range from 0.4 to 6%/1000 h at temperatures ranging from 650 °C to 850 °C and current densities ranging from 0.26 to 1 A/cm² [42].

2.2. Evaluating the pros and cons of electrolysis

In order to meet the Hydrogen Energy Earth shot target of bringing down the price of hydrogen that is clean by 80% to \$1 per kilogramme in ten years, electrolysis is the most prominent way of producing hydrogen. With respect to the nature of the electricity applied, the electrolysis of hydrogen may result in no emissions of greenhouse gases. When assessing the advantages and financial sustainability of producing hydrogen by means of electrolysis, the source of the necessary electricity—including its price and effectiveness alongside the emissions produced by electricity generation—must be taken into account. As a consequence of the greenhouse gases that are discharged and the volume of fuel needed due to the inefficiency of the electricity production process, many areas of the country do not have an ideal power grid for supplying the electricity needed for electrolysis [53].

The electrolysis of hydrogen is being investigated for nuclear and renewable energy sources (solar, wind, geothermal, and hydro). When compared to more established carbon-based methods like natural gas reforming, these methods for producing hydrogen emit almost no greenhouse gases or other measurable pollutants. Nevertheless, the price of production needs to be substantially reduced [36,54].

There are benefits and drawbacks to every electrolysis technology. So, when choosing the technology, it is important to take the project-specific needs into account. The most well-known technology that produces the greatest nominal output is AEL. However, PEMEC electrolysis has the greatest potential for utilising varying renewable energies because of its adaptable and dynamic characteristics. PEMEC electrolyzers are particularly advantageous for dynamic operations due to their ability to adjust rapidly to power input changes, a common characteristic of renewable energy sources such as solar and wind. Unlike traditional electrolysis systems, PEMEC electrolyzers can start and stop quickly without significant energy losses, making them ideal for environments where electricity generation is intermittent. The high current densities of PEMEC electrolyzers also allow for more excellent hydrogen production rates during peak power availability, enhancing overall efficiency. However, it is important to recognise the enormous potential of SOE, particularly in the future. The cost of investing will keep declining. For the PtX process, it is particularly intriguing that a synthesis gas can be generated directly for additional Fischer-Tropsch uses.

Additionally, it should be remembered that electrolysis studies are still being done not just in terms of the development of the techniques that are currently being used but also in terms of emerging technologies. An additional technology is anion exchange membrane (AEM) electrolysis, which has the potential to be a viable solution in the years to come. The pros and cons of different types of electrolysis are depicted in Table 2.

Electrolyzers function more effectively at less load, which has an unexpected effect on the cost of hydrogen. In contrast to most power-related assets, PEMEC electrolyzers run more effectively at reduced loads. The alkaline technique has generally been used at constant load to meet industrial purposes since it was not initially intended to be flexible. Despite this, recent developments should be recognised, making the ALK system suitable for the rapid delivery of grid-connected services [44,52,55,56]. Nevertheless, the ALK system is currently less adaptable than PEMEC technology, which, in the end, reduces the quantity of additional money that the operator would be able to generate through flexibility. A comparison of the crucial factors affecting the dynamic functioning of PEMEC and ALK electrolyzers is provided in Table 3.

Table 2
The pros and cons of different types of electrolysis technologies.

	PEMEC	AKL	SOE
Pros	1 High-purity H ₂ . 2 Significant load gradient with excellent dynamic properties: ideal for fluctuating RES. 3 Cold start takes just 15 min.	1 Plants with a significant nominal throughput (greater than 100 MW) 2 Proven technology. 3 Does not necessitate the use of essential raw materials 4 Most minimal costs of investment (€1000/kW) and a long lifespan.	1 Most significant efficiency (80%) 2 Appropriate for co-electrolysis: direct synthesis gas production
Cons	1 Costlier investments (2000 euros per kW). 2 The use of precious metal electrodes.	1 Comparatively lengthy cold start time (50 min). 2 Sensitivity to product gas contaminants	1 Highest cold start duration (a number of hours). 2 Currently, the process is ongoing. 3 Investments with the highest costs (2500 euros per kW)

Table 3
The dynamic function of PEMEC and ALK electrolysis.

	PEMEC	ALK
Shutdown	In few seconds	1–10 min
Warm-cold (Start-up)	1 s to 5 min	1–10 min
Load range	Nominal load of 0–160 %	Nominal load of 15%–100%
Ramp-down/ramp-up	100% per second	0.2%–20% per second

The most pressing difficulties right now are achieving technological scale-up and cost savings through wider usage, mostly for PEMEC as well as for ALK electrolyser makers (see Table 4). To maintain enhanced power density, longevity, and balance of plant efficiency, further R&D activities are also required. As time passes, several fascinating research directions open up that may help us comprehend PEM electrolyzers and how they fit into dynamic energy systems on a deeper level. Future studies on developing advanced diagnostic techniques aimed at thoroughly monitoring the health conditions of PEM electrolyzers are highly desirable. Real-time sensing of different performance parameters, including temperature distribution, membrane integrity, catalyst degradation, and gas crossover, may be included in these techniques. By incorporating these diagnostic tools, researchers can acquire useful knowledge about the operating circumstances that result in a decline in performance or system malfunctions. Implementing this proactive strategy has the potential to establish predictive maintenance procedures, which would improve the durability and dependability of PEM electrolyzers in ever-changing energy situations. Several academics are doing groundbreaking investigations to develop non-invasive technologies for monitoring and evaluating the health of high-capacity electrolyzers. The primary objective is to utilise the capabilities of the power converter to observe the electrochemical process while minimising interference accurately. An option is to obtain crucial data regarding the electrolyser’s condition by utilising the inherent monitoring capability

Table 4
Parameters for the solar current calculation example eqn (2). These setup-specific parameters include the number of serially n_s and parallelly n_p connected photo-voltaic cells, the open-cell voltage U_{oc} , the short-circuit current I_{sc} , the non-ideality factor m , the parallel resistance R_p , and the serial R_s , T_c , the assumed constant cell temperature.

Short-circuit current I_{sc}	Parallel resistance R_p	The serial R_s	Assumed constant cell temperature T_c	Open-cell voltage U_{oc}	Non-ideality factor m	Number of parallel pathways n_p	Number of serial n_s
A	Ω	Ω	$^{\circ}\text{C}$	V	–	–	–
5.98	20	0.099	48	4.615	1.6	2	9

of the power conversion system without disrupting its regular functioning. This may facilitate advancing more effective and resilient diagnostic procedures for improved PEM electrolyser technologies.

Control methods and algorithms will need to be the main focus of future research to fully achieve the potential of PEM electrolyzers in dynamic energy systems. Incorporating dynamic models into control frameworks presents opportunities to enhance PEM efficiency, responsiveness, and performance. Predictive control algorithm development also presents a promising avenue to maximise hydrogen production while preserving system stability. These algorithms can predict future system behaviour and make proactive operational parameter adjustments using historical data and predictive dynamic models. This strategy can enhance efficiency by managing transient states, reducing overpotentials, and enhancing overall energy conversion efficiency [57, 58]. Furthermore, with the increasing prevalence of combining PEM electrolyzers with renewable energy sources [59,60], it is crucial to explore sophisticated hybrid control systems. These techniques can adaptively transition between several operating modes, such as optimising hydrogen production when there is abundant renewable energy and switching to energy-saving modes during periods of low energy. This level of adaptability can enhance the effectiveness of hydrogen generation and the stability of the power grid and energy management [61,62]. Offshore hydrogen refers to integrating hydrogen production systems with renewable energy sources. Several nations have successfully achieved their climate objectives and are progressing toward complete carbon neutrality. Offshore hydrogen, in this particular situation, has the potential to facilitate a swift and large-scale shift towards climate-neutral energy. Several wind farms are located in offshore clusters more than 100 km from the shore. These industrial islands are highly automated and instantly transform wind energy into hydrogen. Within these clusters, the wind turbines are combined with electrolyzers that produce hydrogen through electrolysis using desalinated saltwater. Chemical facilities on specialised platforms subsequently utilise a portion of the hydrogen by mixing it with nitrogen to create ammonia or carbon dioxide to generate alternatives to fossil fuels [63].

So, long-term hydrogen production has a great deal of promise when combined with renewable energy sources, energy storage, and PEM electrolyzers. These hybrid systems contribute to lowering emissions, boosting energy resilience, and quickening the shift to cleaner energy sources. Ongoing research aims to solve technological issues and improve system functioning and design for real-world applications. Incorporating PEM electrolyzers into the broader hydrogen supply chain is a subject of fascination in the realm of renewable energy and sustainable hydrogen generation. While a network of this nature is not yet in existence, dynamic electrical models, which are sophisticated computational tools employed to simulate the temporal behaviour of electrical systems, can be utilised to enhance the functioning and efficiency of individual electrolyzers within the overarching system.

2.3. Renewable energy sources for electrolysis

The integration of electrolysis using alkaline water and renewable energy is critical for long-term hydrogen generation without large CO₂ emissions. Although wind and solar power are widely used for solar base loads because of their widespread accessibility, other forms of renewable power, such as geothermal energy, hydropower, and biomass, are

also extensively utilised [64]. Because of the imbalance between energy demand and supply, as well as the limited storage capacity for electricity, the direct use of renewable energy in the power grid is problematic. As a result, extra electric energy ought to be chemically stored in hydrogen and used afterwards [6]. Alkaline H_2O electrolyzers have to be dynamic in operation because of the variable and intermittent behaviour of wind and solar electricity [65]. While alkaline electrolyzers have been traditionally favoured for their lower cost and robustness, PEMEC electrolyzers present a compelling case for use with fluctuating renewable energy sources. Their ability to operate effectively under variable electrical outputs makes them suitable for coupling solar and wind energy systems, which often produce electricity with significant fluctuations. The rapid response of PEMEC electrolyzers to changes in power input ensures optimal utilisation of available renewable energy, reducing wastage and increasing the adaptability of the system. Furthermore, the technological advancements in membrane and catalyst design are continuously improving the operational stability of PEMEC and reducing its reliance on precious metals, thus addressing one of the primary barriers to its widespread adoption. To assess the needs, local meteorological data may be utilised to derive the amplitudes and frequencies of variations.

In Fig. 5, average time-associated patterns for wind speed and solar radiation are displayed. The information was collected by a weather sensor located on the rooftop of a college facility at Clausthal University of Technology. Unlike the wind speed, which has a mean value of about 3.8 m/s^{-1} , the major solar radiation is only present during the day. Therefore, 233 W m^{-2} for a bright day and just 29 W m^{-2} for a gloomy day represent the average value throughout the course of the day.

The amount of hydrogen that is produced directly corresponds to the renewable energy pattern of the operation. Considering the gas purity, which is determined by the system volume, there is only a brief delay that may be felt. This method is ideal for producing renewable hydrogen since it allows for direct linkage between solar panels and water electrolysis [66,67]. In regions such as Northern Europe and the Great Plains of the United States, where installation and maintenance costs for solar panels are comparatively high, and wind resources are abundant, wind power is frequently chosen for commercial hydrogen generation. This geographical specificity helps underline the regional variations in renewable energy deployment that directly impact the economic feasibility of hydrogen production technologies [68,69]. Wind energy exhibits a higher degree of volatility and is far more intermittent than solar energy. Therefore, the dynamic functioning of Alkaline water electrolyzers is more difficult [64]. By 2050, approximately one-third of the necessary solar and wind electricity will be allocated for water electrolysis, generating hydrogen. This will result in a cumulative electrolyser capacity of around 17 TWe. The current capacity of 20 GWe

presents significant potential for growth, which may be further realised through mass production, volume expansion, and scaling up the size of the electrolyser unit. As these factors come into play, the cost of electrolysis is expected to fall [70].

In order to create appropriate system designs and run current systems safely and effectively, it is possible to exploit the dynamic behaviour of an alkaline water electrolyser. The potentially available renewable energy may be computed and utilised as an input during the system design since measurements of solar radiation and wind velocity are frequently available for a specific site. There are several methods for calculating the power of wind turbines and solar photovoltaic systems. While the power of wind turbines is a proportion of the maximum attainable wind power, which is determined by the wind speed and a performance coefficient, the current-voltage properties of photovoltaic panels may be represented as a function of supplier data and solar radiation [71].

2.3.1. Solar photovoltaic (PV) systems

The behaviour of solar panels may be characterised using two-diode and single-diode models of different complexity. When more detailed models are used, the solution must frequently be found iteratively or numerically. Basic models with computational capabilities are an emerging study focus, as online characterisation and optimisation of current systems might need minimal processing time [72,73]. Fig. 6 depicts the connection options of an alkaline water electrolyser with solar PV panels. Further losses from a DC/DC transformer can be eliminated when the systems are coupled directly. Alternatively, the transformation assures the integration of the two systems through an indirect connection [74].

The point of intersection of the current-voltage lines can be used to identify the potential operation locations when a direct linkage between the two systems is desired. Equation (1) is an example of a typical current-voltage characteristic of an alkaline water electrolyser. An appropriate single-diode model may be used Equation (2) to represent the resultant current of a photovoltaic cell I_{PV} as a function of the voltage U_{PV} . The photocurrent I_{ph} , reverse saturation current I_s , and thermal voltage U_T must thus be calculated using particular information from the photovoltaic (PV) panel and the surrounding environment. Additionally, it must be possible to access the serial R_s and parallel R_p resistance of solar panels.

$$U_{\text{cell}} = U_{\text{rev}} + [(r_1 + d_1) + r_2 \cdot \theta + d_2 \cdot p] \cdot j + s \cdot \log \left[\left(t_1 + \frac{t_2}{\theta} + \frac{t_3}{\theta^2} \right) \cdot j + 1 \right] \quad \text{Equation 1}$$

$$I_{PV} = I_{ph} - I_s \cdot \left[\exp \left(\frac{U_{PV} + I_{PV} \cdot R_s}{U_T} \right) - 1 \right] - \frac{U_{PV} + I_{PV} \cdot R_s}{R_p} \quad \text{Equation 2}$$

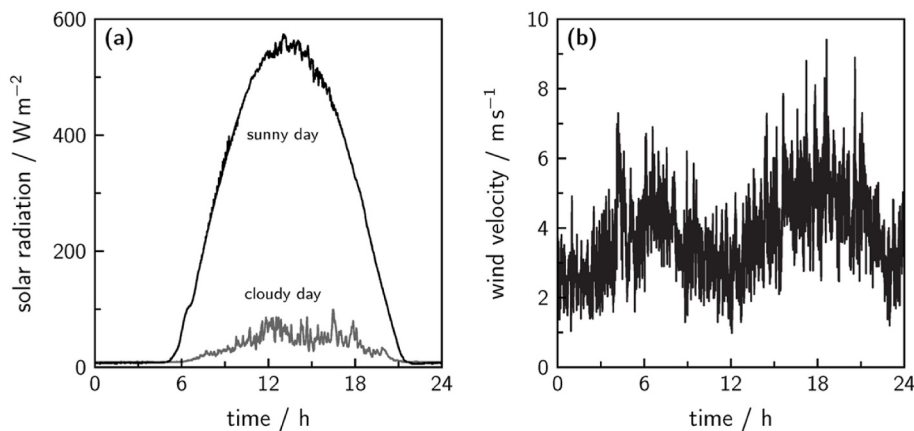


Fig. 5. Standard time-associated profiles of (a) solar radiation and (b) wind speed, as determined by the meteorological station at the Clausthal University of Technology. Wind speed exhibits sinusoidal variations despite the noontime solar radiation peak [64].

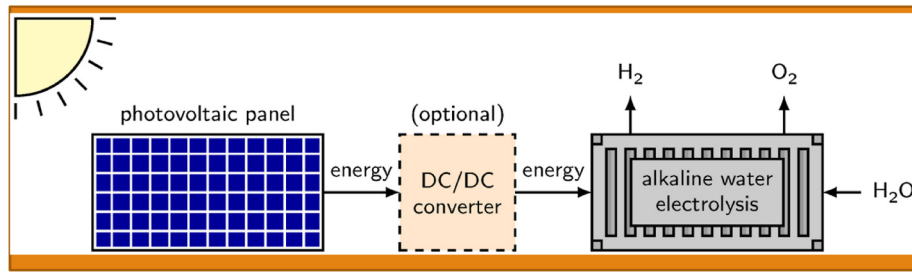


Fig. 6. Diagram of solar-powered alkaline water electrolysis. Photovoltaic systems transform solar energy into electricity, which may then be used to power the system. The use of a DC/DC power converter is voluntary because of the indirect and direct connections. [75].

The photocurrent I_{ph} is specified in Equation (3), and it has a linear connection with the amount of solar energy E_{sun} that the photovoltaic cell is able to absorb. The photocurrent rises as the cell temperature T_c rises.

$$I_{ph} = \left(0.003 \text{ m}^2 \text{V}^{-1} + 10^{-7} \text{ m}^2 \text{V}^{-1} \text{K}^{-1} \cdot T_c \right) \cdot E_{sun} \quad \text{Equation 3}$$

By using the short-circuit current I_{sc} , the open-cell voltage U_{oc} , and the thermal voltage U_T , One may compute the reverse saturation current using Equation (4). The producer supplies the open-cell and short-circuit currents, but the physical characteristics determine the thermal voltage.

$$I_s = \frac{I_{sc}}{\exp\left(\frac{U_{oc}}{U_T}\right) - 1} \quad \text{Equation 4}$$

Equation (5) depends on the Boltzmann constant k_B ($1.3806 \cdot 10^{-23} \text{ JK}^{-1}$) and the electron charge e ($1.60219 \cdot 10^{-19} \text{ C}$) [76], gives an expression for the thermal voltage. The number of serially linked cells, n_s , and cell temperature are also necessary. Additionally, any departures from the theoretical behaviour are contained in the non-ideality factor m .

$$U_T = m \cdot \frac{n_s \cdot k_B \cdot T_c}{e} \quad \text{Equation 5}$$

In addition to the above equations, calculating the resultant current of a photovoltaic cell necessitates an understanding of the serial (R_s) and parallel (R_p) resistances of the system. When parallel photovoltaic cells are added, the current increases by the number of parallel pathways (n_p). Table 1 shows the appropriate characteristics of a current photovoltaic cell arrangement. The temperature of the solar cell is considered constant in this example computation. Alternatively, the absorbed solar

radiation raises the temperature of the cell. Although simple linear techniques produce consistent results with experimental data, a comprehensive energy balance is the most effective way to precisely predict the temperature [66].

Fig. 7 displays the final results of the hypothetical computation. Fig. 7a shows a typical polarization curve for an alkaline water electrolyser (10 cm^2 electrode area) together with the current-voltage properties for various solar radiation intensities from 200 to 1000 W m^{-2} . Fig. 7b displays the power-voltage curves of the solar cell. In both figures, a dot indicates the maximum power point (MPP) of every radiation level.

The properties of an alkaline water electrolyser differ from the MPP curve in Fig. 7a. The total efficiency of the solar cell falls as a result of its inability to produce the maximum amount of electricity. Therefore, both systems ought to be tuned to their maximum potential until the alkaline water electrolyser operates close to its potential. The other option would be to integrate a DC/DC converter with an efficiency of roughly 90%, which likewise involves losses and an indirect connection between both systems [79].

2.3.2. Wind turbines

Wind power is an additional significant energy source for the renewable generation of hydrogen because solar energy is only accessible during the day. Fig. 8 displays the notion in a diagrammatic form. An AC/DC converter is necessary to put traditional wind turbines into operation. Additionally, an AC or DC conversion efficiency is around 90% [64].

The precise wind speed at the height of the turbine rotor must be determined in order to calculate the power of the wind turbine. The height of a wind turbine, measuring around 100 m, is much higher than the wind velocity, which is frequently monitored at roofs or other

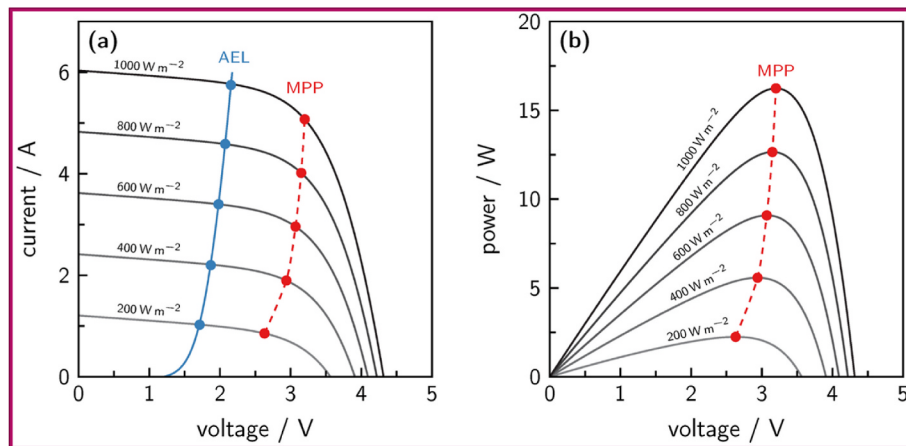


Fig. 7. Samples of the calculation findings for the (a) current-voltage properties of a photovoltaic panel at various solar radiation intensities and the related (b) power-voltage curve. The implementation of the current-voltage features of an alkaline water electrolyser is also included. The operational points that could be used are determined by the junctions. The MPP should be reached for an effective operation [77,78].

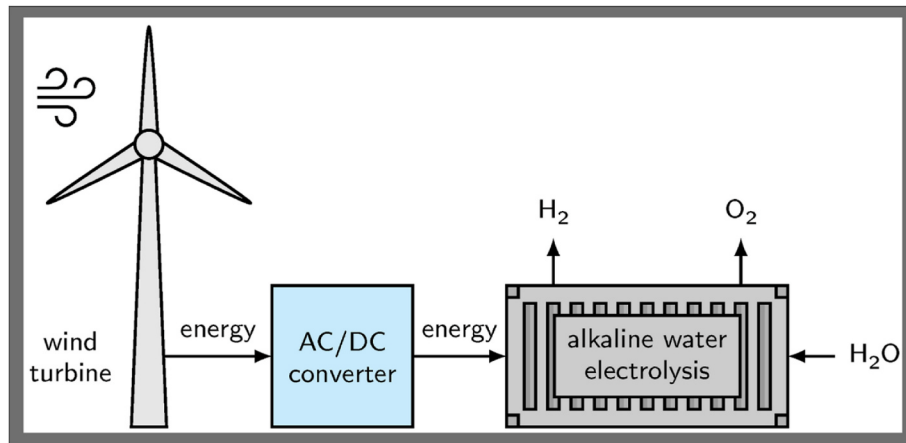


Fig. 8. Diagram for wind-powered electrolysis of alkaline water. Wind turbines transform the readily accessible wind energy into electricity that is useful for the process. It is essential to use an appropriate AC or DC converter [71].

dedicated measuring facilities with a specified height of about 10 m [80]. Consequently (Equation (6)), should be added to the measured data to adjust it to the required height.

$$v_{\text{wind}} = v_{\text{wind,ref}} \cdot \frac{\ln\left(\frac{z_{\text{wind}}}{z_0}\right)}{\ln\left(\frac{z_{\text{wind,ref}}}{z_0}\right)} \quad \text{Equation 6}$$

The observed wind velocity v_{wind} at the height z_{wind} , in conjunction with the degree of terrain roughness z_0 , may be used to calculate the wind velocity $v_{\text{wind,ref}}$ at the height $z_{\text{wind,ref}}$ [48]. The theoretical wind power P_{wind} must first be computed using (Equation (7)) in order to determine the output power of the wind turbine. Hence P_{turbine} . Hence, the air density (between 1.22 and 1.3 kgm^{-3}), the area covered by the rotor blades A , and the wind velocity is required [71].

$$P_{\text{wind}} = \frac{1}{2} \cdot \rho \cdot A \cdot v_{\text{wind}}^3 \quad \text{Equation 7}$$

Even with the best wind conditions, wind turbines cannot produce all of the available electricity. The performance coefficient (CP), which decreases the maximum achievable power output, takes this situation into account when it is implemented. By multiplying the wind power by the performance coefficient in (Equation (8)), the real wind turbine power is obtained.

$$P_{\text{turbine}} = P_{\text{wind}} \cdot C_p \quad \text{Equation 8}$$

Empirical correlations and simulation studies using computational fluid dynamics (CFD) are used to determine the proper performance coefficient, which is a whole study area in and of itself. The correlations between the measures are frequently fitted using experimental data [71]. The performance coefficient sample equation is displayed in (Equation (9)).

$$C_p = 0.22 \cdot \left(\frac{116}{\lambda_i} - 0.4 \cdot \beta - 5 \right) \cdot \exp\left(-\frac{12.5}{\lambda_i} \right) \quad \text{Equation 9}$$

As a result, the turbine blade β pitch angle must be established, and the ratio of tip speed λ must be computed in (Equation (10)) using the wind speed, turbine blade radius R , and rotational speed ω [71].

$$\lambda = \frac{R \cdot \omega}{v_{\text{wind}}} \quad \text{Equation 10}$$

The parameter λ_i , which is given by (Equation (11)) based on the ratio of the tip speed and the blade pitch angle, is also needed to calculate the performance coefficient.

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \cdot \beta} - \frac{0.035}{\beta^3 + 1} \quad \text{Equation 11}$$

The blade radius is estimated to be 46.5 m, which is the standard blade length for a wind turbine with a 2 MW rated output [71]. Fig. 9 illustrates the computation findings for the performance coefficient based on the turbine power and tip speed ratio at various wind speeds. Traditional wind turbines have a maximum performance coefficient of $C_p = 0.593$ [71]. For the sake of this illustration, a blade pitch angle of $\beta = 0^\circ$ results in a maximum performance coefficient of roughly $C_p = 0.450$. The highest value of the performance coefficient drops and swings towards smaller tip speed ratios as the pitch angle increases.

A pitch angle of 6° is taken as the starting point for calculating the turbine power in Fig. 9b. The maximum power point value rises with increasing wind speed and moves towards faster rotational speeds. The rated wind speed of this model wind turbine is 11 m/s, and its rotational speeds range from 6 to 17 min/s. The cut-in and cut-out wind speeds are three m/s and 22 m/s, respectively. The polarization curve of alkaline water electrolyser cannot be easily optimised towards the MPP trajectory, in contrast to the power properties of solar panels, as the best operation point greatly relies on the wind turbine configuration and the weather. In order to preserve the efficient functioning of an alkaline water electrolyser, an effective AC or DC converter is the ideal choice [64,71,72].

2.4. Challenges of green hydrogen production

The problems and difficulties with H_2 electrolyser are highlighted in this portion of the article. By overcoming these obstacles, hydrogen electrolyser usage will increase. Based on an analysis of different articles, the difficulties and potential developments of the H_2 electrolyser system, which took into account the unstable and varying electricity produced by renewable energy, modelling limitations, restrictions on the capacity, longevity, and characteristics of the electrolyser, significant upfront investments and operational costs, storage and safety challenges, and electrolyser effectiveness, are summarised as follows:

Although generating green hydrogen via RES (wind, solar) is fascinating, unstable electricity is a problem [81]. Bakhtiari and Naghizadeh [82] list low solar irradiance and wind speed as challenges for a single hybrid RES. The adaptability of electrolysis aids in the integration of renewables [83]. An excessive amount of H_2 is employed to stabilise upcoming energy systems if there is enough storage. Further analysis is also necessary for complex electrolysis plants with variable and erratic electricity output that are completely powered by on-grid or off-grid wind power or solar PV plants. Future research should pay more attention to modelling a dynamic electrolyser using plant tests.

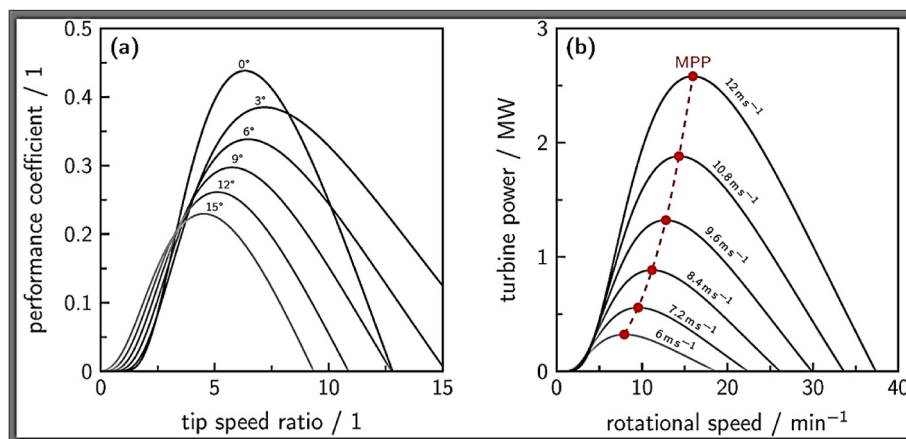


Fig. 9. Examples of the calculated outcomes include (a) the performance coefficient using Equation (9) for different rotor blade pitch angles and (b) the wind turbine power using Equation (8) for various wind velocities. The trajectory of the MPP is shown [71].

The modelling of multi-phase species transfers through current collectors and separator plates, the development of a physically-based system for determining humidification in regards to pressure, temperature, and density of current, and the creation of a model for forecasting exchange current for catalysts pose typical problems facing electrolyzers. It is essential to model every part and take into account all operating scenarios. The characterisation protocol for the subsystem must take into account these circumstances [84].

The traditional electrolyser implementation with Renewable energy highlighted the limitations of industrial electrolyzers, particularly their operational capacity and manufacturer-permitted stops. The procedure is designed to safeguard against harmful H₂ - O₂ mixtures. In the event that the module output falls below the lower working threshold, it may be feasible to employ an approach where the electrolyser can continue to function for a predetermined period of time. Utilising a battery bank is another option for storing surplus energy [85]. The storage system is intended to use the extra power produced when the nominal value of the electrolysis module exceeds the limit to increase the availability of an electrolyser when electricity production tends to fall below the limit.

The operating and investment costs associated with the installation of pressurised alkaline and PEMEC are high. A breakdown of total investment expenses, capital expenditures, and revenues is given in Ref. [86]. Based solely on their analysis of electrolyser-based H₂ production, 2050 will see an enormous rise in the number of hours of operation and a decrease in expenditures on investments in H₂ production. By generating H₂-based added-value compounds or liquid biofuels, the electrolyser may actually enhance its business approach. Future techno-economic analyses ought to look into how producing biomethane and luxury goods affects profit margins when energy prices are low.

The storage and safety concerns of H₂ electrolyzers need to be solved. Fuel cells need to meet requirements for cost, longevity, and durability in order to operate efficiently and safely. Both FC optimisation and industry reshaping are essential. FC innovation ought to be properly implemented by skilled experts or knowledgeable staff. Affordable FC vehicles are necessary for H₂ to function effectively as a transportation fuel. Additionally, Abe et al. [25] pointed out that the techno-economic viability of the currently available hydrogen storage methods is not met, necessitating extensive research into H₂ storage. It is important to investigate the safety and dependability of delivering H₂ to end users. Environmental restrictions and sustainability concerns should be taken into account when creating site plans [87].

Water electrolysis processes presently function at nearly maximum efficiency. In accordance with the study by Ref. [88], the PEMEC, SOE, and AEL stack voltage efficiency ranges from 60 to 80%. The efficiency of electrochemical reactions can be increased by optimising the thermal

management of SOFCs. It is possible to improve the stabilisation of nanofluids in a PEMEC electrolyser by adding surfactants to the operating fluids or functionalised nanoparticles. Between 67% and 74%, more efficiency is expected from a PEMEC system [87]. For RE to be fully integrated, Commercialised electrolyser technologies needed to be enhanced. Enhancing the resilience of the electrolysis stacks and lowering the working limit of the electrolyser will prolong and improve performance. Academic researchers and businesses must conduct more research and development to improve the viability and effectiveness of electrolyzers.

3. Technology for electrolysis systems

3.1. Balance of plant (BOP) and system design

Even though the stack is the primary component of an electrolysis structure, there are numerous other components that are needed in order for the electrochemical cells to operate correctly and for the system to acquire gases under the conditions necessary. The balance of plant (BOP) is made up of the aforementioned group of auxiliary systems [89].

According to general principles, the BOP of a low-temperature electrolysis structure (PEMEC or alkaline) is made up of a number of components, which include.

- Subsystem for gas manufacturing: This is the area where the actual electrolysis of water occurs. It consists of the stack, where hydrogen and oxygen bubbles are produced. The stack top section is drawn up with the liquid, where it travels to the separation component subsystem.
- Liquid-gas separation configuration: In the instance of PEMEC electrolysis, the produced gases exit the stack submerged in H₂O, while in the instance of alkaline electrolysis, the liquid is an aqueous electrolyte. These multiple-phase mixtures are transported to deposit separators, and there, they are split into two streams, one with gas (hydrogen or oxygen, based on the deposit) and the other with H₂O or an electrolyte. After that, the stack receives a second supply of this liquid. This recirculation can be carried out by employing recirculation pumps or natural convection.
- Deionized H₂O configuration: This is required to replenish the H₂O used in electrolysis. To prevent potential pollution of the catalyst and diaphragm or membrane, the supplied H₂O needs to be deionized with a specific quality and conductivity.
- Pressure control configuration: In an electrolyser, pressure is produced by maintaining the oxygen and hydrogen that are generated in the system so that they build up to the set point of the pressure-

regulating valves. Because of the structure of the cells of the alkaline electrolysis systems, which employ porous diaphragms as separators, this technique is particularly crucial because it results in the diffusion of gases via the diaphragm micropores irrespective of pressure differences of just five mbar among the anode and cathode compartments. The deposit separators are typically linked by interacting vessels in order to reduce the difference in pressure, which makes it possible to control the level as well as the pressure of the systems more precisely. Because of the inclusion of a polymeric membrane that is virtually gas-impermeable in PEMEC electrolyzers, the impact is reduced to a minimum, and distinct pressures can be employed in the anode and cathode compartments.

- The thermal control configuration: Because the method is irreversible, a significant portion of the electric energy provided to the stack is converted to heat. A system of refrigeration is needed to regulate the temperature. The electrolyte, or H_2O , that is circulated back to the cells is cooled to achieve this control.
- Drying configuration: The gaseous currents that exit the deposit separators travel via a conditioning system composed of coalescence filters, condensate traps, desiccant filters, and cooling systems. These enable the gaseous stream to drag as little liquid as attainable, acquiring hydrogen as dryly as feasible.
- Drying configuration: The gaseous currents that exit the deposit separators travel via a conditioning system composed of coalescence filters, condensate traps, desiccant filters, and cooling systems. These enable the gaseous stream to drag as little liquid as attainable, acquiring hydrogen as dryly as feasible.
- Purification configuration: When greater hydrogen purity is required, a de-oxo reactor must be installed to eliminate the dragged oxygen contaminants. These methods rely on a catalyst, typically made of palladium, where the remaining oxygen reacts with the hydrogen in an exothermic reaction to create H_2O vapour, which is subsequently condensed to eliminate it. Alkaline electrolysis, in which the purity produced is lower than in PEMEC electrolysis structures, necessitates the use of this system more than other electrolysis processes.
- Subsystem for analysing the gases generated: To gauge the pureness of the gases generated, a small sample of hydrogen and oxygen is transmitted to analysers.
- Power supply configuration: Because the electric power delivered to the stack must be continuous, power electronics designed for integration with the available power supplies must be incorporated into the system.
- Control and monitoring configuration: This collects all information from sensors and takes actions that are required to ensure a suitable and secure operation of the system.

It is also necessary to take into account subsystems like the following when dealing with high-temperature electrolyzers (SOE).

- Heating stack subsystem: Solid oxide cells must operate at high temperatures, so the stack must be built into a furnace that can increase and maintain the temperature of the fluids entering the stack and also the electrolytic cell elements themselves.
- Subsystem for production of steam: Compared to low-temperature electrolyzers, this electrolysis method requires water to be provided as steam at the required operating temperatures.
- Air supply subsystem: The anode typically receives a flow of pre-heated air. This air stream regulates the temperature and ensures proper temperature circulation within the stack, preventing degradation rise.
- Subsystem for steam and hydrogen supply: hydrogen is combined with the initially produced steam before being added to the cathode compartment. For the Ni electrode to remain depleted and avoid oxidation, this mixture must have a minimum hydrogen content of 5%.

- Subsystem for nitrogen supply: This is a crucial component for the system to start up because it allows the electrolytic cells to be heated and prepared to operate at the proper temperature.

The electrolysis structure, the method under consideration, the capacity of hydrogen generation, and the key operational factors will determine every final configuration of these subsystems. Additionally, since various electrolysis methods are modular, the capacity of electrolysis structures can range from a few watts to an MW when connecting multiple systems and stacks. This makes it a very adaptable technology in terms of its intended use.

4. Integration of renewable energy and electrolysis

High-purity hydrogen may be produced using the process of H_2O electrolysis, and the monetary value of the power needed to produce it largely determines how much it costs to produce. As a result, a successful energy shift may require an effective hydrogen production process from renewable energy sources. By controlling and storing the surplus energy produced by renewable sources, hydrogen as an energy carrier enables the integration of these sources; on the other hand, it also enables the distribution of this energy to various societal sectors, including transportation, construction, and industry, enabling a gradual carbon reduction of these sectors [26,36,90,91].

- Re-electrification: The hydrogen created may be utilised once again to generate electricity on an industrial level using fuel cells, turbines, or internal combustion engines, returning this electricity to the grid with the aim of balancing demand and production (power-to-power operations).
- Transport: Hydrogen may be utilised as an alternate fuel in fuel cell electric vehicles (FCVEs), providing a low-carbon transportation alternative with performance on par with that of standard automobiles. Hydrogen is perhaps the most viable alternative on the market for heavy-duty vehicles, which include buses, trains, and ships.
- Residential: Existing systems could continue to function as normal without any changes to natural gas (NG) systems, but emissions could be reduced by pumping pure hydrogen or artificially produced NG that had previously been made by mechanising hydrogen (power-to-gas (P2G) operations) into the natural gas grid. In this manner, the NG system would gradually become decarbonised. This makes it possible to incorporate fuel cell-based cogeneration facilities as well.
- Industrial: Hydrogen is presently utilised extensively as a raw material across many various industrial areas; as a result, using hydrogen in a low-carbon method results in a decarbonised process.

Numerous demonstration projects have been executed thus far that combine the electrolytic generation of hydrogen with renewable power sources, particularly wind and solar energy. Since alkaline electrolysis is now the most advanced commercially developed method (there are systems with a capacity of up to 6 Megawatts accessible), it has provided the foundation for the majority of these initiatives. Throughout the twentieth century, substantial facilities based on alkaline electrolysis (>100 MW) have been created, notably hydroelectric facilities in distant locations with significant electric surpluses. A few of these include Aswan (Egypt, 1960), which used 288 electrolyzers to produce 40,000 Nm^3 per hour; Glomfjord (Norway, 1949), which produced 27,100 Nm^3 per hour; and Kwekwe (Zimbabwe), which produced 27,100 Nm^3 per hour [42].

Alternately, in recent years, the introduction of power-to-gas methods to make synthesised methane from carbon dioxide and hydrogen generated by electrolysis has led to a significant advancement in the scale of electrolysis methods, notably in PEMEC [92]. While these electrolyzers were previously used mostly for manufacturing hydrogen on a modest scale, the method has just begun to be commercialised in

systems larger than 1 Megawatt [41,55]. The systems that are now accessible in the case of SOE are still on the order of a couple of kilowatts, with a majority of them currently in the study stage.

However, industrial electrolyzers are built to continuously create hydrogen under normal working circumstances. Nevertheless, because of their heavy reliance on climate variables, renewable energy sources have several challenges related to their fluctuation and intermittent nature. In electrolysis structures, these variations may result in various issues, including corrosion, the production of explosive mixtures, pressure dips, or fluctuations in internal temperature.

Numerous studies have been conducted to enhance the performance and robustness of integrating renewable energy and electrolyzers to analyse these impacts. Some of these ideas involve refining the designs and components of an electrolyser. Other options suggest enhancing the BOP regulation to deal with the rapid variations that may occur when electricity is generated from a renewable source. Another great tactic that, when combined with the right power electronics, enables the most steady and gradual supply to the electrolyser is the utilisation of batteries alongside other accumulation components.

4.1. Grid integration and energy storage

Green hydrogen production offers sustainable ways of addressing and dealing with climate change caused by CO₂ emissions from power generation, transportation, heating, and industrial activities. Grid-integrated electrolysis refers to the integration of hydrogen technologies into the power grid, to facilitate the development of energy systems that are both efficient and stable. Electrolyzers and fuel cells are the primary grid integration technology for hydrogen applications. Electrolyzers generate hydrogen through the electrolysis process, functioning as a load within the power grid. The hydrogen produced by electrolyzers is subsequently employed in fuel cells to facilitate the generation of electricity [93–96]. Integrating water electrolysis with renewable energy sources offers notable benefits since surplus electrical energy may be effectively stored in hydrogen by chemical means. This allows for mitigating disparities between energy demand and production [97]. Furthermore, electrolyzers can enhance grid stability by participating in demand response programs and adjusting hydrogen production in response to grid demand signals. This capability makes electrolyzers act as flexible loads that help balance load variations and stabilise the grid. This is especially valuable in systems with high penetration of intermittent renewable energies, such as wind and solar, where electricity production can be highly variable. Participating in electricity reserve markets allows electrolyzers to reduce the levelized cost of green hydrogen further. Electrolyzers can decrease operational costs significantly by operating during periods of low electricity prices or excess renewable output. Additionally, by contributing to peak shaving and emergency reserve services, electrolyzers can generate additional revenue, further improving the economic outlook of hydrogen production facilities. Grid integration and energy storage are achieved in major facilities by producing hydrogen by electrolysis using renewable power and storing it in storage tanks, particularly when the renewable energies are excess until needed. We can say that grid integration and green hydrogen storage occur sequentially to generate megawatt-scale power for buildings, facilities, or community grids.

Several approaches/techniques for integrating hydrogen energy systems into the power grid have been demonstrated in the literature, and some challenges have been highlighted [98]. proposed a self-sustaining hybrid energy storage system that utilised renewable energy sources (RES) and hydrogen to ensure a consistent and reliable supply of high-quality power in remote islands. In a typical study, different assessments were conducted to examine the self-sustainability of the power system. Specifically, they focus on determining the necessary capacities of the system components to meet energy demands while also minimising costs. The proposed energy system was found suitable for uninterrupted power supply in the targeted location, in

addition to a 20% reduction in total cost. Furthermore, Li et al. [99] We present a grouped hybrid storage system to simulate the operational characteristics of fuel cells, electrolyzers, hydrogen tanks, and batteries. We place more emphasis on system control than on achieving optimal sizing. The selection of the power management system (PMS) is contingent upon both the specific configuration of the system and the intended purpose of the application. Fig. 10 illustrates the stabilisation of the power grid with the introduction of electrolyser. Photovoltaic panels and wind turbines are interconnected to a direct current (DC) bus through appropriate converters, enabling the provision of electricity to alkaline water electrolyzers [100]. The generated hydrogen can be stored for subsequent utilisation in fuel cells. It is possible to utilise the generated oxygen instead of atmospheric air to enhance fuel cell efficiency. Consequently, the provision of an extra storage tank necessitates additional expenditures. The fuel cells are additionally linked to the direct current (DC) bus, enabling the power to be harnessed by the energy system through direct current to alternating current (DC/AC) converters [85,101–103]. Hydrogen can be generated and utilised as an energy source during periods of reduced energy requirements. When an abundance of energy is present, energy storage systems can be charged to their maximum capacity, ensuring that the stored energy is readily accessible when required. Difficulties in maintaining constant power frequency commonly encountered in power grids with a larger share of renewable energies can be addressed by hydrogen energy devices such as alkaline water electrolyzers.

The CO₂ emissions that come with hydrogen production can be greatly reduced when synthesised by renewable energy and integrated with the electricity grid to support electricity generation. In addition, the capacity to produce hydrogen in a versatile manner through the process of water electrolysis can contribute to the efficient functioning of the electrical grid by aiding in the preservation of grid stability and the mitigation of operational expenses. Zhang et al. [104] simulated electrolysis-based hydrogen production integrated with the United States Western Interconnection (WI) power systems. In a typical analysis, 5.3 million fuel cell electric vehicles (FCEVs) were exclusively allocated to California, with no FCEVs being considered outside the boundaries of this particular state. Additionally, hydrogen refuelling on grid operation cost was captured by suitable electrolysis sizing and flexibility assumptions using a comprehensive power system model constructed in PLEXOS. Their result demonstrates that enhancing the flexibility of hydrogen production leads to a reduction in both the costs associated with hydrogen and electricity generation and emissions of CO₂. However, it is important to note that a trade-off exists between decreasing operational costs and increasing the capital costs of the electrolyser. As a result, the total system cost reaches its minimum at a specific size, corresponding to an annual capacity factor ranging from 80% to 90%, assuming a future electrolyser cost of \$300/kW. An ensemble learning framework was recently used to facilitate co-design optimisation in integrated renewable energy-powered hydrogen productions consisting of PV arrays, wind farms, water electrolyzers and pumped hydro storages (Fig. 11) [105]. The integration of renewable energy sources and local loads is achieved by establishing a link between them, which a power management unit facilitates. This unit plays a crucial role in coordinating the operation of these renewables, ensuring that the voltage levels at the connection points of the power grid remain within acceptable limits. To provide consistent and dependable functioning of the distributed hydrogen production systems, essential power converters have been specifically engineered to facilitate energy transfer from the power grid. Power converters can also be utilised in wind farms and photovoltaic arrays to effectively transmit renewable energies to the power grid.

A recent study by Zghaibeh et al. [107] focuses on optimising green hydrogen production in a hybrid (photovoltaic and hydroelectric) power station in southern Oman connected to the power grid. In a typical analysis, solar radiation and average flow stream were the fundamental parameters used to examine the hydrogen produced and energy utilised

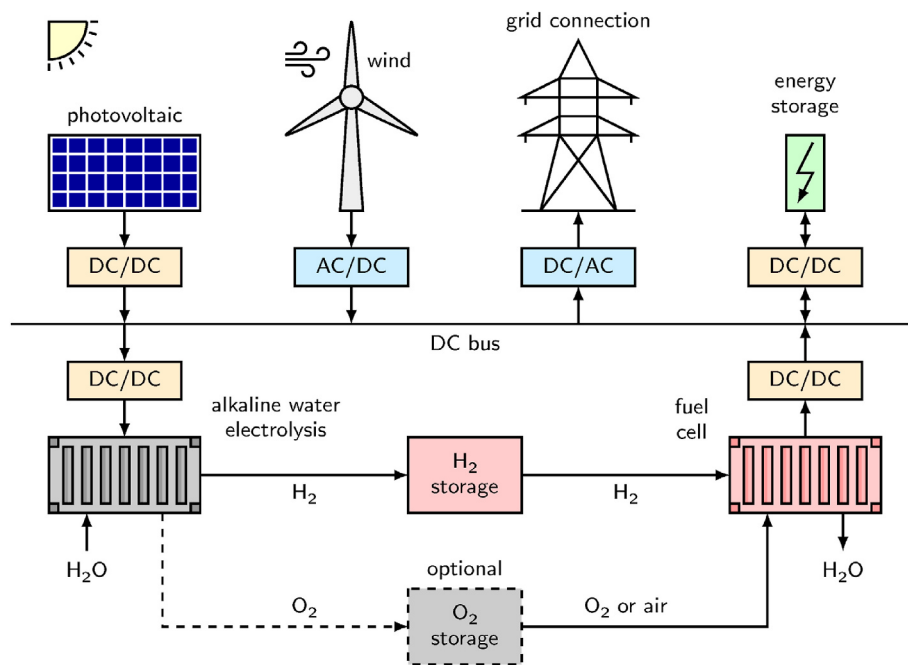


Fig. 10. Schematic diagram of grid-connected hydrogen energy system [64].

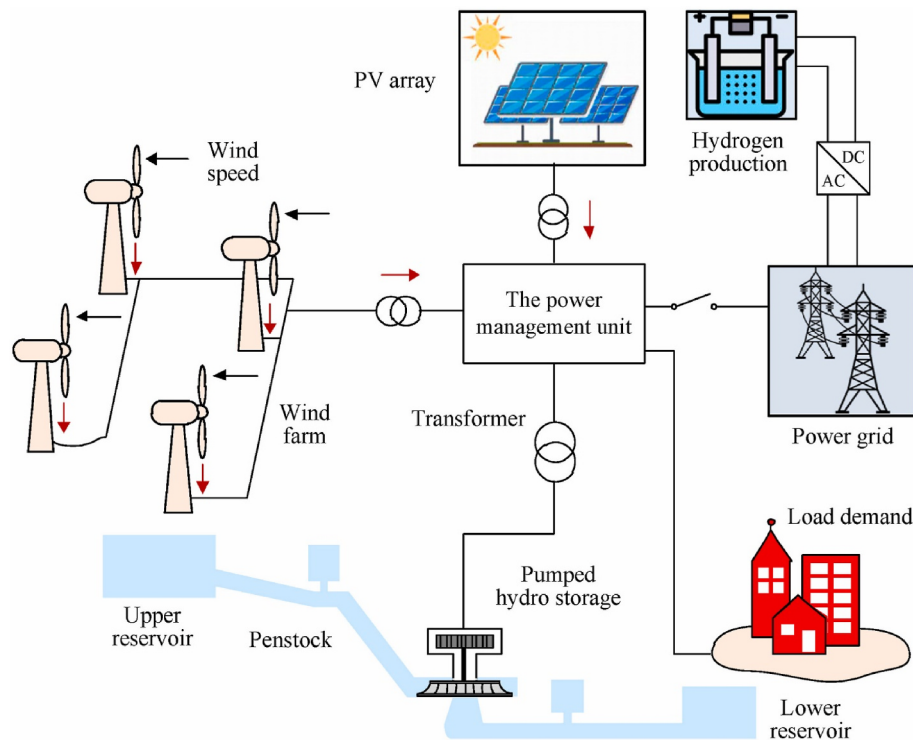


Fig. 11. The grid-connected green hydrogen production system [106]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

for conversion to green hydrogen from the grid. Upon conducting a comprehensive analysis, they concluded that the net profit is important in optimising the levelized cost of green hydrogen, which amounts to €2.25 per kilogram. This analysis offers researchers the option to do a techno-economic analysis of hydrogen generation and explore its utilisation in promoting green transportation, ultimately reducing greenhouse gas emissions.

The economic feasibility of grid-connected electrolysis is an

important assessment that can convince investors to consider the technology for development [108]. presented a comprehensive economic analysis of connected electrolysis using Danish electricity market cost to compare the suitability of the system. Economic assessments, including scale-up impacts, reveal significant distinctions between proton exchange membrane (PEMEC) and alkaline electrolyzers, regarded as established technologies, and solid oxide electrolyzers, considered emerging technologies. The cost reduction capabilities upon scaling up

are 33%, 34%, and 50% for alkaline, PEMEC, and solid oxide electrolyzers, respectively. However, subsidisation can further strengthen these capabilities to 56%, 59%, and 70%. The findings suggest that solid oxide electrolyzers possess comparable economic viability to alkaline and PEMEC electrolyzers. Nevertheless, grey hydrogen appears to maintain its competitive advantage until there are provisions for subsidised power and/or modifications to carbon taxes. Also, Şevik [109] conducted a techno-economical assessment of an integrated hybrid renewable hydrogen production system located on a university campus with more emphasis on hydrogen and electricity production costs in various cases. The energy payback period for the photovoltaic (PV) plant, throughout its projected lifespan of 20–25 years, has been determined to range from 6.47 to 6.94 years. LCOE values for the Scenario having PV canopy, low scenario, and high scenario were 0.063 \$/kWh, 0.061 \$/kWh, and 0.06 \$/kWh, respectively. Also, the range of the levelized cost of hydrogen (LCOH) for hydrogen generation was shown to be between 0.054 \$/kWhH₂ (1.78 \$/kgH₂) and 0.103 \$/kWhH₂ (3.4 \$/kgH₂).

Demand response modifies electricity usage patterns according to grid conditions, pricing signals, or system reliability requirements. Deploying electrolyzers in demand response applications can enhance grid flexibility, support renewable energy integration, reduce peak demand, and contribute to a more efficient and resilient electricity system. Electrolyzers are adaptable instruments that can react rapidly to changes in grid demand because they can provide auxiliary services to the grid, such as voltage regulation, frequency control, congestion management, and black start [110]. An electrolyser as a variable load can effectively control grid frequency and enhance the integration of renewable energy sources into the grid. This serves as an “ancillary service” that can be monetised [111]. Because they may dispatchably ramp up and down in response to high- and low-cost periods, electrolyzers make it possible to produce hydrogen cheaply by working effectively when energy prices are high.

An electrolyser-based hydrogen production and storage system can be economically valuable when used as a demand response tool for grid management. This can help offset the cost of hydrogen generation, making it a viable option for high-value applications like transportation fuel. Incorporating electrolyzers into upcoming power systems is expected to gain advantages from their capacity to adjust operating levels and function rapidly in a standby mode. This capability reduces the levelized cost of hydrogen (LCOH) and minimises frequent starting and stopping expenses. By deploying electrolyzers in electricity markets, one might potentially reduce curtailments in renewable energy by achieving lower average wholesale power prices and more equally distributed electrolyser use throughout markets [112].

Water electrolyzers are crucial for decarbonisation efforts as they enable the production of green hydrogen, which is essential for reaching net-zero emissions in the energy sector [113]. Integrating significant electrolyser capacity to decarbonise energy-intensive sectors can influence the electricity transmission grid. This can increase stress on power grids, surpassing standard electricity demand levels and leading to additional grid congestion. Integrating the flexible demand of electrolyzers into the European power system can effectively incorporate variable renewable energies, reduce the waste of renewable energy, and facilitate the generation of cost-effective low-carbon hydrogen.

To summarise, incorporating electrolyzers into demand response systems poses technological hurdles regarding technology advancement and grid control. Still, it brings economic advantages such as reducing hydrogen production expenses and decreasing energy prices. Moreover, electrolyzers have the potential to be crucial in decarbonisation initiatives and aid in reducing the environmental consequences of unpredictable renewable sources.

4.2. Electricity reserve market

The worldwide shift towards a low-carbon economy has generated enthusiasm for green hydrogen as an environmentally friendly and

adaptable energy carrier. Green hydrogen, generated via electrolysis with renewable energy sources, provides a sustainable substitute for fossil fuels in multiple areas such as transportation, industry, and power generation. Nevertheless, the expense associated with manufacturing green hydrogen, commonly quantified as the levelized cost of hydrogen (LCOH), continues to be a substantial obstacle. The involvement of electrolyser operators in electricity reserve markets contributes to the levelized cost of hydrogen (LCOH) in green hydrogen production. Electricity reserve markets are essential for maintaining the stability and dependability of the grid because they offer extra capacity to handle unforeseen changes in supply or demand. In these markets, players often offer their generating or demand response resources as contracts or auctions for reserve capacity, which they promise to be available when needed. Investigating the impact of involvement in electricity reserve markets on the life cycle analysis of hydrogen produced in the context of green hydrogen production is worthwhile. The volatility of the electrical grid rises with the proportion of VRE in the system. As a result, additional reserve is required to guarantee its dependability. Increasing the flexibility of the electrical grid through demand response is one strategy to improve grid dependability. The dynamic operating of PEM electrolyzers can supply a portion of the flexibility required to guarantee the dependability of the grid.

The impact of Germany's reserve market earnings in 2030 on the levelized cost of green hydrogen was modelled by Ref. [114]. It was discovered that the advantages of increased reserve market revenues and enhanced efficiency exceed the rise in capital costs. According to Bertuccioli et al., green hydrogen can be produced for about 45% less expensive when the electrolyser runs at 50% of its capacity and provides the grid with both positive and negative power balancing. On the other hand, it was believed that the deterioration rate would be the same under both dynamic and constant operation. The dynamic operation will increase degradation, which will shorten the lifetime of the PEM electrolyser and decrease its hydrogen output. This factor will raise the levelized cost of green hydrogen and impact the two studies' economic analyses. By harnessing inexpensive renewable electricity and generating revenue from the electricity reserve market, dynamic operations can effectively decrease the levelized cost of green hydrogen. When optimising off-grid VRE systems and ensuring a renewable source of electricity in on-grid systems, it is important to consider the extra expense of an on-site energy storage system. This system enhances the capacity factor of the electrolyser. Furthermore, the deterioration, efficiency, capacity factor, and operational safety limits of the electrolyser are influenced by the actions done by the operator and modifications made to the operating settings [115,116].

4.3. Power-to-gas (P2G) systems

Power-to-gas (P2G) systems are innovative energy conversion technologies crucial in facilitating the seamless integration of renewable energy sources, such as wind and solar, into the wider energy framework. Excess electricity generated from renewable energy sources is used to produce gases such as hydrogen (H₂) or methane (CH₄), which can be stored, transported, and utilised for a range of applications [117–120]. The hydrogen produced from this novel process could be integrated into the grid and displaced conventional fossil fuel, reducing greenhouse gas (GhG) emissions. P2G has been identified as an effective way of transitioning to greener natural gas. Although power-to-gas (P2G) technology is still in its early stages of development, it stands out as one of the limited feasible choices for implementing energy storage systems on a global scale. The conversion of surplus renewable energy into methane enables the storage of substantial energy quantities over extended periods within pre-existing gas infrastructures. There has been a lack of consensus between industry and scholars over the vocabulary for renewable Power-to-Gas (P2G) products. Various terminology has been employed, including synthetic gases, wind gas, solar gas, and power-based gases. The initial stage of the procedure involves

the generation of synthetic hydrogen (H_2) through the process of electrolysis, utilising water and renewable power sources. The hydrogen can be employed in two ways: firstly, by immediately incorporating it into the current gas mixture, and secondly, by subjecting it to a subsequent process wherein it combines with carbon dioxide to generate methane (CH_4) [121].

The first concept of Power-to-Gas (PtG) was linked to water dissociation through electrolyzers, which enables the direct production of hydrogen from an electrical input. Therefore, the early mentions of the Power to Gas concept were exclusively focused on the generation of hydrogen (referred to as Power to Hydrogen) from renewable energy sources [26]. With significant efforts towards achieving the UN sustainable development goals, many P2G projects/facilities are now being proposed and investigated [122–124]. Experts from the Rhein Mains University of Applied Science in Germany presented a technical and economic analysis of the full-scale P2G facility “Energiepark Mainz” [125]. The plant is linked to an 8 MW wind farm and utilises surplus wind energy to generate hydrogen gas. The process is achieved by employing three proton exchange membrane (PEMEC) electrolyzers, each capable of generating a maximum power of 6 MW and producing a hydrogen output of $1000 \text{ Nm}^3/\text{h}$ [126]. Subsequently, the hydrogen undergoes compression to achieve a pressure of 80 bar, after which it is kept within tanks possessing a volumetric capacity of around $10,000 \text{ Nm}^3$. The hydrogen derived from these tanks is either introduced into the natural gas grid or subjected to a subsequent compression step, resulting in a pressure of 225 bar. The hydrogen, which is subjected to compression at a pressure of 225 bar, is subsequently loaded onto trailers for transportation to either hydrogen fuelling stations [126]. Energiepark Mainz does not employ hydrogen as a technique to generate power using a fuel cell. Hydrogen finds utility in the three applications above, namely as an additive within the natural gas grid, as a reactant in chemical companies, or as a commodity supplied to hydrogen fuelling stations [126].

The facility aims to produce an estimated yearly production of 200 tonnes of hydrogen. The investigation demonstrates a marginal decline in efficiency as the load increases. According to the cited source, the efficiency of electrolyzers is around 64% when operated at a rated power of 4 MW and approximately 59% when operated at a peak capacity of 6 MW [126]. This phenomenon is depicted in Fig. 12, which presents the electrolyser efficiency and hydrogen production rate. The data demonstrates a rapid increase in efficiency up to its maximum value at approximately 1 MW (equivalent to 1/6 of peak power), followed by a gradual decline in efficiency as power increases. The rate of hydrogen production exhibits a natural positive correlation with increasing power. It is important to consider that electrolyzers have a limited capacity to operate at peak power, with a maximum duration of 15 min. However, they can sustain continuous operation at their rated power or power

levels below the rated capacity [126]. The findings from September 2015 indicated an average efficiency of almost 60%, whereas the results from October 2015 revealed an average efficiency of around 54%. The efficiencies discussed refer to the collective efficiencies of the entire Power-to-Gas (PtG) complex, encompassing all associated equipment such as compressors, transformers, pumps, and other relevant components [126]. According to economic analysis, it was more financially advantageous for the PtG facility to get electricity through the market for control reserve instead of utilising surplus wind energy or procuring from the European Power Exchange (EPEX). The study suggests that the profitability of a PtG facility can be achieved by selecting the most advantageous power procurement and operation approach. According to the authors, there is a need for enhancements to decrease capital and fixed costs, as well as to enhance efficiencies [126]. Additionally, it has been suggested that the introduction of cost premiums for hydrogen generated by low-emission methods could enhance the competitiveness of such facilities [126].

As of early 2019, there were a total of 95 Power-to-Gas installations in operation, collectively generating a combined load of 38.6 MW_{el} , and it is anticipated that there will be a significant exponential growth in the global installed PtG-capacity by 2050 [128]. The great perspective offered by this technology accounts for the annual increase in P2G projects and the proposed launch of new ones. Techno-economic feasibility studies have been conducted on this wonderful technology. For instance, Schiebahn et al. [129] presented a robust economic and technological analysis of Germany’s P2G process chain (Fig. 13) by potential end-users. In a typical analysis, the three alternative routes involve hydrogen production from renewable energy sources and CO_2 methanation into the natural gas grid, as well as economic evaluation, assuming that the interest rate assigned to the capital charge was established at 8%. The authors of the study assumed that the annual operation and maintenance expenditures would amount to 3% of the total investment. Fig. 14 Depicts the outcomes of the economic computations conducted for the three scenarios. It provides a comprehensive breakdown of the overall expenses, encompassing power, operation and maintenance, capital, and capital charge expenses. All expenses are exclusive of taxes.

In scenario 1, the computed costs for hydrogen integration into the natural gas grid amounted to € 0.15 per kilowatt-hour thermal. Approximately two-thirds of the total electricity expenses are attributed to this factor, indicating the significant influence of electric energy prices. Compared to the current natural gas feedstock costs of € 0.04/kWh_{th}, the figure above signifies a fourfold increase in expenses. The omission of the supplementary expenses associated with modifying the natural gas grid to accommodate the elevated hydrogen concentration was overlooked in this context [129]. The expenses associated with the production of synthesised methane in scenario two have risen to € 0.23/kWh_{th}. This increase can be attributed to decreased efficiency and the need for further investment, resulting in the lower attractiveness of RPM and RPH as potential alternatives to natural gas in industrial applications. Fuel cell vehicles exhibit nearly double the efficiency of combustion-engine vehicles that rely on petrol. Hence, the acceptable price for hydrogen stands at € 0.16 per kilowatt-hour of thermal energy. If the energy efficiency was to be enhanced from 1 kgH_2 per 100 km to 0.7 kgH_2 per 100 km, the permissible price would experience a subsequent increase to € 0.23/kWh_{th}. The findings of the computation indicate that at power rates of € 0.06/kWh_{el} and € 0.09/kWh_{el}, the expenses incurred for hydrogen at the refuelling station equate to € 0.20/kWh_{th} and € 0.24/kWh_{th}, correspondingly [129]. Therefore, considering the current efficiency rate of 1 kgH_2 per 100 km, the cost of hydrogen is approximately 23% higher than the corresponding range-based quantity of petrol. This cost differential makes hydrogen a more economically viable option than its alternate application as a substitute for natural gas. The payback period of Power-to-Gas (PtG) systems directly correlates with the energy-generating methodology. Several studies have found project payback periods lasting 20 years or more [130]. Other

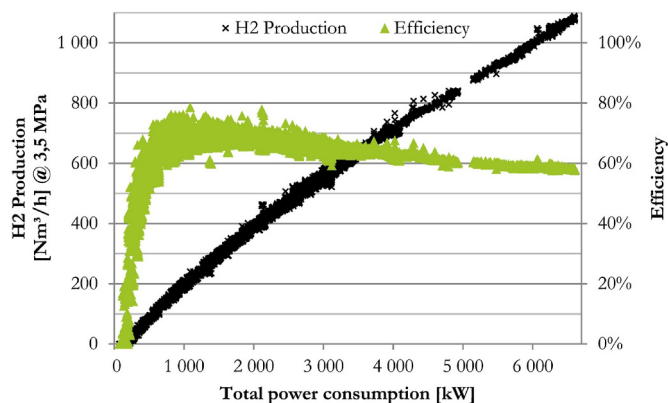


Fig. 12. Hydrogen production rate and efficiency of Energiepark Mainz about overall power consumption [126].

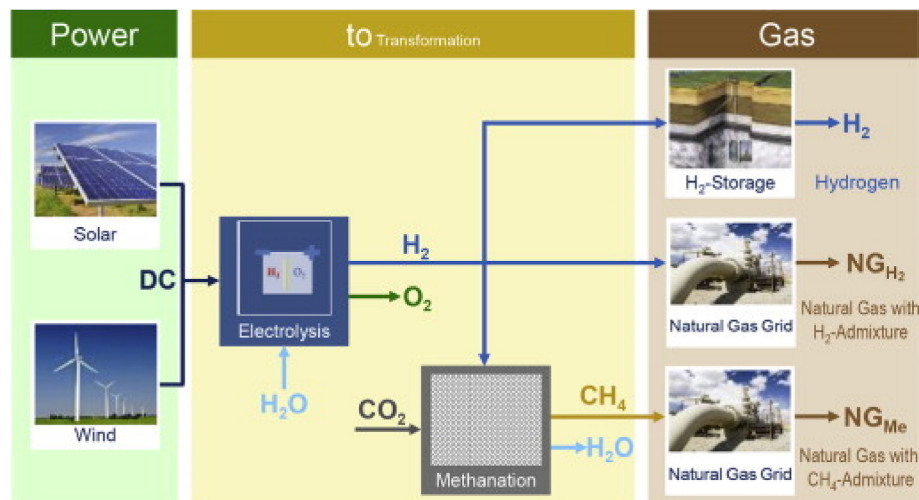


Fig. 13. Power-to-gas routes.

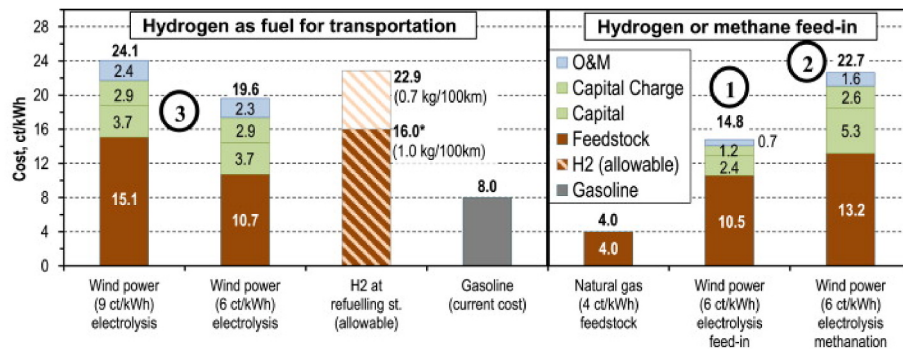


Fig. 14. Power-to-gas systems chain alternatives cost comparison [127].

relevant projects proposed by various researchers show the potential of the P2G system for sustainable energy generation [131–137].

P2G is poised to experience substantial expansion in the foreseeable future due to the increasing demand for environmentally friendly hydrogen, the decreasing capital costs of electrolyzers, and the availability of affordable renewable energy sources that power the grid. Renewable energy sources (RES) are commonly preferred to mitigate greenhouse gas emissions in the power generation sectors. However, these sources exhibit limitations due to their intermittent and unpredictable characteristics. The P2G system effectively manages the inherent uncertainty in renewable energy sources (RES) by employing a mechanism that involves storing surplus power generated when the energy demand is lower than the available supply. The need to accommodate the intermittent nature of renewable generation on a daily, weekly, and seasonal basis necessitates enhancing balancing capacities, resulting in an augmentation of storage capacity. Converting power into gases presents numerous storage possibilities and facilitates the interconnection of diverse energy markets. Renewable energy systems encounter the issue of energy storage and CO₂ utilisation that incorporate large-scale energy storage and power-to-gas (P2G) technologies. P2G presents a viable method for achieving electric grid balance and offers the potential for reducing the inherent uncertainty associated with dispatch techniques.

4.4. Hybrid renewable energy systems for green hydrogen

A stable and uninterrupted power supply is very important to boost green hydrogen production. Hybrid renewable energy systems (HRES) are a promising approach to ensure a more stable and reliable energy

supply by optimally using all individual components of the systems, such as wind turbines and photovoltaic panels, electrolyzers, fuel cells, and hydrogen storage [138,139]. HRES can provide a reliable source of green hydrogen to achieve a sustainable and decarbonised energy system. Several studies have been conducted on numerous configurations of HRES and their distinctive features, as well as limitations currently experienced on such systems, which are reported [59,140–150]. Ourya et al. [151] presented an economic and technological evaluation of HRES incorporating photovoltaic panels and wind turbines using modelling and simulation techniques. In a typical analysis, five Moroccan cities were analysed with detailed examinations of several important parameters, such as the levelized cost of hydrogen, water desalination cost, net present cost, storage capacity, and PV/wind ratio. The findings indicate that the integration of photovoltaic panels with wind turbines in Morocco contributes to the cost-effective production of hydrogen, particularly in the region of Dakhla, where the cost is estimated at 2.54 \$/kg. The cost in Morocco is somewhat lower than in prior studies. The findings also demonstrate the significance of employing hydrogen tanks as a means of energy storage. A similar study utilised a Monte Carlo-based model to examine the economic aspect of green hydrogen at various stages of its technological and commercial development [152]. It was revealed that central and southern Poland regions exhibit the most favourable cost-effectiveness indicators, namely in terms of levelized cost of hydrogen (LCOH) when employing solar-powered electrolyzers. Nevertheless, the locations in the northern part of the country exhibit the lowest values of levelized Cost of Hydrogen (LCOH) for wind-based production. The LCOH, using current PEMEC technology, exhibits a range of 6.37–13.48 dollars per kilogramme.

The study conducted by Gu et al. [153] examined the methanol

production process in Ordos, China, focusing on utilising green hydrogen. The hybridisation of solar and wind energy has been identified as the most economically efficient method for hydrogen production. The findings additionally demonstrate that the expenses associated with wind turbines significantly influence the economic aspects of the system. Green hydrogen production plants that utilise solar PV and wind were analysed at various sites in Egypt [154]. The cost of production varies between \$4.54 per kilogramme and \$7.48 per kilogramme, while the efficiency falls within the range of 7.69%–9.37%. Fig. 15 shows the schematic representations of the analysed systems, which consist of four main modules: the power generation module, power conditioner unit, water electrolyser, and hydrogen storage and compression unit. Al-Ghussain et al. [155] proposed a 100% renewable energy system made from a hybrid PV/wind system and explored its hydrogen fuel production and district heating capabilities in Estonia. In a typical analysis, polymer electrolyte membrane (PEMEC) electrolysis, PV and wind systems, and a generic optimiser were employed to achieve demand and supply stability without affecting the cost. The findings illustrate the viability of all solutions in meeting both demands and generating a profit, as opposed to directly selling surplus electricity. Nevertheless, the photovoltaic (PV) system exhibited a significant demand for system capacity and surplus energy due to the constraints imposed by Estonia's low sun resources. The wind system exhibited similarities to the hybrid system, albeit with a notable difference in storage capacity, which was 75.77% higher. The hybrid photovoltaic (PV)/wind-driven system necessitated a combined capacity of 194 GW (GW), with most of this capacity allocated to the wind system. Furthermore, the production of green hydrogen demonstrated superiority in both quantities, with a total of 15.05×10^9 tonnes and cost priced at 1.42 USD/kg.

The performance of grid-connected and off-grid HRES systems consisting of wind and solar energy was evaluated using MATLAB/Simulink software [157]. Based on the findings, an annual energy production of 20,186 kW-hours (kWh) is seen in the on-grid system. At the same time, a storage capacity of 3273 standard cubic metres (sm^3) of hydrogen gas (H_2) is recorded. The off-grid system is investigated for Scenario-1 and Scenario-2, employing two distinct wind turbine (WT) rated power values. The annual energy production in Scenario-1 and Scenario-2 amounts to 95,145 kWh and 83,511 kWh, respectively. The quantities of 17,942 sm^3 and 14,370 sm^3 of H_2 are stored yearly. Upon analysing the on-grid and off-grid systems, the LCOE was determined to be 0.223 \$/kWh for the on-grid system.

For the off-grid systems, Design-1 and Design-2 exhibited LCOE values of 0.416 \$/kWh and 0.410 \$/kWh, respectively. Optimisation of hydrogen production and electricity generation in HRES was conducted by Akarsu and Genc using HOMER Pro [158]. The HRES system under consideration exhibits superior economic efficiency, with an energy cost of 0.376 \$/kWh. In addition, it should be noted that the utilisation of a 68% renewable ratio results in the minimal emission of CO_2 when fulfilling the energy demands of residential areas. An algorithm for simultaneously determining the optimum size of a microgrid system while considering many economic and technical constraints. The results indicated that the algorithm effectively fulfilled the required demand

and adhered to the optimisation conditions. Also, integrating fuel cells into the microgrid, alongside the electrolyser and steam methane reformer, substantially reduces CO_2 emissions. The concentration of CH_4 exhibits a decrease of 10.6% during the summer and 11.5% during the autumn season. Implementing an electrolyser system results in a 15.15% reduction in the overall quantity of CH_4 .

Power-to-gas systems, grid integration of green hydrogen and hybrid renewable energy systems (HRES) are interconnected in the context of integrated renewable energy sources in tandem with electrolysis and have been demonstrated in the literature as the way to go for sustainable hydrogen production, load balancing, grid stability, and GHG emissions reduction. The electrolysis technology and hydrogen infrastructure cost is still very high compared to conventional energy sources. More research should be geared towards achieving a low unit cost of hydrogen production to make green hydrogen-based energy systems economically viable.

5. Green hydrogen: evaluating the opportunity

Green hydrogen, which is created by splitting H_2O molecules into H_2 and O_2 using renewable electricity, has a great deal of potential to help meet the world's energy needs while also advancing goals for climate change [159].

In 2020, the demand for H_2 was stated to be 87 million metric tonnes (MT), and by 2050, it is anticipated to increase to 500–680 million metric tonnes. The hydrogen production market was worth 130 billion dollars in 2020 and is expected to increase by up to 9.2% annually through 2030. However, there is a catch: only a tiny portion of the current H_2 production, which accounts for over 95% of it, is “green.” Currently, 6% of the world's natural gas and 2% of its coal are used to produce H_2 [160]. However, there is a resurgence of interest in environmentally friendly H_2 production techniques. This is because potential applications of H_2 are growing in a variety of fields, including fuel cells for electric vehicles, power generation, manufacturing processes in the cement and steel industries, heavy transportation like shipping, the production of green ammonia for fertilisers, refrigeration, cleaning products, and grid stabilisation. Additionally, the financial feasibility of green H_2 production has increased due to the declining cost of renewable energy sources, decreasing electrolyser costs, and improved effectiveness brought on by technological advancements [161]. The forecast of the levelized cost of H_2 production for significant projects worldwide through 2050 is depicted in Fig. 16.

Bloomberg New Energy Finance estimates that by 2050, green H_2 could be produced for \$0.70 to \$1.60 per kg in most of the world, making it competitive with natural gas if the prices keep decreasing. According to NEL, the biggest manufacturer and producer of electrolysers worldwide, the cost parity (or simply superiority) of green H_2 production with fossil fuels could be reached as early as 2025. Given this sharp increase in demand, the volume of input energy needed to produce 500 million metric tonnes of green H_2 annually (22,000 TWh of green electricity) and the similarities between the fossil fuel value chain and the H_2 value chain (with downstream, upstream, and midstream components), the green H_2 sector should attract investments.

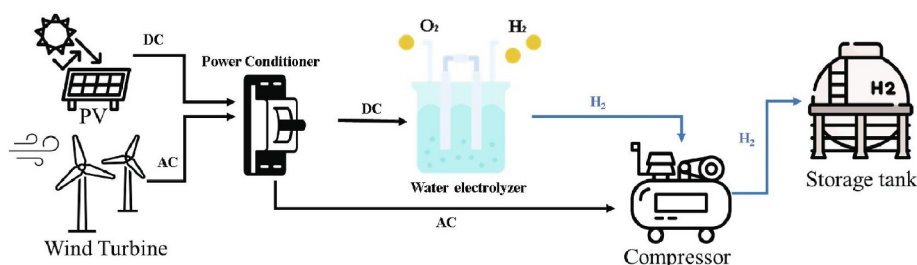


Fig. 15. Schematic representation of hybrid renewable energy system for hydrogen production [156].

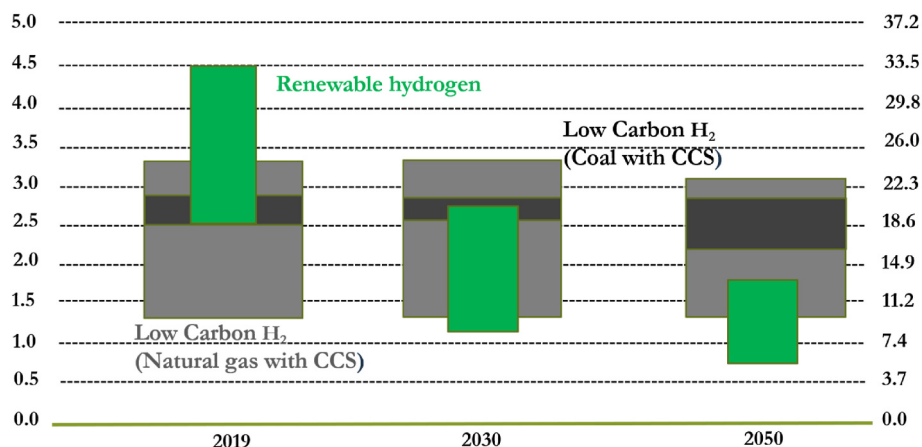


Fig. 16. The projected levelized cost of producing H₂ for major global projects through 2050. They were adopted from BloombergNEF. Renewable hydrogen costs are based on large projects with optimistic projections for capex. Coal prices range from \$30–116/t, and natural gas prices from \$1.1–10.3/MMBtu.

Currently, most H₂ produced globally is “grey,” meaning it is derived from natural gas. Grey hydrogen is cost-effective (between \$1 and \$2 per kilogramme) in the absence of a cost on carbon emissions, but it makes it harder to achieve greater sustainability for the environment [162]. Conversely, green H₂ is produced by electrolysis of water to produce H₂ and O₂ using renewable electricity. Green H₂ is a more effective long-term option for decarbonising economies because it does not need fossil fuels. However, green H₂ is more costly than grey, with prices ranging from €3 to €8/kg in some regions.

The markets with many readily available, inexpensive renewable energies are the most appealing for producing green hydrogen. For instance, green hydrogen could be produced between €3 and €5 per kg in some regions of Australia, the Middle East, Russia, Africa, and the US. The production price in Europe ranges from €3 to €8 per kg. The lower end of these ranges can be attained the easiest in areas with inexpensive renewable energy plants.

However, as the cost of producing renewable energy continues to decline, economies of scale, the lessons learned from ongoing projects, and technological advancements will lead to a gradual decline in production costs. Green H₂ will consequently cost less money. The difficult part is recognising those trends and taking timely action.

The demand for H₂ will only slightly increase each year through 2030 [160,163–167]. First, regardless of expanding capacities, most H₂ projects are still in the pre-commercial stage and have small electrolyser capacities, usually 50 MW. While the electrolyser capacities of the proposed plants are more significant—100 MW or more—than those of the existing grey H₂ production facilities, they are still small. Second, constructing the necessary facilities for significant H₂ applications, such as import and export terminals or pipelines, will take a long time [38]. For instance, planning and constructing a pipeline can take seven to twelve years. To guarantee that by 2030, H₂ can be traded and carried in sufficient quantities, it is ideal that the required facilities be constructed concurrently with rising H₂ demand at decreasing costs. The demand for H₂ will become more significant starting in 2030 and again beginning in 2035 under all medium- and elevated-ambition scenarios [168]. Planning for the necessary infrastructure must start immediately to fulfil the Paris climate goals.

6. Conclusion

In this review, we have conducted a comprehensive and critical analysis of the latest research findings and practical cases of green hydrogen production. Our exploration has deepened our understanding of effectively integrating renewable energy sources with electrolysis technologies to facilitate this sustainable production process. We have identified and discussed various innovative approaches that enhance the

efficiency and cost-effectiveness of green hydrogen production systems. Moreover, we emphasised the critical roles of policy support, standardisation, and market acceptance in the widespread adoption of green hydrogen technologies. These contributions lay a robust foundation for the ongoing research and practical applications of green hydrogen as a future clean energy solution, highlighting its vast potential to mitigate climate change impacts across various industrial sectors.

Integrating renewable energy with advanced electrolysis technologies has positioned green hydrogen as a game changer in achieving a carbon-neutral future. This synergy enhances the sustainability of energy systems and supports global efforts to reduce carbon emissions. Through detailed examinations of alkaline, proton exchange membrane, solid oxide electrolysis, grid integration, and energy storage solutions, this review has highlighted significant advancements that improve the efficiency and scalability of green hydrogen production. These technological developments are crucial for green hydrogen to play a transformative role across various sectors, including industrial processes, transportation, and power generation.

Furthermore, integrating these technologies facilitates a more reliable energy system, enabling the broader adoption of renewable solutions and balancing energy supply and demand. This is particularly important for stabilising grid operations and unlocking additional renewable energy capacity. The prospects for expanding green hydrogen production are promising, driven by ongoing technological innovations, supportive policies, and economic feasibility. The transition towards a hydrogen-driven economy appears increasingly attainable, promising a future where green hydrogen can significantly contribute to global sustainability goals.

As we continue to advance our understanding and capabilities, it becomes clear that green hydrogen offers a viable solution to energy challenges and stands as a beacon of hope for a sustainable and self-sufficient energy future. The path forward will require ongoing research, particularly in optimising system integrations and enhancing electrolyser designs to reduce costs further and improve operational efficiencies. The section on ‘Further studies for Green Hydrogen Production’ provides a focused discussion on these future research directions and challenges, ensuring a comprehensive approach to overcoming obstacles in deploying green hydrogen technologies.

7. Further studies for green hydrogen production

While tremendous progress has been achieved in understanding and applying the combination of renewable energy with electrolysis to create green hydrogen, there are still several areas for more study and exploration. These research fields will continue to contribute to the efficient and successful operation of variable energy.

- Optimising the performance of the electrolysis process is still an important topic of study. Further research should concentrate on producing sophisticated equipment to improve electrolyser performance, minimise energy usage, and boost longevity. Exploring innovative catalyst designs, materials, and process strategies can lead to innovations that will enhance the overall efficiency of electrolysis.
- As renewable energy penetration grows, integrating green hydrogen generation into the grid becomes more complicated. Advanced grid integration solutions that optimise energy transport, storage, and conversion should be investigated in the future. This includes studies on virtual power plants, demand response strategies, and complex energy systems that assure a continuous renewable energy network, energy storage, and hydrogen generation.
- Access to innovative energy storage technologies will be vital to consistently generating green hydrogen. More research should be conducted to examine innovative energy storage technologies, such as solid-state batteries and chemical storage solutions, which may increase the stability and capabilities of integrated renewable energy systems. Furthermore, research will be critical in establishing a complete hydrogen system to enable increased green hydrogen intake, including storage, transport, and distribution.
- An additional study should be conducted to analyse the environmental effect and sustainability of green hydrogen-producing technologies. This entails examining the whole lifespan of the system, from raw material disposal through end-of-life disposal, to assess its real worth in terms of greenhouse gas emissions, energy consumption, and material utilisation.

CRediT authorship contribution statement

Somtochukwu Godfrey Nnabuife: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **Abdulhammed K. Hamzat:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Visualization. **James Whidborne:** Supervision, Writing – review & editing. **Boyu Kuang:** Formal analysis, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Karl W. Jenkins:** Formal analysis, Resources, Visualization, Writing – review & editing.

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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Integration of renewable energy sources in tandem with electrolysis: a technology review for green hydrogen production

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