

# Integrating Marine Renewable Energy with Green Hydrogen Production from Seawater: Feasibility and Future Prospects for Sustainable Energy Development in Indonesia

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## Abstract

This study examines the feasibility and prospects of integrating marine renewable energy (MRE) with green hydrogen production in Indonesia. As global energy demand increases and the environmental impacts of fossil fuels become more pronounced, the search for sustainable alternatives intensifies. Indonesia, with its extensive maritime resources, presents a unique opportunity to harness tidal wave and offshore wind energy for green hydrogen production from seawater. This research explores various electrolysis methods, particularly those that eliminate the need for desalination, thereby enhancing efficiency and reducing costs. The findings indicate that advanced electrolysis techniques can significantly lower energy and production costs while maintaining environmental sustainability by avoiding harmful chemicals and ensuring minimal ecological footprints. Moreover, the utilization of Indonesia's extensive marine resources can foster energy independence, boost economic growth, and lower carbon emissions, which highlights the need for ongoing research and optimization to improve the economic and environmental feasibility of these technologies. This review article provides an in-depth analysis of the potential for MRE and green hydrogen production in Indonesia, outlining a viable path toward sustainable energy development.

**Keywords** Marine renewable energy; Green hydrogen; Green hydrogen production; Seawater electrolysis; Sustainable energy

## 1 Introduction

The energy demand is essential, given that technological

### Article Highlights

- The study explores the integration of Marine Renewable Energy (MRE) like tidal, wave, and offshore wind with green hydrogen production from seawater to support sustainable energy development in Indonesia.
- Various advanced electrolysis methods that eliminate the need for desalination are examined, focusing on catalysts and electrolyzers suitable for high-salinity environments.
- The study compares three methods of seawater-based green hydrogen production—Photoelectrochemical Seawater Splitting (PSS), Anion Exchange Membrane (AEM) electrolysis, and Direct Seawater Electrolysis (DSE)—evaluating each for material durability, efficiency, cost, and scalability, with DSE emerging as the most efficient.
- Utilizing MRE for green hydrogen reduces fossil fuel dependence, cuts carbon emissions, promotes energy independence, and supports environmental sustainability in coastal areas.

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advancements driven by the progression of time rely heavily on energy input as the primary force behind energy conversion systems and devices (Shabalov et al., 2021). Nonrenewable energy sources, such as coal, oil, nuclear energy, and natural gas (Wang et al., 2023a), have been widely employed in multiple sectors. Oil is used as fuel for vehicles and machinery (Troisi et al., 2016; Awodumi and Adewuyi, 2020) and plays a crucial role in producing plastics, synthetic fibers, explosives, and fertilizers. Coal is mainly utilized for generating electricity and in industrial processes (Putri et al., 2021), fueling numerous power stations globally. Natural gas is highly adaptable (Lin and Ullah, 2024), being used for electricity generation, heating, and various industrial purposes. Nuclear energy produces electricity through nuclear fission in power plants. Although these energy sources are extensively used because of their availability and ease of extraction, their limited supply and environmental impact have prompted the pursuit of renewable energy alternatives (Jiang et al., 2024b; Wang, 2024).

Renewable energy is derived from natural resources that are continuously replenished (Akhtar and Rehmani, 2015; Han et al., 2023b), including wind, solar, water, and geothermal heat. The utilization of these sustainable sources

decreases the dependence on finite fossil fuels, which significantly contribute to climate change. The most promising is marine renewable energy (MRE), which is a specific type of renewable energy that captures power from oceanic elements, such as waves, tides, currents, and temperature variations, to produce electricity (Samsó et al., 2023; Agye-kum et al., 2024). This largely untapped resource includes technologies for current energy, temperature differential energy, wave energy, and tidal energy. In the US (Scroggins et al., 2022), MRE met approximately 60% of the annual electricity requirements and successfully reduced the emissions caused by the nonrenewable energy process (Liguo et al., 2022). In addition, MRE has the potential to supply power to remote communities, support offshore industries, and help achieve a carbon-free energy sector. Although MRE is still in the developmental phase, it holds significant potential. Current research aims to address the challenges, such as the corrosive ocean environment, and enhance the efficiency and cost-effectiveness of these technologies.

With potential technologies that will require further studies and development, this review article specifically focuses on MRE and green hydrogen. Because green hydrogen production from seawater is among the most promising renewable energy sources, it has substantial potential to lower greenhouse gas emissions and combat climate change (Pérez-Vigueras et al., 2023; Weidner et al., 2023). International studies confirm its technical and economic viability. The method leverages renewable energy from offshore wind and marine sources to stabilize the power grid and decrease fossil fuel dependency (Hassan et al., 2023b). Using seawater rather than freshwater for electrolysis is advantageous because of its abundance and reduced environmental impact (Bian et al., 2023). MRE can power the electrolysis process, boosting the overall efficiency. Most research emphasizes the feasibility of direct seawater electrolysis (DSE), underscoring the need to optimize catalysts and electrolyzer designs to enhance efficiency and reduce costs, highlighting the potential of this technology in the renewable energy sector (d'Amore-Domenech et al., 2020; Hausmann et al., 2021). One major limitation of seawater-based green hydrogen production is the high energy needed for electrolysis, which hinders its commercial viability (IRENA, 2020). In addition, the use of seawater can create corrosive compounds that damage electrolysis equipment, increasing operational costs (Zhao et al., 2024a). The efficient splitting of seawater into hydrogen and oxygen requires advanced technologies, including specialized electrolyzers and catalysts that work effectively in high salt concentrations and other impurities (IRENA, 2021; Patonia and Poudineh, 2022). Despite these challenges, the potential for seawater-based green hydrogen production is significant. The development of global research to improve the efficiency and cost-effectiveness of this process has already attracted investments from several companies.

A systematic analysis of research trends in green hydrogen production reveals numerous innovative findings and increasingly advanced methods, promising significant development in Indonesia, a country with vast maritime territory and substantial potential in this field (Haris, 2023). MRE and green hydrogen production are critical components in transitioning to sustainable and low-carbon energy solutions. The integration of MRE (such as wind and wave energy) with green hydrogen production provides a comprehensive and sustainable approach to meeting future energy demands and reducing carbon emissions. MRE sources, such as offshore wind and wave energy, are strong candidates for sustainable hydrogen production because of their high energy capacity and minimal environmental footprint. In particular, wave energy provides a reliable and consistent power output, making it an attractive option. A proposed system for offshore hydrogen production, which operates independently of the grid and is powered by wave energy, integrates polymer electrolyte membrane (PEM) electrolyzers, a desalination plant to produce the required low-conductivity water, and a compression unit to store hydrogen. This system can produce approximately  $1.595 \text{ N}\cdot\text{m}^3$  of hydrogen daily, with an energy consumption rate of  $4.2 \text{ kWh}/(\text{N}\cdot\text{m}^3)$  hydrogen. The system efficiently harnesses wave energy, which can generate up to 1 MW, with 88% of the energy used in electrolysis, 9% of the energy used in compression, and 3% of the energy used in desalination and other processes (Serna and Tadeo, 2014). Strategic utilization of these resources can significantly contribute to global efforts to achieve sustainable energy in the future. Extensive studies of the feasibility of green hydrogen production from oceanic energy highlight the technical and economic viability of harnessing MRE for hydrogen generation. These studies underscore the importance of leveraging marine resources to produce green hydrogen, serving as a clean fuel for various applications, including transportation and industrial processes (Pérez-Vigueras et al., 2023). In North America, the exploration of hydrogen production and its potential applications has highlighted both opportunities and challenges in integrating renewable energy with hydrogen systems. Biomass gasification, particularly through supercritical water gasification, emerges as a highly promising approach for sustainable hydrogen generation. This process, which utilizes various biomass sources, such as sunflower, corncob, leather waste, and coal, shows notable improvements in gas yields and char formation predictions when using a refined Gibbs free energy model. For instance, the gas yields and char formation from sunflower, corncob, leather waste, and coal are improved by 85.37%, 62.52%, 89.30%, and 34.05%, respectively, compared with those of the basic model (Mohamadi-Baghmolaei et al., 2022). Effective policy support is crucial to further promote the adoption of green hydrogen within the energy sector (Madadi Avargani et al., 2022). In Morocco, the use of

MRE for green hydrogen production has been identified as a key strategy to achieve sustainable development and energy security (Taroual et al., 2024). The potential of green hydrogen also significantly supports the energy transition of Europe, with the Hydrogen Roadmap Europe (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019), which could cover 24% of the global energy demand by 2050. The economic impact is projected to contribute €820 billion to the European economy, alongside the creation of approximately 5.4 million jobs by 2050. The achievement of this potential requires cross-sector collaboration and substantial investment in technology and infrastructure.

Recent studies categorize green hydrogen production methods into several main groups, including water electrolysis using renewable energy, biomass reforming, and photocatalysis (Hassan et al., 2024; Zainal et al., 2024). In the context of seawater electrolysis, material classification is crucial, focusing on developing corrosion-resistant and efficient electrolyzers and catalysts for high salinity conditions (Jiang et al., 2022; Liu et al., 2023; Kasani et al., 2024). The techno-economic analysis of PEM water electrolysis coupled with offshore wind turbines conducted by Groenemans et al. (2022) reveals a promising integration that significantly reduces costs and enhances efficiency. The levelized cost of hydrogen could be as low as \$2.09/kg H<sub>2</sub>, compared with \$3.86/kg using traditional methods. This approach leverages the direct current power of wind turbines and eliminates multiple electrical conversion steps, resulting in higher efficiency and lower capital expenditures. Durability and efficiency analyses indicate that noble metals, such as platinum and iridium, are often used as catalysts because of their high efficiency (Hota et al., 2022). However, their high costs have driven research toward more economical alternatives, such as nickel-based materials (Almomani et al., 2024). The integration of insights from the recent study conducted by Sari et al. (2024) of the ecological balance of Bawean Island with the potential for green hydrogen production from seawater ensures a comprehensive understanding of how Indonesia can leverage its maritime resources for sustainable development. The systematic analysis of one of the representative islands of Indonesia underscores the importance of balancing technological advancements and ecological preservation, a theme also central to the development of green hydrogen technologies. Comparative studies of various methods of green hydrogen production, such as DSE, highlight the need to achieve high efficiency, low cost, and durability in seawater environments. By integrating these findings with the challenges and potentials identified, a novel approach to sustainable energy production emerges. For instance, the potential integration of MRE, such as wave and tidal energy, with green hydrogen production could address both energy needs and environmental concerns, reducing the reliance on fossil fuels and minimizing ecological impacts.

Therefore, the environmental impacts of these technologies must be carefully considered, ensuring that the development of green hydrogen aligns with the broader goals of ecological preservation and socioeconomic sustainability. By leveraging data from international studies and focusing on enhancing the efficiency, cost-effectiveness, and durability of green hydrogen production, Indonesia can harness its maritime resources to drive sustainable development. The findings from Bawean Island indicate that an integrated approach, combining renewable energy technologies with ecological management strategies, can provide a pathway to low-carbon and sustainable energy in the future. This comprehensive strategy, supported by continuous research and collaboration among stakeholders, will be crucial in realizing the full potential of green hydrogen production in coastal regions of Indonesia, ensuring that these initiatives contribute positively to both the environment and local communities.

## 2 Marine renewable energy

MRE is the method that harnesses vast resources, such as tidal, wave, and offshore wind energy, to generate electricity (Taveira-pinto et al., 2019). This method provides a clean and sustainable alternative to traditional fossil fuels because it does not emit greenhouse gases or contribute to climate change (Hasan et al., 2024). In Canada, MRE has the potential to produce over 2 300 GW of electricity (Forrest et al., 2022), which is more than 20 times the current hydroelectric capacity of the country. However, development is hindered by regulatory challenges, high costs, and competition from land-based renewables. Despite these obstacles, MRE holds promise for helping Canada achieve its net zero emissions goal by 2050, especially given that it can provide more predictable and consistent energy than terrestrial options. Tidal energy uses the predictable movements of the tides to drive turbines, providing a reliable power source (Berkowitz, 2023). Wave energy harnesses the power of surface waves to generate electricity, taking advantage of the consistent wave activity found in many coastal areas. The potential for wave energy worldwide is significant, with estimates ranging from 8 000 TWh to 80 000 TWh annually, depending on the specific location and wave conditions. For instance, the Asian and Australasian regions have wave energy potentials of 6 200 and 5 600 TWh/year, respectively, whereas North and South America contribute 4 600 and 4 000 TWh/year, respectively (Satriawan et al., 2021). Offshore wind energy employs turbines placed in bodies of water where wind speeds are higher and more consistent than on land, resulting in more efficient energy production (Perveen et al., 2014). The implementation of these marine renewable systems has significant economic and environmental benefits, including

job creation in manufacturing, installation, and maintenance, particularly in coastal areas, and reducing fossil fuel dependence, thereby decreasing air pollution and mitigating climate change can coexist with other marine activities, such as fishing and tourism, promoting balanced use of marine resources (Ringwood, 2022). Green hydrogen production from seawater stands out as a highly promising and lucrative technology within MRE. This assertion finds support in a collaborative report from the International Renewable Energy Agency (IRENA) and Bluerisk (IRENA, 2023), as shown in Table 1, which delves into a detailed examination of the water implications associated with the global hydrogen industry that underscores the crucial necessity of integrating water considerations with energy planning, especially in regions confronted with water scarcity, to ensure the sustainable and resilient development of both the energy and water sectors.

Recent empirical data underscore the vast potential of MRE, with global ocean energy resources estimated at 32 000 GW, outpacing both solar and wind energy. Among the various MRE technologies, wave and tidal energy are the most advanced, with wave energy alone projected to generate between 16 000 TWh and 18 500 TWh annually. These figures highlight the critical role that MRE can play in transitioning to sustainable energy, particularly because of the predictability and reliability of tidal energy, which provides a competitive advantage over other renewable sources (Agyekum et al., 2024). In Indonesia, a country endowed with extensive marine resources, MRE presents a significant opportunity to diversify the national energy mix and enhance energy security. Indonesia's commitment to increasing the share of renewable energy is evident in its Renewable Energy Development Acceleration Program (REDAP) and various Presidential Regulations aimed at expanding renewable energy sources (Trijono, 2023). The

integration of MRE with the blue economy has also emerged as a significant driver for its adoption. In some regions, such as the Iberian Peninsula, the development of MRE is closely tied to the growth of the blue economy, as these technologies align with sustainable economic practices. Similarly, in Indonesia, the blue economy is a crucial component of the national economic strategy, focusing on the sustainable use of marine resources. Leveraging MRE within this framework can contribute to economic diversification, job creation, and sustainable utilization of marine ecosystems (Lafoz et al., 2024).

Despite its potential, MRE development faces several challenges, including regulatory and economic barriers, which necessitate a supportive legal and policy framework. Indonesia has been actively refining its renewable energy regulations to encourage investment and development, as stated in Presidential Regulation No. 112 of 2022 (Presiden RI, 2022), which accelerates the development of renewable energy sources. Maritime spatial planning is essential in resolving space use conflicts and enabling MRE to coexist with other marine activities, such as fishing and tourism. In addition, the advancement of energy storage technologies and offshore infrastructure is vital for the success of MRE projects. The pace of technological innovation and access to comprehensive metocean data significantly impact MRE development (Presiden RI, 2006; Taveira-pinto et al., 2019). Furthermore, the synergy between MRE and green hydrogen production has been growing, particularly through the use of offshore wind energy to power electrolysis processes (Peiffer et al., 2024). This synergy presents a unique opportunity to scale up green hydrogen production, which could play a pivotal role in decarbonizing various sectors. Indonesia's REDAP and its commitment to reducing greenhouse gas emissions align with the potential benefits of integrating MRE with green

**Table 1** Roadmap to green hydrogen production

2022–2023	2024–2026	2029–2036
<ul style="list-style-type: none"> <li>• Three or more potential pathways identified to achieve Hydrogen Shot goals.</li> </ul>	<ul style="list-style-type: none"> <li>• Conducted 10 or more demonstrations involving renewables (including offshore wind), nuclear, and waste/fossil fuels with CCS.</li> </ul>	<ul style="list-style-type: none"> <li>• Generate at least 10 million metric tons of clean hydrogen annually from diverse sources by the year 2030.</li> </ul>
<ul style="list-style-type: none"> <li>• Conducted 10 000 h of high-temperature electrolyzer testing.</li> </ul>	<ul style="list-style-type: none"> <li>• Achieve \$2/kg clean hydrogen from large-scale electrolysis by 2026.</li> </ul>	<ul style="list-style-type: none"> <li>• Achieve \$1/kg clean hydrogen production from diverse resources at scale.</li> </ul>
<ul style="list-style-type: none"> <li>• Assessed three or more paths for life cycle emissions and incorporated 1.25 MW of electrolyzers with nuclear power for producing hydrogen.</li> </ul>	<ul style="list-style-type: none"> <li>• Low-temperature electrolyzers to have 51 kWh/kg efficiency, 80 000 h lifespan, and \$250/kW cost.</li> </ul>	<ul style="list-style-type: none"> <li>• Low-temperature electrolyzers to have 46 kWh/kg efficiency, 80 000 h lifespan, and \$100/kW uninstalled cost.</li> </ul>
<ul style="list-style-type: none"> <li>• Approved two or more conditional loan program agreements.</li> </ul>	<ul style="list-style-type: none"> <li>• High-temperature electrolyzers to have 44 kWh/kg efficiency, 60 000 h lifespan, and \$300/kW cost.</li> <li>• Deployed 20 MW of nuclear heat extraction, distribution, and control to facilitate electrolysis.</li> </ul>	<ul style="list-style-type: none"> <li>• High-temperature electrolyzers to have an 80 000 h lifespan and \$200/kW cost while maintaining or improving efficiency.</li> </ul>

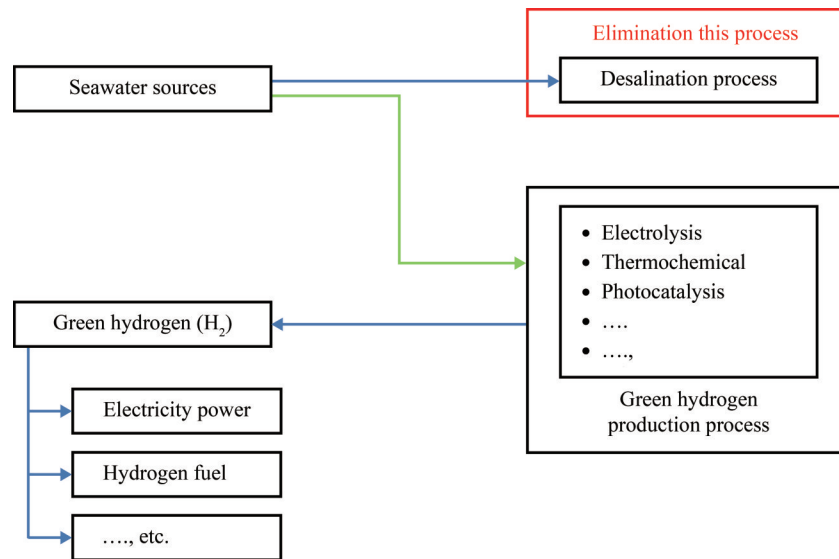
hydrogen technologies. However, realizing this potential requires overcoming technical, societal, and environmental challenges, alongside the establishment of robust policy frameworks to support the integration of these technologies.

### 3 Green hydrogen production from seawater

Green hydrogen production from seawater involves utilizing renewable energy sources, such as solar, wind, or tidal power, to electrolyze seawater into hydrogen and oxygen (Rezaei et al., 2018; Squadrito et al., 2023). This approach provides numerous benefits by integrating renewable energy, decreasing reliance on fossil fuels, and mitigating greenhouse gas emissions (Rezaei et al., 2018). The use of seawater, which is abundant and renewable, reduces the demand for freshwater and minimizes the environmental impact of water extraction. For instance, a study of decommissioned offshore platforms in Malaysia determined that converting these platforms into solar-powered hydrogen production sites could generate 8.6–18 kg of green hydrogen daily, depending on the configuration of the system and the type of electrolyzer used (Simoes et al., 2021; Alias and Go, 2023). Green hydrogen serves as a clean energy carrier, replacing fossil fuels in several sectors, such as transportation, power generation, and industry, thereby supporting energy system decarbonization (Osman et al., 2022). Green hydrogen production also creates job opportunities and stimulates economic growth, particularly in coastal areas (New Climate Institute, 2023). The methods for green hydrogen production from seawater involve various electrolysis techniques, namely, standard electrolysis powered by renewable energy; cost-effective and efficient alkaline electrolysis (Horri and Ozcan, 2024); proton exchange membrane electrolysis (El-Shafie, 2023), which provides higher efficiency and purity; and solid oxide electrolysis, which is known for its high efficiency and durability in hydrogen production from seawater. For example, solid oxide electrolysis can reach an energy conversion efficiency of up to 72.47% under specific conditions, maintaining stable operation even after 420 h of continuous use (Liu et al., 2021). The thermochemical process involves using high-temperature and high-pressure conditions to separate seawater into hydrogen and oxygen through reactions driven by catalysts. This method is particularly suitable for large-scale hydrogen production because of its scalability and capability to utilize various thermochemical cycles, such as two-step and three-step processes, which operate at lower temperatures to enhance efficiency. For example, two-step thermochemical cycles can produce hydrogen at temperatures ranging from 500 °C to 1 800 °C, and hybrid thermochemical methods that incorporate renewable energy sources, such as solar or wind, can further improve efficiency and reduce costs (Lee et al., 2021; Pein et al., 2021). Photocata-

lysis utilizes light energy and photocatalysts to generate hydrogen efficiently and affordably on a large scale (Kuspanov et al., 2023; Zhang et al., 2024a). Advances in this field have demonstrated the use of mesoporous carbon nitride photocatalysts, which have achieved hydrogen production rates of 0.22 L/kWh with a solar-to-hydrogen (STH) conversion efficiency of up to 0.12% in large-scale reactors exposed to natural sunlight (Schröder et al., 2015). This technique presents a cost-effective and energy-efficient alternative to hydrogen generation. The biological method utilizes microorganisms, such as bacteria and archaea, to produce hydrogen gas through anaerobic respiration. This method is environmentally friendly and potentially cost-effective, with certain bacterial strains capable of producing up to 2.5 mL hydrogen/h under optimal conditions (Harirchi et al., 2022). The combination of these methods is a promising approach for sustainable and large-scale green hydrogen production (Faisal et al., 2022), providing an environmentally friendly and potentially economical alternative. These methods collectively enhance the feasibility and scalability of green hydrogen production from seawater, contributing to sustainable and resilient energy in the future.

Because of the high salt content in seawater, certain green hydrogen production methods require a desalination process, which adds extra energy demands (Dokhani et al., 2023; Sajna et al., 2024). For example, reverse osmosis, a widely used desalination technique, has improved significantly, reducing energy consumption from 20 kWh/m<sup>3</sup> in the 1970s to approximately 2.5 kWh/m<sup>3</sup> today. Despite these advances, desalination remains energy-intensive, with reverse osmosis accounting for approximately 70% of the total energy consumption in desalination plants (Loomba et al., 2023). In addition, the integration of desalination with electrolyzers can increase the cost by approximately \$0.1/kg of hydrogen produced, illustrating the financial impact of using desalinated water in hydrogen production. Furthermore, desalination processes may leave residual ions and particulates in the water, leading to issues, such as biofouling or membrane blockage, during electrolysis (Baldinelli et al., 2022). Eliminating the desalination process in green hydrogen production from seawater and advancing to a one-step process, as shown in Figure 1, can further enhance efficiency and financial viability. Desalination, which is the process of removing salt and impurities from seawater, is highly energy-intensive. By eliminating the need for desalination and directly applying the energy to electrolysis, efficiency can be increased, and costs can be reduced. Eliminating the desalination process for green hydrogen production from seawater has several notable benefits. Wet cooling, which utilizes water to cool the electrolyzer, typically has lower investment and energy costs than dry cooling. According to the research conducted by Spang et al. (2020), wet cooling has lower investment and energy costs than dry cooling; it is especially true in hot and arid regions,



**Figure 1** Process of green hydrogen production from seawater

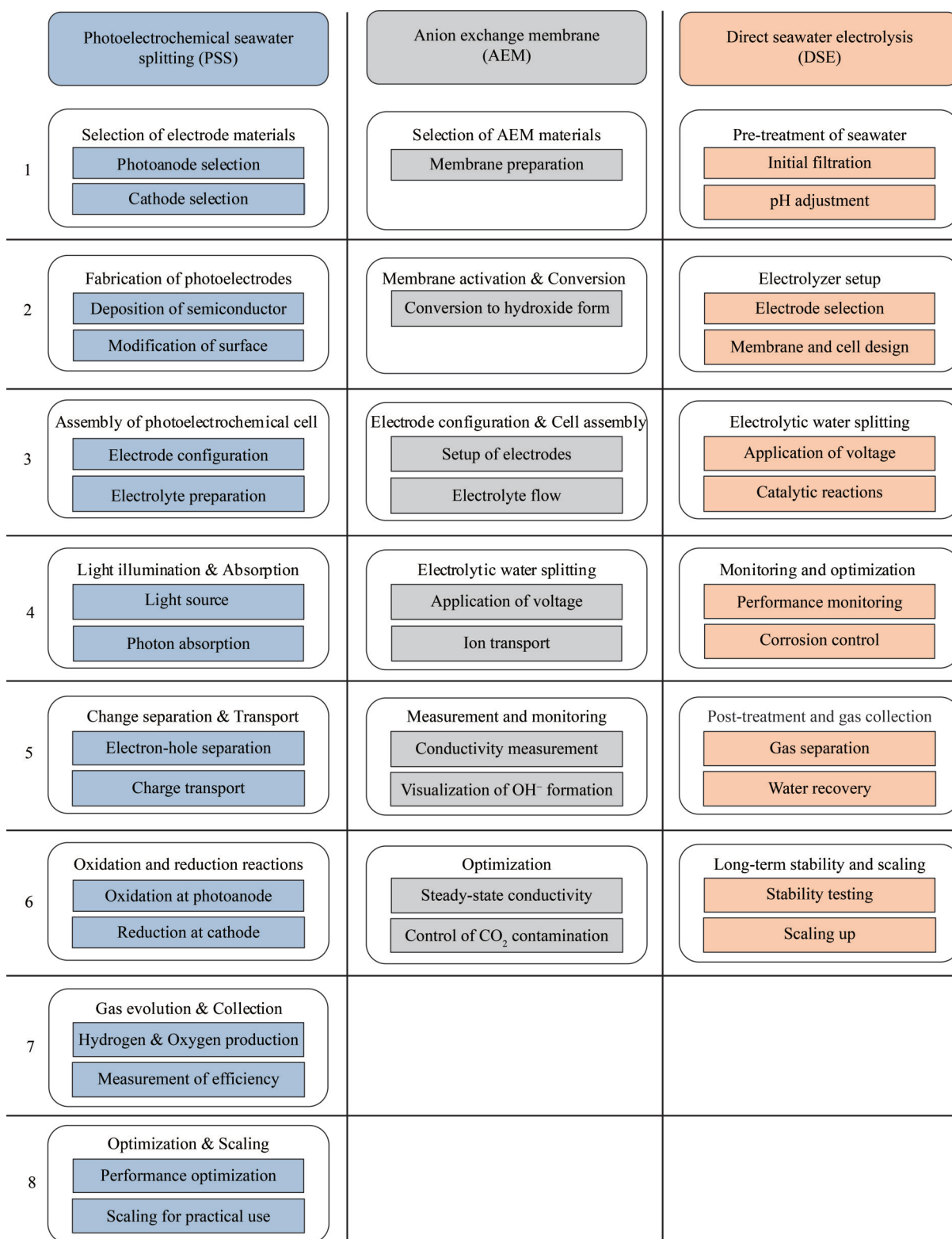
where dry cooling operates less effectively, leading to energy savings ranging from 15% to 30%. The reduced energy demand for wet cooling systems makes them a more economically efficient choice, particularly in settings where water is readily available. In addition, the cost of water purification for desalination is relatively low, at well below USD 1/m<sup>3</sup>. However, reducing desalination can still lead to significant cost savings, especially when the water demand is high. The actual water consumption for green hydrogen production is higher than initially estimated. Initially, 9–11 L of freshwater was believed to be necessary per kilogram of hydrogen. However, the cooling process can elevate this demand to between 22 kg and 126 kg of water per kilogram of hydrogen, influenced by factors such as solar radiation and electrolyzer efficiency (IRENA, 2020). Moreover, avoiding the desalination process can mitigate the environmental impact of brine disposal, which increases salinity and reduces dissolved oxygen levels in seawater, thereby harming marine ecosystems. Overall, reducing or eliminating the desalination process in green hydrogen production from seawater can lead to substantial energy and

cost savings, lower water consumption, and reduce environmental impacts, making it a more efficient and sustainable method (Altın, 2024). The direct use of seawater for electrolysis also addresses global water scarcity by eliminating the need for freshwater, thereby supporting sustainable development (Khan et al., 2021; Yu et al., 2023). From a financial perspective, bypassing desalination diminishes the significant expenses linked with this procedure, thereby decreasing the total cost of green hydrogen production and enhancing its competitiveness against conventional energy sources (Zarzo and Prats, 2018; Abdelsalam et al., 2023). Combining these innovative methods with the direct utilization of seawater for electrolysis presents a strong case for advancing green hydrogen technology in a more efficient, cost effective, and sustainable manner. According to the analysis, green hydrogen production from seawater without desalination can be divided into three main types, as indicated in Table 2 and illustrated in Figure 2.

As shown in Figure 2, photoelectrochemical seawater splitting (PSS), anion exchange membrane (AEM) electrolysis, and DSE are sophisticated methods for producing

**Table 2** Three main types of green hydrogen production from seawater

Method	Explanation
Photoelectrochemical seawater splitting (PSS)	Produces green hydrogen from seawater using semiconductor materials to split water into hydrogen and oxygen under sunlight, mimicking natural photosynthesis (Holmes-Gentle et al., 2018; Huang and Wang, 2018; Prasad et al., 2018; Xu et al., 2018).
Anion exchange membrane (AEM)	Employing an AEM for the electrolysis of seawater facilitates the separation of hydrogen and oxygen. During this process, hydroxide ions (OH <sup>-</sup> ) permeate the membrane, whereas hydrogen ions (H <sup>+</sup> ) at the cathode are converted into hydrogen gas (H <sub>2</sub> ), and hydroxide ions (OH <sup>-</sup> ) at the anode produce oxygen gas (O <sub>2</sub> ) and water (Cao et al., 2019; Du et al., 2022; El-Shafie, 2023).
Direct seawater electrolysis (DSE)	Employing an electrolyzer to split seawater directly into hydrogen and oxygen, thereby eliminating the need for desalination (Dresp et al., 2019; Fei et al., 2023).



**Figure 2** Processes of the three main types of green hydrogen production from seawater

hydrogen from seawater, each characterized by unique features and experimental setups. PSS harnesses solar energy to directly drive the water-splitting process in seawater that involves selecting semiconducting materials, such as Fe<sub>2</sub>O<sub>3</sub>

or BiVO<sub>4</sub>, for photoanodes (Jiang et al., 2017; Fehr et al., 2023), which are deposited on conductive substrates. Then, the photoelectrochemical (PEC) cell is assembled in a three-electrode configuration. When exposed to light, the photo-

anode absorbs photons, leading to the generation of hydrogen at the cathode and oxygen at the anode. The efficiency of PSS is largely influenced by the properties of the materials used and the effectiveness of light absorption, requiring continuous optimization to improve performance.

Alternatively, AEM electrolysis operates in an alkaline environment, using an AEM to facilitate the movement of hydroxide ions produced during electrolysis. Materials, such as hexamethyl-*p*-terphenyl poly(methylbenzamidozium), are converted into their hydroxide form by immersion in a KOH solution (Henkensmeier et al., 2024). The electrolyzer is typically assembled with a membrane placed between a cathode and an anode in a four-electrode setup. A voltage is applied to start the water-splitting process, with hydroxide ions migrating through the membrane to the anode, where they are oxidized to oxygen. Continuous monitoring and optimization are crucial, with a focus on achieving stable conductivity and minimizing CO<sub>2</sub> contamination.

DSE, designed for direct hydrogen production from seawater, is especially useful in coastal areas where seawater is abundant but freshwater is scarce. The seawater undergoes basic filtration and pH adjustment to optimize the oxygen evolution reaction (OER) while minimizing the chlorine evolution reaction (CIER). The electrolyzer employs selective anode materials, such as NiFe-layered double hydroxides, to favor OER over CIER (Xing et al., 2023), with AEM supporting ion transport. Voltage is applied to split water into hydrogen and oxygen, with selective catalysts ensuring minimal chlorine production. Ongoing monitoring of performance and corrosion control is essential, and the system may produce freshwater as a by-product.

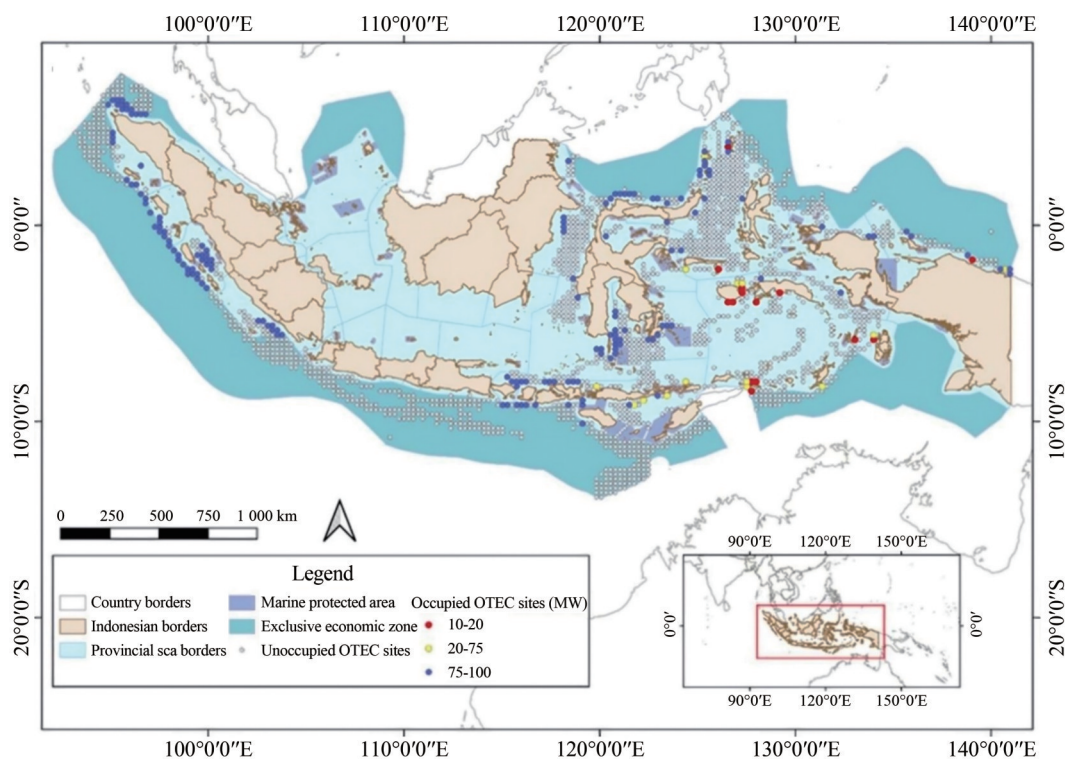
Each method has specific benefits depending on the application, resource availability, and environmental conditions. PSS takes advantage of solar energy, AEM is efficient under alkaline conditions, and DSE uses seawater directly, reducing the demand for freshwater. The choice of method depends on the specific requirements for hydrogen production, with ongoing research aimed at optimizing these techniques for large-scale renewable energy systems. The efficiency of these methods varies depending on several factors, such as material choice, operating conditions, and integration with renewable energy sources. AEM electrolysis generally achieves the highest efficiency, often between 60% and 80% (Campagna Zignani et al., 2022), whereas PSS typically has lower efficiency but benefits from direct solar energy use. The efficiency of DSE ranges from 50% to 70%, depending on the control of unwanted side reactions and corrosion (Chang and Yang, 2023; Saada et al., 2024). Overall, AEM electrolysis exhibits the highest efficiency under controlled conditions, whereas PSS and DSE are more suited to specific environmental and resource conditions, particularly in the context of renewable energy integration and seawater use.

## 4 Feasibility study of marine renewable energy and green hydrogen production from seawater for future development in Indonesia

The feasibility of integrating MRE with green hydrogen production along the coast of Indonesia from neighboring countries or areas is assessed to gauge development potential based on previous research (Tjahjono et al., 2023). This method, backed by studies emphasizing the importance of considering regional and global trends in MRE resources, sheds light on the potential of Indonesia (Li et al., 2021). Adiputra et al. (2023) highlighted the shallow waters of Indonesia as conducive to economically viable offshore wind turbine installations, with vast ocean renewable energy resources, such as ocean thermal energy, offshore wind, wave energy, and tidal energy, as shown in Figure 3. Studies also pinpoint potential sites for ocean thermal energy conversion, such as North Maluku and the Sunda Strait, with a total energy potential of 43 GW and a levelized cost of energy for 1 MW of \$38.10/kWh, which is expected to decrease with the increase in capacity.

Japan's strategy of integrating renewable energy, particularly in its remote islands, provides a pertinent comparison for Indonesia. Japan's renewable energy projects have managed to reduce hydrogen production costs to approximately \$6.22/kg by utilizing offshore wind and ocean currents. With wind capacity factors between 30% and 35% and solar capacity factors averaging 20%, Japan's experience indicates that Indonesia, with its higher average solar irradiance and more robust coastal winds, could achieve even lower hydrogen production costs by adopting similar technologies (Wang et al., 2023b). Similarly, South Korea has pioneered a cost-effective and stable method for hydrogen production using carbon-based cathodes in seawater electrolysis (Jwa et al., 2024), achieving approximately 100% faradaic efficiency and reducing overall production costs by 15% compared with traditional platinum-based systems. These innovations position South Korea to target hydrogen production costs of approximately \$5.50/kg by 2030, a goal that Indonesia could potentially surpass by harnessing its abundant marine resources and favorable climatic conditions.

Another valuable concept from Kazakhstan (Tleuberanova et al., 2023), which is not a maritime nation but has a strategy for integrating renewable energy with green hydrogen production, provides valuable lessons in managing resource limitations. Kazakhstan requires approximately 50 GW of solar capacity and 67 GW of wind capacity to produce 5 million tons of green hydrogen annually, with a water consumption footprint estimated at 0.18 km<sup>3</sup>/year—approximately 3% of the total industrial water usage. With the vast water resources and offshore wind potential of Indonesia, similar large-scale projects could be more easily



**Figure 3** Potential marine renewable energy areas in Indonesia (Langer et al., 2021)

implemented, facilitating substantial hydrogen production without overwhelming existing water or energy infrastructure.

Vietnam’s coastal regions, which share similarities with Indonesia’s coastal regions, boast significant renewable energy potential, particularly in offshore wind. Vietnam has already started exporting hydrogen, aiming to lower production costs to below \$4/kg by 2035 (Ta et al., 2024). Vietnam’s integrated approach, which combines wind power with solar photovoltaic could serve as a model for Indonesia, especially in several regions, such as Sulawesi and Maluku, that have comparable geographic and climatic conditions. In addition, the Philippines, with its archipelagic geography similar to that of Indonesia, is focused on maximizing its ocean energy potential, including tidal and wave energy, which accounts for an estimated 10% of the total renewable energy capacity of the country (Agaton et al., 2022). This approach has enabled the Philippines to maintain competitive hydrogen production costs, illustrating that Indonesia could benefit from further exploring these under-

utilized energy resources.

These comparative research and findings underscore the importance of leveraging international data and best practices to evaluate the MRE potential of Indonesia. By learning from the experiences of the aforementioned countries, Indonesia can develop a customized approach that capitalizes on its unique geographic advantages while addressing potential challenges in infrastructure, costs, and environmental impact. This cross-national perspective lays a solid foundation for guiding investment and policy decisions in the MRE sector of Indonesia (Abhold et al., 2022). Hence, a review of the literature was conducted, examining previous studies of the waters of neighboring countries to Indonesia. This review serves as empirical evidence supporting the feasibility of both the analysis and technical aspects of previous studies (Genauer et al., 2022). Subsequently, the economic considerations and financial viability for implementation in Indonesia will be explored, as illustrated in Tables 3, 4, and 5.

**Table 3** Literature review of previous research on hydrogen production from seawater with PSS type

Material	Durability	Efficiency	Advantages	Disadvantages	Author
<ul style="list-style-type: none"> <li>• Titanium (IV) butoxide</li> <li>• Titanium tetrachloride</li> <li>• Cadmium nitrate</li> </ul>	<ul style="list-style-type: none"> <li>• High durability and stability</li> <li>• Enhanced by Mn doping</li> </ul>	<ul style="list-style-type: none"> <li>• Photocurrent density: 2.73 mA/cm<sup>2</sup></li> <li>• Photoconversion efficiency: 2.19%</li> </ul>	<ul style="list-style-type: none"> <li>• High efficiency</li> <li>• Cost-effective</li> <li>• Stable</li> </ul>	<ul style="list-style-type: none"> <li>• Complex synthesis</li> <li>• Scaling challenges</li> <li>• Requires further validation</li> </ul>	Ahmad et al. (2022)

**Table 3** Literature review of previous research on hydrogen production from seawater with PSS type (continued)

Material	Durability	Efficiency	Advantages	Disadvantages	Author
<ul style="list-style-type: none"> <li>• BiVO<sub>4</sub> (bismuth vanadate)</li> <li>• <math>\alpha</math>-Cr<sub>2</sub>O<sub>3</sub> (chromium (III) oxide)</li> </ul>	<ul style="list-style-type: none"> <li>• High durability</li> <li>• Significant photocorrosion protection</li> </ul>	<ul style="list-style-type: none"> <li>• Photocorrosion protection efficiency: up to 54.3%</li> <li>• Enhanced photocurrent density</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced photocorrosion</li> <li>• Cost-effective</li> <li>• Improved performance</li> </ul>	<ul style="list-style-type: none"> <li>• Precise control needed</li> <li>• Scaling challenge</li> <li>• Further stability studies required</li> </ul>	Tezcan et al. (2022)
<ul style="list-style-type: none"> <li>• Sulfur-doped graphitic carbon nitride (S-gC<sub>3</sub>N<sub>4</sub>)</li> <li>• Bismuth oxychloride (BiOCl)</li> <li>• Cobalt (Co) cocatalyst</li> </ul>	<ul style="list-style-type: none"> <li>• High durability</li> <li>• Effective charge separation</li> </ul>	<ul style="list-style-type: none"> <li>• Photocurrent density: 393.0 <math>\mu</math>A/cm<sup>2</sup></li> <li>• Applied bias photon-to-current efficiency: 0.11%</li> </ul>	<ul style="list-style-type: none"> <li>• High efficiency</li> <li>• Cost-effective</li> <li>• Stable</li> </ul>	<ul style="list-style-type: none"> <li>• Precise control needed</li> <li>• Scaling challenges</li> <li>• Further investigation required</li> </ul>	Vinoth et al. (2021)
<ul style="list-style-type: none"> <li>• Tungsten oxide (WO<sub>3</sub>) nanosquare arrays</li> <li>• Ag nanoparticles</li> <li>• ZnFe-layered double hydroxide (ZnFe-LDH)</li> </ul>	<ul style="list-style-type: none"> <li>• High durability</li> <li>• 90% activity retention after 6.67 h</li> </ul>	<ul style="list-style-type: none"> <li>• Photocurrent density: 1.15 mA/cm<sup>2</sup></li> <li>• Photoelectrochemical (PEC) hydrogen production: 38.18 <math>\mu</math>mol/h</li> <li>• Faradaic efficiency: Nearly 100%</li> </ul>	<ul style="list-style-type: none"> <li>• High efficiency</li> <li>• Stable</li> <li>• Cost-effective</li> <li>• Scalable</li> </ul>	<ul style="list-style-type: none"> <li>• Precise control needed</li> <li>• Scaling challenges</li> <li>• Further investigation required</li> </ul>	Liu et al. (2020)
<ul style="list-style-type: none"> <li>• Graphene oxide</li> <li>• Graphitic carbon nitride</li> <li>• Ni</li> <li>• IrO<sub>2</sub></li> <li>• RuO<sub>2</sub></li> <li>• Platinum</li> </ul>	<ul style="list-style-type: none"> <li>• High durability and stability</li> <li>• Non-noble metal alternatives discussed</li> </ul>	<ul style="list-style-type: none"> <li>• Levelized cost of hydrogen: \$8.43/kg for PEC systems, \$6.22/kg for electrochemical systems</li> </ul>	<ul style="list-style-type: none"> <li>• High efficiency</li> <li>• Potential cost reductions</li> <li>• Comprehensive material understanding</li> </ul>	<ul style="list-style-type: none"> <li>• High production costs</li> <li>• Supply risks</li> <li>• Technological challenges in real-world applications</li> </ul>	Singh et al. (2024)
<ul style="list-style-type: none"> <li>• Bismuth vanadate (BiVO<sub>4</sub>)</li> </ul>	<ul style="list-style-type: none"> <li>• Emphasis on developing stable photoanode materials</li> </ul>	<ul style="list-style-type: none"> <li>• Theoretical STH efficiency: ~9.2%</li> <li>• Photocurrent density: 7.6 mA/cm<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>• Overview of advancements</li> <li>• Modification strategies</li> <li>• Challenges and future directions</li> </ul>	<ul style="list-style-type: none"> <li>• Review does not provide experimental data</li> <li>• Further research needed</li> </ul>	Chi et al. (2022)
<ul style="list-style-type: none"> <li>• Bismuth vanadate (BiVO<sub>4</sub>)</li> <li>• Nickel nitrate (Ni(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O)</li> <li>• Ferric chloride (FeCl<sub>3</sub>)</li> <li>• FTO glass substrates</li> </ul>	<ul style="list-style-type: none"> <li>• High stability</li> <li>• 86% photocurrent density retention after 5 h</li> </ul>	<ul style="list-style-type: none"> <li>• Photocurrent density: 3.02 mA/cm<sup>2</sup></li> <li>• Surface separation efficiency: 73.3%</li> <li>• Bulk separation efficiency: 67.7%</li> <li>• IPCE: 90.1%</li> </ul>	<ul style="list-style-type: none"> <li>• Enhanced efficiency</li> <li>• Charge separation, cost-effective</li> <li>• Scalable synthesis method</li> </ul>	<ul style="list-style-type: none"> <li>• Further optimization needed</li> <li>• Precise control required</li> <li>• Further validation required</li> </ul>	Chen et al. (2023)
<ul style="list-style-type: none"> <li>• Tungsten trioxide (WO<sub>3</sub>)</li> <li>• Sodium tungstate hydrate (Na<sub>2</sub>WO<sub>4</sub>·2H<sub>2</sub>O)</li> <li>• Citric acid</li> <li>• HCl</li> <li>• FTO glass substrates</li> </ul>	<ul style="list-style-type: none"> <li>• Good stability in neutral chloride media</li> <li>• Significant dissolution in acidic sulfate media</li> </ul>	<ul style="list-style-type: none"> <li>• Faradaic efficiency: Nearly 100%</li> <li>• High photocurrent density</li> </ul>	<ul style="list-style-type: none"> <li>• High efficiency</li> <li>• Stability in neutral chloride media</li> <li>• Cost-effective</li> <li>• Scalable</li> </ul>	<ul style="list-style-type: none"> <li>• Significant dissolution in acidic sulfate media</li> <li>• Complex chlorine oxo species chemistry</li> </ul>	Parvin et al. (2024)
<ul style="list-style-type: none"> <li>• TiO<sub>2</sub></li> <li>• BiVO<sub>4</sub></li> <li>• Various heterojunctions and composites</li> </ul>	<ul style="list-style-type: none"> <li>• High stability and durability</li> </ul>	<ul style="list-style-type: none"> <li>• Achieving 10% STH efficiency target</li> </ul>	<ul style="list-style-type: none"> <li>• Comprehensive overview</li> <li>• Key trends</li> <li>• Influential researchers</li> <li>• Emerging topics</li> </ul>	<ul style="list-style-type: none"> <li>• No specific experimental data</li> <li>• Bibliometric analysis focus</li> </ul>	Nabgan et al. (2024)
<ul style="list-style-type: none"> <li>• Titanium butoxide (TBOT)</li> <li>• Thiourea</li> <li>• Sodium hypochlorite (NaClO)</li> <li>• Citric acid</li> <li>• Sodium chloride (NaCl)</li> <li>• HCl</li> <li>• Sodium sulfate</li> </ul>	<ul style="list-style-type: none"> <li>• High stability and durability</li> <li>• Enhanced resistance to degradation and chlorine corrosion</li> </ul>	<ul style="list-style-type: none"> <li>• Photocurrent density 34.4 mA/cm<sup>2</sup></li> <li>• Reduced ClO<sup>-</sup> production: 6 mM after 1 h</li> </ul>	<ul style="list-style-type: none"> <li>• High efficiency</li> <li>• Reduced chlorine by-products</li> <li>• Cost-effective</li> <li>• Scalable synthesis method</li> </ul>	<ul style="list-style-type: none"> <li>• Primarily laboratory-scale focus</li> <li>• Further research is needed for industrial scale-up</li> <li>• Long-term stability investigation</li> </ul>	Zhao et al. (2024b)

**Table 4** Literature review of previous research on hydrogen production from seawater with AEM type

Material	Durability	Efficiency	Advantages	Disadvantages	Author
<ul style="list-style-type: none"> <li>Nickel foam (NF)</li> <li>Nickel sulfide (NiS)</li> <li>Metal phosphates (FePi, NiCoPi)</li> <li>1 and 6 M KOH</li> </ul>	<ul style="list-style-type: none"> <li>High durability</li> <li>Stable performance over prolonged periods</li> <li>Crystalline–amorphous structure</li> </ul>	<ul style="list-style-type: none"> <li>OER overpotential: 345 mV at 1 000 mA/cm<sup>2</sup></li> <li>HER overpotential: 223 mV at 1 000 mA/cm<sup>2</sup></li> <li>Cell voltage: 1.712 V at 1 000 mA/cm<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>High catalytic performance</li> <li>Excellent stability</li> <li>Cost-effective</li> <li>Significant energy savings</li> </ul>	<ul style="list-style-type: none"> <li>Further optimization needed</li> <li>Scaling challenges</li> <li>Complex electrode preparation process</li> </ul>	Guo et al. (2024)
<ul style="list-style-type: none"> <li>Commercial AEM (Fuji type II)</li> <li>L-dopa</li> <li>Gentamicin</li> <li>N-chloramine</li> <li>Copper sulfate (CuSO<sub>4</sub>)</li> <li>Hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>)</li> <li>Sodium hypochlorite (NaClO)</li> </ul>	<ul style="list-style-type: none"> <li>High durability</li> <li>Stable antibacterial and antibiofilm activities</li> <li>Minimal impact on membrane properties</li> </ul>	<ul style="list-style-type: none"> <li>Antibacterial efficiency: over 99% against E. coli, improved against S. aureus</li> <li>Surface area resistance: 4.59 Ω cm<sup>2</sup></li> </ul>	<ul style="list-style-type: none"> <li>High antibacterial efficiency</li> <li>Cost-effective</li> <li>Stable</li> <li>Potential for membrane-based processes</li> </ul>	<ul style="list-style-type: none"> <li>Further optimization and validation needed</li> <li>Scaling challenges</li> <li>Long-term environmental impact of antibiotics</li> </ul>	Yao et al. (2023)
<ul style="list-style-type: none"> <li>Ion exchange membranes (AEM, cation exchange membranes, and bipolar membranes)</li> </ul>	<ul style="list-style-type: none"> <li>High durability and efficiency in various applications</li> </ul>	<ul style="list-style-type: none"> <li>Electrodialysis (ED): 7–15 kWh/m<sup>3</sup></li> <li>Bipolar membrane electrodialysis (BMED): 1.18 MJ/kg CO<sub>2</sub>, CO<sub>2</sub> electrochemical reduction</li> </ul>	<ul style="list-style-type: none"> <li>High efficiency</li> <li>Cost-effective, scalable</li> <li>Versatile, potential for renewable energy integration</li> </ul>	<ul style="list-style-type: none"> <li>High initial cost</li> <li>Scaling challenges</li> <li>Membrane fouling and degradation</li> <li>Continuous research needed</li> </ul>	Wang et al. (2022)
<ul style="list-style-type: none"> <li>Polysulfone tetramethylammonium (PSU-TMA) membranes</li> <li>Sodium chloride (NaCl)</li> </ul>	<ul style="list-style-type: none"> <li>Good durability</li> <li>Stable performance in simulations</li> </ul>	<ul style="list-style-type: none"> <li>Accurate prediction of ion diffusion coefficients</li> <li>Integration of MD and DFT methods</li> </ul>	<ul style="list-style-type: none"> <li>Accurate predictions</li> <li>Comprehensive understanding</li> <li>Good agreement with experimental values</li> </ul>	<ul style="list-style-type: none"> <li>Computationally intensive</li> <li>Time-consuming, high-level resources and expertise needed</li> </ul>	Salvo et al. (2021)
<ul style="list-style-type: none"> <li>Brominated poly(2, 6-dimethyl-1, 4-phenylene oxide) (BPPO)</li> <li>Tertiary amines</li> <li>Polyelectrolytes</li> <li>Sodium salts</li> </ul>	<ul style="list-style-type: none"> <li>High durability and stability</li> <li>Enhanced selectivity without compromising structural integrity</li> </ul>	<ul style="list-style-type: none"> <li>Cl<sup>-</sup>/SO<sub>4</sub><sup>2-</sup> selectivity: 11.7</li> <li>F<sup>-</sup>/SO<sup>-</sup> selectivity: 8.3</li> </ul>	<ul style="list-style-type: none"> <li>High selectivity</li> <li>Cost-effective</li> <li>Scalable</li> <li>Environmentally friendly</li> </ul>	<ul style="list-style-type: none"> <li>Complex synthesis</li> <li>Scaling challenges</li> <li>Further validation needed</li> </ul>	Tekinalp et al. (2023)
<ul style="list-style-type: none"> <li>Nickel foam (NF)</li> <li>Nickel molybdate (NiMoO<sub>4</sub>)</li> <li>Platinum (Pt)</li> <li>Phosphorus (P)</li> </ul>	<ul style="list-style-type: none"> <li>High durability</li> <li>Stable performance over 110 h</li> <li>Enhanced by substitutional P doping</li> </ul>	<ul style="list-style-type: none"> <li>Current density: 1.0 A/cm<sup>2</sup> at 80 mV</li> <li>Stability: 120 h at 500 mA/cm<sup>2</sup></li> <li>Faradaic efficiency: High</li> </ul>	<ul style="list-style-type: none"> <li>High catalytic activity</li> <li>Significant chloride ion reduction</li> <li>Cost-effective</li> <li>Durable</li> </ul>	<ul style="list-style-type: none"> <li>Complex synthesis and doping</li> <li>Scaling challenges</li> <li>Further validation needed</li> </ul>	Xu et al. (2024)
<ul style="list-style-type: none"> <li>Nickel foam (NF)</li> <li>Nickel phosphide (Ni<sub>2</sub>P/Ni<sub>3</sub>P<sub>4</sub>)</li> <li>Ruthenium chloride (RuCl<sub>3</sub>)</li> </ul>	<ul style="list-style-type: none"> <li>High durability</li> <li>Stable performance over 120 h</li> </ul>	<ul style="list-style-type: none"> <li>HER overpotential: 128 mV</li> <li>OER overpotential: 450 mV</li> <li>Overall voltage: 1.83 V at 1 000 mA/cm<sup>2</sup></li> <li>Faradaic efficiency: ~100%</li> </ul>	<ul style="list-style-type: none"> <li>High efficiency</li> <li>Low overpotential</li> <li>Excellent corrosion resistance</li> <li>Cost-effective</li> <li>High energy efficiency</li> </ul>	<ul style="list-style-type: none"> <li>Complex synthesis</li> <li>Scaling challenges</li> <li>Further validation needed</li> </ul>	Xia et al. (2024)
<ul style="list-style-type: none"> <li>Nickel foam (NF)</li> <li>Nickel molybdate (NiMoO<sub>4</sub>)</li> <li>Platinum (Pt)</li> <li>Nickel</li> <li>Iron</li> <li>Cobalt sulfides</li> </ul>	<ul style="list-style-type: none"> <li>High durability</li> <li>Stable performance over 300 h</li> </ul>	<ul style="list-style-type: none"> <li>Current density: 100 mA/cm<sup>2</sup> at 245 mV</li> <li>Stability: 300 h at 400 and 600 mA/cm<sup>2</sup></li> <li>Faradaic efficiency: ~100%</li> </ul>	<ul style="list-style-type: none"> <li>High efficiency</li> <li>Cost-effective, durable</li> <li>Efficient OER</li> </ul>	<ul style="list-style-type: none"> <li>Complex synthesis</li> <li>Scaling challenges</li> <li>Further validation needed</li> </ul>	Na et al. (2024)

**Table 4** Literature review of previous research on hydrogen production from seawater with AEM type (continued)

Material	Durability	Efficiency	Advantages	Disadvantages	Author
<ul style="list-style-type: none"> <li>Nafion membranes</li> <li>PiperION membrane</li> <li>Iridium oxide (IrOx)</li> <li>Platinum black (Pt)</li> </ul>	<ul style="list-style-type: none"> <li>High durability</li> <li>Improved lifetimes over PEMWE</li> <li>Stability over 100 h</li> </ul>	<ul style="list-style-type: none"> <li>Current density: 250 mA/cm<sup>2</sup></li> <li>Voltage for 500 mA/cm<sup>2</sup>: ~3.3 V</li> <li>Faradaic efficiency: 0.005% for Cl<sup>-</sup> oxidation</li> </ul>	<ul style="list-style-type: none"> <li>High Cl<sup>-</sup> oxidation resistance</li> <li>Durable</li> <li>Effective ion transport</li> <li>Selective oxidation control</li> </ul>	<ul style="list-style-type: none"> <li>Higher operating voltages</li> <li>Sensitivity to ion impurities</li> <li>Complex fabrication</li> </ul>	Marin et al. (2023)
<ul style="list-style-type: none"> <li>High-entropy metal oxide</li> <li>Graphene oxide</li> <li>Carbon cloth substrate</li> </ul>	<ul style="list-style-type: none"> <li>High durability and stability over extended periods</li> </ul>	<ul style="list-style-type: none"> <li>HER overpotential = -482 mV at 10 mA/cm<sup>2</sup></li> <li>OER overpotential: 597 mV at 10 mA/cm<sup>2</sup></li> <li>Full-cell performance: 0.19 A at 3 V</li> </ul>	<ul style="list-style-type: none"> <li>High efficiency</li> <li>Cost-effective, durable</li> <li>Large surface area enhances reaction rates</li> </ul>	<ul style="list-style-type: none"> <li>Complex synthesis</li> <li>Scaling challenges</li> <li>Further validation needed</li> </ul>	Kumar et al. (2023)

**Table 5** Literature review of previous research on hydrogen production from seawater with DSE type

Material	Durability	Efficiency	Advantages	Disadvantages	Author
<ul style="list-style-type: none"> <li>Montmorillonite-rich marine mud</li> <li>Stainless steel (304) mesh electrodes</li> <li>NaOH 1 M solution</li> </ul>	<ul style="list-style-type: none"> <li>Stable conductivity</li> <li>Resistance to flocculation</li> <li>Durable electrodes</li> </ul>	<ul style="list-style-type: none"> <li>Voltage efficiency: 42%</li> <li>Gas collection efficiency: 50%</li> <li>Auxiliary power efficiency: 60%</li> <li>Overall energy efficiency: 13%</li> </ul>	<ul style="list-style-type: none"> <li>Low-cost materials</li> <li>Effective gas separation</li> <li>Enhanced conductivity</li> </ul>	<ul style="list-style-type: none"> <li>Lower overall energy efficiency</li> <li>High viscosity requiring more pump power</li> <li>Scaling challenges</li> </ul>	Biggs et al. (2023)
<ul style="list-style-type: none"> <li>Bipolar membrane (BPM)</li> <li>Pt-coated Ti mesh electrodes</li> <li>NaOH anolytes</li> <li>Various saline catholytes</li> </ul>	<ul style="list-style-type: none"> <li>Durable</li> <li>Stable electrolyte concentration and pH</li> <li>Corrosion-resistant electrodes</li> </ul>	<ul style="list-style-type: none"> <li>Faradaic efficiency: 96% for hydrogen, 85% for oxygen</li> <li>High-purity hydrogen and oxygen</li> </ul>	<ul style="list-style-type: none"> <li>Utilizes natural seawater</li> <li>Reduced energy consumption</li> <li>Prevents chlorine evolution</li> <li>Stable and long-lasting</li> </ul>	<ul style="list-style-type: none"> <li>Initial higher cell voltage</li> <li>Optimization needed</li> <li>Scaling challenges</li> </ul>	Han et al. (2022)
<ul style="list-style-type: none"> <li>Nickel foam (NF)</li> <li>Sodium hydroxide (NaOH)</li> <li>Sodium chloride (NaCl)</li> <li>Seawater from Xinghai Bay</li> </ul>	<ul style="list-style-type: none"> <li>Good durability</li> <li>Enhanced OER activity</li> <li>Decreased HER stability with the increase in ion concentrations</li> </ul>	<ul style="list-style-type: none"> <li>OER efficiency: nearly 100%</li> <li>HER efficiency: nearly 100%</li> <li>Cell voltage: Improved with the increase in NaCl concentration</li> </ul>	<ul style="list-style-type: none"> <li>Detailed analysis</li> <li>Optimal conditions for enhanced activity</li> <li>Comprehensive corrosion understanding</li> </ul>	<ul style="list-style-type: none"> <li>Increased HER electrode corrosion</li> <li>Complexity in balancing ion concentrations</li> <li>Higher solution viscosity</li> </ul>	He et al. (2023)
<ul style="list-style-type: none"> <li>Dual MoC–Mo<sub>2</sub>C heterostructure</li> <li>Carbon nanotubes (CNTs)</li> <li>Nickel foam (NF)</li> <li>Various chemicals</li> </ul>	<ul style="list-style-type: none"> <li>High durability</li> <li>Stable performance over 50 h</li> </ul>	<ul style="list-style-type: none"> <li>HER overpotential: 95 mV</li> <li>OER overpotential: 279 mV</li> <li>Cell voltage: 1.57 V for simulated seawater</li> </ul>	<ul style="list-style-type: none"> <li>High efficiency</li> <li>Cost-effective</li> <li>Durable</li> <li>Efficient seawater splitting</li> </ul>	<ul style="list-style-type: none"> <li>Contamination and poisoning potential</li> <li>Optimization needed for long-term performance</li> </ul>	Wang et al. (2024)
<ul style="list-style-type: none"> <li>Treated wastewater</li> <li>Natural seawater</li> <li>Bipolar membrane (BPM)</li> <li>Titanium fibers coated with Ru/Ir</li> <li>NaOH</li> </ul>	<ul style="list-style-type: none"> <li>Good durability</li> <li>Effective acidification mechanism</li> <li>Minimizes electrode fouling and precipitation</li> </ul>	<ul style="list-style-type: none"> <li>Faradaic efficiency for H<sub>2</sub> = 73% to 90%</li> <li>Energy consumption: 6.7 kWh/Nm<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>Utilizes treated wastewater</li> <li>Effective acidification</li> <li>Enhances water resilience</li> <li>Minimizes fouling</li> </ul>	<ul style="list-style-type: none"> <li>Higher energy consumption</li> <li>Further optimization needed</li> <li>Development of corrosion-resistant electrocatalysts required</li> </ul>	Han et al. (2023a)
<ul style="list-style-type: none"> <li>Co-(NiFe) N@NiS<sub>x</sub>@NF anode</li> <li>NiVN@NF cathode</li> <li>Phosphate buffer</li> <li>Synthetic seawater</li> <li>3D printed cell</li> <li>Titanium mesh</li> </ul>	<ul style="list-style-type: none"> <li>High stability and durability under near-neutral pH</li> <li>Stable performance over 50 h</li> </ul>	<ul style="list-style-type: none"> <li>Cell voltage: 2.61 V</li> <li>Faradaic efficiency: 94.8% to 92.1%</li> <li>Hydrogen crossover: 0.18%</li> </ul>	<ul style="list-style-type: none"> <li>Cost-effective</li> <li>Scalable</li> <li>High stability</li> <li>Low hydrogen crossover</li> <li>Near-neutral pH reduces corrosion</li> </ul>	<ul style="list-style-type: none"> <li>Higher cell voltage</li> <li>Optimization challenges</li> <li>Long-term stability in real seawater conditions</li> </ul>	Badreldin et al. (2024)

**Table 5** Literature review of previous research on hydrogen production from seawater with DSE type (continued)

Material	Durability	Efficiency	Advantages	Disadvantages	Author
<ul style="list-style-type: none"> <li>• Non-PGM electrocatalyst</li> <li>• Polymeric hydrogel membranes</li> <li>• Seawater filtration systems</li> </ul>	<ul style="list-style-type: none"> <li>• Trend toward durable</li> <li>• Corrosion-resistant electrocatalysts</li> <li>• Non-PGM materials for cost-effectiveness</li> </ul>	<ul style="list-style-type: none"> <li>• Importance of developing high-efficiency electrocatalysts and system designs</li> </ul>	<ul style="list-style-type: none"> <li>• Comprehensive technological mapping</li> <li>• Identification of key players and trends</li> <li>• Potential for renewable energy integration</li> </ul>	<ul style="list-style-type: none"> <li>• Patent analysis focus</li> <li>• Potential challenges in commercial-scale application</li> <li>• Continuous monitoring needed</li> </ul>	Moura et al. (2024)
<ul style="list-style-type: none"> <li>• NiMoN</li> <li>• S-CoP</li> <li>• <math>\text{CoP}_x\text{@FeOOH/NF}</math></li> <li>• NPNNS, NiCoN</li> </ul>	<ul style="list-style-type: none"> <li>• High durability</li> <li>• Stable performance at elevated temperatures</li> <li>• Improved efficiency with the increase in temperature</li> </ul>	<ul style="list-style-type: none"> <li>• Cell voltage: 2.4 V to 1.9 V</li> <li>• HER overpotential: 351–246 mV</li> <li>• OER overpotential: 568–394 mV</li> <li>• Cell efficiency: 78%–97%</li> <li>• Hydrogen production: 0.015 to 0.020 <math>\mu\text{mol}/\text{cycle}</math></li> </ul>	<ul style="list-style-type: none"> <li>• Self-powered system</li> <li>• Membraneless design</li> <li>• High efficiency</li> <li>• Durable catalyst materials</li> </ul>	<ul style="list-style-type: none"> <li>• Initial setup may require specific environmental conditions</li> <li>• Further optimization is needed for large-scale applications</li> <li>• Potential challenges in maintaining consistent performance</li> </ul>	Elahi and Seddighi (2024)
<ul style="list-style-type: none"> <li>• Single-walled carbon nanotubes (SWCNTs)</li> <li>• High-entropy alloy nanowires</li> <li>• KOH</li> <li>• Various chemicals</li> </ul>	<ul style="list-style-type: none"> <li>• Excellent durability</li> <li>• Stable performance over 100 h</li> <li>• High stability in seawater</li> </ul>	<ul style="list-style-type: none"> <li>• Seawater evaporation efficiency: 1.22 <math>\text{kg}/\text{m}^2/\text{h}</math></li> <li>• HER overpotential: 27 mV</li> <li>• OER overpotential: 274 mV</li> <li>• Cell voltage: 1.52 V</li> <li>• Hydrogen productivity: <math>1.04 \times 10^4</math> L/day</li> <li>• Faradaic efficiency: ~93.5%</li> </ul>	<ul style="list-style-type: none"> <li>• High efficiency</li> <li>• Solar energy utilization</li> <li>• Robust materials</li> <li>• Environmentally friendly</li> </ul>	<ul style="list-style-type: none"> <li>• Specific setup conditions</li> <li>• Scaling challenges</li> <li>• Long-term durability under varying conditions</li> </ul>	Zhang et al. (2024b)
<ul style="list-style-type: none"> <li>• Iron foam (IF)</li> <li>• Copper sulfate pentahydrate</li> <li>• Nickel chloride hexahydrate</li> <li>• Sodium sulfide nonahydrate</li> <li>• Sodium chloride</li> <li>• Potassium hydroxide</li> </ul>	<ul style="list-style-type: none"> <li>• High durability</li> <li>• Excellent electrocatalytic performance</li> <li>• Stable and active over prolonged electrolysis</li> </ul>	<ul style="list-style-type: none"> <li>• SOR potential: 0.300 V</li> <li>• HER potential: 0.203 V</li> <li>• Cell voltage: 0.619 V</li> <li>• Power consumption: 1.48 <math>\text{kWh}/\text{m}^3 \text{H}_2</math></li> </ul>	<ul style="list-style-type: none"> <li>• Substantial energy reduction</li> <li>• Chlorine-free process</li> <li>• Effective sulfide upcycling</li> <li>• High durability</li> </ul>	<ul style="list-style-type: none"> <li>• Scaling challenges</li> <li>• Optimization needed for maximum efficiency and longevity in seawater conditions</li> </ul>	(Jiang et al., 2024a)

Tables 3, 4, and 5 provide an extensive comparison of several methods for green hydrogen production from seawater and categorizes these methods into three main types, namely, PSS (Hassan et al., 2023a), AEM (Park et al., 2021), and DSE (Oraby and Shawqi, 2024), all of which do not require the desalination process. For each method, the table details the materials used, the durability of these materials, their efficiency, advantages and disadvantages, and the contributing authors that employed key performance metrics, such as photocurrent density, faradaic efficiency, overpotential, and overall cell voltage. These key performance metrics facilitate a comprehensive grasp of the operational and technical facets of each approach, providing insight into its practical applicability.

Given the climatic conditions in tropical regions of Asia, which include high temperatures and humidity levels, methods that prioritize stability and resistance to environmental factors are particularly suitable. The table indi-

cates that PSS methods using materials such as titanium butoxide (TBOT), bismuth vanadate ( $\text{BiVO}_4$ ), and tungsten trioxide ( $\text{WO}_3$ ) are frequently utilized in these regions. These materials are noted for their high durability and enhanced photocorrosion protection, making them ideal for consistent and efficient green hydrogen production in environments where solar irradiance is abundant.

## 5 Economic aspect and financial feasibility

As highlighted in the previous section, the choice of method for green hydrogen production from seawater is influenced not only by technical and environmental factors but also by the economic and financial viability of each approach. The comparison in Tables 3, 4, and 5 underscores the diversity in material costs, synthesis complexity, and

operational efficiency among the three methods—PSS, AEM, and DSE. These differences play a critical role in determining the overall cost-effectiveness of hydrogen production, particularly in meeting the US Department of Energy's target of \$2/kg to \$4/kg for practical hydrogen production by 2026 (Harrison et al., 2010; United States-Department of Energy, 2023a, 2023b).

Achieving this cost target necessitates optimizing the current production methods while considering the economic landscape across various regions, where resource availability, technology adoption, and energy costs can differ significantly. The following subsections delve into the economic prospects, technological challenges, and regional applicability of the three primary methods, i.e., PSS, AEM, and DSE, providing a comprehensive understanding of their financial feasibility and potential for large-scale deployment.

### 5.1 Photoelectrochemical seawater splitting

PSS utilizes photoactive materials, such as TBOT, BiVO<sub>4</sub>, and WO<sub>3</sub>, to harness solar energy and drive the water-splitting reaction. These materials exhibit exceptional durability and generate substantial photocurrent densities. For instance, a study of BiVO<sub>4</sub> conducted by Chi et al. (2022) reported an STH conversion efficiency of 10% and a lifespan exceeding 10 years, with costs below US \$200/m<sup>2</sup>. WO<sub>3</sub>, when combined with dual cocatalysts, provides effective protection against photocorrosion mechanisms, as determined in the research conducted by Liu et al. (2020). Although the initial production costs are relatively high because of the complexity of synthesis and the need for precise control during manufacturing, cost reductions as technology advances and economies of scale can be achieved.

Over time, the cost-effectiveness of this method improves, particularly in regions with abundant solar energy. In several areas, such as the Middle East and North Africa, where sunlight is plentiful, these methods show significant potential to further reduce production costs compared with other regions (Katakam and Bahadur, 2024). The stability and durability of these materials make them promising candidates for large-scale deployment in regions with high solar energy availability, providing long-term economic benefits despite the initial higher costs.

### 5.2 Anion exchange membrane

The AEM method utilizes materials such as nickel foam (NF), Nafion membranes, high-entropy metal oxides, and various metal phosphates to facilitate ion exchange in seawater electrolysis. These materials provide excellent stability and catalytic performance over extended periods, resulting in significant energy savings because of their high catalytic activity. For instance, NF has been shown to yield a hydrogen production cost of \$0.924 per gasoline gallon equivalent (GGE; Xu et al., 2024), whereas Nafion mem-

branes exhibit an efficiency of approximately 67% across different current densities, with a hydrogen production cost of \$1/GGE H<sub>2</sub> (Marin et al., 2023).

Although the initial costs range from medium to high because of the need for advanced materials and complex synthesis techniques, the long-term operational savings and high energy efficiency make this method economically viable. This method is particularly well-suited for extensive applications, especially in scenarios where energy efficiency and integration with renewable energy sources are critical. The cost-effectiveness of this approach improves as production scales up and synthesis processes are refined. This method is especially viable in regions with developed renewable energy infrastructure, such as East and Southeast Asia, where integration with existing renewable energy sources can further lower operational costs (Li et al., 2022). As production expands and synthesis techniques are optimized, the economic viability of AEM methods is likely to increase, enhancing its appeal for broader applications.

### 5.3 Direct seawater electrolysis

DSE uses materials, such as bipolar membranes, NF, and various anolytes and catholytes, to directly electrolyze seawater, producing hydrogen and oxygen. The cost of hydrogen production through this method has been estimated at \$0.924/GGE (Han et al., 2022). This approach provides high durability and excellent corrosion resistance, making it particularly suitable for operation in saline environments. The initial material costs are relatively low, and the use of natural seawater eliminates the need for expensive feedstock. However, optimization is necessary to enhance long-term efficiency and reduce energy consumption.

Economically, this method is especially viable in coastal regions where seawater is abundant and readily accessible. In regions such as Southeast Asia, where seawater resources are plentiful and membrane technology has advanced, costs have been reduced compared with other areas. The low material costs and potential for high durability make this method attractive, especially when operational efficiency is optimized. The economic feasibility is further improved in areas with low feedstock costs and high availability of renewable energy, potentially leading to significant cost savings.

## 6 Discussion

The conventional process of green hydrogen production from seawater typically involves desalinating seawater using different techniques, such as reverse osmosis or thermal distillation; however, these techniques are energy-intensive and costly. Once desalinated, the freshwater is used for electrolysis to produce hydrogen. The initial investment

required to establish desalination facilities can be substantial, ranging from \$1 000/m<sup>3</sup> per day to \$3 000/m<sup>3</sup> per day of installed capacity (Sun et al., 2022). For instance, a plant with a capacity of 100 000 m<sup>3</sup>/day could require an investment between \$100 million and \$300 million. In addition, operational expenses for desalination can be significant, varying between \$0.50/m<sup>3</sup> and \$3.00/m<sup>3</sup> of desalinated water (Al-Karaghoul and Kazmerski, 2013), leading to annual costs ranging from \$18 million to \$109.5 million. Energy consumption is another major cost driver, with usage ranging from 3 kWh/m<sup>3</sup> to 10 kWh/m<sup>3</sup> of water (Mehanna et al., 2010) and maintenance costs typically adding another 15% to 20% to the operational expenses (Luo et al., 2011).

To address the high costs and energy demands associated with desalination, several innovative methods, such as PSS, AEM, and DSE, have been developed. These methods bypass the desalination step entirely by using seawater directly for hydrogen production, significantly reducing both costs and energy consumption (Khan et al., 2021). Eliminating the desalination step can reduce overall costs by approximately 40–60% (Horri and Ozcan, 2024). For a plant with a capacity of 100 000 m<sup>3</sup>/day, this reduction can lower costs to between \$1.50 and \$3.60/m<sup>3</sup>, resulting in total annual costs of \$54.75 million to \$131.4 million. Empirical studies have also shown that these innovative processes can save 30–50% in energy costs compared with conventional methods (Dokhani et al., 2023), with some studies indicating potential cost reductions of up to 60% (Badea et al., 2022).

In addition to economic benefits, the environmental impact and sustainability of these methods are also crucial considerations. For instance, PSS utilizes materials such as TBOT (Ahmad et al., 2022; Zhao et al., 2024b), BiVO<sub>4</sub> (Vinoth et al., 2021; Chi et al., 2022; Tezcan et al., 2022; Chen et al., 2023), and WO<sub>3</sub> (Liu et al., 2020; Parvin et al., 2024), which effectively harness abundant solar energy and avoid the use of harmful chemicals, ensuring a safe and sustainable process. The technical feasibility of green hydrogen production from seawater using advanced methods has been increasingly supported by advancements in materials science. For example, tungsten oxide (WO<sub>3</sub>) has been identified as a promising material for photoanodes due to its stability and efficiency in chloride-rich environments, common in seawater. In addition, BiVO<sub>4</sub>, combined with protective core-shell structures such as  $\alpha$ -Cr<sub>2</sub>O<sub>3</sub>, has shown significant improvements in both durability and efficiency under solar irradiation. The integration of these materials into PEC systems indicates the potential to overcome traditional challenges associated with seawater electrolysis, such as chloride-induced corrosion and low energy efficiency.

The AEM technique, involving materials such as NF (Guo et al., 2024; Na et al., 2024; Xia et al., 2024; Xu et al., 2024), Nafion membranes (Marin et al., 2023), and high-

entropy metal oxides (Kumar et al., 2023), provides high energy efficiency and long-term operational savings, making it economically viable despite relatively high initial costs. DSE, utilizing materials such as NF (He et al., 2023; Elahi and Seddighi, 2024; Wang et al., 2024) and bipolar membranes (Han et al., 2022; Han et al., 2023a), capitalizes on readily available resources and avoids hazardous chemicals and harmful by-products. However, this method requires careful seawater management to mitigate potential environmental impacts.

To further enhance the feasibility and commercial viability of green hydrogen production from seawater, future research should focus on optimizing the efficiency and scalability of these innovative methods. Key areas of exploration include material optimization, system integration, environmental impact assessments, and comprehensive economic analyses. By addressing technical, economic, and environmental considerations, these innovative methods could play a pivotal role in the global transition to sustainable energy. For example, research should explore the long-term environmental impacts of large-scale hydrogen production facilities, particularly on marine ecosystems, and further investigate advanced materials that can withstand the harsh conditions of seawater electrolysis. Microbial desalination cells, which have exhibited the capability to reduce salinity by up to 90% while concurrently producing hydrogen at a rate of 0.16 m<sup>3</sup> H<sub>2</sub>/m<sup>3</sup> per day (Mehanna et al., 2010), provide promising avenues for integrating desalination with hydrogen production, maximizing efficiency, and minimizing environmental impact.

Recent advancements in materials science have also been instrumental in enhancing the efficiency and durability of electrolysis methods used in green hydrogen production. For example, the development of high-entropy metal oxides has improved the efficiency of AEM by 20% to 30% and reduced material degradation by 15% compared with traditional materials. Advances in catalyst technologies, such as platinum-based catalysts, have increased hydrogen production rates by up to 50% in microbial electrolysis cells. These innovations have reduced the susceptibility of these systems to corrosion and other forms of degradation, making them more viable for long-term operation. However, further research is needed to enhance the cost-effectiveness and scalability of these materials.

The technical feasibility of various electrolysis methods depends on specific materials and environmental conditions. For instance, PSS can achieve an STH efficiency of up to 12% but requires precise control over the synthesis and application of photoactive materials (Chen et al., 2023). AEM, with an efficiency of 67%, exhibits high energy efficiency but is more complex and expensive to produce (Marin et al., 2023). DSE, which has been shown to reduce hydrogen production costs to \$0.924/GGE, is particularly viable in coastal regions where seawater is abundant but

requires careful management to avoid issues, such as fouling and reduced efficiency over time. Future research should prioritize the development of hybrid systems that combine multiple renewable energy sources with hydrogen production to maximize efficiency and minimize environmental impact. Pilot projects that assess the scalability and economic viability of these technologies across different regions should be emphasized, as they will provide essential insights for large-scale implementations. By embracing a holistic approach that integrates the technical and environmental aspects of green hydrogen production, Indonesia has the potential to become a leader in the sustainable utilization of maritime resources.

This research builds upon a study conducted by Sari et al. (2024), which stressed the importance of harmonizing technological progress with ecological conservation. Drawing on these insights, the discussion here advocates for a holistic approach that integrates both the technical and environmental dimensions of green hydrogen production, ensuring that innovations are sustainable and consistent with broader environmental objectives. Indonesia, with its extensive maritime landscape, has significant potential for the development of green hydrogen as a sustainable energy source. Bawean Island, rich in natural resources, particularly in its coastal areas, exemplifies the broader possibilities across Indonesia's archipelago. The strategic position and diverse ecosystems, including coral reefs, mangrove forests, and varied marine life, of the island present both opportunities and challenges for sustainable growth. The incorporation of green hydrogen production with coastal resource management on another of Indonesia's islands could be a practical solution to some of the key issues, such as the scarcity of clean water, coastal erosion, and economic difficulties faced by the local community.

Green hydrogen production, especially through DSE, eliminates the need for desalination, thereby easing the burden on limited freshwater resources and providing a sustainable alternative to fossil fuels. The experience of Bawean Island underscores the critical need to balance technological development with ecological preservation in Indonesia. The advancement of renewable energy technologies, including green hydrogen, must consider potential environmental impacts, particularly in sensitive archipelagic ecosystems. For example, the construction of offshore hydrogen production facilities must be carefully planned to avoid disrupting marine life and damaging coral reefs, which are essential to the tourism and fishing industries of the island. In addition, the socioeconomic benefits of green hydrogen production can play a vital role in advancing sustainable development on Bawean Island. By creating new employment opportunities in the renewable energy sector, local communities can be empowered to engage in and benefit from the transition to a green economy. This strategy aligns with the need to diversify the economy of the island,

reducing its dependence on traditional industries that may not be sustainable in the long term.

In summary, the potential for green hydrogen production from seawater in Indonesia, particularly in areas that provide significant opportunities, presents a chance to leverage the maritime resources of the nation for sustainable growth. By combining advanced technologies with ecological and socioeconomic considerations, Indonesia has the opportunity to set a benchmark for the responsible and effective utilization of its coastal resources, ensuring that development efforts contribute to both the environmental sustainability and prosperity of local communities. This holistic approach, supported by continuous research and collaboration among government, industry, and local stakeholders, will be essential in fully realizing the potential of green hydrogen production in the maritime regions of Indonesia.

## 7 Conclusions

This study provides a comprehensive evaluation of the feasibility and future prospects of integrating MRE with green hydrogen production in Indonesia, emphasizing the substantial potential for advancing sustainable energy solutions in the region. By exploring advanced electrolysis methods, particularly those that eliminate the need for desalination, the research demonstrates how Indonesia can achieve significant cost reductions of up to 60% in overall production costs and 30% to 50% in energy costs compared with traditional methods. Thus, technologies such as DSE and PEC methods, using materials such as NF and BiVO<sub>4</sub>, become highly suitable for application in the coastal regions of Indonesia because of their minimal environmental impact and avoidance of hazardous chemicals. The vast maritime resources of Indonesia, including tidal waves and offshore wind energy, position the country as an ideal environment for large-scale green hydrogen production. By harnessing these resources, Indonesia can significantly enhance its energy independence, drive economic growth, and contribute to global efforts in reducing carbon emissions, and this aligns well with the sustainability goals and international commitments of the country.

The study also emphasizes the critical need for ongoing research and continuous optimization of these technologies, including the development of innovative materials and methods that can further enhance the efficiency, durability, and commercial viability of seawater-based green hydrogen production. Such efforts will be crucial in supporting Indonesia's transition to low-carbon and sustainable energy in the future. Moreover, the integrated approach highlighted in this research ensures that the development of green hydrogen technology not only meets the energy demands of the nation but also contributes positively to environmental

preservation and the well-being of local communities. By fostering collaboration among government, academia, and industry, Indonesia can position itself as a leader in the global transition to renewable energy, paving the way for a sustainable and independent energy system. Overall, the study outlines a clear and promising pathway for Indonesia to achieve energy independence and sustainability through the strategic integration of MRE with green hydrogen production. This approach not only addresses current energy challenges but also sets the stage for long-term economic and environmental benefits.

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