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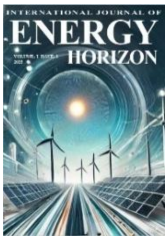

Review Article

Alkaline Water Electrolysis: A review on technological progress, market dynamics, and environmental implications

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ABSTRACT

As global climate change continues to change rapidly, the development of sustainable and environmentally friendly energy technologies that can replace fossil fuels has become one of the top priorities in energy policy and research. Renewable energy sources such as geothermal, wind, and solar energy play a critical role in low-emission energy production; however, due to structural limitations such as intermittency and dependence on weather conditions, they cannot alone provide a continuous and reliable energy supply. In this context, hydrogen energy stands out as a strategic energy carrier that offers a solution to the intermittent nature of renewable energy sources, thanks to its high energy density, broad potential for use across different sectors, and long-term energy storage capacity. Green hydrogen, in particular, is of critical importance in terms of converting and storing excess renewable electricity production for reuse when needed. This eliminates the temporal mismatch between energy production and consumption, minimizing the carbon footprint of energy systems. Among current hydrogen production methods, alkaline water electrolysis (AWE) stands out due to its commercial maturity, relatively low investment and operating costs, stable operating performance, and ability to adapt to variable renewable energy inputs. Considering this, current developments in alkaline electrolyzer technologies are systematically examined in terms of principles, components and materials, performance optimization approaches, market dynamics, techno-economic assessments, and environmental and sustainable dimensions.

1. INTRODUCTION

Energy is one of the most basic needs not only for humans but for all living things, and global energy demand is increasing day by day. Due to its direct correlation with global warming and its impact on the environment, green energy is distinguished as an indispensable and sustainable solution to meet this demand. It is expected that global energy demand will increase by 2.2% in 2024, which is significantly higher than the average annual growth rate of 1.3% seen during the period from 2013 to 2023. Besides, total energy-related CO_2 emissions reached an all-time high of 37.8 Gt CO_2 in 2024, marking a 0.8% increase. This increase led to record-breaking atmospheric CO_2 concentrations of 422.5 ppm in 2024, which was approximately 3 ppm higher than in 2023 and 50% higher than pre-industrial levels [1]. Global warming and the resulting environmental problems are increasingly severe, and this is having a detrimental effect on the world. Fossil fuels, in all their forms, are extensively utilized due to their relatively inexpensive and readily available nature, yet this is the primary cause of these issues. While current energy demands may be met by the continued use of fossil fuels, irreversible damage is caused to all living things and the environment. Renewable energy sources such as solar [2,3], wind [3,4], hydroelectric [5], geothermal [6], biomass [7], tidal energy [8] and wave energy [9] are the first solution that comes to mind at this point, and these resources are becoming more important than ever. In contrast to fossil fuels, these energy sources engender negligible or near-zero greenhouse gas emissions, thereby contributing to the endeavour to combat climate change and air pollution. Their plentiful supply and long-term financial benefits make them a practical and lasting answer to the world's increasing energy requirements. Conversely, while renewable energy sources are sustainable, they are susceptible to erratic production due to meteorological conditions and seasonal fluctuations. Moreover, the effective management of energy resources and the establishment of infrastructure such as wind farms and solar power plants necessitate substantial land areas. Additionally, the existence of appropriate

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storage solutions and grid integration is a critical requirement for these resources, as these elements can have a direct impact on the efficiency and reliability of renewable energy systems. The intermittent nature of renewable energy sources and the associated production and storage requirements are increasing the need for alternative and flexible energy carriers. Hydrogen, a high energy content and carbon-free fuel, plays a crucial role in overcoming these problems and occupies a strategic position in the future of the energy sector [10,11]. Furthermore, as an energy carrier, it can directly contribute to clean energy production with the aid of technologies based entirely on renewable energy sources. In this context, the main method used to split water into hydrogen and oxygen using renewable energy sources is water electrolysis. Various types of electrolyzers with different designs and operating principles have been developed, each offering specific advantages and limitations. This diversity enables adaptation to different application areas and energy sources in hydrogen production [12-15]. However, the four main electrolysis technologies that have attracted the most attention in the literature and industry are those that stand out for their technological maturity and performance characteristics: Alkaline water electrolysis (AWE), proton exchange membrane water electrolysis (PEMWE), solid oxide electrolysis cell (SOEC) and anion exchange membrane water electrolysis (AEMWE) [16-18]. The characterization of these technologies are presented in a comparatively in Table 1.

Table 1. The characterization of the four types of water electrolysis technologies [19,20].

	AWE	**PEMWE**	**AEMWE**	**SOEC**
Operating Temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating Pressure	1-30 bar	<70 bar	<35 bar	1 bar
Cathode Reaction	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Anode Reaction	$2OH^- \rightarrow H_2O + \frac{1}{2} O_2 + 2e^-$	$H_2O \rightarrow 2H^+ + \frac{1}{2} O_2 + 2e^-$	$2OH^- \rightarrow H_2O + \frac{1}{2} O_2 + 2e^-$	$O^{2-} \rightarrow \frac{1}{2} O_2 + 2e^-$
Overall Reaction	$H_2O \rightarrow H_2 + \frac{1}{2} O_2$	$H_2O \rightarrow H_2 + \frac{1}{2} O_2$	$H_2O \rightarrow H_2 + \frac{1}{2} O_2$	$H_2O \rightarrow H_2 + \frac{1}{2} O_2$
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or $NaHCO_3$ 1$molL^{-1}$	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Nafion	Fumatech	Solid electrolyte YSZ
Electrode/ Catalyst (Oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (LSCF, LSM)
Electrode/ Catalyst (Hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous Transport Layer Anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous Transport Layer Cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass
H_2 purity	99.5–99.9998%	99.9–99.9999%	99.9–99.9999%	99.9%
Efficiency	50%–78%	50%–83%	57%–59%	89% (laboratory)
Development status	Mature	Commercialized	R & D	R & D
Lifetime (stack)	60 000 h	50 000–80 000 h	>30 000 h	20 000 h
Capital costs (stack) min. 1 MW	USD 270/kW	USD 400/kW	Unknown	>USD 2000/kW
Capital costs (stack) min. 10 MW	USD 500–1000/kW	USD 700–1400/kW	Unknown	Unknown

Table 2. The technical advantages and limitations of four types of water electrolysis [20].

	AWE	PEMWE	AEMWE	SOEC
Advantages	➢ Commercial usage for industry applications. ➢ Well-known technology ➢ Relatively inexpensive ➢ Long-term stability	➢ Operating in high current densities. ➢ Quick response ➢ High purity gases ➢ Compact system design	➢ Noble metal-free electrocatalysts ➢ Low concentrated (1 M KOH) liquid electrolyte	➢ High working temperature ➢ High efficiency
Challenges	➢ Limited current density ➢ High concentrated (5-7 M KOH) liquid electrolyte ➢ Crossover of the gases	➢ Expensive cost of cell component ➢ Acidic electrolyte ➢ Electrocatalysts made from noble metals	➢ Restricted stability ➢ Under development	➢ Confined stability ➢ Under development

Table 2 provides a comparison of the technical advantages and limitations of four types of water electrolysis. Notwithstanding the fact that PEMWE technology currently proffers considerable advantages such as high current density, expeditious start-up/stop capability, and rapid response to fluctuating renewable energy inputs, it has only seen significant progress in commercialization in recent years due to the high cost of materials, such as iridium/platinum-based catalysts [21]. In contrast, AEMWE technology is still in the early stages of development and is currently being researched at laboratory scale. Moreover, in view of its compatibility with non-precious metal catalysts in alkaline environments, AEMWE boasts considerable potential in comparison with PEMWE with regard to cost [22]. Nevertheless, the effectiveness and capability of this technology are contingent on the creation of state-of-the-art anion exchange membranes (AEMs) with high conductivity and stability. Current AEMs exhibit limited stability and low ionic conductivity, particularly at high temperatures, which poses a significant challenge to the technology's widespread adoption. Therefore, there is a pressing need for extensive research and development endeavours to foster heightened competition among the four electrolysis technologies and to enhance the commercial viability of AEMWE. On the other hand, SOEC technology significantly reduces energy consumption during electrolysis thanks to its high energy conversion efficiency and annihilates the requirement for noble metal catalysts. The development of this technology is being limited by two main factors. Firstly, the requirement to operate at high temperatures. Secondly, the need to maintain chemical and mechanical stability in high-humidity environments [23-24]. Among these technologies, AWE is distinguished by its comparatively low cost, long lifespan, suitability for large-scale industrial applications, high-purity hydrogen production capacity, and eco-friendliness. Indeed, AWE was the first electrolysis technology used for industrial-scale hydrogen production, which is a significant development in the field. Moreover, it has accomplished the production of green hydrogen on a megawatt scale, establishing itself as a favoured commercialization approach and a dependable solution for large-scale, cost-effective production of hydrogen of a high purity [25]. This review article aims to thoroughly analysis of the key role of (AWE) technology, which is highly developed, in producing green hydrogen. The piece's structural framework includes an analysis of AWE's essential principles, electrode reactions, components, and materials used, as well as an investigation of performance enhancement methods. Additionally, a thorough outlook on AWE is provided by exploring market trends, techno-economic evaluations, and environmental and sustainability considerations. The study gives a brief overview of the main results, explaining the current role of AWE and its possible future use in green hydrogen production.

2- FUNDAMENTALS OF ALKALINE WATER ELECTROLYZER (AWE)

The operating principle of an alkaline water electrolyzer is predicated on the separation of water into its constituent parts by means of electrical energy. This process is known as electrochemical water splitting. The process of electrochemical water splitting can be viewed as a pair of half-cell reactions: one at the cathode (the hydrogen evolution reaction, or HER) and the other at the anode (the oxygen evolution reaction, or OER). These reactions are commonly carried out in highly conductive alkaline electrolyte solutions such as potassium hydroxide (KOH) or sodium hydroxide (NaOH). The cathode undergoes a reduction reaction, producing hydrogen gas, while the anode undergoes an oxidation reaction, producing oxygen gas. The working principle of AWE is presented schematically in Figure 1.

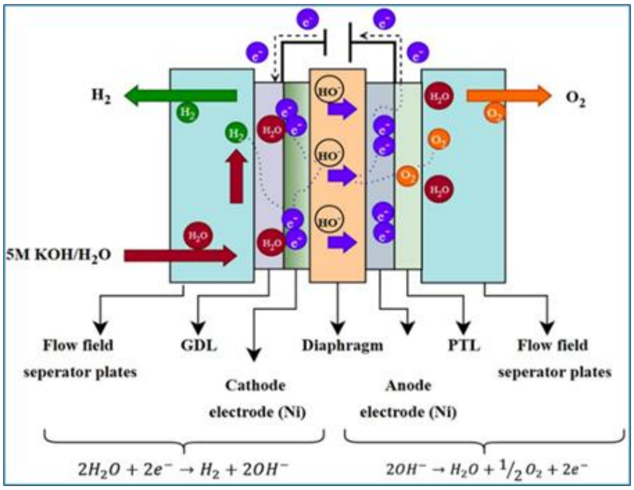

Figure 1. Schematic representation of the working principle of AWE. Adapted from Kumar, S. S., & Lim, H. (2022), [20], licensed under CC BY 4.0.

2.1. Electrochemical Reactions

2.1.1. Hydrogen Evolution Reaction (HER) Mechanism

The rate of HER in alkaline media is much slower, with a reaction rate that is roughly two to three orders of magnitude lower than in acidic media. The main reason for this sluggishness is the need for a water dissociation step at the start of the reaction, which creates an extra energy barrier [26,27].

The HER process in alkaline media follows the Volmer–Heyrovsky or Volmer–Tafel step, as demonstrated in the following equations [28-29]:

Volmer step:

$$H_2O+e^-\rightarrow OH^-+H^* \tag{1}$$

Heyrovsky step:

$$H_2O+e^-+H^*\rightarrow OH^-+H_2 \tag{2}$$

Tafel step:

$$H^*+H^* \rightarrow H_2 \tag{3}$$

The splitting of water molecules and the adsorption of hydrogen are explained by the Volmer step. The next step is to produce hydrogen using either the Heyrovsky process or the Tafel process. Figure 2 shows alkali HERs, which consist of adsorption and desorption processes.

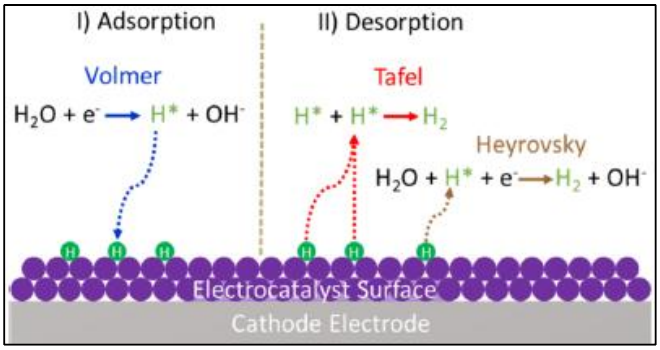

Figure 2. A representation of the alkaline hydrogen evolution reaction mechanism. Reproduced from Tüysüz, H.(2024), [30], licensed under CC BY 4.0.

2.1.2. Oxygen Evolution Reaction (OER) Mechanism

The OER is a complex and kinetically slow reaction. It involves four electron transfers. It is generally considered the main bottleneck. This limits the overall efficiency of water electrolysis. The overall OER equation in an alkaline environment is [31,32]:

$$4OH^- \rightarrow O_2 + H_2O(l) + 4e^- \qquad (4)$$

The schematic of the alkaline OER mechanism on the catalyst surface is shown Figure 3. Two primary models have been proposed to explain the OER mechanism. The first is the classical adsorbed evolution mechanism (AEM). The second is the novel lattice oxygen-mediated mechanism (LOM).

2.1.2.1. Absorbed Evolution Mechanism

This is the most widely accepted process, which goes through four successive proton-electron transfer stages involving intermediates attached to active sites (*) on the catalyst surface [33,34].

$$OH^- + * \rightarrow HO^* + e^- \qquad (5)$$

$$HO^* + OH^- \rightarrow O^* + H_2O + e^- \qquad (6)$$

$$O^* + OH^- \rightarrow HOO^* + e^- \qquad (7)$$

$$HOO^* + OH^- \rightarrow * + O_2 + H_2O + e^- \qquad (8)$$

2.1.2.2. Lattice Oxygen Mechanism

This alternative mechanism, which has been suggested for certain catalysts (particularly perovskites and oxyhydroxides), involves oxygen atoms from the catalyst's crystal structure participating in the reaction. Lattice oxygen mechanism has the potential to disrupt the conventional scaling relationships of the adsorbed evolution mechanism, thereby lowering the energy barrier and consequently enhancing catalytic activity [35,36].

2.2. Historical Evolution and Industrial Maturity

The origins of water electrolysis technology date back more than 200 years. This expedition, which commenced with the observation of the electrolytic water splitting occurrence by Paets van Troostwijk and Rudolph Deiman in 1789, was established on a scientific basis with the creation of Faraday's Law in 1833. This law defined the concept of water electrolysis scientifically by establishing the quantitative relationship between the electrical energy consumed and the amount of gas produced [37]. The scaling up of this technology accelerated in the early 20th century. For instance, between 1885 and 1887, an electrolyzer was developed by d'Arsonval to produce pure oxygen for his physiological experiments. A perforated iron cylinder was used as an electrode, a cloth bag was used as a diaphragm, and a 30% KOH solution was used as the electrolyte [38].

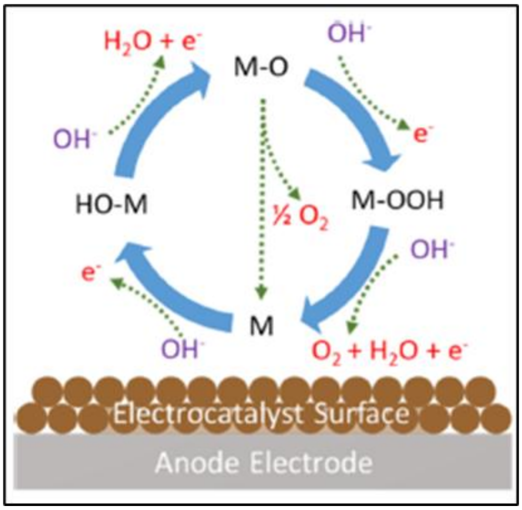

Figure 3. A representation of the alkaline oxygen evolution reaction mechanism. Reproduced from Tüysüz, H.(2024), [30], licensed under CC BY 4.0.

Significant milestones in the development of industrial hydrogen production techniques were the discovery of alkaline water electrolysis by Dmitry Lachinov in 1888 and the commercialization of asbestos as a separator (diaphragm) in 1890. In the early 1900s, nickel-based materials were recognized as excellent candidates for catalysing the oxygen and hydrogen evolution reactions (OER and HER). Modern alkaline water electrolysis (AWE) technology was established in the 1920s [39]. The growing demand for hydrogen in industrial applications, particularly in the production of ammonia fertiliser, has led to the rapid development of this technology. In 1939, the first large-scale water electrolysis factory with a capacity of 10,000 Nm³ of hydrogen per hour went into operation, and in 1948, the first pressurized industrial electrolyzers, such as the LURGI system, were manufactured [38]. AWE is the most mature and economical technology, having been used commercially for over a century. Because of its advanced technology readiness rating and minimal financial outlay, it is at the vanguard of green hydrogen manufacturing [40]. Moreover, understanding the historical development of AWE technology is important for grasping the industry's evolutionary progress. Indeed, the chronological representation of industrial progress in AWE is shown in Figure 4.

3. KEY COMPONENTS AND MATERIALS

Alkaline electrolyzers consist of basic components, including electrodes, an electrolyte and a membrane. One of the significant advantages of AWE technology is that these systems do not require precious metals or high-cost materials. The electrolyzer's reliability, efficiency and safety depend directly on the design and long-term stability of its fundamental components, as well as their material properties.

3.1. Electrodes

Electrodes are the reaction zone where water molecules undergo electrochemistry to form oxygen and hydrogen. Two electrodes are used in alkaline electrolyzers: an anode and a cathode. Each has its own specific function and importance. Electrolyzers that perform water electrolysis are similar to fuel cells in that they also consist of an anode and a cathode separated by an electrolyte [42]. The electrodes are in direct contact with the electrolyte. In alkaline electrolyzers, the electrodes are separated from the electrolyte and membrane.

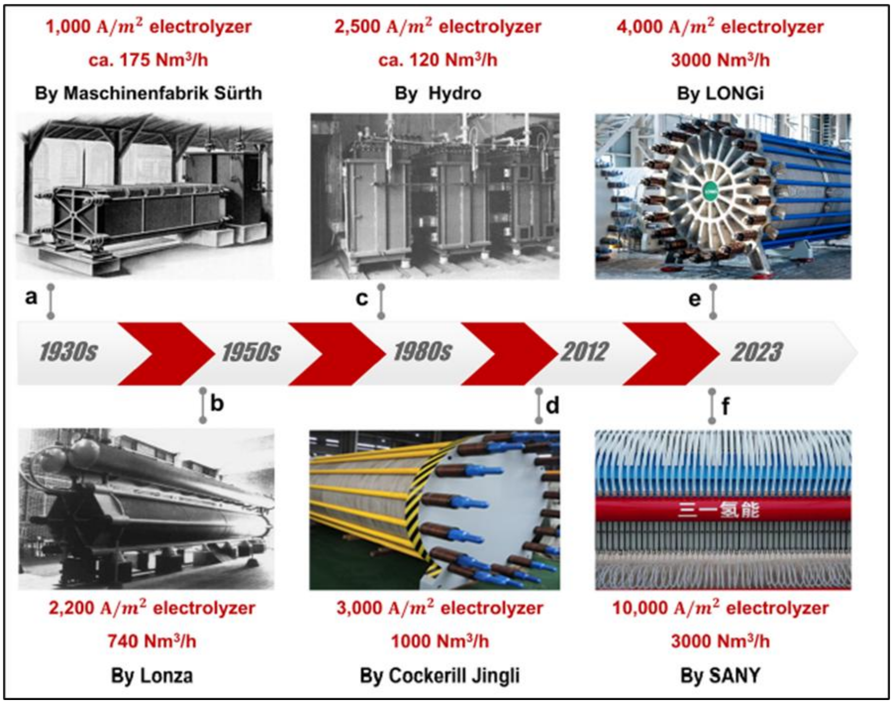

Figure 4. A diagram illustrates the progression of industrial advancements within the AWE domain. Reproduced with permission from Deng, L. et al. (2024), [41].

In other words, the electrodes that connect the electrochemical cells to an external electrical circuit carry out electron transfer. During the reaction, gas bubbles containing hydrogen and oxygen form on the cathode and anode surfaces, respectively [43]. The selection of materials is a critical factor that directly affects the efficiency of reactions occurring at electrodes. Therefore, selecting the right electrode materials is crucial for designing a high-performance alkaline electrolyzer. The two electrodes must be able to withstand corrosion in alkaline environments, have high electrical conductivity and be structurally stable. Although noble metals such as platinum (Pt) and iridium (Ir) can be used to achieve these properties, the most significant advantage of alkaline electrolyzers is that they can be manufactured using low-cost materials. That's why, high-cost noble metals are usually not used in designs. Nickel (Ni) and nickel alloys are widely used due to their high electrocatalytic activity, corrosion resistance and affordability [44]. The materials used in alkaline electrolyzer electrodes are shown in Table 3.

Table 3. The various materials used in electrodes and their properties [45]

Electrode Material	Catalytic Activity	Corrosion Resistance	Electrical Conductivity	Stability	Typical Compositions/Examples	References
Nickel-based	High	Good	Moderate	Good	Ni, Ni-Fe, Ni-Mo, Ni-Mo-Cd, Ni-Zn, Ni-Al, Ni-Sn, Ni-Co, Ni-Cr, Ni-Cu, Ni-P, Ni-W, Ni-Mn	[44,46,47]
Oxide-Based	Moderate to High	Excellent	High	Excellent	NiO, Co3O4, FeOOH, NiFe2O4, LaNiO3, La0.6Sr0.4CoO3, Ba0.5Sr0.5Co0.8Fe0.2O3-δ	[48,49]
Platinum-group	Excellent	Excellent	High	Excellent	Pt, Pt-Ir, Pt-Ru,Pt-Ni, Pt-Co, Pt-Dy, Pt–Ce, Pt–Sm, Pt–Ho	[50,51]
Transition Metal Oxides	Moderate	Good	Moderate to High	Good	RuO2, IrO2, TiO2, WO3, MnOx, FeOx	[52,53]
Perovskite Oxides	High	Good	High	Good	LaNiO3, La0.6Sr0.4CoO3, Ba0.5Sr0.5Co0.8Fe0.2O3-δ,SrNb0.1Co0.7Fe0.2O3-δ	[54,55]
Nanostructured Materials	High	Good to Excellent	High	Excellent	Ni nanoparticles, NiO nanotubes, Co3O4 nanowires, Pt-Ni nanowires	[56-60]

3.2. Electrolyte

The type and concentration of the electrolyte, as well as the temperature conditions, determine ion conductivity. This directly impacts intracellular resistance and overall efficiency. A stable ion environment and high conductivity reduce energy consumption while increasing the rate of hydrogen production. The main role of the electrolyte in alkaline electrolyzers is to facilitate the movement of ions between the electrodes, thereby supporting the electrochemical process. The electrolyte's role is to carry the required hydroxide (OH^-) ions to the electrodes during the process of water decomposition, thereby enabling the reactions to take place. Therefore, the electrolyte solution must be selected carefully to ensure the performance and efficiency of alkaline water electrolysis systems is optimized. The most common electrolytes used in alkaline electrolyzers today are solutions of potassium hydroxide (KOH) and sodium hydroxide (NaOH) [44]. The most common types of electrolyte are these two because they supply high levels of hydroxide ions and minimize ohmic losses. When comparing these two substances, producers of alkaline electrolyzers generally prefer potassium hydroxide to sodium hydroxide because of its superior electrolyte conductivity at temperatures between 50°C and 80°C. The most frequently cited electrolyte type is potassium hydroxide's aqueous solution, with a concentration of 25% to 30% by weight [61,62]. The efficiency of an electrolyzer is significantly affected by electrolyte concentration. Elevating the electrolyte concentration of potassium hydroxide and sodium hydroxide concomitantly augments the hydroxide ions within the electrolyte. An increase in hydroxide ions precipitates a marked acceleration in the rate of water decomposition. This, in turn, leads to an increase in the rate of hydrogen production. Although this may appear to be an effective way to increase electrolyzer efficiency, it is not. It is crucial to determine the appropriate electrolyte concentration because high concentrations can have negative side effects on the system. For instance, an elevated electrolyte concentration has the capacity to impede ion and electron flow, diminish cell voltage efficiency, and curtail the aggregate energy efficiency of the electrolysis process, thereby diminishing the overall system efficiency [63]. Therefore, selecting the correct electrolyte concentration is key to optimize the performance of an alkaline electrolyzer, in terms of both ion transport and temperature control, as well as maintaining appropriate pH conditions. Research is ongoing into developing electrolyte solutions that can improve the performance of alkaline electrolyzer systems [44,64]. In particular, research on lithium hydroxide (LiOH) and barium hydroxide ($Ba(OH)_2$) has shown promising results. These alternative electrolytes have the potential to offer advantages such as higher ionic conductivity and reduced electrode degradation in certain applications [44]. Furthermore, alkaline electrolyzers can use different types of electrolytes. A comparison of these electrolyte types and their basic properties is provided in Table 4.

Table 4. Properties of the most commonly used electrolytes

Electrolyte Solution	Concentration [44]	Conductivity [62]	Corrosiveness [65]	Safety [44]	Carbonation Sensitivity [62,66]
Potassium Hydroxide (KOH) Concentrated (45%)	High	High	High	Low	High
Diluted Potassium Hydroxide (KOH) Concentration (20-30%)	Moderate	Moderate	Moderate	Moderate	High
Sodium Hydroxide (NaOH)	High	High	High	Low	High
Potassium Carbonate (K_2CO_3)	High	High	Moderate	Moderate	Low
Lithium hydroxide (LiOH)	High	High	High	Moderate	Moderate
Barium hydroxide (Ba(OH_2))	High	High	High	Low	Moderate
Alkaline Polymer	Variable	Variable	Low	High	Low
Solid-State	Variable	Variable	Low	High	-
Electrolyte Trisodium phosphate (Na_3PO_4)	High	High	Moderate	Moderate	Low
Sodium bicarbonate ($NaHCO_3$)	High	Moderate	Low	High	Low
Sodium metaborate ($NaBO_2$)	High	Moderate	Moderate	Moderate	Low
Sodium hydrogen phosphate (Na_2HPO_4)	High	High	Moderate	Moderate	Low

3.3. Membrane

The main objective of the membrane in an alkaline electrolyser is to separate the produced hydrogen and oxygen gases. While the membrane separates these gases, it must allow hydroxide ions to pass through. Therefore, it can be said that the membrane is the most complex element of the alkaline electrolyzer. Additionally, the membrane operates in a highly alkaline environment with a pH of around 14, so it must be corrosion-resistant in the long term. In general, membranes can be split into two types: microporous membranes and exchange membranes [67]. Both membranes have the same principal purpose which is being ion-permeable while setting apart produced hydrogen and oxygen gases. Microporous membranes are lightweight, permeable materials with pores that are usually between 0.1 and 10 µm in size. Size exclusion and other filtration techniques are used in the design of these membranes to selectively permit the passage of some molecules, ions, or particles while obstructing others. On the other hand, Ion-selective membranes called exchange membranes are made to allow the passage of some ions while obstructing the passage of others. The kind of ion that these membranes transport determines their classification. If an exchange membrane allows positively charged ions transportation, then it is called cation exchange membranes. Moreover, a membrane that allows negative ion exchange, is named anion exchange membranes. A suitable membrane has to perform high quality of gas separation at working current densities. Also, it must show low ionic resistance for not to decrease the efficiency of the system. In the early stages of the development of alkaline electrolyzers, asbestos was widely used as the primary material for diaphragms and membranes. Nevertheless, owing to the significant health hazards it presented during setup and upkeep, its usage was progressively discontinued and substituted by more secure and long-lasting membrane techniques. Zirconium oxide-filled polyolefin-based diaphragms, such as Zirfon®, are the most common materials developed today to replace asbestos [68,69]. Thanks to its high mechanical strength, chemical stability and low gas permeability, Zirfon has become the standard in commercial alkaline electrolyzers. Polyolefin-based polymers, composite ceramic-polymer membranes, and alkaline-stable polymer membranes are also prominent material groups in AWE applications. Membrane/diaphragm materials are generally divided into four basic categories: Ion-conductive polymer membranes (e.g., perfluorosulfonic acid-based membranes), Alkali-stable polymer membranes (e.g., aryl ether ketone or polyethylene-based membranes), Composite membranes (e.g., polymer/ceramic hybrid structures), Gel electrolyte membranes. The safety of gas separation, ion conductivity and long-term stability of alkaline electrolyzers has been significantly improved by these developments [70]. Figure 5 shows a schematic representation of the historical development of membrane types.

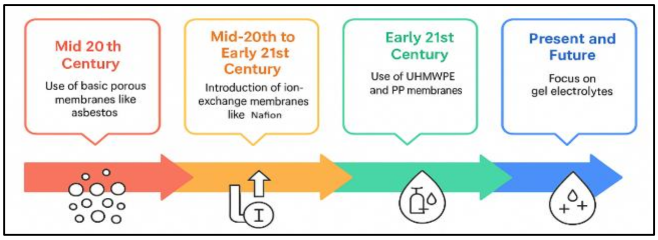

Figure 5. Evolution of Electrolyzer Membranes: From asbestos to gel electrolytes

3.4. Cell Design

Containment part of the alkaline electrolyzers is called cell frame or housing. It provides the system with structural integrity and support, ensuring that the electrolyzer operates unaffected by environmental conditions. The prevention of electrolyte and produced gas leakage is also the responsibility of the cell frame. When assembled in stacks, the cell frame functions as a connecting element, thereby uniting individual cells. It connects the cells in series electrically. Consequently, the production of hydrogen increases when individual cells are connected. The specified requirements are typically met by selecting nickel-plated steel or other corrosion-resistant materials for the cell frame [45].

3.4.1. Cell Design Configurations

The quality of alkaline electrolyzers is affected by the design and configuration of the cells. The aim of cell design is to optimize system performance by arranging its key components as specified. These key components have been configured to provide ionic conductivity and the separation of production gases, as well as reducing energy losses during electrochemical reactions. Cells are assembled into stacks, with connections between them either in series or in parallel. There are three main types of cell design, as described in the literature: monopolar, bipolar and zero-gap [71,72].

3.4.1.1. Monopolar Design

The monopolar cell design is notable for its adaptability and simplicity, allowing cells to be easily added or removed. In this set-up, the cells are arranged side by side, with each cell having its own electrode and electrolyte housing. Furthermore, as each electrode is connected directly to an external power source, it is possible to connect all cells in parallel. All monopolar cells have the same voltage applied to each electrode pair [45,71]. The monopolar design offers a modular structure and ease of maintenance. This design's primary configuration is characterised by the following advantages. In contrast, the disadvantages of the monopolar designinclude insufficient energy efficiency, high electrical resistance and limited current density. Consequently, most commercial alkaline electrolyzer manufacturers prefer a bipolar design for their cells [37]. Figure 6 shows a schematic representation of the monopolar design.

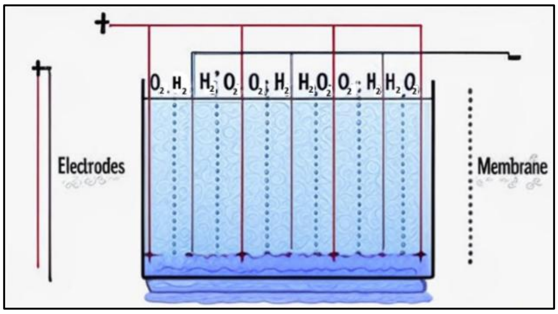

Figure 6. Monopolar Cell Design. Adapted from Scott, K. (2019), [67].

3.4.1.2. Bipolar Design

In a bipolar cell design, the cells are connected in series. This is achieved by connecting only the side electrodes to the direct current (DC) power source. This means that each cell shares an electrode with its neighbouring cell [45]. The result of this is that the flowing current polarises each electrode. Oxidation reactions take place at one of them, while reduction reactions take place at the other electrode [67]. The bipolar cell design is notable for its significant advantages, including its compact structure, reduced ohmic losses and more homogeneous current distribution. The system can be designed more compactly by applying the electric current only to the end (side) electrodes in this configuration. Therefore, a greater number of cells can be accommodated within the same volume compared to the monopolar design. Connecting the cells directly reduces the distance between the electrodes, thereby decreasing ohmic losses and ensuring the electrical current is used efficiently. Furthermore, many commercially produced electrolyzers use a bipolar design, which increases current densities while reducing cell voltage [67]. However, the bipolar cell design also has some disadvantages, which include the fact that it is less efficient and more costly than other designs. It has a more complex structure than the monopolar configuration. This requires more sophisticated production and installation processes, which increases costs. Furthermore, as all cells are connected in series, identifying a faulty cell when a malfunction occurs is difficult. This results in higher maintenance costs and the necessity for specialized knowledge in maintenance procedures [71]. Figure 7 shows a schematic representation of the bipolar design.

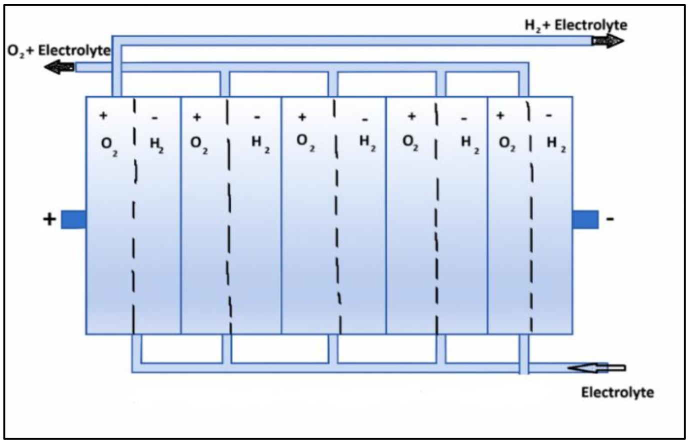

Figure 7. Bipolar Cell Design. Adapted from Scott, K. (2019), [67].

3.4.1.3. Zero-Gap Design

The main aim of zero-gap design is to reduce the space between electrodes, even bringing the electrodes into direct contact with the membrane to get rid of ohmic losses and thus boost current density as much as possible. Selecting this design improves mass transport within the cell, reduces ohmic losses and achieves higher current densities. Furthermore, preventing damage caused by gas bubbles makes cell performance more stable [72,73]. However, achieving long-term suitability for a zero-gap design requires the use of specialised electrode and separator materials. Furthermore, electrolyte management poses a significant challenge in this configuration [45]. In summary, although it offers improved performance, the zero-gap design is considered to be a more complex, costly and highly specialised approach. The zero-gap design is shown schematically in Figure 8. A comparison of the monopolar, bipolar and zero-gap cell designs of alkaline electrolyzers is given in Table 5.

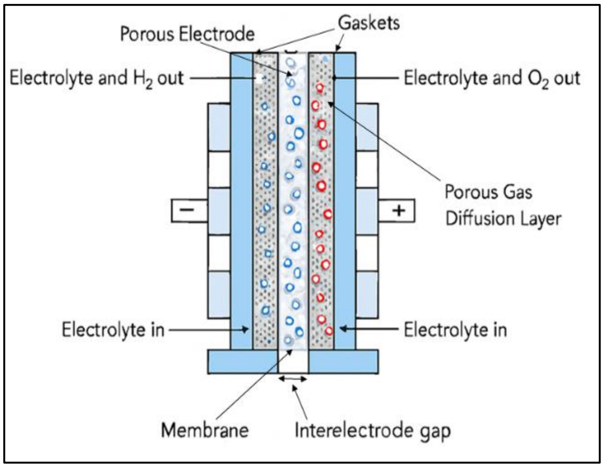

Figure 8. Zero-gap Cell Design. Adapted from Scott, K. (2019), [67].

Table 5. A comparison of monopolar, bipolar and zero-gap cell designs in alkaline electrolyzer.

	Monopolar [45,71]	**Bipolar [45,71]**	**Zero-gap [72,73]**
Advantages	➢ Simple and adaptable design ➢ Easy addition and removal of cells ➢ Low production cost	➢ Compact Design ➢ Lower ohmic losses ➢ Better current distribution ➢ Common in commercial application	➢ Minimum distance between electrodes ➢ Reduction in ohmic losses ➢ Higher current density ➢ Improvement in mass transfer ➢ Reduction in gas bubble effects
Challenges	➢ Requires a larger volume ➢ High ohmic losses ➢ Lower current density	➢ More complex production and installation ➢ Higher cost ➢ Difficulty in detecting faults. ➢ High maintenance cost	➢ Requires specialized membrane/electrode materials ➢ Electrolyte management is challenging ➢ More complex and costly design

4. PERFORMANCE OPTIMIZATION STRATEGIES

Many factors influence the performance of alkaline electrolyzers. These include the operational system conditions, gas bubble dynamics, gas crossover, porosity, computer-aided design (CAD) studies, and system integration. These factors have a direct impact on intracellular processes, playing a decisive role in energy efficiency, gas purity and long-term stability. Consequently, a methodical evaluation of these factors is paramount for enhancing performance and conducting a thorough analysis.

4.1. Operating Conditions

The three key operating factors to consider when using an alkaline electrolyzer are temperature, pressure and current. The value of these parameters is directly affected by the current density and the properties of the electrode surface. Controlling these parameters properly improves system performance and increases energy efficiency. Moreover, ensuring optimal operating conditions significantly reduces production costs and enhances system safety. Temperature effect: via raising the working temperature enhances the conductivity of electrolytes and electrode reaction rates and decreases cell voltage. In a zero-gap cell of 0.1 mm thick diaphragm, about 1.8 A/cm^2 nominal current density at about 100 °C was observed [74]. According to Ren et al. [75], it is possible to achieve high current densities while maintaining a low cell voltage of 80°C. Their research demonstrated that high current densities can be achieved with low voltage values, particularly at this temperature. According to Abdin et al. [76]: The best range of temperature was between or raises reaction rates and reduces the problem of handling heat.

Pressure effect: This effect is useful for minimizing power usage, since direct compression of hydrogen can be achieved. Solovey et al. [77] observed efficiency improvements of up to 15% in membrane-less cells operated at 60–70 MPa. Similarly, Valderrama [78] emphasized the economic benefits of high-pressure systems. However, the probability of gas crossover and mechanical strain increases with high pressure. Simulations indicate that the optimal pressure for achieving Faraday efficiency and gas purity is around 5 bar, but pressures of around 8 bar can make operation at low loads difficult [74]. Successful outcomes also report a cell voltage of 2.29 V at 1.67 A/cm^2 [79]. Intermediate levels of current density offer the best balance between monetary efficiency and production volume. The surface characteristics of the electrode are as follows: Roughness and porosity of electrodes maximizes the electrochemically active area, thereby increasing the rate of reaction. However, Abdin et al. have shown that high roughness can reduce efficiency due to increased gas adsorption, and that moderate roughness provides the best performance [76]. Performance can also be enhanced by techniques such as moulding with ice, which eliminates ohmic resistance in nickel-based electrodes [80]. Lithographically generated microstructures that allow bubbles to be separated twice as fast offer twice the efficiency.

In conclusion, the optimization of temperature, pressure, current density and electrode surface morphology together contributes significantly to both increasing the energy efficiency and hydrogen production potential in alkaline electrolyzers. Table 6 illustrates the impact of different parameters on performance.

Table 6. The performance effects on the parameters.

Parameter	**Range**	**Performance Effect**	**References**
Temperature	25–100 °C	Low cell voltage at high temperatures, high conductivity, high efficiency	[75,76]
Pressure	1–70 MPa	Up to 15% increase in efficiency, direct hydrogen compression; increased crossover at high pressure	[74, 77, 78, 81]
Surface roughness	Low-Medium	Medium roughness is optimal; excessive roughness increases gas retention; special microstructures accelerate bubble separation	[76,80]

4.2. Bubble Dynamics

The bubbling of hydrogen and oxygen produced during the electrolysis process in alkaline electrolyzers has a significant impact on its efficiency. Due to the accumulation of bubbles on the electrode surface, the liquid layer transferred towards the electrolyte thickens, decreasing ion conductivity and exerting a screening effect on the liquid layer [82]. Additionally, the presence of freely circulating bubbles in the liquid phase expands ion transport and causes a 'void effect' that increases the internal resistance of the cell [82]. Bubble formation occurs via three primary mechanisms: nucleation and growth; reaching a critical size; and detachment from the surface. Before reaching a critical size, bubbles accumulate on the surface and cover the active sites of the electrodes, reducing the surface area available for reaction. This effect becomes more pronounced with increasing current densities, ultimately leading to increased energy consumption [66,83]. Some studies have shown that pressure changes facilitate the removal of bubbles from the surface, thereby reducing ohmic losses [84]. Haverkort and Rajaei found that maintaining a gap of just 0.2 mm between the electrode and diaphragm significantly reduces bubble-induced ohmic losses [73]. However, although zero-gap designs are highly energy efficient, they are difficult to implement in practice due to their complexity and the materials required [85]. Figure 9 shows the schematic diagram illustrating the distribution of bubble formation locations on the electrode surface.

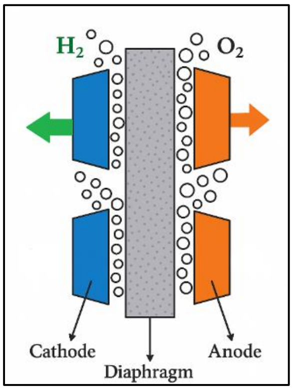

Figure 9. Spatial Distribution of Bubble Generation Sites on the Electrode Surface. Adapted from Ding, S. et al. (2022), [86].

There are various strategies for improving bubble separation. The first involves applying external influences. For example, external stimuli such as magnetic fields (Lorentz force) or ultrasonic vibrations can be employed to increase the separation of bubbles from the surface. These methods enhance reaction efficiency by maintaining an active electrode interface. Indeed, experimental studies have shown that applying ultrasound results in a 10–25% reduction in cell voltage and a significant increase in Faraday efficiency [87]. Another method is surface modification. Superhydrophobic or superaerophobic coatings applied to electrode surfaces can inhibit bubble coalescence, enabling the formation of smaller bubbles that dissociate more quickly. To illustrate, nickel electrode surfaces boasting circular microarray structures have been documented as offering elevated bubble dissociation rates in comparison to flat surfaces, effecting an approximate doubling of the reaction rate [82]. Therefore, the dynamics of bubble formation must be considered alongside electrode surface design and operating conditions. The impact of different parameters on performance is illustrated by Table 7.

4.3. Gas Crossover

Some of the hydrogen produced in alkaline electrolyzer cells can pass through the diaphragm or membrane to the counter electrode. This reduces cell efficiency and decreases gas purity, as well as posing a safety risk. Excessive gas concentration in the liquid phase is one of the main causes of increased crossover tendency [88]. The influence of operating parameters is crucial for hydrogen permeation. Trinke et al. measured the hydrogen permeation level to be 3–5 mA/cm² at a current density of 1 A/cm², and found that the permeation rate increased dramatically with temperature [89]. Furthermore, while 20–60 times supersaturation can be seen in zero gap cells at the diaphragm–electrode interface, this value drops to 2–4 times with the addition of a 0.5 mm gap between the electrodes [90]. It is suggested that adding a gap, particularly on the cathode side, can greatly reduce hydrogen permeation.

The role of membrane materials in limiting hydrogen permeation and improving electrolyzer performance is critical. The development of membranes that can simultaneously prevent gas permeation and provide high ionic conductivity has been achieved for this purpose. The Zirfon® (ZrO_2/polysulfone)-based structure is the most widely used membrane in industry today. However, further performance enhancement is possible with new-generation composite membranes. To illustrate, a 0.35 mm-thick PVA-coated Zirfon membrane reduced surface resistance to less than 0.17 Ω cm² and almost completely eliminated liquid flow thanks to its porous PVA coating [91]. Another innovative approach is the PPS/YSZ composite membrane. This membrane provides superior performance, delivering a high bubble pressure of 2.93 bar, minimum surface resistance of just 0.21 Ω cm² and 99.9% hydrogen purity [92]. Wettability and porosity are critical parameters that directly impact the performance of the diaphragm. When the wettability of the diaphragm surface drops below 30%, the membrane resistance increases and the current density decreases accordingly. This can have a negative impact on the overall efficiency of the electrolyzer [86]. On the other hand, when the diaphragm's porosity exceeds 30%, the separation of gas is possible more rapidly. However, excessively high porosity can lead to unwanted gas leakage. Therefore, achieving the optimum porosity level is critical for balancing performance, as it maintains ionic conductivity while limiting gas permeation. Table 8 presents the gas crossover rates observed in different membrane/diaphragm materials at 80 °C with a 30% KOH electrolyte.

Table 7. The performance impact on the parameters.

Parameter	Range/Property	Effect	Ref.
Electrode–diaphragm distance	0–0,2 mm	Ohmic losses decrease at small distances	[73,85]
Bubble size	Small – Medium	Small size results in rapid separation and low surface coverage	[66]
Surface modification	Superhydrophobic/ micro-patterned Ni	Prevents bubble coalescence and increases separation rate	[82]
External stimulus	Ultrasonic, magnetic field	Ohmic losses decrease by 10–25%, increasing efficiency	[84]

Table 8. The gas crossover rates observed in different membrane/diaphragm materials

Die Type / Material	Current Density (mA/cm²)	Voltage (V)	Resistance (Ω·cm²)	H_2 Gas Crossover (mol·cm⁻¹·s⁻¹·bar⁻¹)	References
Zirfon PERL (ZrO_2/polysulfone)	771–1765	2,0–2,6	0,27	$1{,}85 \times 10^{-11}$	[93]
Thin Zirfon with PVA coating	861–1890	2,0–2,6	0,267	$1{,}12 \times 10^{-11}$	[91,94]
PPS/YSZ composite	—	—	0,21	—	[92]
ZTA (ZrO_2 toughened Al_2O_3)	2000	2,1	0,15	$10{,}7 \times 10^{-12}$	[95]

4.4. Porosity

Porosity is a fundamental structural parameter that plays a decisive role in the ion conductivity, gas separation, and mass transfer of both electrodes and diaphragms. Pore size, distribution, and total porosity ratio directly affect both cell impedance and gas leakage. It is possible to examine the porosity phenomenon under two basic headings, namely electrode porosity and diaphragm porosity. Electrode porosity: Porous electrodes (e.g. nickel foam with a porosity of over 90%) increase the reaction area by expanding the active surface area. This reduces overpotentials and increases current density. In industrial applications, braided or mesh-structured nickel electrodes are generally preferred. However, very high porosity levels can cause gas bubbles to become trapped in the pores and block them. To overcome this problem, channeled or asymmetric pore structures have been developed. Kim and colleagues, for instance, came up with a design that involved using pores measuring 5 μm on one electrode surface and 100 μm on the other. This structure enables gases to exit through the small pores and separate rapidly from the large pores, achieving outstanding performance at a current density of approximately 0.5 A/cm² [82]. Diaphragm porosity: Diaphragms must have a controlled pore structure that permits the free movement of ions while preventing gas permeation. Standard Zirfon UTP 500 diaphragms are composed of a porous material reinforced with inorganic fillers and reinforced with polyethylene fabric [91]. The porosity of such diaphragms is generally below 30%, which limits ion conductivity and increases intracellular resistance. As an alternative option, greater levels of porosity can encourage the movement of ions while simultaneously boosting gas permeation. Ding and colleagues have indeed observed that high porosity can enhance reaction efficiency by facilitating the rapid decomposition of certain gases. However, this increase in efficiency can also result in an elevated risk of gas crossover [86]. Table 9 shows the effect of porosity on the component.

Table 9. Effect of porosity on the components

Component	Porosity (%) / Structural Feature	Effect	References
Ni foam	>90	High active surface, low overpotential, high current	[82]
AsymmetricNi	5–100 μm pores	Rapid gas separation, high performance	[95]
Zirfon UTP 500	Medium	High ion conductivity, limited gas passage	[91]
PVA-coated membrane	Medium + coating	Low gas passage, low resistance	[94]
Low porosity membrane	<30	High resistance, low efficiency	[94]

4.5. CAD Studies

In recent years, CAD-based numerical modelling and CFD simulations have become an important area of research in the optimization of the performance of alkaline electrolyzers, complementing experimental studies. Rodríguez and Amores [96] used COMSOL software to compare their two-dimensional (2D) CFD model with experimental data and validate polarization curves with an error of less than 1% under different operating parameters (temperature, electrolyte conductivity and electrode–diaphragm distance). This study enabled more accurate modelling of current density distribution, gas-liquid profiles and ohmic losses by examining the effects of both electrochemical and fluid dynamics simultaneously. On the other hand, Xue et al. [97] used a three-dimensional (3D) Euler-Euler approach to model two-phase flows with CFD, studying various channel geometries (single, double and triple inlet) and spherical protrusions. Electrolytic structures exhibiting a variety of geometric models are demonstrated in Figure 10.

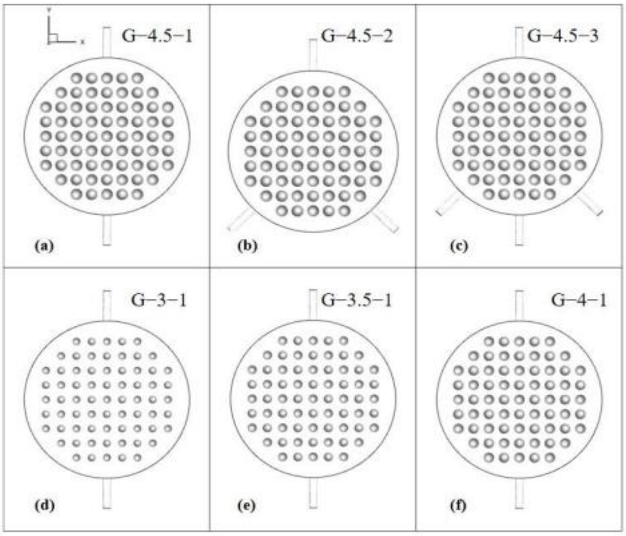

Figure 10. Electrolytic chambers with various geometric design. Reproduced from Zue, L. et al. (2024), [97], licensed under CC BY 4.0.

The model defined the area of the porous media membrane, implemented user-defined functions (UDFs) based on Faraday's law for the gas generation source terms and used an optimized mesh structure with refined regions. The findings indicate that the three-inlet model reduces the outlet hydrogen concentration by around 22% compared to the benchmark model while significantly improving flow and temperature distribution. It was also demonstrated that increasing the radius of the spherical protrusions improves flow uniformity and reduces gas accumulation. Figure 11 shows the electrolyte velocity distribution, electrolyte temperature distribution and H_2 gas volume fraction distribution in electrolytic cells with different input numbers.

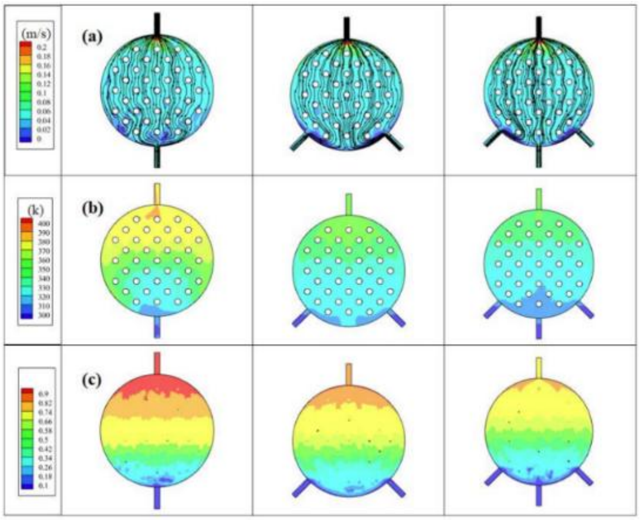

Figure 11. In electrolytic cells with various inlet quantities: (a) the distribution of electrolyte velocity, (b) the distribution of electrolyte temperature, and (c) the distribution of H_2 gas volume fraction. Reproduced from Zue, L. et al. (2024), [97], licensed under CC BY 4.0.

CFD-based simulations directly impact flow channel design, gas-liquid separation and energy efficiency. Therefore, CFD has the potential to be a highly effective design tool for future industrial-scale electrolyzer applications.

4.6. System Integration

Alkaline electrolyzers contribute to grid balancing, particularly when used alongside renewable energy sources. Integrating them into a traditional energy system increases energy usage efficiency and reduces grid load by converting excess electrical energy into hydrogen production [98]. In this context, the integration of an electrolyzer requires a combined evaluation of multi-component systems, such as power electronics, thermal management and control strategies. For instance, Zhao et al. modelled a 500 kW alkaline electrolyzer system by analysing the medium voltage converter topology and control algorithms. The study tested the system's resilience in the face of voltage fluctuations, demonstrating that the DC link voltage could be maintained at 95% [99]. The performance of electrolyzer systems depends critically on power electronics and grid connection. These systems are usually connected to the grid via a direct current (DC) link and a power converter. The quality of power is subject to direct influence from parameters such as grid impedance (short-circuit ratio) and switching frequency [100]. The model developed by Zhao and colleagues suggests that the short-circuit ratio is a key factor in determining total harmonic distortion. Additionally, it has been reported that the designed control system can maintain 95% of the DC link voltage even with a 20% voltage drop [99]. Thermal Management and Balance of Plant (BoP): Efficient thermal management involves maintaining the electrolyzer stack at a constant temperature and removing the generated waste heat effectively. However, in dynamic operating modes, heat transfer delays can lead to fluctuations in stack temperature, which can have a negative impact on the efficiency of the system as a whole. Jiang et al. [98] developed a model based on the equivalent circuit approach, demonstrating that heat transfer delays can cause the stack temperature to temporarily overheat by up to 10°C, thereby shortening the system's lifespan. Dynamic control strategies: In order to adapt to the fluctuating nature of renewable energy sources, the current and voltage of the electrolyzer must be adjusted quickly. In this context, the performance and service life of cells are directly affected by dynamic operating modes (e.g. load-following or current ramp control). Jiang et al. [98] investigated how the system responds to random changes in the current. They showed that transient thermal extremes arising during this process can significantly shorten the stack's life. Figure 12 shows that provides a general overview of a system for the industrial-scale production of green H_2 in AWE.

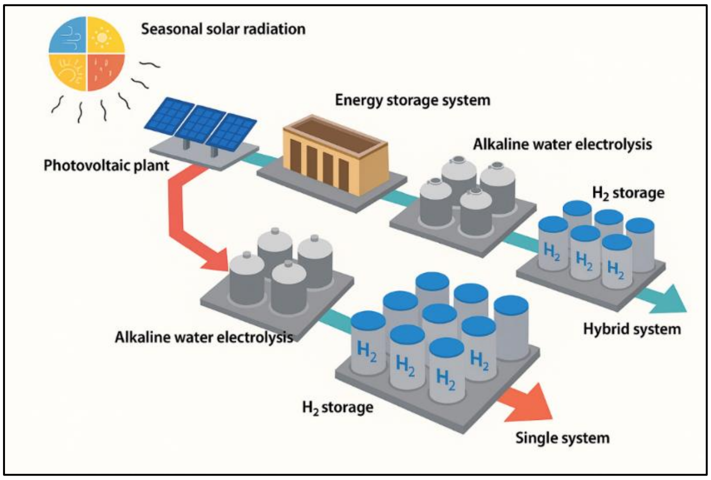

Figure 12. General overview of a system for the industrial-scale production of green hydrogen. Adapted from Lee, H. et al. (2022), [101].

5. MARKET OUTLOOK AND TECHNO-ECONOMICS

Global energy transition pathways increasingly position hydrogen as a cross-sector decarbonization vector, enabling energy storage, industrial feedstock substitution, and deep-abatement in hard-to-electrify segments. The International Energy Agency projects that demand for low-emission hydrogen could approximately triple by 2030 in its net-zero aligned framing, while remaining below total potential demand without stronger policies [102]. Complementing this, system-wide scenarios indicate clean hydrogen demand could expand to roughly 125–585 $Mt \cdot y^{-1}$ by 2050 depending on transition pace and technology learning [103]. Against this backdrop, alkaline water electrolyzers (AWEs)—owing to their cost advantage, commercial maturity, durability, and use of abundant non-noble catalysts—are strategically positioned for large-scale, renewable-integrated hydrogen supply. In line with current EU regulations, "renewable hydrogen" is defined as RFNBO-compliant under the 2023 Delegated Acts, which impose additionality and temporal/geographic correlation requirements, while "low-carbon hydrogen" is classified as meeting a life-cycle GHG intensity ≤ 3.38 kg CO_2e/kg H_2 (≈ 70 % below the fossil comparator) under the EU Gas Decarbonisation Package [104,105]. Table 10 summaries recent quantitative hydrogen deployment targets across the EU, Türkiye and selected MENA states. These policy ambitions—ranging from the EU's 40 GW electrolyzer goal by 2030 to Türkiye's 2–5 GW roadmap and multi-megaton hydrogen export plans in Oman and the UAE—provide direct signals to investors and technology developers [106-111]. These targets and definitions are not just high-level aspirations; they actively shape deployment priorities, steering capital toward AWE configurations that combine techno-economic feasibility with sectoral fit in the near to medium term.

Table 10. National and regional hydrogen deployment targets (EU, Türkiye, MENA)

Region / Country	Electrolyzer / H_2 Target	Hydrogen Type	Timeline	References
European Union	6 GW by 2024; 40 GW by 2030; 10 Mt domestic + 10 Mt imports by 2030	Renewable	2024–2030	[106,107]
Türkiye	2 GW by 2030; 5 GW by 2035; 70 GW by 2053; H_2 cost < USD 2.4/kg (2035) → USD 1.2/kg (2053)	Renewable	2030–2053	[108]
UAE	1.4 Mtpa low-carbon H_2 by 2031; 15 Mtpa by 2050	Low-carbon focus	2031–2050	[109]
Oman	1 Mtpa by 2030; 3.75 Mtpa by 2040; 7.5–8.5 Mtpa by 2050	Low-carbon focus	2030–2050	[110]
Saudi Arabia (NEOM)	~600 t/day green H_2 (as ammonia) under construction	Low-carbon focus	2026 (start-up)	[111]

5.1. Large-Scale Applications

5.1.1. Industrial Decarbonization Use-Cases

Alkaline water electrolysis (AWE) is emerging as a key technology for the industrial production of hydrogen, providing a reliable and cost-effective alternative to methods based on fossil fuels. Unlike steam methane reforming, the AWE process is clean by nature, producing only hydrogen and oxygen at the point of manufacture. Thanks to its durability and longevity, AWE technology is a suitable solution for the continuous, large-scale supply of hydrogen for processes such as ammonia synthesis, methanol production, refining and the production of direct reduced iron (DRI) in steelmaking. Furthermore, when used alongside suitable post-stream conditioning techniques, hydrogen purities of over 99–99.99% can be attained, thereby meeting the stringent feedstock requirements of these industrial processes [61,112]. The success of the industrial-scale implementation of alkaline water electrolysis (AWE) hinges on the compatibility of the hydrogen produced with the specific needs of downstream processes. In this context, three key integration elements stand out: delivery pressure, feed buffering and purification. These elements ensure the reliable application of AWE technology in processes such as ammonia synthesis, methanol production, refining and steelmaking using direct reduced iron (DRI). In particular, the hydrogen delivery pressure must be tailored to the target sector. Synthesis processes in ammonia and methanol plants, for example, typically require hydrogen feed pressures in the 30–50 bar range, whereas refinery fuel gas networks usually operate at 2–4 bar. Similarly, DRI-based steelmaking requires a hydrogen feed pressure of 30–50 bar to maintain stable reducing conditions [113,114]. In hydrogen supply management, recycling loops and buffer storage are as critical as pressure optimization. Ammonia and methanol plants often incorporate recycling circuits to maximize the efficiency with which they utilize hydrogen, while refineries utilize buffer storage solutions to balance demand-related fluctuations. In DRI applications, specialized hydrogen buffer systems help to maintain stable furnace atmospheres and prevent fluctuations in metallisation rates [115]. Purification strategies also play a decisive role in meeting the stringent purity requirements of each process. In the production of ammonia and methanol, pressure swing adsorption (PSA) systems are usually employed to attain a hydrogen purity level of at least 99.999%. Depending on process flexibility, refiners can choose between PSA and membrane separation technologies. Similarly, PSA systems are widely used in direct reduced iron (DRI) steel production to ensure the quality of the raw materials [116].

5.1.2. System Scaling and Balance-of-Plant

Integrating AWE systems with renewable energy and grid infrastructure significantly increases their scalability and economic viability. Assuming certain conditions, economic assessments have reported hydrogen production costs of approximately \$2.94–\$3.32 per kilogram for solar-powered AWE systems, and of \$6.33–\$8.87 for hybrid PV–wind configurations [117]. Furthermore, continuous advances in cell architecture and nickel-based electrode technologies enhance the durability of systems and improve their tolerance to variable renewable energy inputs. At the plant scale, balance-of-plant (BoP) components such as rectifiers, DC–DC converters, gas–liquid separators, dryers, deoxidisers, compression and storage units, and safety systems play a decisive role in determining both the system's footprint and its reliability.

5.1.3. Gas Purity, Crossover, and Safety

Increased gas permeation through the diaphragms can be caused by part-load operation, which can in turn reduce product purity. Carbon-based supercapacitor architectures have been proposed as a solution to this problem. These architectures enable the separation of hydrogen and oxygen evolution over time, thereby reducing gas crossover. Furthermore, the system can support high current densities of 0.952 $A \cdot cm^{-2}$ at 70°C [118]. Furthermore, multi-stage purification systems (gas-liquid separation, cooling/condensation, adsorption, drying, and palladium-based deoxidation) are critical for ensuring product purity at an industrial level. In practice, these systems can achieve a purity level of 99.999%, rendering hydrogen safe for use [119].

5.1.4. Comparative Context (AWE vs PEMWE vs SOEC)

Global hydrogen demand is rapidly increasing in line with decarbonization targets in industry, transportation, and energy storage. In this context, large-scale electrolyzer systems (particularly AWE, PEMWE, and SOEC technologies) play a critical role in low-carbon hydrogen production by integrating with renewable energy sources. The characterization of these technologies for large-scale applications are presented in a comparatively in Table 11. As of 2023, global electrolysis capacity reached approximately 1.4 GW, and annual production capacity reached 25 GW. An installed capacity of 230-520 GW is projected by 2030; however, only approximately 20 GW of these projects have reached final investment decisions [102].

Table 11. Comparative Characteristics of AWE, PEMWE, and SOEC Technologies for Large-Scale Applications

Feature	AWE	PEMWE	SOEC	Reference
Technology Maturity	Mature, widely deployed	Medium, rapidly adopted	Emerging, pilot-scale	**[120]**
Operating Voltage	1.8–2.0 V	1.8–2.2 V	1.0–1.3 V (at high temperature)	**[120]**
Efficiency (HHV)	60–70%	65–75%	80–90%	**[102]**
Dynamic Response	Slow, less flexible	Fast, suitable for intermittent power	Moderate, sensitive to thermal cycling	**[120]**
Lifetime & Durability	Long, robust materials	Medium, requires PGM electrodes	Medium, ceramic degradation risk	**[120]**
CAPEX	Low	Medium	High	**[102]**
OPEX	Low	Medium	Medium–High	**[102]**
LCOH (\$/kg H_2)*	2–4	3–6	4–7	**[102]**
BoP Considerations	Standard rectifiers, compressors, storage	DC-DC converters, high-pressure systems	High-temperature heat integration, specialized components	**[120]**

Relative to PEMWE, AWEs typically operate at lower current densities but with lower specific capital cost and non noble catalysts; compared with SOEC, AWEs avoid high temperature materials challenges and offer higher commercial maturity today. Consequently, AWEs often dominate in large, base loaded installations where capex and stack replacement costs drive levelized costs, while PEM's faster dynamics may be preferred for highly intermittent duty cycles [102]. In terms of application, AWE stands out with its low investment cost and long lifespan, particularly in baseload generation. PEM, with its high dynamic response, is preferred for direct integration with intermittent sources such as wind and solar. SOEC, on the other hand, stands out with its high temperature efficiency (80-90% HHV), but due to its technological maturity and high capital expenditures, it has not yet reached widespread commercial use. At the industrial scale, these technologies are actively implemented in ammonia, methanol, and steel production, energy storage, and grid balancing projects [102].

5.1.5. Transitional/Near-Term Applications

In transitional applications, oxyhydrogen (H_2/O_2) generated by small-scale alkaline water electrolyzers (AWEs) has been investigated for combustion enhancement in compression-ignition (CI) engines. For example, experiments on a 10 HP single-cylinder diesel engine demonstrated approximately 14% fuel savings at optimized HHO flow rates, alongside significant reductions in CO (~23%) and NO_x (~15.5%) emissions, without requiring major engine modifications [121, 122]. Exhaust emissions in these studies were quantified using a full-flow constant-volume dilution tunnel system, with non-dispersive infrared (NDIR) analyzers for CO/CO_2 and chemiluminescence detectors for NO_x, following ISO 8178 test cycle protocols [123]. This ensured repeatable measurements under standardized load conditions. Despite these promising results, scalability to large marine, heavy-duty, or stationary power plants remains constrained due to: the relatively low volumetric energy density of HHO, the parasitic electrical demand of in-situ electrolyzers, and the diminishing net efficiency gains at higher power outputs. Consequently, HHO-assisted combustion is generally considered a niche or bridging solution, suited for targeted emission mitigation and incremental efficiency improvements in existing diesel fleets, until fully decarbonized alternatives (e.g., 100% hydrogen combustion or fuel cells) become economically and infrastructurally viable**.**

5.2. Renewable Integration

Integrating alkaline water electrolyzers (AWEs) with renewable energy infrastructure can significantly increase the scalability and economic viability of systems. Studies have shown that integrating AWE with large-scale photovoltaic (PV) and wind energy systems can significantly reduce hydrogen production costs, achieving competitive prices and high efficiency under optimal operating conditions. For instance, the cost of producing hydrogen has been reported to range from $2.94–$3.32 per kg when using solar energy alone. In contrast, for integrated configurations using both PV and wind systems, the cost ranges from approximately $6.33–$8.87 per kg [124]. Furthermore, improvements in electrolysis design and system integration are enhancing the technology's durability, operational flexibility and compatibility with variable renewable energy sources. The combination of renewable energy and AWE shows great promise in meeting hydrogen needs in areas such as energy storage, transportation, chemical synthesis, and other industrial applications. This shows that AWE will be crucial in developing a sustainable hydrogen economy [125]. AWEs can absorb surplus wind generation, mitigating curtailment and converting variability into storable hydrogen for later use in industry, transport, or power. In high-wind penetration regions, curtailment can reach 5–15% of annual potential output—equivalent to >1 TWh/year in some European and Chinese provinces [102]. If captured for electrolysis, this surplus could produce over 200 kt H_2 annually in certain markets.

5.2.1. Multi-Energy System

Multi-energy systems (MES) represent an innovative approach that aims to optimize energy production and consumption by integrating different energy streams, such as electricity, heat and hydrogen, thereby providing cross-sectoral flexibility. In this context, alkaline water electrolysis units (AWEs) play a critical role in MES structures due to their capacity to convert renewable electricity into green hydrogen and their ability to recover heat generated during the process. Integrating AWEs increases system efficiency and enables the development of operational strategies that support sustainability and economic benefits [126,127]. Alkaline water electrolyzers (AWEs) produce hydrogen and significantly improve energy utilization by recovering waste heat generated during electrolysis. A detailed dynamic model has been developed to characterize the interactions between electricity, heat and hydrogen, and to capture the non-linear relationship between electrolysis efficiency, temperature and energy flows. The Economic Model Predictive Control (EMPC) approach optimizes daily operations by integrating a mixed integer linear programming (MILP) framework with the nonlinear P2H2 model. This achieves high computational efficiency while maintaining model accuracy. Indeed, this methodology demonstrates that cost savings can be achieved by 59% compared to rule-based strategies and 38% compared to traditional economic strategies without the P2H2 model. Using AWEs within the MES framework enables the storage of excess renewable energy as hydrogen, mitigates wind disruption and enables heat recovery for district heating systems (DHSs). In the context of Denmark's Bornholm Energy Island, for example, AWEs have played an active role in dynamically balancing energy flows by integrating with wind turbines, combined heat and power (CHP) plants, and battery energy storage systems (BESS) [127,128].

5.2.2. Grid Services and Operational Flexibility

When equipped with the right power electronics and control systems, alkaline water electrolyzers (AWEs) can help balance the grid by providing limited load-following capabilities. By contrast, PEM electrolyzers can typically handle load increases of around 5–10% of their nominal capacity per second, whereas slower-responding AWE systems operate at load ramp rates of around 1–5 MW per minute. However, AWEs can maintain minimum stable loads of around 10–20% of their nominal capacity, but require a cold restart that takes several minutes. Although there is less precise performance data for AWEs in the literature than for PEM systems, industrial-scale dynamic performance studies have confirmed these operational limitations [129,130,131]. In order to expand the operational range of alkaline water electrolyzers (AWEs) and reduce degradation caused by frequent cycling, intensive research is being conducted into new diaphragm materials and advanced control strategies. Meanwhile, AWEs and other electrolyzer technologies are increasingly being recognized as flexible resources capable of providing ancillary services such as frequency regulation, rotational reserve and voltage support. The ability of these systems to operate as controllable loads is dependent on their ability to adjust their power draw according to grid needs. However, the economic viability of these services depends not only on technical capabilities, but also on supportive regulatory frameworks, appropriate market structures (e.g. minimum bid sizes) and favourable operating conditions. From a market balance perspective, the participation of electrolyzers in ancillary services is largely limited by policy and market factors. This results in only a small amount of an electrolyzer's capacity being allocated to such services [131,132].

5.3. CAPEX, OPEX and LCOH

The design and economic evaluation of alkaline electrolyzers is predominantly informed by a cost-benefit analysis of capital expenditure (CAPEX) and operational expenditure (OPEX). Whilst alkaline systems generally offer lower capital costs (CAPEX) compared to PEM electrolyzers, both CAPEX and operating costs (OPEX) must be considered when selecting a technology. In the context of business operations, particularly with regard to the field of operations management, OPEX can exert considerable influence on the overall cost structure. Comprehensive capital expenditure (CAPEX) and operating expenditure (OPEX) modelling, incorporating financial metrics such as return on investment (ROI) and net present value (NPV), allows for more accurate investment evaluations and contributes to risk management by providing insights into equipment failures, maintenance requirements, and electricity price fluctuations.

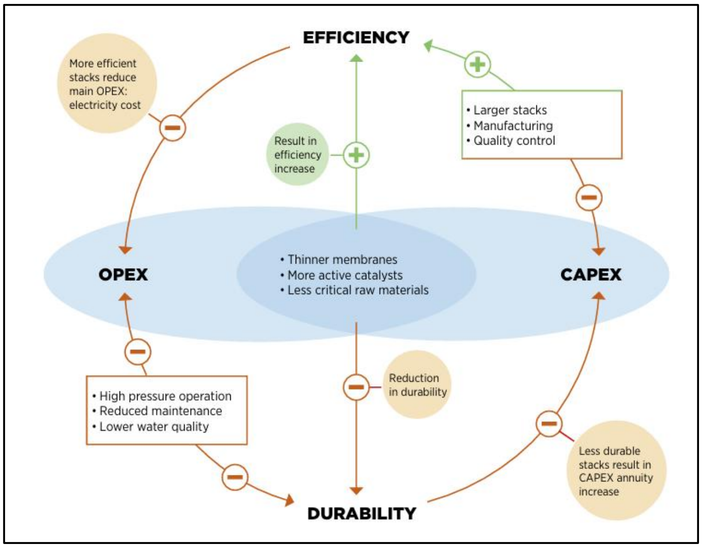

Figure 13. The relationship between efficiency, durability and cost in electrolyzers. Reproduced from IRENA (2020), [19].

From an operational perspective, labour, maintenance, and minor consumables (e.g. deionized water and KOH) constitute the second-highest cost items after electricity. The enhancement of economic sustainability can be achieved through the improvement of system performance and the strategic utilization of affordable renewable electricity. In general, considering CAPEX and OPEX calculations in conjunction with performance criteria and energy efficiency considerations enables the development of cost reduction strategies for large-scale applications and forms the basis for both the economic and environmental sustainability of alkaline electrolyzer projects [133]. Figure 13 provides a schematic representation illustrating the interplay between efficiency, durability, and cost in electrolyzers [19].

As stated in the 2020 report by the International Renewable Energy Agency (IRENA), the integration of reduced electricity production costs and the utilization of high-efficiency, long-life electrolyzers has the potential to offset approximately 80% of the costs associated with hydrogen production. It is projected that, in the long term, there will be a reduction in the cost of green hydrogen production by up to 85%, attributable to a combination of factors, including a reduction in electricity supply costs, increased capital investments in electrolyzers, and optimization of system efficiency [19]. As illustrated by Figure 14, a hypothetical cost-reduction scenario is proposed for the production of hydrogen.

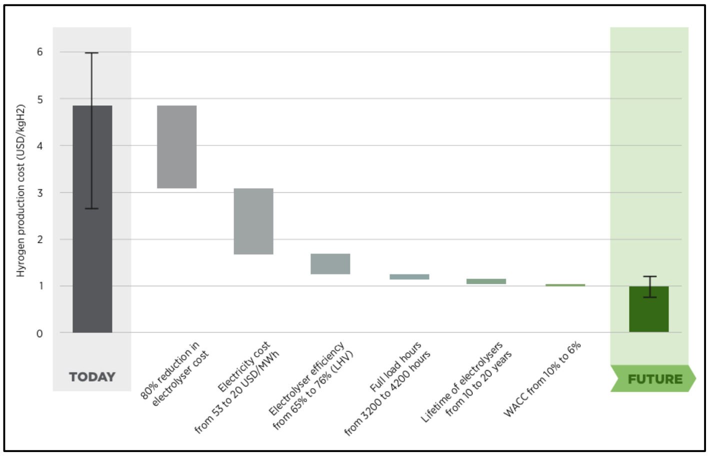

Figure 14. Scenario for reducing hydrogen production cost. Reproduced from IRENA (2020), [19].

5.3.1. OPEX (Operational Expenditure) Analysis

Operating costs (OPEX) for alkaline electrolyzers represent a pivotal factor in determining the economic sustainability of the system. Electricity consumption has been identified as the primary operational expenditure (OPEX) item, with approximately 60-80% of hydrogen production costs directly associated with electricity costs. In addition to electricity, labour, maintenance and repair activities, and minor consumables (e.g. deionized water, sealants) constitute other important components of OPEX. The proportion of total operating costs accounted for by electricity is typically between 50 and 80 per cent, depending on the scale of the plant, thus making it the largest component of OPEX. For instance, at a pilot manufacturing facility located in the city of Seongnam, the augmentation of its daily operational hours from four to twenty-four hours led to an escalation in electricity expenditures from 54% to 71%. Concurrently, expenditures on labour and the depreciation of equipment diminished [134]. This clearly demonstrates that an increase in operating hours has a direct impact on the relative cost of labour and maintenance, while concomitantly increasing the weight of energy costs in OPEX. The cost of electricity, which is the largest contributor to OPEX in alkaline electrolyzers, strongly depends on the energy source. Renewable options such as solar PV and onshore wind are preferred for green hydrogen production; however, their intermittent availability can limit operational hours and, consequently, affect OPEX. According to the U.S. Energy Information Administration, the levelized cost of electricity (LCOE) for new resources entering service in 2028 is estimated in Table 12 [135]. This table highlights that selecting low-cost renewable electricity can significantly reduce OPEX in green hydrogen production, emphasizing the importance of energy source choice for economic sustainability. Operating costs are slightly affected by the water feedstock. For every kilogram of hydrogen produced, large-scale alkaline electrolyzers require approximately 14 liters of deionized water [136]. Similarly, the electrolyte potassium hydroxide (KOH), currently sold at approximately $0.563 per kilogram, contributes negligibly to operating costs [137].

Table 12. Estimated LCOE for new resources entering service in 2028 [135].

Technology	Source	LCOE [USD/kWh]
dispatchable	ultra-super critical coal	0.089 $/kWh
	biomass	0.077 $/kWh
	advanced nuclear	0.071 $/kWh
	combined-cycle	0.042 $/kWh
	geothermal	0.037 $/kWh
resource-constrained	wind, offshore	0.100 $/kWh
	hydroelectric	0.057 $/kWh
	PV-battery hybrid	0.036 $/kWh
	wind, onshore	0.031 $/kWh
	solar PV	0.023 $/kWh
capacity resource	combustion turbine	0.128 $/kWh
	battery storage	0.118 $/kWh

The facility's configuration and operating method have a significant impact on labor and maintenance costs. Generally, operating, maintenance, and administrative labor costs account for 15–18% of total operating costs, ranging from $42,890 to $171,560 annually [134]. The main component of maintenance is chimney replacement, which has historically cost approximately half the original chimney price. However, if such a replacement is undertaken with the objective of extending the system's lifespan, it can be considered a capital expense (CAPEX) [136]. Consequently, the OPEX analysis reveals that electricity accounts for the largest share of operating costs, while labour, maintenance, and consumables have more limited but still notable secondary effects. Strategic focus on energy efficiency, low-cost renewable electricity, and optimized maintenance and workforce planning can substantially enhance the economic viability of alkaline hydrogen production.

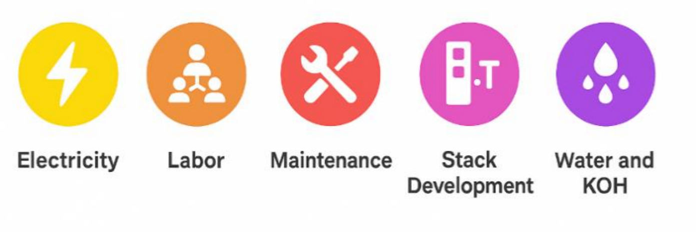

Figure 15. OPEX Components of AWE System

5.3.2. CAPEX (Capital Expenditure) Analysis

Capital expenditures (CAPEX) refer to the initial costs associated with the installation and long-term operation of alkaline electrolyzers. Key elements of CAPEX include the electrolyzer stack, the membrane electrode assembly (MEA), and Balance of Plant (BoP) systems, in addition to installation and engineering, procurement, and construction (EPC) activities. It is imperative to comprehend the concept of capital expenditure (CAPEX) in order to assess the economic viability of green hydrogen production, especially in the context of scaling and technological considerations. As demonstrated in Figure 16, the cost breakdown for a 1 MW Alkaline electrolyzer system is illustrated.

The electrolyzer stack is the central component, where the electrochemical reactions occur. Stack costs typically account for 40–50% of total CAPEX, with electrodes and diaphragms comprising the largest portion [19]. The accompanying material summary in Table 6 illustrate the components used in baseline (2020) and advanced (2030) AE stack designs. Such advancements in materials, combined with higher current densities and improved manufacturing processes, are projected to reduce stack costs from 242–388 €/kW in 2020 to 52–79 €/kW by 2030 [138,139]. Automation, learning-by-doing, and economies of scale are highlighted as critical factors driving these reductions. As illustrated in Table 13, the materials selected for the fundamental and sophisticated design of the AWE stack have been meticulously delineated.

Table 13. Materials used in baseline and advanced design AWE stack [138]

Components	Baseline (2020)	Advanced (2030)
Separator	Zirfon UTP 500	Zirfon UTP 220
Cathode	Ni plated perforated Carbon steel (156 μm)	Ni Mesh
Anode	Ni plated perforated Carbon steel (156 μm)	Raney Ni Coating (75 μm) Ni Mesh
Mattress	Not applicable	Ni mattress
Frames	Carbon steel (NEL design)	PSU+ 30% Glass Fiber
Gasket	Rubber	PTFE
Bipolar Plate	Ni plated Carbon steel (200 μm)	Ni plated Carbon steel (200 μm)
End Plates	Carbon Steel	Carbon Steel

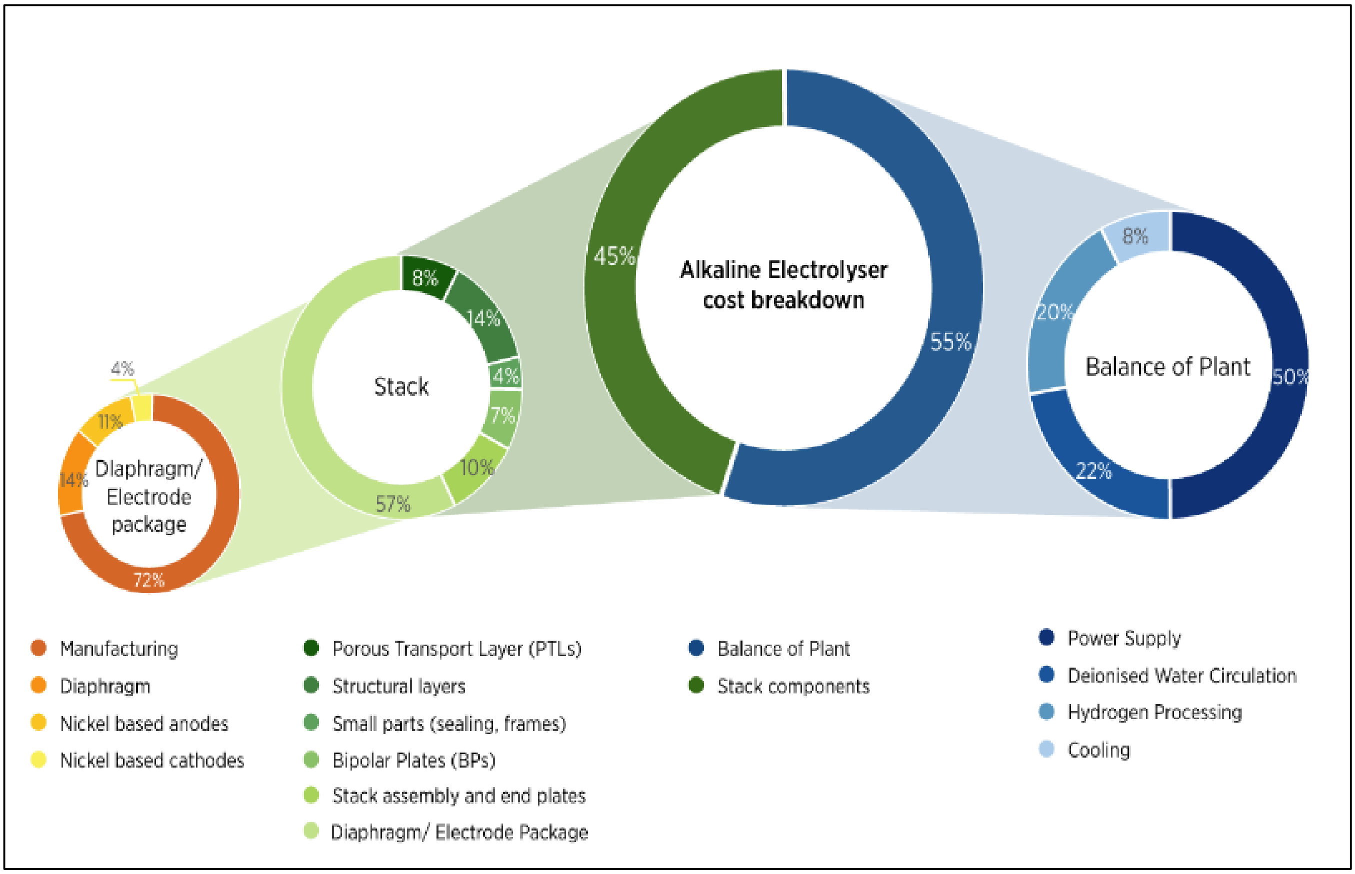

Figure 16. Cost breakdown for 1 MW AWE System. Reproduced from IRENA (2020), [19]

5.3.3. Levelized Cost of Hydrogen (LCOH)

Water treatment units, pumps, compressors, tanks for storing hydrogen and oxygen, electrical infrastructure, mechanical piping, and instrumentation are among the crucial auxiliary systems that make up the BoP. BoP's proportional share declines with scaling, even though it can account for as much as 60% of the overall system cost for small-scale electrolyzers [140]. The most expensive components of BoP are cooling systems and power electronics, particularly AC/DC rectifiers; however, modular designs and system optimization can reduce costs by up to 10% [141]. For instance, a 100 MW system's mechanical BoP is expected to drop from \$515 to \$418/kW, but the electrical BoP might marginally rise as a result of increased power demands [139]. Installation and commissioning, including EPC activities, are additional CAPEX components. These cover site preparation, mechanical and electrical connections, technical design, and logistics. Future projections for 1 MW alkaline systems estimate total CAPEX in the range of USD 700–1000/kW, with costs decreasing further for larger-scale plants due to economies of scale and design optimization [140,142,143].

The levelized cost of hydrogen (LCOH) is a critical metric for evaluating the long-term economic viability of a system. The term 'LCOH' is defined as a holistic function of factors such as total capital expenditures (CAPEX), operating expenses (OPEX), electricity price, system life, and annual production [144]. Therefore, the application of LCOH analysis provides a comprehensive evaluation of technological efficiency. In addition to this, it also reflects fluctuations in price, as well as economies of scale effects that occur within the domain of energy markets. LCOH for electrolyzers using renewable electricity has been estimated in a number of studies. Shaner et al. discovered 6–12 USD/kgH_2 for alkaline electrolyzers integrated with PV systems [145], while Yu et al. reported a range of 2.28–7.43 USD/kgH_2 in various countries [146]. With estimates of 3.50 to 5.46 USD/kgH_2 for nuclear PWR-powered systems, AE technologies can also make use of current nuclear power, resulting in lower hydrogen costs [147]. Renewable-based LCOH may eventually reach levels competitive with nuclear-powered systems as a result of declining material costs and seasonal intermittency issues as renewable energy technologies advance [148]. Regional analyses further demonstrate the influence of energy source and grid integration on LCOH. For instance, based on electrolyzer costs of \$250/kW reported by IRENA, the LCOH for a 0.7 MW small-scale facility operating 20 hours per day is approximately \$12.8/kgH_2, slightly lower than the \$15.6/kgH_2 calculated using actual operational data [19,134]. When grid electricity was added to solar-only systems in Japan's Kyushu region, the LCOH went down from \$3.61/kgH_2 to \$3.20/kgH_2. Wind-only systems went down from \$3.57/kgH_2 to \$2.49/kgH_2 under the same conditions [149]. The LCOH in Saudi Arabia changes based on how renewable energy is combined with electrolyzers and fuel cells. The LCOH values for PV-FC systems are between 40 USD/kgH_2 in Jeddah and 45.4 USD/kgH_2 in Dhahran. Wind-FC systems usually cost more, with prices ranging from 55.8 USD/kgH_2 in Jeddah to 57.7 USD/kgH_2 in Dhahran. The lowest LCOH value for hybrid PV-Wind-FC setups is 47.2 USD/kgH_2 in Riyadh, and the highest is 63.8 USD/kgH_2 in Toronto. These results highlight that both the choice of renewable energy technology and regional factors, such as solar and wind resource availability, significantly influence hydrogen production costs [150]. As illustrated in Table 14, a comparative analysis of hydrogen production costs per kilogramme is presented, with data drawn from various countries and technologies. Table 14 provides a comparative overview of the costs associated with hydrogen production per kilogramme across various countries and technologies. The data presented in the Table 14 unequivocally demonstrates that LCOH is not a static figure, but a dynamic metric requiring multidimensional analysis. Geographic and regional factors have been identified as having a significant impact on final costs. For instance, the high wind potential in Ireland allows for a competitive LCOH target of 2.75 €/kgH2. Conversely, analysis for China assuming a thermal-dominated grid results in a significantly higher LCOH of approximately 3.996 €/kgH2 (RMB 33.30/kg) [152,153]. This indicates that the cost of green hydrogen is contingent on the cost and carbon intensity of the electricity utilized. It has been demonstrated by a considerable number of studies that electricity costs account for more than 60-70% of total LCOH [151-155]

Table 14. Levelized cost of hydrogen values in various countries and technologies.

LCOH Value ($/kg or €/kg)	Production Method / Technology	Region / Country	Main Focus	Ref.
For AWE; 4.605 $/kgH$_2$ (unsubsidized) 1.605 $/kgH$_2$ (with IRA) For PEMWE: 5.485 $/kgH$_2$ (unsubsidized) 2.485 $/kgH$_2$ (with IRA)	Wind-powered Electrolysis, Green H$_2$,(AWE, PEMWE)	USA (Wyoming)	The Inflation Reduction Act (IRA) tax credits have a dramatic effect on reducing costs for LCOH.	[151]
For 2030 Projection: ranges from 3.53 €/kgH$_2$ to 4.01 €/kgH$_2$ For 2040 Projection: ranges from 2.75 €/kgH$_2$ to 3.34 €/kgH$_2$	Green H$_2$ (PEMWE)	Ireland (Dublin, Wexford, Cork)	The impact of the potential of regional renewable resources (Wind offshore and Solar PV) on LCOH and future cost projections.	[152]
For SMR: 17.60 RMB/kg For CGH: 10.70 RMB/kg For SMR+CCUS: 20.06 RMB/kg For ATR+CCUS: 19.94 RMB/kg For CGH+CCUS: 11.45 RMB/kg For MSW: 10.95 RMB/kg For AWE: 33.30 RMB/kg For PEMWE: 34.85 RMB/kg For SOEC: 38.42 RMB/kg (1 RMB ≅ 0,14 $)	Natural gas hydrogen production (SMR, SMR + CCUS, ATR + CCUS), Coal hydrogen production (CGH, CGH + CCUS), municipal solid waste hydrogen production (MSW), and AWE, PEWE, SOEC	China	To analyse the production costs and cost structures of nine hydrogen production processes operating at the same scale.	[153]
For Grid; LCOH with oxygen: 7.91 €/kgH$_2$ LCOH without oxygen: 7.44 €/kgH$_2$ For Grid+PV: LCOH with oxygen: 6.75 €/kgH$_2$ LCOH without oxygen: 6.28 €/kgH$_2$	Green H$_2$ (AWE)	Germany	In order to ascertain the most profitable financial model for the energy system project. two scenarios were examined: the operation of the on-site water electrolysis with electricity from the grid only, or with a combination of its own PV system and PV electricity supplied from the grid.	[154]
For Gray H$_2$ (SMR): LCOH between 1.50 and 2.50 $/kgH$_2$ For Blue H$_2$ (SMR+CCS): LCOH between 2.00 and 3.50 $/kgH$_2$ For Green H$_2$ (Electrolysis): LCOH between 3.50 and 6.00 $/kgH$_2$	Gray H$_2$ (SMR) Blue H$_2$ (SMR+CCS) Green H$_2$ (Electrolysis)	USA	A thorough and detailed techno-economic assessment of hydrogen production for different hydrogen colors, including an analysis of cost structures, investment feasibility, infrastructure challenges and policy-driven market dynamics.	[155]

5.3.3.1. LCOH Results for Base Current and Future Cases

A decline in LCOH is expected worldwide by 2050. On average, there was a decline of approximately 35% by 2030, followed by a further 30% by 2050. An average cost of approximately 0.67 to 2.6 USD/kg is expected for 2050 [156]. These trends can be linked to energy policies, electricity costs, and access to renewable energy in different regions. The average LCOH value for Europe is set at $2/kg in 2022, with further declines expected [157]. However, the United Arab Emirates is projected to reach similar values to Europe by 2050 [158]. Europe is particularly cost-advantaged using renewable energy sources. A detailed LCOH analysis employing the H2A model was conducted in a report published by the National Renewable Energy Laboratory (NREL). The study evaluated both low-pressure (LP) and high-pressure (HP) existing centralized scenarios, as well as future centralized LA technology scenarios. The analysis was predicated on the assumption that the plant would operate at a capacity factor of 97%, and that the electricity price would be $0.03/kWh. In such circumstances, the total installation cost of a 100 MW plant was estimated at $125.9 million, while the cost of a 1 GW plant was estimated at $779.5 million. However, given the recent technological advances and the impact of economies of scale, significant cost reductions are anticipated. Indeed, it is predicted that in the future, the installation cost of a 100 MW system could fall to $85.3 million, and the cost of a 1 GW system could fall to $516.2 million [139]. The findings indicate that both technological advances and scale-up play critical roles in making AWE systems more competitive in the long term. Consequently, LCOH analysis is a critical tool for determining the economic competitiveness of AWE technology. As demonstrated in Figure 17, the competitiveness of alkaline electrolyzers in hydrogen production at costs below $2/kg is contingent on the accessibility of low-cost electricity supply and the scalability advantages offered by the technology.

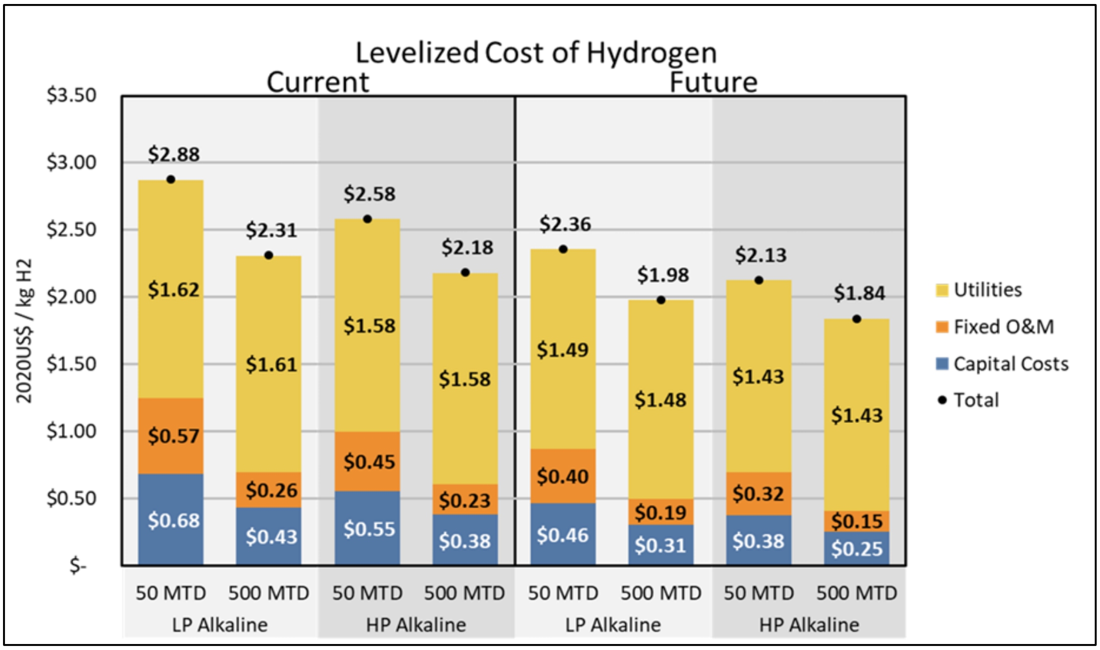

Figure 17. Projected levelized cost of hydrogen (LCOH) summarized by sub-component for low pressure (LP) and high pressure (HP) Alkaline. Reproduced from Acevedo, Y. M. et al. (2023), [139], licensed under CC BY 4.0.

6. ENVIRONMENTAL AND SUSTAINABILITY CONSIDERATIONS

While alkaline water electrolyzers (AWEs) offer significant economic advantages in scaling up green hydrogen production, they also require comprehensive environmental and sustainability assessment. In this context, life cycle analyses (LCAs), water use, gas purity, and recycling strategies are of critical importance in order to understand the technology's long-term environmental impacts and its sustainability potential.

6.1. Lifecycle Analysis (LCA)

As delineated by the ISO 14040 and ISO 14044 standards, life cycle analysis (LCA) constitutes a pivotal environmental management instrument. This analytical framework involves the examination of the prospective interactions between a technical system (techno sphere) and the surrounding environment. A thorough Life Cycle Assessment (LCA) of alkaline electrolyzers necessitates the evaluation of the environmental implications at each stage of the process, encompassing raw material extraction, production, operation, end-of-life disposal, and recycling [159]. For instance, Hoppe and Minke's study demonstrates that the production of an AWE system from recycled materials results in a 50% reduction in global warming potential (GWP) in comparison with copper materials [160]. In addition, the research conducted by Koj et al. on the German case study has revealed a crucial link between nickel usage and water treatment processes, and the substantial environmental impact of AWE systems. However, the same study posits that emissions will gradually decrease, falling from 27.5 kg CO_2-eq per kg H_2 produced to 1.33 kg CO_2-eq by 2045, thanks to technological advances and increased integration of renewable energy [161]. The issue of end-of-life disposal remains a critical consideration for the environmental sustainability of alkaline electrolyzers. In this regard, the development of closed-loop recycling systems has the potential to both minimize waste and reduce reliance on raw material extraction. A number of studies have been conducted that suggest implementing effective recycling strategies can reduce the environmental impact of the system by as much as 30% [162,163].

6.2. Water Use, Gas Purity and Recycling Strategies

Water, the primary input for hydrogen production, is a key factor to consider in AWE's environmental assessment. It is estimated that approximately 9 liters of pure water are required to produce 1 kilogram of hydrogen. This underscores the critical importance of effective water management in large-scale hydrogen production projects. It is evident that seawater desalination and wastewater reuse are two sustainable strategies that are of particular importance in regions experiencing water stress [164,165]. AWE systems have also been demonstrated to be capable of producing hydrogen of a high degree of purity (>99.9%), however, the effective maintenance of gas purity is dependent upon the effective use of pressure swing adsorption (PSA), membrane separation, and gas-liquid separators. Moreover, the recovery and reuse of the KOH electrolyte solutions employed in the system have been shown to result in a reduction of environmental waste and a corresponding decrease in operating expenses. Within this paradigm, closed-loop recycling strategies are pivotal to ensure the long-term environmental sustainability of AWE [160,163].

6.3. Comparison with Other H_2 Production Methods

The impact of AWE on environmental sustainability is more clearly delineated when compared to other hydrogen production methods. Steam methane reforming (SMR), the predominant method of hydrogen production, with a global share exceeding 90%, has been found to generate approximately 8–10 kg of CO_2 per 1 kg of hydrogen [19,166]. Furthermore, coal gasification has an even higher emissions intensity. Conversely, AWE produces negligible direct emissions when operated with renewable energy [161]. While PEM electrolysis offers higher current densities and compact designs, the use of rare and costly metals such as platinum and iridium represents a significant sustainability constraint. Systems utilising SOEC technology demonstrate considerable potential for efficiency enhancement; however, they are also susceptible to long-term stability and material durability concerns arising from the elevated operating temperatures [20,45]. In this context, AWE is distinguished as the most mature and viable option in terms of balancing sustainability and environmental benefits, owing to its inexpensive, abundant nickel-based electrode materials and long-life design.

7. CONCLUSION

This study comprehensively examines the role of alkaline water electrolysis (AWE) technology in green hydrogen production, a technology central to the global energy transition. In the context of the global climate change emergency, there is an increasing need for low-carbon energy carriers, and the strategic importance of hydrogen is becoming ever more apparent. This study provides substantial evidence to support the conclusion that AWE is a significant technology in the production of green hydrogen, owing to its commercial maturity, low investment and operating costs, stable performance, and its capacity for integration with renewable energy sources. The performance and economic viability of AWE are directly related to the design and material properties of key components such as electrodes, electrolytes, membranes, and separators. Recent advancements in membrane technologies, electrode materials with enhanced corrosion resistance, and more efficient electrolyte solutions have contributed to increased energy efficiency and extended system life. Furthermore, advancements in cell design, exemplified by bipolar and zero-gap configurations, have facilitated enhanced current densities and diminished ohmic losses, thereby augmenting the technology's competitiveness. Nevertheless, challenges such as efficiency losses at part loads and limited dynamic response time persist as areas for improvement in the domains of material utilization and system control. From an economic perspective, analyses of capital expenditure (CAPEX), operating expenditure

(OPEX) and levelized cost of hydrogen (LCOH) calculations demonstrate that AWE offers a sustainable and viable solution for large-scale green hydrogen production. The affordability of low-cost renewable electricity sources, economies of scale, and advanced control strategies have been shown to have a significant impact on the cost of hydrogen production. Projections from organizations such as the National Renewable Energy Laboratory (NREL) and the International Renewable Energy Agency (IRENA) indicate that, with technological advancements, it may be possible to achieve hydrogen production costs below $2/kg, which would render AWE a significant component of energy markets in the long term. In this context, in countries with high renewable energy potential – especially Türkiye – AWE is expected to emerge as a competitive option for both energy storage solutions and industrial process integration. However, in order to achieve this potential, it is essential that infrastructure, storage, and distribution investments are supported by a comprehensive national roadmap. The present study evaluates alkaline water electrolysis (AWE) technology from multiple perspectives, including, but not limited to, electrochemical and material considerations. Additionally, the investigation encompasses a holistic framework that considers market dynamics, policy objectives, and environmental sustainability. In addition, the study provides an analytical assessment that comprehensively examines the strategic roadmaps of Türkiye and the MENA region, relating these objectives to electrolyzer efficiency, cell/system design, and cost drivers. It thereby demonstrates the potential of regional energy transformation with concrete technical and economic indicators. A review of the extant literature indicates that research on next-generation membranes and catalysts for AEM and SOEC is currently fragmented, and that differences in CAPEX–OPEX methodologies and currencies limit the comparability of results. It is vital to enhance the scale and scope of experimental and modelling research on the integration of renewable energy, in order to adapt technologies to actual real-world field conditions and develop robust business models. Therefore, the present study is distinguished not only by its comprehensive review of the relevant literature, but also by its integration of the policy-market-technology axis. This integration provides a guiding framework for the design of future research and the development of future applications. In conclusion, the advantages of AWE technology in terms of environmental sustainability, economic viability and technical maturity position it at the center of green hydrogen production. Future studies are advised to concentrate on the following areas: high-performance electrode and membrane materials, advanced electrolyte solutions, new cell designs and intelligent control strategies. In addition, the implementation of solutions in areas such as system integration and the recovery of waste heat, in addition to adaptation to multi-energy systems (MES), is expected to enhance AWE's efficiency, thereby contributing to the promotion of both economic and environmental sustainability. This will enable AWE to become a leading technology not only in today's clean energy systems, but also in future ones.

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