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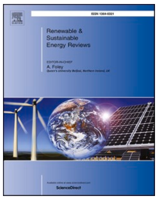

Marine renewable energy for hydrogen production: Advancing towards a sustainable future through technological, economic, and environmental frontiers– a review

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ABSTRACT

The accelerating urgency to mitigate global climate change has intensified research into cleaner, more sustainable energy solutions. This review explores the convergence of marine renewable energy (MRE) and green hydrogen production as a promising pathway toward a decarbonized energy future. It provides a comprehensive analysis of MRE technologies including tidal, wave, ocean thermal energy conversion (OTEC), and salinity gradient power detailing their working principles, recent technological advancements, and current deployment status. Special attention is given to the integration of these resources with hydrogen production via water electrolysis, focusing on technologies such as proton exchange membrane (PEM), alkaline, and solid oxide electrolyzers (SOEC), which have demonstrated conversion efficiencies of up to 90 % under optimal conditions. The review assesses the technical feasibility of these hybrid systems, highlights key operational challenges (e.g., intermittency, offshore infrastructure, corrosion), and discusses potential advantages such as proximity to coastal hydrogen markets and energy security. The economic dimension is critically examined, with current green hydrogen production costs ranging from $2.50 to $6.80 per kilogram, and future targets aiming for $1/kg by 2030. Case studies including the Sealhyfe offshore pilot project in France, capable of producing up to 400 kg/day of hydrogen are presented to illustrate real-world progress. Environmental impacts, regulatory frameworks, and marine spatial planning considerations are also addressed. By synthesizing technical, economic, and environmental perspectives, this review offers a strategic overview of the role marine energy can play in large-scale hydrogen production. It aims to support researchers, policymakers, and industry stakeholders in identifying opportunities, addressing barriers, and accelerating the deployment of MRE-to-hydrogen systems. Ultimately, the study contributes to outlining pathways for a resilient, low-carbon, and integrated energy future.

Nomenclature:

OWC	Oscillating Water Column	η	efficiency of the system
PEM	Proton exchange membrane	ρ	density of seawater
SOEC	Solid Oxide Electrolysis Cell	C_P	specific heat of seawater
ESMR	Electro-Supercritical Methanol Reforming	ΔT	temperature difference between warm and cold seawater
AEM	Anion Exchange Membrane:	R	Tidal range
DAE	Direct Air Capture Electrolysis	S	Surface area of the tidal basin
BES	Biological Electrochemical Systems	T	period of the tidal cycle
OTEC	Ocean Thermal Energy Conversion	π	Osmotic Pressure
P	Power output	P_r	Power Density
V	Wind Speed	SGE	salinity gradient energy
H_s	Significant Wave Height (m)	RED	reverse electrodialysis
T	Wave Period (s)	PRO	pressure retarded osmosis
Q	flow rate of the working fluid (kg/s)		

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1. Introduction

Ocean energy holds great promise for meeting the world's growing

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energy needs while reducing environmental impact. Today, cutting-edge research is exploring how to tap into marine renewable resources and improve hydrogen production, offering fresh, sustainable ways to power our future. By using seawater electrolysis combined with ocean energy, we can produce hydrogen in an eco-friendly and cost-effective way without relying on precious freshwater supplies. This method also opens up new opportunities for storing and transporting hydrogen directly at sea. Supported by government incentives and programs, the shift toward sustainable energy systems is gaining momentum and driving major changes in how we generate and use energy. A variety of innovative strategies are being developed to capture ocean energy for hydrogen production, addressing both the technical hurdles and practical challenges involved. Kumano et al. [1], for instance, introduced a revolutionary hydrogen energy system that harnesses the electrical energy from ocean currents, offering a solution that efficiently converts seawater into hydrogen without encountering issues such as frequency changes or transmission losses. Moreover, Zini et al. [2] expanded the perspective by discussing various renewable energy sources including hydroelectricity, tidal energy, wave energy, ocean thermal energy, solar thermal energy, and biomass as alternatives for hydrogen production, thereby broadening the scope beyond just wind and solar photovoltaic energy. In addition, Sánchez-Dirzo et al. [3] reviewed engineering projects aimed at hybridizing renewable energy sources from the seas, with a particular focus on hydrogen storage for power generation. Similarly, Blanco-Fernández et al. [4]explored the feasibility of offshore installations using wave energy to extract hydrogen, potentially paving the way for hydrogen-powered ships. Meanwhile, Leonard et al. [5] proposed an innovative ocean-powered hydrogen generation system consisting of a transportable ocean vessel equipped with a generator that converts ocean kinetic energy into electrical energy, alongside a dissociator that separates seawater into hydrogen and oxygen. Furthermore, Serna Cantero et al. [6,7] developed a model predictive control strategy for an offshore platform in the Atlantic Ocean, where hydrogen is produced by harnessing both wind and wave energy; this operation is optimized to maximize the efficient use of available energy resources. Altogether, these different approaches underline the growing interest and immense potential of ocean energy in sustainable hydrogen production, offering promising solutions for the future energy landscape.

At the global level, energy demand continues to increase in 2025, driven by economic development and population growth. Renewable energies such as wind, solar, and hydro are expanding but still represent a minority share in the global energy mix [7–9]. Countries like Morocco aim to increase renewable electricity production to 52 % by 2030 [10–12]. Hydrogen is increasingly viewed as a key energy vector to decarbonize hard-to-electrify sectors like heavy transport and industry. National strategies, such as France's, set ambitious targets for green hydrogen production through electrolysis by 2030 and 2035 [13]. The versatility of hydrogen, used in fuel cells and as a feedstock for synthetic fuels, reinforces its strategic role in the energy transition [14]. Despite technological and economic challenges, investments in hydrogen production, storage, and distribution infrastructure are rapidly growing at both European and international levels [15].

The oceans represent abundant renewable energy sources, including thermal energy from temperature differentials, kinetic energy from tides and waves, chemical energy from oceanic chemicals, and biological energy from marine biomass. Various studies provide differing estimates of the annual energy potential from oceans [16]. Derakhshan et al. [17] propose a range of 4–18 million tonnes of oil equivalent (mtoe), whereas Wahyudie et al. [18] suggest a global electricity collection potential of up to 32 TW (TW). De Andres et al. [19] Highlight the possibility of deploying ocean energy converters capable of generating 337 GW (GW), which could produce 885 TW-hours (TWh) of electricity annually. Khan et al. [20] provide a detailed breakdown, estimating that tidal energy could offer around 800 TWh annually, wave energy 2000 TWh, osmotic energy between 8000 and 80,000 TWh, and thermal gradient energy between 10,000 and 87,600 TWh.

Given the growing significance of hydrogen production leveraging abundant renewable energy sources, a comprehensive literature search was conducted across various databases using keywords such as "hydrogen production," "green hydrogen," "marine energies," "offshore wind energy," and "electrolysis." From an initial pool of 598 articles published between 2000 and 2023, 258 were selected based on their relevance [13]. Following a more detailed evaluation, 50 articles were classified into four categories: case studies, technical and economic evaluations, environmental analyses (LCA), and system design and performance [13]. Fig. 1 illustrates the classification and the number of articles within each category. Our research provides a comprehensive analysis of hydrogen production through electrolysis using marine-based sources such as wind and marine currents. We focus on evaluating operational conditions for energy and hydrogen generation, technical aspects, economic feasibility, and environmental impact. This study aims to offer valuable insights for advancing green hydrogen production technology in marine environments, emphasizing its potential for energy generation and storage. We also address challenges and opportunities in the hydrogen industry to inspire new scientific and technological advancements.

This review paper is organized into six main sections to provide a logical and coherent flow of discussion. First, we examine Green Hydrogen Production, outlining its principles, current technologies, and the role it plays in the global energy transition. Next, we explore Marine Renewable Energy Technologies, including offshore wind, wave, and tidal systems, emphasizing their potential as sustainable energy sources. Following this, we discuss the Integration of Electrolyzers with Marine Energy, highlighting the technical considerations, system designs, and operational strategies required for effective coupling. Subsequently, we evaluate the Feasibility and Advancements in Marine Energy for Hydrogen Production, focusing on economic, technical, and environmental aspects. In the fifth section, we present Green Hydrogen Production at Sea: Recent Advances, reviewing state-of-the-art research, pilot projects, and technological breakthroughs. Finally, we offer Outlooks and Future Perspectives, identifying promising research directions, innovative concepts, and emerging trends that could enhance the efficiency, cost-effectiveness, and sustainability of marine-based hydrogen production.

This review paper is organized into four main sections: Green Hydrogen Production, Marine Renewable Energy technologies, Feasibility and Advancements, and Conclusions. Our conclusions highlight promising research directions and cutting-edge technologies that could

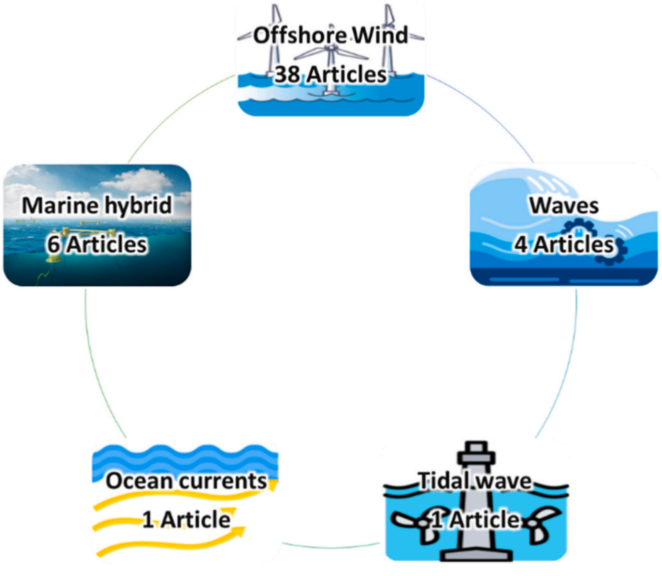


Fig. 1. Article classification framework.

enhance the efficiency, cost-effectiveness, and sustainability of hydrogen supply.

2. Green hydrogen production

Green hydrogen is produced through water electrolysis, powered by renewable sources like solar and wind, or even residual industrial heat, offering a zero-emission alternative. As depicted in Fig. 2, the process faces three key challenges: improving hydrogen production efficiency, developing advanced storage technologies, and designing cost-effective fuel cells. Effective hydrogen storage is crucial, ensuring stable energy distribution and overcoming geographical limitations, thus playing a vital role in the transition to a sustainable energy system.

2.1. *Water electrolysis technologies*

Green hydrogen production employs several advanced electrolysis technologies, each characterized by its specific strengths and challenges. Proton Exchange Membrane (PEM) electrolyzers are widely recognized for their high energy efficiency, rapid dynamic response, and operational flexibility, making them ideal for integrating variable renewable energy sources. However, their reliance on precious metal catalysts such as platinum and iridium translates into high capital costs, which currently limit large-scale deployment. In contrast, Solid Oxide Electrolyzer Cells (SOECs) operate at elevated temperatures (typically 700–900 °C), which significantly enhances electrochemical reaction kinetics and thermodynamic efficiency, enabling achievable conversion efficiencies up to 90 %. Nevertheless, SOECs face substantial material degradation and durability issues over long operational periods, posing a barrier to widespread commercialization [20]. These electrolysis technologies have evolved significantly, representing five generations of innovation since the 18th century [21], as detailed in Fig. 3.

Recent advancements have introduced promising variants and complementary approaches to further reduce emissions and improve sustainability. Direct Air Electrolysis (DAE) innovatively extracts water vapor directly from the atmosphere for electrolysis, thereby minimizing the dependency on freshwater resources and facilitating off-grid hydrogen generation. Electric Steam Methane Reforming (ESMR) integrates renewable electricity with traditional steam methane reforming, substantially lowering carbon emissions compared to conventional fossil-based methods [22]. Anion Exchange Membrane (AEM) electrolysis combines the cost advantages of alkaline electrolyzers with the higher efficiency and flexibility more typical of PEM systems, positioning it as a competitive mid-term solution [23,24]. Additionally, bioelectrochemical systems (BES), such as Microbial Electrolysis Cells (MECs), utilize microorganisms as biological catalysts to produce hydrogen from organic substrates, offering an innovative route that simultaneously treats waste and generates energy.

Currently, green hydrogen production costs vary widely, approximately ranging from $2.50 to $6.80 per kilogram depending on the technology, scale, and regional energy prices [25]. However, ongoing declines in the cost of renewable electricity and improvements in electrolyzer performance are expected to bring these costs closer to parity with blue hydrogen, which is produced using fossil fuels coupled with carbon capture. The U.S. Department of Energy has set an ambitious target to decrease green hydrogen production costs to $1 per kilogram by 2030, driven by technology innovation, economies of scale, and supportive policy frameworks [26].

Fig. 4 summarizes these cutting-edge technologies SOEC, ESMR, AEM, DAE, and BES highlighting their roles in boosting efficiency and lowering lifecycle greenhouse gas emissions [22–27]. While SOECs and AEM systems are approaching commercial readiness, BES and DAE remain at earlier Technology Readiness Levels (TRL), necessitating further research to resolve challenges related to system scalability, operational stability, and cost-effectiveness [28–30]. The successful development and integration of these diverse technologies will be critical to decarbonizing the hydrogen economy and achieving a sustainable, low-carbon energy future.

2.2. *Advanced materials for sustainable hydrogen production*

Efficient and durable catalysts and membranes are essential for sustainable hydrogen production. Nickel-based catalysts, known for their low cost and good electrocatalytic activity in hydrogen and oxygen evolution reactions, are widely studied [22]. Molybdenum-phosphorus (Mo-P) catalysts show promise for CO_2 methanation due to their balanced activity and stability [23]. Emerging materials like single-atom catalysts, metal-organic frameworks, perovskites, and layered double hydroxides offer further performance improvements [24,25]. Membrane technologies, such as proton exchange membranes (PEMs) and gas separation membranes, play a critical role in selective ion and gas transport, impacting system efficiency and durability [26]. Catalytic membrane reactors that combine reaction and separation enhance conversion and selectivity [27]. However, integrating these components poses challenges, including chemical and mechanical compatibility, catalyst–membrane interactions, scaling from lab to industry, cost reduction, and ensuring long-term stability against degradation and corrosion [28].

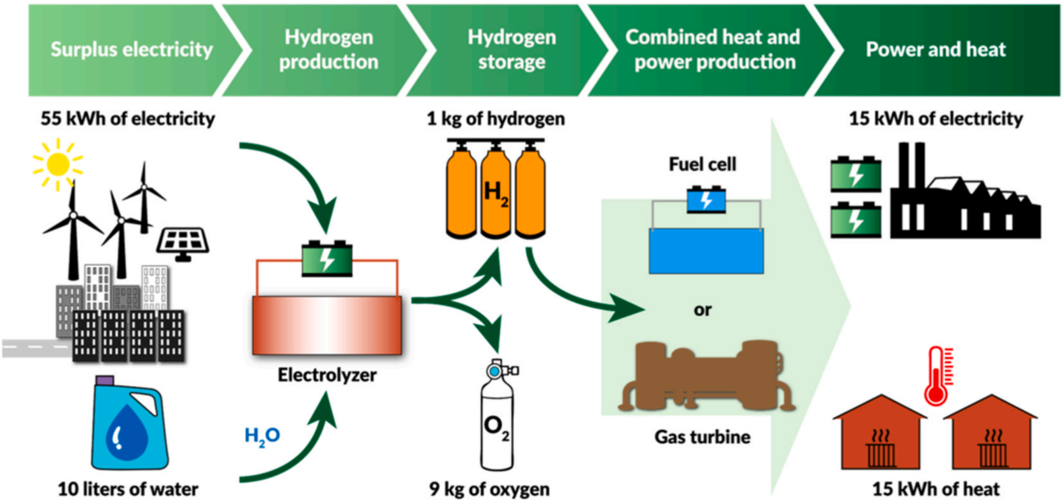


Fig. 2. Green hydrogen value chain, reproduced with permission from [15] (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

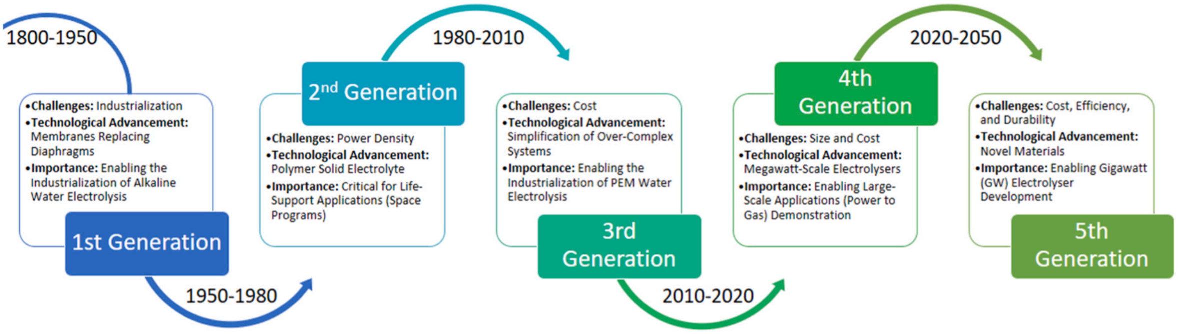


Fig. 3. Development Stages of Water Electrolysis, reproduced with permission from [21].

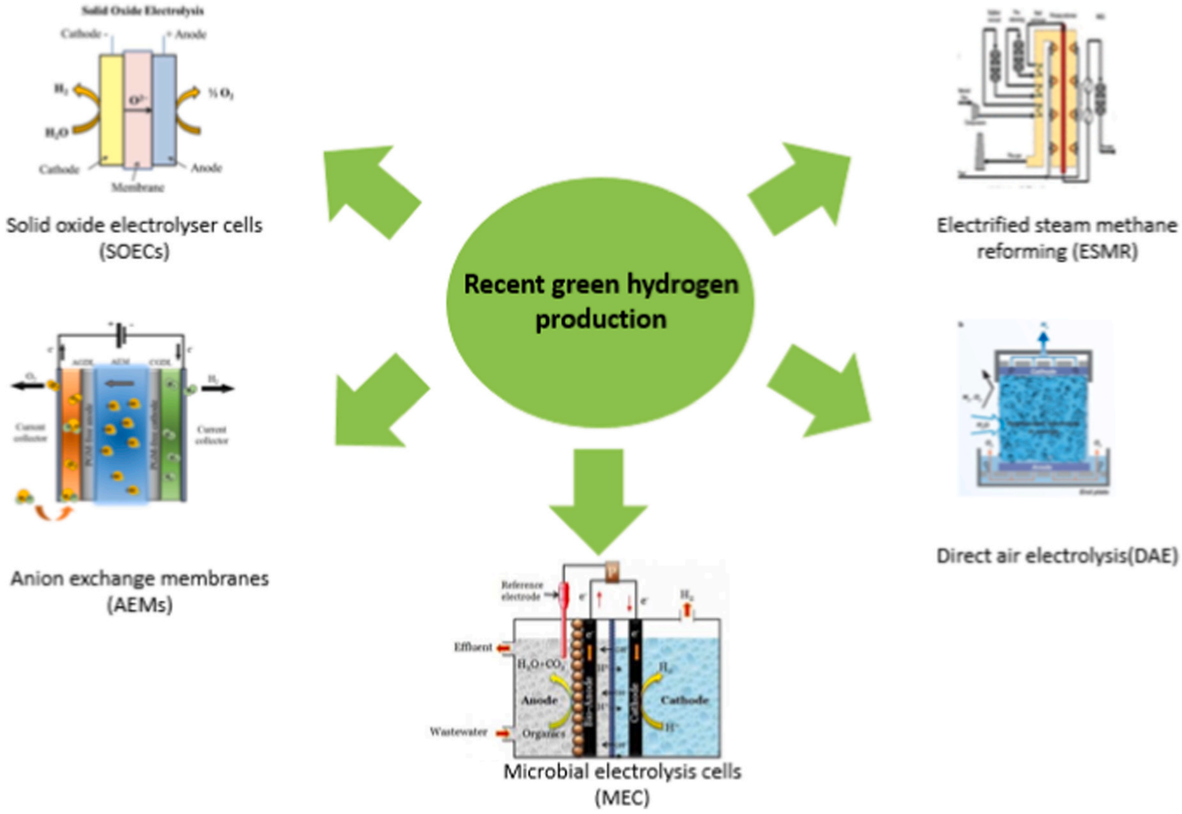


Fig. 4. Recent advances in green hydrogen production technologies. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Addressing these barriers demands a multidisciplinary approach that combines fundamental research with practical engineering. Strong partnerships between academia and industry, supported by public-private initiatives and international collaboration, are critical to accelerate the development and deployment of clean hydrogen technologies. These efforts will underpin the global energy transition by enabling cost-effective, durable, and efficient hydrogen production at scale. Building on these technological foundations, it is important to understand that hydrogen production itself can proceed via different methods, each exhibiting unique characteristics in terms of cost, carbon footprint, and scalability, see Table 1. The three primary pathways widely considered today are grey hydrogen, blue hydrogen, and green hydrogen each playing distinct roles in the evolving energy landscape.

3. Marine Renewable Energy Technologies

Marine renewable energies, including tides, waves, currents, and

Table 1
Comparative characteristics of hydrogen production pathways[31–34].

Hydrogen type	Estimated cost	Emissions (CO_2)	Scalability potential	Key cost and feasibility drivers
Grey [31]	€1.50 – €2/kg	9–19 kg CO_2/kg H_2	High, due to existing infrastructure	Natural gas price; infrastructure availability
Blue [31]	€1.5 – €3/kg	1–4 kg CO_2/kg H_2	Medium, depends on CCS capacity	CO_2 price; CCS system efficiency
Green [32–34]	€3 – €7/kg	0 kg CO_2 direct if 100 % renewable electricity	High potential with renewable energy expansion	Renewable electricity cost; electrolyzer efficiency

temperature variations, hold great potential to meet electricity demand [35,36]. With an estimated capacity of 57,000 TWh/year, these sources are vital for the clean energy transition [37]. Their development requires policies, stakeholder involvement, and sustainable practices [38]. Integrating marine energy into seaports can reduce emissions and shift from fossil fuels, with frameworks like the Analytical Hierarchy Process aiding in energy source selection [39]. Technologies such as wave converters, tidal turbines, and ocean current turbines harness kinetic energy. The European Commission targets 1 GW by 2030 and 40 GW by 2050 [31–34]. Ocean energy includes tides, currents, waves, salinity gradient, and OTEC systems, as shown in Fig. 5 [40].

3.1. *Tidal energy*

3.1.1. *Advancements in tidal power technology for sustainable energy*

Tidal power, a sustainable hydrogen production method, is gaining interest, especially in the Sea of Okhotsk for East Asia's energy needs [41–43]. Tidal energy converters with hydrogen storage enhance efficiency [44]. Tidal plants harness predictable tidal movements, with plants in France, Canada, China, and Russia [32]. The UK plans a large tidal power station in the Severn Estuary, despite environmental concerns [45]. Tidal power, driven by gravitational forces from the Moon and Sun, has global potential of 100 GW, with major players like Canada, France, the UK, and the USA [46,47]. Morocco's Mediterranean, particularly Agadir and Tangier, shows promise [48–52]. Various methods are proposed for harnessing tidal energy [53]. Despite their diversity, the core principle remains converting tidal movements' kinetic or potential energy into electricity [53–55]. The three primary methods include Tidal Barrages, Tidal Lagoons, and Tidal Streams [56,57]. Tidal Barrages utilize potential energy from tidal height differences, Tidal Lagoons capture kinetic energy within a contained area, and Tidal Streams employ underwater turbines to harness kinetic energy, see Fig. 6. These methods collectively offer promising pathways for sustainable tidal energy production [20,53–55].

3.1.2. *Tidal power calculation*

Newton's law of universal gravitation governs the Sun-Moon-Earth interactions, causing ocean tides and full moons, as shown in Fig. 7 [20,58]. Tidal cycles include [58]:

- A 12.4-h cycle from Earth's rotation in the lunar gravitational field.
- A 14-day cycle of spring and neap tides from the Moon and Sun's combined forces.
- A half-year cycle with highest tides between March and September due to the Moon's orbital inclination.

Tidal fluctuations in the open ocean are typically under 1 m, but near coastlines, factors like shelving, funneling, reflection, and resonance can amplify tides [60]. Tidal amplitude increases with decreasing ocean depth (shelving), narrow coastlines (funneling), and constructive reflection. Resonance occurs at estuary mouths when the tide's frequency matches the natural propagation frequency [20,58].

The equation governing the maximum power output P of a tidal energy system is expressed as [20,58,61]:

$$P = \frac{\rho g R^2 S}{2T} \tag{1}$$

Where P is power generated (in watts), ρ is the density of water (1025 $\mathrm{kg/m^3}$), g is gravitational acceleration, R is the tidal range, S is the surface area of the tidal basin, and T is the period of the tidal cycle (12.4 h).

3.2. *Wave energy*

3.2.1. *Wave energy technology advancements*

Wave energy offers potential for hydrogen production and renewable electricity. Wave Energy Converters (WECs), such as CorPower Ocean's, capture wave energy to generate electricity [62–64]. The first operational generator in Portugal highlights this [65]. In the USA, despite high potential, challenges remain in ocean conditions and optimization [65–68]. As shown in Fig. 8, devices like Oscillating Water Columns (OWCs) drive turbines using wave motion, with improved designs by IDOM Inc. [63,69,70]. Point Absorbers and Oscillating Wave Surge Converters (OWSCs) adapt to marine environments and produce up to 100 kW [63,66]. Examples like CalWave's xWave and Columbia Power's StingRAY produce 45 and 50 kW, respectively, ideal for remote areas [63]. These technologies complement other renewable sources for clean energy [62,63,66].

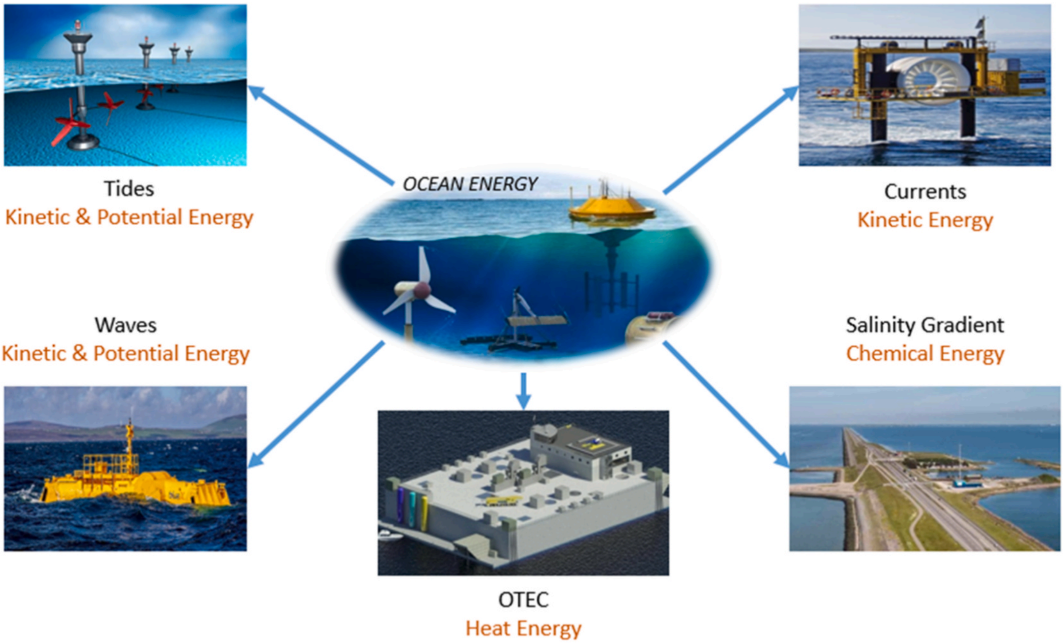


Fig. 5. Classification of ocean energy.

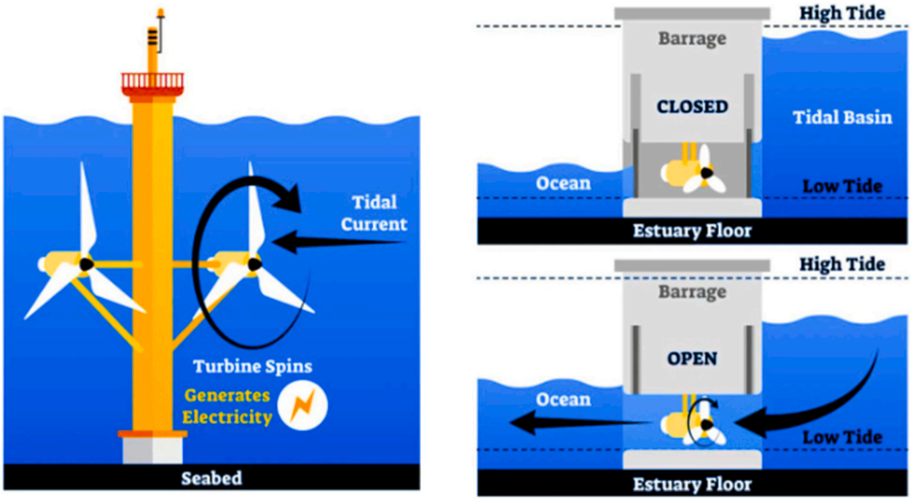


Fig. 6. Tidal Energy Generation Process, reproduced with permission from [53].

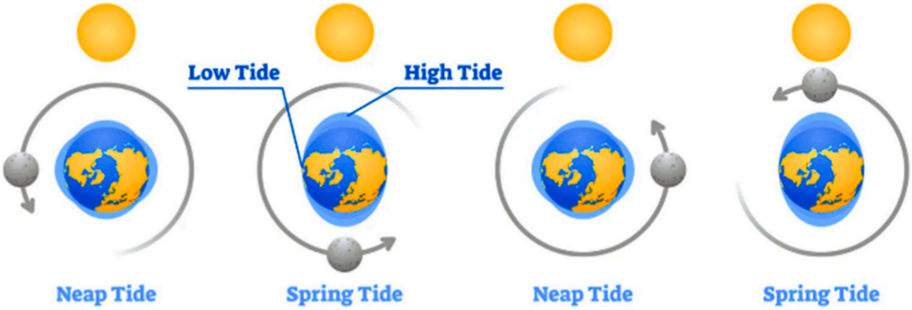


Fig. 7. Natural Progression of Spring and Neap Tides Across Sea and Ocean Surfaces, reproduced with permission from [20,59].

3.2.2. *Wave power calculation*

The wave energy model described in the passage allows for the estimation of wave power per unit crest length. This power assessment relies on factors such as wave height H_s and wave period T. The formula used is as follows [50,74,75]:

$$P = \frac{1}{64\pi}\rho g^2 H_s^2 T \tag{2}$$

In this equation:

- P represents the wave power per unit crest length (kW/m).
- ρ is the water density (kg/m^3).
- g is the acceleration due to gravity (m/s^2).
- H_s is the significant wave height (m).
- T is the wave period (s).

3.3. *Ocean thermal energy conversion (OTEC)*

3.3.1. *The potential of ocean thermal energy conversion (OTEC)*

Ocean Thermal Energy Conversion (OTEC) uses the temperature difference between warm surface and cold deep water to generate electricity, as shown in Fig. 9. It offers minimal environmental impact, continuous operation, and potential as a base load power source without additional storage [76,77]. Feasibility depends on factors such as distance from shore, ocean floor depth, and the size of the thermal resource [78]. Challenges like efficiency, biological fouling, and energy requirements remain, requiring further development [79,80]. OTEC systems, including open, closed, and hybrid cycle variants, convert thermal energy into electricity using heat exchangers and active fluids [81].

OTEC generates clean energy by using the temperature difference between surface and deep waters, especially in the tropics(20–25 °C gradient) [81,82].There are two main systems (Fig. 9):

- **Closed Cycle**: A low-boiling-point fluid (e.g., ammonia) is vaporized by warm seawater to drive turbines, then condensed for reuse [81].
- **Open Cycle**: Warm seawater is boiled to produce steam that drives a turbine, also yielding desalinated water [81].

3.3.2. *OTEC power calculation*

OTEC offers higher energy outputs than other ocean energy options, especially in tropical regions. Despite efficiency and technology challenges, it is a clean energy solution with minimal environmental impact [82,84]. Power output calculations depend on system design and parameters [85–87] and follow this equation [86,87]:

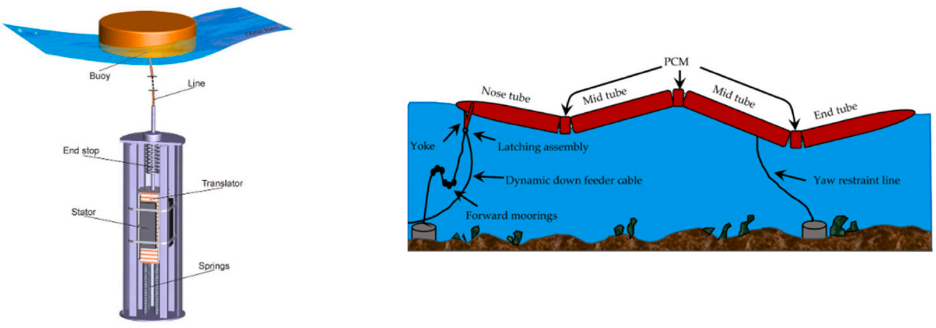
$$P = Q\,\eta\,C_P \Delta T \tag{3}$$

Where P represents the power (kW), Q is the flow rate of the working fluid (kg/s), η is the net efficiency of system (0.061 for an 85 % efficient turbine), ρ is the density of seawater (106 gm m-3), C_P is the specific heat of seawater (4.2 J gm-1 °C-1), and ΔT is the temperature difference between warm and cold seawater (21.5 °C).

3.4. *Salinity gradient power*

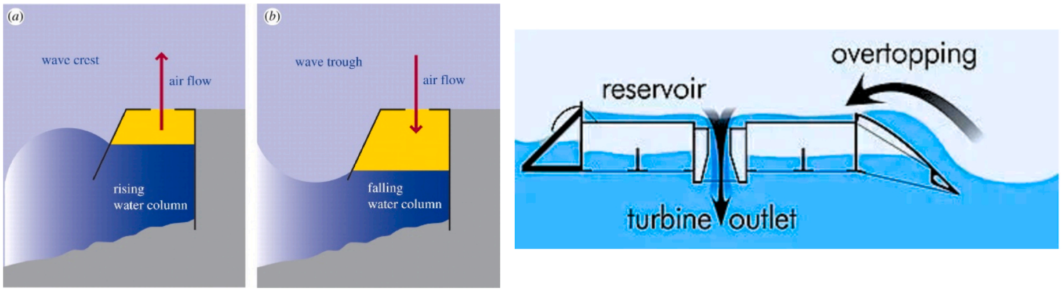
3.4.1. *Salinity gradient power: renewable energy from salinity differences*

Salinity Gradient Power (SGP) utilizes the salinity difference between fluids to produce electricity and hydrogen [88–90]. As shown in Fig. 10, this involves mixing solutions like seawater and treated wastewater, often integrated with other ocean energy sources [91]. Technologies like reverse electrodialysis (RED) and pressure retarded



Point Absorber

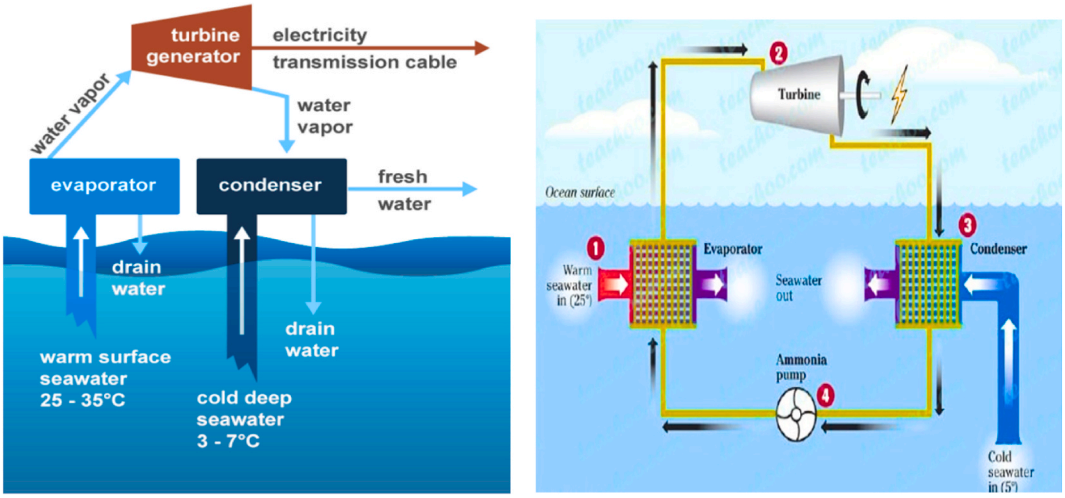
Attenuators



Oscillating water column/terminator

Overtopping

Fig. 8. Different Wave Energy Converter Technologies, reproduced with permission from Refs. [69–73].



a) open-cycle

b) closed-cycle

Fig. 9. A basic diagram of an ocean thermal energy conversion system, with options for an open-cycle a), reproduced with permission from Ref. [82] and a closed-cycle b), reproduced with permission from Ref. [83].

osmosis (PRO) are crucial [92]. Despite challenges like high membrane costs, SGP, with an estimated potential of 647 GW, shows promise for large-scale hydrogen and electricity production [92–94].

3.4.2. Calculating salinity gradient power

- Osmotic Pressure (π)

Osmotic pressure can be calculated using van't Hoff's law[96–98]:

$$\pi = i \cdot C \cdot R \cdot T \tag{4}$$

Where:

i: The ionization constant (e.g., for NaCl, $i \sim 2$).
C: The molar concentration of the solution (moles/L).
R: The universal gas constant (8.314 J/mol\cdotpK).
T: The absolute temperature in Kelvin

- Osmotic Pressure Difference ($\Delta\pi$)

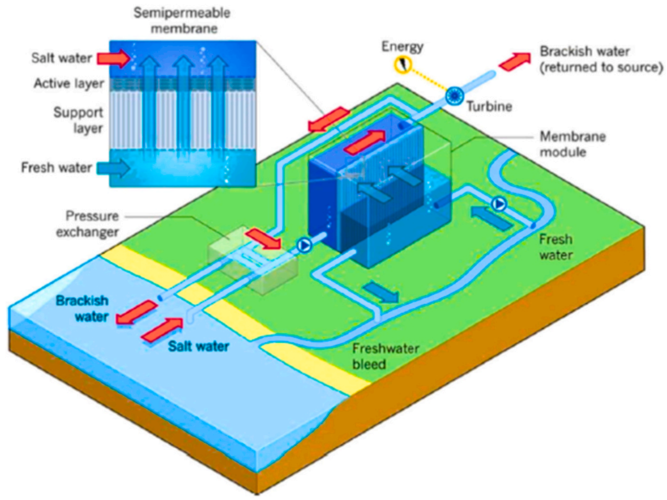


Fig. 10. Schematic Diagram of an Energy Generation System Using Pressure Retarded Osmosis (PRO) from Salinity Gradients, reproduced with permission from [95,96].

The osmotic pressure difference between seawater and freshwater is given by Ref. [99]:

$$\Delta\pi = \pi_{seawater} - \pi_{freshwater} \quad (5)$$

- Power Density (P_r)

The power density in Pressure Retarded Osmosis (PRO), represented as P_r, is defined by the formula [96,100]:

$$P_r = A \cdot \Delta\pi \cdot \Delta V \quad (6)$$

Where:

A: The membrane area (m^2).

$\Delta\pi$: The osmotic pressure difference (Pa).

ΔV: The volumetric flow rate of water through the membrane (m^3/s).

- Overall Power Output (P)

Total power output can be calculated by multiplying the power density by the total membrane area [96,101,102]:

$$P = P_r \cdot A \quad (7)$$

Or more simply:

$$P = A \cdot \Delta\pi \cdot \Delta V \quad (8)$$

These formulas form the basis for calculating theoretical power output from salinity gradients, supporting the evaluation of osmotic power potential.

4. Integration of electrolyzer with marine energy

The transition to a low-carbon future hinges on adopting innovative and sustainable energy solutions, among which Ocean Renewable Energy Resources (ORERs) play a critical role. ORERs encompass a diverse array of marine energy types, including wave energy, tidal energy, offshore wind, ocean thermal energy conversion (OTEC), and salinity gradient energy all of which harness the vast and constant dynamics of the ocean to generate clean electricity. Wave energy exploits the kinetic and potential energy of surface waves generated by wind, offering significant energy density and predictability in coastal regions. Tidal energy derives from the gravitational forces of the moon and sun, manifested as cyclical rises and falls in sea levels (tidal range) and the kinetic flow of tidal currents. These can be harnessed via tidal barrages or modular tidal stream turbines, respectively, to produce reliable, predictable power. Offshore wind energy, often considered alongside ORERs due to its marine location, taps the powerful and consistent winds over the ocean surface with large-scale turbine arrays, providing one of the most mature and rapidly advancing renewable technologies. OTEC utilizes the temperature difference between warm surface seawater and cold deep ocean water to drive thermodynamic cycles for electricity generation, enabling continuous baseload power in suitable tropical and subtropical regions. Salinity gradient energy, obtained from the osmotic pressure difference where freshwater from rivers meets salty ocean water, harnesses chemical potential energy using membrane technologies like pressure-retarded osmosis to produce power.

When combined with hydrogen production via water electrolysis where electricity splits water molecules into hydrogen and oxygen these ORERs offer a compelling and integrated pathway for producing green hydrogen. This approach addresses key challenges in the energy transition, such as intermittent renewable generation by enabling long-duration energy storage in the form of hydrogen, enhancing energy system flexibility, and providing a carbon-neutral fuel source for sectors difficult to electrify. As depicted in Fig. 11, ORER-driven electrolyzers operate independently of the land-based grid, enhancing energy security and resilience, particularly in remote or island regions, while delivering the dual benefits of grid independence and carbon neutrality. The integration of these technologies heralds a new frontier in marine energy utilization, where the stable and abundant power generated by the ocean can be strategically converted into hydrogen. This not only diversifies the renewable energy portfolio but also supports decarbonization across power, transport, and industrial sectors, underpinning a sustainable and resilient energy future.

4.1. Wind offshore system

Hydrogen production from offshore wind represents a sustainable energy solution by utilizing abundant marine wind resources and integrating advanced technologies to improve efficiency and reliability. Effective site selection, as demonstrated in Shanghai using a multi-criteria decision-making model, is vital for optimizing location choices [103]. To address production intermittency, hybrid systems combining hydrogen combustion engines with battery storage have proven efficient backup solutions [104], while integrating reverse osmosis desalination enhances electrolysis by purifying seawater and tackling freshwater scarcity [105]. Buffer storage systems also mitigate the impact of wind variability on electrolyser performance and hydrogen transport [106]. Despite these advances, challenges like high initial capital costs and technological integration must be addressed to fully realize the potential of offshore wind-to-hydrogen systems.

4.2. Wave energy system

Hydrogen production from wave energy offers a sustainable solution for maritime fuel, with studies demonstrating its feasibility and economic potential. Alkaline and renewable-powered seawater electrolysis methods have shown promising results, such as the production of 18.58 tons of hydrogen monthly at the Port of Ngqura from wave energy converters [107]. Innovative systems like magnetoelastic generators further enhance sustainable production by achieving high current densities for autonomous hydrogen generation [108]. Economically, the levelized cost of hydrogen from wave energy could drop to 3.6 €/kg in optimal locations, though current costs, such as R96.07/kg at Ngqura, might become competitive with fossil fuels under carbon pricing policies [107,109]. Additionally, hydrogen-powered ships require robust refueling infrastructure supported by wave energy networks, particularly in regions like the Mediterranean [109] (Pompodakis et al., 2024). However, challenges including high infrastructure costs in marine

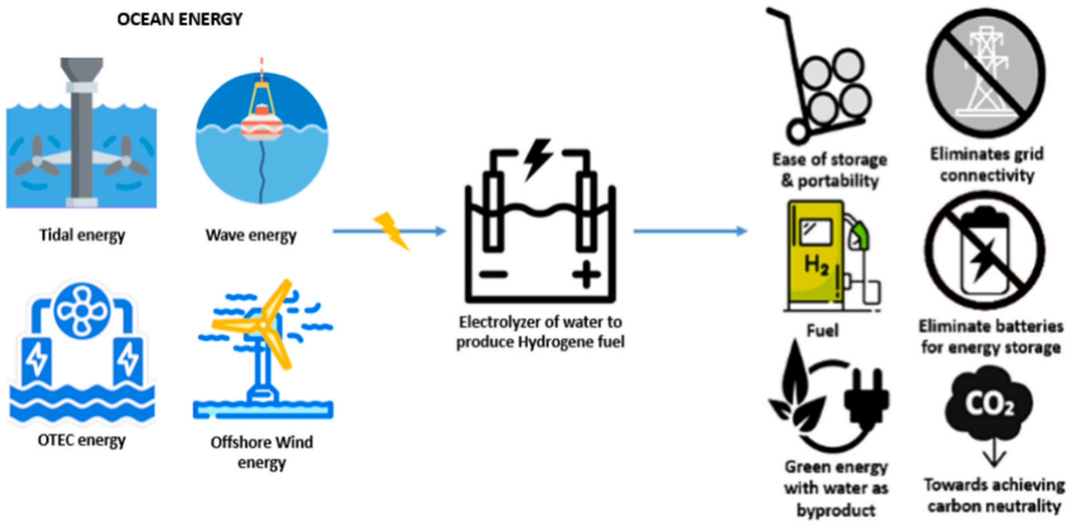


Fig. 11. Schematic showing the use of power from Ocean Renewable Energy Resources (ORERs) like wave, tidal, offshore wind, and OTEC for hydrogen production via electrolysis.

environments [110] and efficiency variability due to wave conditions [111] must be addressed to maximize the potential of wave energy for green hydrogen production in the maritime sector.

4.3. Tidal energy system

Hydrogen production from tidal energy offers a sustainable and efficient solution for meeting energy demands by utilizing tidal power plants (TPPs) to convert the kinetic energy of tidal currents into hydrogen via water electrolysis. Regions like the Sea of Okhotsk demonstrate immense potential, with an estimated 4.5 million tons of hydrogen producible annually from proposed TPPs [44]. Tidal energy's predictability and stability provide a reliable energy source compared to other renewables [112], while modern proton exchange membrane (PEM) electrolyzers enhance conversion efficiency and cost-effectiveness [113]. Additionally, using seawater for electrolysis minimizes freshwater use and pollution, contributing to an environmentally friendly process [114]. Despite these advantages, challenges such as high initial investment costs and potential environmental impacts from TPP construction need to be addressed to fully harness tidal energy's potential in the global energy transition [112].

4.4. OTEC energy system

Hydrogen production from Ocean Thermal Energy Conversion (OTEC) uses the temperature difference between warm surface water and cold deep water for energy conversion. OTEC-based multi-generation systems, such as PV/T collectors combined with reverse osmosis, have achieved hydrogen production rates of 1.349 kg/h with 26.3 % efficiency [115]. Thermodynamic models show that OTEC can produce hydrogen, freshwater, and power, with one model reporting hydrogen generation at 0.0003011 kg/s and net power output of 150.5 kW [116]. OTEC-generated hydrogen also supports CO2 hydrogenation for methanol production with conversion rates over 50 % [117], contributing to decarbonization efforts [118]. Despite challenges, ongoing research aims to overcome these barriers for broader adoption in green hydrogen production.

4.5. Salinity gradient energy system

Hydrogen production from salinity gradient energy (SGE) uses reverse electrodialysis (RED) technology, which converts the ionic current from the salinity difference between saline and freshwater into electricity and hydrogen. RED systems employ ion-exchange membranes, with adjustable membrane pairs to optimize hydrogen or electrical output [119]. Hydrogen production rates of up to 82.12 mL·h−1 and energy conversion efficiencies of 25 % have been reported [120], while advanced multistage RED systems can achieve 0.38 gH2 m−2h−1 with a waste heat input of 1.7 kWh gH2−1 [121]. RED has been used successfully for hydrogen production from seawater and treated sewage, with high current efficiency and theoretical production capabilities [91]. Integrating waste heat enhances production, making RED a promising solution for sustainable energy. However, challenges related to efficiency and scalability require further research for industrial viability.

Table 2 provides a comparison of estimated hydrogen production costs from various marine renewable energy (MRE) sources. These values, drawn from recent literature, highlight the economic variability depending on the technology used. Tidal energy generally appears as the most cost-competitive option, followed by wave energy, while Ocean Thermal Energy Conversion (OTEC) exhibits higher costs due to technological complexity. This data helps to contextualize the economic potential of different pathways for sustainable green hydrogen production (see Table 3).

The integration of marine renewable energy (MRE) with hydrogen production encounters several critical technical challenges that must be carefully addressed to ensure system reliability, efficiency, and economic viability. A primary concern is the degradation of system materials due to the harsh, corrosive marine environment, which can drastically shorten the lifespan of key components and increase maintenance needs. Furthermore, the inherent variability and intermittency of ocean energy sources such as waves and offshore wind complicate the task of maintaining consistent hydrogen production rates, demanding robust system designs capable of flexible, adaptive operation. Operational challenges extend to the logistical difficulties of remote maintenance and repair of offshore installations, which elevate operational costs and necessitate innovative, durable engineering solutions tailored

Table 2
Hydrogen production costs from marine renewable energies

MRE Technology	Estimated Hydrogen Production Cost (€/kg)	Key Reference
Wave Energy	~3.0	[122]
Tidal Energy	2.0–3.0	[123]
Ocean Thermal Energy Conversion (OTEC)	>4.0	[124]

Table 3
Summary of recent studies on Hydrogen Production from Marine Energy

Category	Key Details	References
Hydrogen Production from Marine Energy	Tidal, wave, photovoltaic, and wind energy used for hydrogen production and desalination.	[125]
	Using ocean energy (waves, tides) for hydrogen production.	[126]
	Offshore wind turbine systems for hydrogen production.	[127]
	Harnessing wave energy for electricity and hydrogen.	[63]
Electrolysis & Optimization	Marine energy and low-temperature electrolysis for sustainable hydrogen.	[128]
	Electrolysis of seawater in mangrove areas.	[129]
	Performance improvement using ANFIS and POA for marine applications.	[130]
Hydrogen in Maritime Transport	Hydrogen production, storage, and use in maritime applications.	[131]
	Hydrogen from glucose by Thermotoga Maritima.	[132]
Regional Focus	Utilizing Morocco's marine energy resources for green hydrogen production.	[133]
Hydrogen Storage & Distribution	Hydrogen production from acidified seawater.	[134]
	Offshore system for hydrogen production and transfer to ships.	[135]
	Hydrogen Production from Marine Macro-Algae Biomass and Anaerobic Sewage Sludge Microflora: Algae-based hydrogen production.	[136]
Green Hydrogen in Various Forms	: Sea waves generate electricity, converted to hydrogen.	[137]
	Modeling electrolyzers coupled with OTEC for hydrogen.	[137]
	Ammonia and hydrogen storage, and internal combustion engines.	[131]

for challenging ocean conditions. Overcoming these barriers calls for advancements in material science, the development of resilient system architectures, and novel maintenance strategies that leverage automation and remote monitoring technologies.

A critical component of hydrogen utilization across sectors ranging from transportation to industry and energy storage is hydrogen storage, which faces intrinsic technical challenges due to hydrogen's unique physical properties. Currently, three main hydrogen storage methods are deployed (see Fig. 12):

- Compressed Gaseous Storage: Hydrogen is compressed and stored in high-pressure tanks, typically between 350 and 700 bar. This approach benefits from technological maturity and operational simplicity but requires the use of robust, pressure-resistant materials to ensure safety and containment integrity [127].
- Cryogenic Liquid Storage: By cooling hydrogen to approximately −253 °C, it becomes liquid, achieving a substantially higher volumetric energy density than gaseous storage. However, liquid hydrogen storage demands advanced cryogenic insulated tanks to minimize boil-off losses and involves energy-intensive liquefaction processes, which impact overall system efficiency [138].
- Solid-State Storage: This emerging technology relies on the absorption or adsorption of hydrogen within solid materials—such as metal hydrides, chemical hydrides, or various sorbents—offering advantageous safety profiles and potentially higher energy densities. Nevertheless, solid-state systems currently face challenges including high costs, system weight, and relatively slow hydrogen uptake and release kinetics, requiring further research to become commercially viable [139].

Addressing these technical and operational challenges in both marine hydrogen production and storage mandates collaborative interdisciplinary research. Strong academia-industry partnerships, supported by public-private initiatives and international cooperation, will be instrumental in accelerating breakthroughs and scaling these technologies to effectively contribute to the global energy transition.

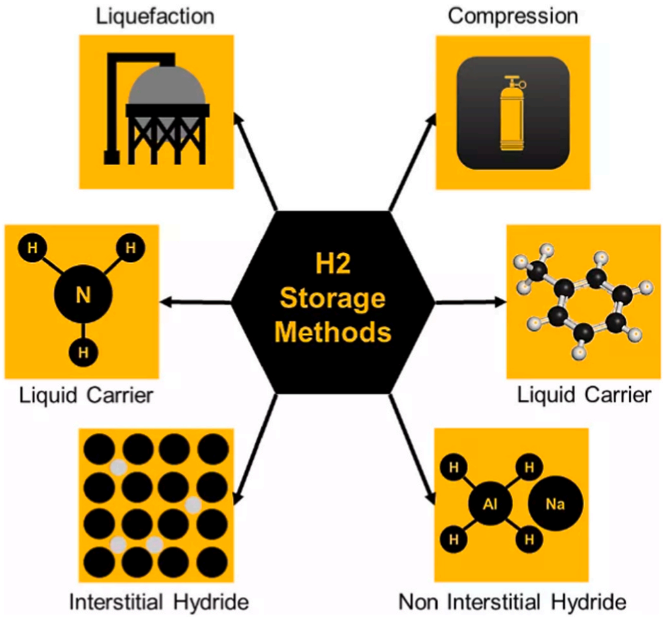


Fig. 12. Different Methods of Hydrogen Storage, reproduced with permission from [140].

5. Feasibility and Advancements in Marine Energy for Hydrogen Production

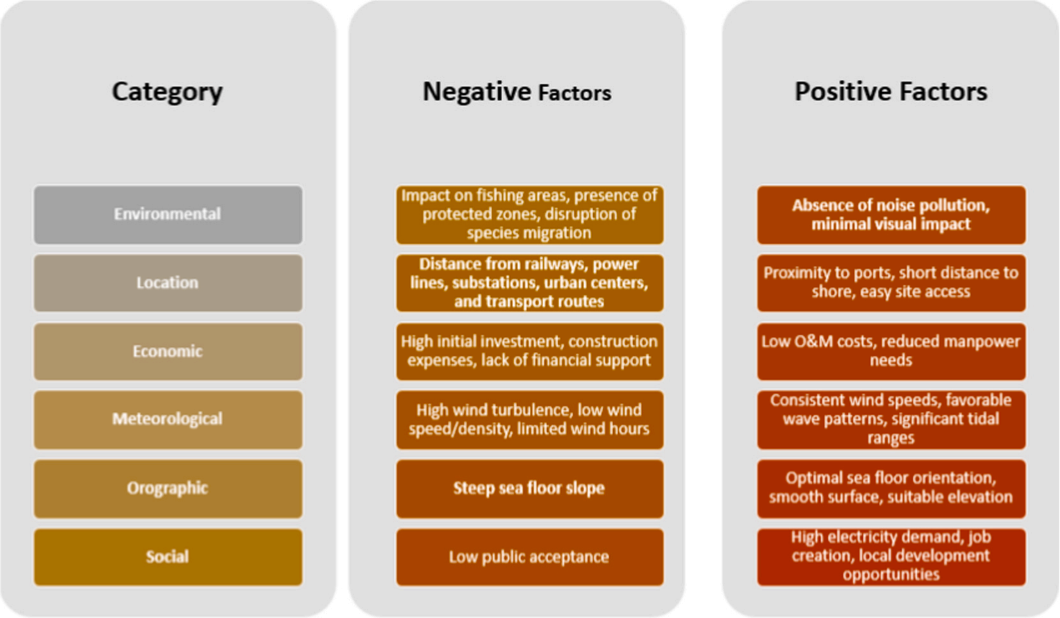
5.1. Harnessing marine energy for hydrogen production

Marine energy is becoming a key source of renewable energy for electrolysis, crucial for hydrogen production. By combining wave, tidal, ocean current, and river current energy, it addresses storage and transportation challenges [141]. Offshore platforms using tidal, wave, photovoltaic, and wind power generate electricity to produce green hydrogen and desalinate seawater [125]. This dual-use strategy reduces emissions and supports sustainability in maritime transport [131]. Several studies highlight the potential of marine energy for green hydrogen production, as shown in the following table.

5.2. Technical aspects

Developing a green hydrogen production project using marine energy requires evaluating site selection, resource assessment, and installation factors. Site selection should consider resource potential, grid proximity, ocean depth, accessibility, and infrastructure. Key marine technologies like offshore wind, hydrokinetic, and wave energy have specific installation needs. Rediske et al. [142], proposed a three-step site selection methodology adaptable to offshore: (1) selecting sites based on marine potential, (2) excluding unsuitable sites (e.g., fishing, maritime traffic), and (3) prioritizing optimal sites. Ocean depth affects construction costs and durability [143]. The distance from the marine farm to the coast impacts hydrogen storage, transport, and costs, as shown in Fig. 13.

Oceanic renewable energy sources including offshore wind, wave energy, and tidal currents demonstrate substantial potential for green hydrogen production via water electrolysis [141,144,145]. These marine energy resources differ significantly in terms of geographic distribution, temporal predictability, resource variability, technological



Category	Negative Factors	Positive Factors
Environmental	Impact on fishing areas, presence of protected zones, disruption of species migration	Absence of noise pollution, minimal visual impact
Location	Distance from railways, power lines, substations, urban centers, and transport routes	Proximity to ports, short distance to shore, easy site access
Economic	High initial investment, construction expenses, lack of financial support	Low O&M costs, reduced manpower needs
Meteorological	High wind turbulence, low wind speed/density, limited wind hours	Consistent wind speeds, favorable wave patterns, significant tidal ranges
Orographic	Steep sea floor slope	Optimal sea floor orientation, smooth surface, suitable elevation
Social	Low public acceptance	High electricity demand, job creation, local development opportunities

Fig. 13. Factors Influencing Site Selection for Ocean Energy Projects, reproduced with permission from [142,144].

maturity, and cost-effectiveness. Fig. 14 presents a comparative analysis of marine renewable energies based on key indicators such as global resource potential, Technology Readiness Level (TRL), variability, predictability, and Levelized Cost of Energy (LCOE) [146]. Water electrolysis, the predominant method for green hydrogen generation, utilizes electrical energy to dissociate water molecules into hydrogen (H_2) and oxygen (O_2). This process is characterized by high conversion efficiency and produces hydrogen with a purity suitable for applications such as low-temperature fuel cells [147]. Among the various electrolyzer technologies, Proton Exchange Membrane (PEM) electrolyzers are

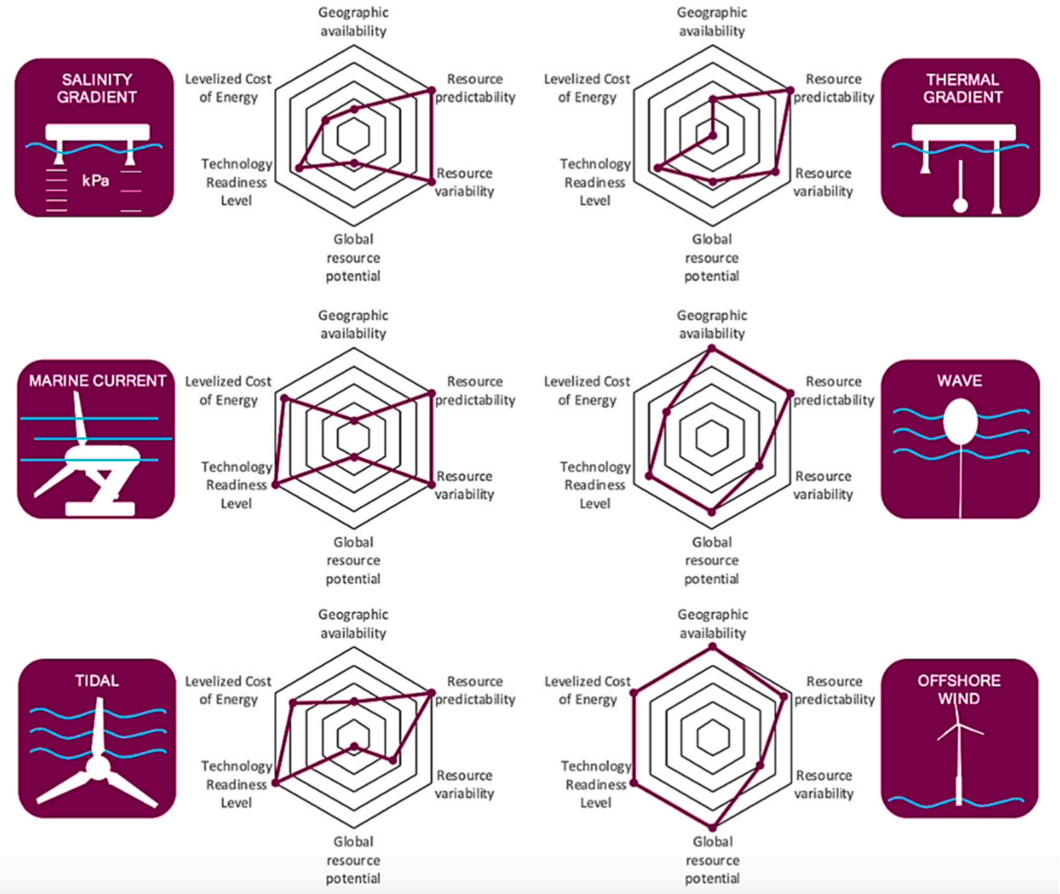


Fig. 14. Overview of Marine Renewable Energy, reproduced with permission from Refs. [128,146].

particularly advantageous due to their high efficiency, rapid dynamic response, and modular scalability, which make them well-adapted for integration with intermittent renewable sources such as marine energies [144,145]. Other electrolysis technologies include Alkaline Water Electrolysis (AWE) [148–150], Solid Oxide Electrolysis (SOE) [151,152], and Microbial Electrolysis Cells (MEC) [153,154]. Each technology exhibits specific operational characteristics and efficiency profiles; however, PEM electrolyzers have emerged as the most promising for offshore and hybrid marine energy systems due to their compactness and operational flexibility [155,156]. Hybrid systems that combine multiple marine energy sources with electrolysis units offer enhanced reliability and operational stability by mitigating the inherent intermittency of individual renewable resources. Such systems optimize energy availability and improve overall hydrogen production efficiency, contributing to the economic viability of marine-based green hydrogen [41,133,145,157].

Nevertheless, the technical feasibility of large-scale offshore hydrogen production is conditioned by challenges including the requirement for seawater desalination prior to electrolysis, offshore installation and maintenance constraints, and the development of effective hydrogen storage and transportation infrastructure. Addressing these challenges through technological innovation and system optimization is essential to advance the deployment of marine renewable energy-driven hydrogen production.

5.3. Economic modeling and theories

The economic assessment of marine renewable energy (MRE)-based hydrogen production is a critical step toward evaluating its feasibility and scalability. A widely used metric is the Levelized Cost of Hydrogen (LCOH), which calculates the average cost per kilogram of hydrogen produced over the system's lifetime, incorporating capital expenditure (CAPEX), operational expenditure (OPEX), electrolyzer efficiency, and the capacity factor of the renewable source [158,159]. The LCOH serves as a benchmark for comparing different hydrogen production pathways and identifying cost-reduction potentials. To complement LCOH, economic indicators such as the Net Present Value (NPV) and Internal Rate of Return (IRR) are frequently applied to assess the profitability and investment attractiveness of MRE-to-hydrogen systems [160]. These tools help stakeholders evaluate long-term returns under various financial and technical scenarios. In addition, the learning curve theory is relevant for emerging technologies such as offshore floating wind turbines and wave energy converters, predicting cost reductions as cumulative installed capacity increases and technological maturity advances [161]. This theory supports strategic planning by projecting future cost trends and justifying early investments in innovation. Sensitivity analysis is also an essential component of economic modeling, allowing researchers and planners to identify the most influential parameters (e.g., electricity price, electrolyzer lifespan, capacity factor) that affect the overall system cost and viability [162]. This approach enhances the robustness of techno-economic evaluations under uncertainty and supports the design of adaptive policy frameworks. Finally, more advanced approaches such as real options analysis are being introduced to value flexibility in investment decisions, especially when dealing with high uncertainty in marine energy resources, hydrogen markets, and technology evolution [163]. Integrating these economic models is crucial for guiding public and private investments and for enabling the large-scale deployment of green hydrogen powered by marine renewables. Technological advancements in electrolyzers and economies of scale are reducing the cost of green hydrogen production, especially when customized techno-economic models optimize system sizing and profitability [141,144,164]. These innovations have enabled marine energy integration into hydrogen production, as seen in Namibia, where wave energy powers hydrogen facilities [164], and in France, where Lhyfe produces green hydrogen from offshore wind and seawater electrolysis [144,164]. Challenges include energy storage, electrolyzer efficiency, and renewable energy intermittency, which require robust models, political support, stakeholder engagement, and environmental policies [60,128,165]. Marine energy-hydrogen systems also offer environmental benefits, such as a reduced ecological footprint and enhanced carbon sequestration with CCS technologies [41,128,157]. The hydrogen economy opens opportunities for coastal regions, promoting economic diversification and contributing to the blue economy by providing power to marine industries. However, current hydrogen production methods still contribute to the carbon footprint [141,157,165,166]. As renewable energy costs decrease, hydrogen production via electrolysis becomes more viable, though electrolyzer costs, load factors, and logistics remain key cost factors [167].

These projects highlight global investments in green hydrogen from marine energy, featuring innovations like recycled offshore barges as production platforms, compact 10 MW PEM electrolyzers, seawater treatment systems, and flexible underwater pipelines for hydrogen export. The goal is to demonstrate the technical and economic viability of large-scale offshore green hydrogen production to meet demand and support the decarbonization of hard-to-reduce sectors. The cost of hydrogen production via electrolysis depends on electrolyzer technology, electricity prices, and plant efficiency. Currently, green hydrogen production is not profitable, requiring technological improvements and cost reductions [168,169]. Alkaline Electrolyzers (AEs) are more cost-effective and efficient than Proton Exchange Membrane Electrolyzers (PEMEs) [170–172]. The Levelized Cost of Hydrogen (LCOH2) rises with distance from the coast due to higher transmission and infrastructure costs [146]. Green hydrogen costs between 3 and 5 €/kg, but operating electrolyzers at 30 % capacity could reduce costs to 2.00–2.50 €/kg H2 [173]. Salt caverns are the most cost-effective for storage, while liquefied hydrogen is the most expensive. Transport via pipelines costs about €5.85/kg H_2, potentially decreasing to €2.20/kg H_2. Shipping hydrogen becomes more cost-effective for distances over 150–250 km, and liquefaction is ideal for long distances, as shown in Table 4 [170].

Additionally, Fig. 15 highlights the key factors influencing hydrogen costs. The cost of the electrolyzer is particularly critical, as it plays a central role in the electrolysis process. Other significant factors include the electrolyzer's load factor, which should ideally exceed 50 % to minimize production costs, and logistics costs. reducing the cost of green hydrogen will require advancements in technology and improvements in transport methods [146,170,173]. The main technologies for hydrogen transport and storage include compression, liquefaction, composite tanks, salt caverns, pipelines, and cryogenic ships [174]. Hydrogen can be transported as compressed gas or cryogenic liquid via pipelines, trucks, or ships. Alternative carriers such as ammonia or liquid organic hydrogen carriers (LOHCs) are also being explored to facilitate logistics [175,176]. Storage options include compressed gas, cryogenic liquid, and metal hydrides, the latter still under development. Each solution involves trade-offs regarding cost, energy efficiency, safety, and compatibility with existing infrastructure. Optimizing hydrogen logistics is therefore essential to ensure the viability and competitiveness of green hydrogen systems within the energy transition.

Table 4
Storage methods and green hydrogen production/transport scenarios [144].

Distance	Storage	State	Transport	Notes
≤ 10 km	Steel/ Composite	Gas	Submarine cable	Steel: Low cost, onshore. Composite: Offshore use.
50–100 km	Steel/ Composite	Gas	Pipeline	Pipeline preferred for transport efficiency.
> 1000 km	Underground/ Liquid	Gas/ Liquid	Tanker ship	Best for very long distances. Less economical.

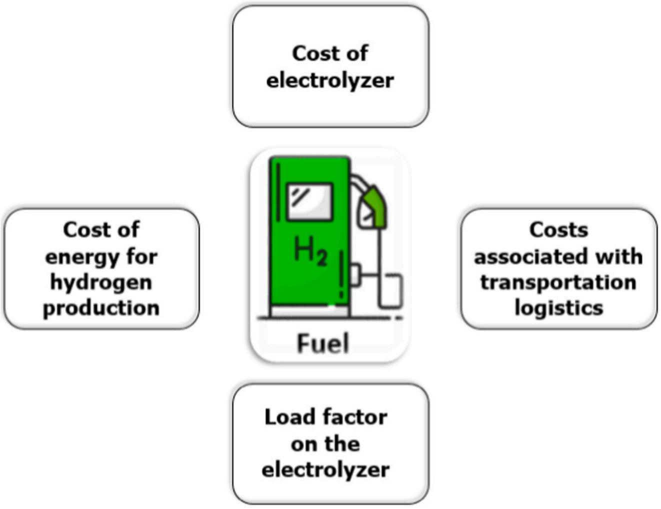


Fig. 15. Factors Influencing the Final Cost of Hydrogen, reproduced with permission from [167].

6. Green hydrogen production at sea: Recent Advances

The production of green hydrogen at sea is gaining momentum, driven by innovative projects utilizing ocean resources. The Sealhyfe project in France, led by Lhyfe, integrates floating wind turbines with an electrolyzer to produce hydrogen from seawater and renewable electricity. Launched in June 2023, Sealhyfe produces 400 kg of hydrogen daily, with plans to scale up to 4 tons per day by 2026. The hydrogen is transported to the mainland via pipeline, demonstrating a feasible integration of offshore energy and hydrogen infrastructure [177,178]. The EU aims for 10 million tons of renewable hydrogen annually by 2030, supporting projects like Sealhyfe to promote energy independence, sustainability, and climate action [179].

Recent advancements are transforming offshore green hydrogen production, enhancing cost-efficiency and sustainability. One breakthrough is the direct use of seawater for hydrogen production, eliminating the need for desalination and reducing costs. Companies like Dongfang Electric in China have pioneered such systems, improving scalability [180]. Electrolysis of seawater also benefits the environment by producing oxygen, which aids marine ecosystem sustainability [181]. French start-up Gen-Hy has developed an efficient alkaline electrolyzer using nickel nanoparticles and non-noble metal catalysts, achieving efficiencies over 85 %, see Fig. 16 [182]. With hydrogen production rates of 518 kg/day from a 1 MW electrolyzer, this technology advances offshore hydrogen production [182,183]. These innovations, combined with projects like Sealhyfe, are accelerating the offshore hydrogen sector's role in the renewable energy transition.

Researchers from RMIT in Australia have created a catalyst based on nickel-molybdenum phosphide doped with nitrogen, as illustrated in Fig. 17, allowing for seawater electrolysis without harmful emissions, which could reduce the cost of hydrogen to 1.3 euros per kilo [184,185].

Researchers at the University of California have discovered a revolutionary method to produce hydrogen at room temperature using aluminum nanoparticles and gallium, as illustrated in Fig. 18. This technique, which works with various types of water including wastewater and seawater, eliminates the need for external energy, making hydrogen production more efficient and cost-effective [187].

6.1. *International opportunities*

Renewable hydrogen from marine resources could play a crucial role in India's energy transition, though its 7516 km coastline remains underutilized [167]. Challenges include grid integration and transportation of generated electricity [167,189]. Hybrid approaches, such as combining photovoltaic cells with ocean thermal energy conversion (OTEC) systems for seawater electrolysis, are being explored in Iran and Germany, showing competitive costs for hydrogen production [190]. Hydrogen offers great potential for the maritime sector, with projects in Norway, the US, Switzerland, and France, including hydrogen-powered ferries and emissions reductions from ships at dock [191]. Green hydrogen at sea is advancing, with Europe leading in setting ambitious goals. For India, hybrid solutions could reduce fossil fuel dependence and promote cleaner energy. Exploring hydrogen as fuel for naval vessels and hybrid solutions are vital steps in the energy transition. Table 5 compares approaches and innovations in green hydrogen production, with critiques.

Table 6 outlines various global projects that integrate marine

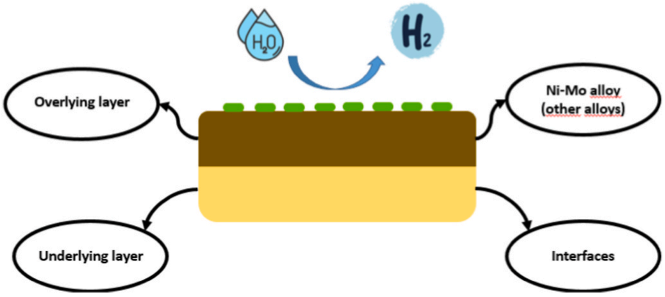


Fig. 17. Schematic Representation of the Cross-Section from the Substrate to the Electrocatalyst Surface, reproduced with permission from [186].

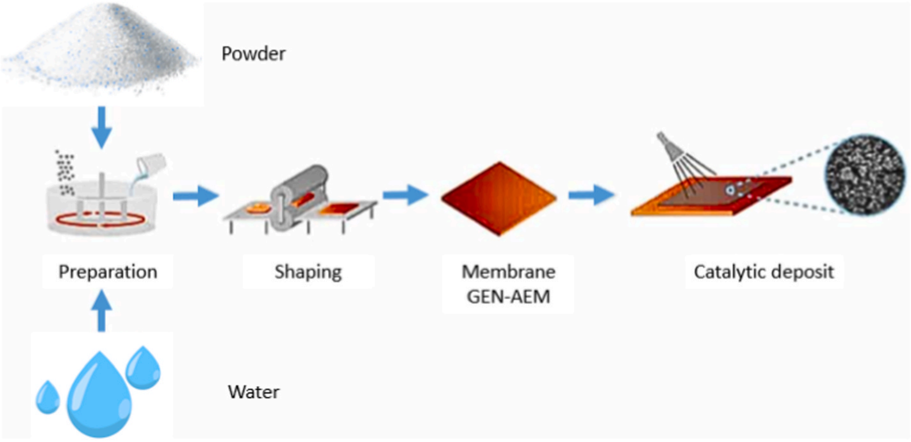


Fig. 16. Overview of Gen-Hy's Catalytic Deposition Process, reproduced with permission from [182].

Fig. 18. Generating hydrogen through water splitting using a Ga-Al composite, reproduced with permission from Ref. [188].

Table 5
Comparative table of approaches and innovations in green hydrogen production [182,186,190,191].

Aspect	Gen-Hy	Australia Innovations	Hybrid Approaches	Maritime Sector
Technology	Nickel catalysts, Gen-AEM® membranes	Nickel-molybdenum, cobalt oxide catalysts	PV and OTEC integration	Hydrogen-powered ships, "cold ironing"
Efficiency	>85 %	+30 % hydrogen production	Economic potential	Emissions reduction
Advantages	Low-cost catalysts, no chlorine emissions	Reduced rare metal use	Durable, renewable integration	Emission reduction, hydrogen adoption
Challenges	Impurity management, grid integration	Economic scale, climate dependency	High technology costs	Infrastructure investments
Impact	Material extraction risks	Marine ecosystem concerns	Climate performance variance	High infrastructure demand
Viability	Cost-effective at scale	Economic scalability issues	Grid integration challenge	High initial cost

renewable energy systems with hydrogen production technologies, highlighting advancements in green hydrogen generation. These projects demonstrate diverse approaches, ranging from offshore wind turbines to wave and tidal energy, aimed at achieving sustainable hydrogen production under real-world conditions. However, despite the remarkable progress in these technologies, their relevance and potential impact on developing countries remain underexplored. Developing nations often face unique challenges, such as limited infrastructure, financial constraints, and energy access disparities, which necessitate tailored solutions. By addressing these challenges and aligning such projects with the specific needs of developing regions, the global transition to clean energy can become more inclusive and impactful. The table serves as a foundation for exploring these opportunities and examining how similar initiatives could be adapted or scaled to drive sustainable energy transitions in developing countries.

7. Outlooks and Future Perspectives

Integrating marine energy and hydrogen production presents technical, environmental, economic, and regulatory challenges. Technically, the low efficiency and high energy demands of electrolysis, along with the need for large or advanced hydrogen storage systems due to its low volumetric energy density, hinder its feasibility [144,192,193]. The design and scaling of hybrid systems combining marine energy with hydrogen production are complex [194]. Environmentally, while marine-based green hydrogen has a reduced ecological footprint, it requires rigorous assessments and monitoring to protect marine ecosystems [144]. Economically, high production costs limit competitiveness against traditional sources, necessitating cost-effective technologies and strong investments [195]. Regulatory challenges involve establishing policies, safety standards, and frameworks to support the integration of marine energy and hydrogen production technologies [144,192,196]. Efforts to adopt hydrogen for maritime transport have shown progress in Norway, the U.S., Switzerland, France, and Morocco. In Norway, NORLED is partnering with WESTCON to create the world's first hydrogen-powered car ferry, expected by year-end. In the U.S., SW/TCH is working on hydrogen-powered ferries in San Francisco Bay. Swiss company ABB and Hydrogène de France are developing hydrogen fuel cell systems for deep-sea vessels [197,198]. In Morocco, projects are exploring hydrogen production from local renewable resources for maritime transport [48,49,133]. Fig. 19 illustrates hydrogen applications in maritime transport.

In addition to the specific challenges of integrating marine energy, there are broader constraints related to hydrogen itself, including the high cost and limited efficiency of electrolysis [199,200], technical difficulties in transport and storage due to its low volumetric energy density [175,201], as well as safety and infrastructure requirements [199,202]. Overcoming these limitations is essential to ensure the effective integration of marine-derived hydrogen into sustainable energy systems.

Green hydrogen production from marine energy sources, such as wave and offshore wind, represents a promising solution for a sustainable and low-carbon energy future [203]. Advances in electrolyzer technologies, particularly PEM systems, and the higher capacity factors of deep offshore wind farms enhance efficiency and reliability [204]. Research on direct seawater electrolysis may further reduce costs by simplifying the process.

Although offshore green hydrogen currently faces higher costs compared to onshore production, technological improvements and economies of scale are expected to lower the Levelized Cost of Hydrogen (LCOH). Environmentally, offshore hydrogen production reduces land use and supports decarbonization across multiple sectors, while integration with circular economy approaches can improve sustainability [50].

Strong policy support and international cooperation are critical to foster market growth and investment. Challenges remain, including managing renewable intermittency, infrastructure development, and public acceptance [203,204]. Nonetheless, continuous innovation and favorable policies provide a positive outlook for the role of marine energy-driven green hydrogen in the global energy transition.

8. Conclusion

In conclusion, integrating marine energy with hydrogen production represents a transformative opportunity to drive a sustainable energy transition and combat climate change. This innovative approach harnesses abundant marine resources to produce green hydrogen, a clean and versatile energy carrier that can decarbonize key sectors such as transportation, industry, and power generation. Despite its immense potential, the path forward is marked by significant technical,

Table 6
Global projects that integrate marine renewable energy systems

Project Name	Location	Type of Marine Energy	Hydrogen Production Capacity	Description
Sealhyfe	Atlantic Ocean, France	Offshore Wind	Up to 400 kg/day (10 MW)	The world's first offshore hydrogen production pilot, connected to a floating wind turbine, producing green hydrogen under real sea conditions [151].
Yongsoo Project	Jeju Island, South Korea	Wave Energy	Not specified	Utilizes an oscillating water column wave energy converter to produce green hydrogen [142].
Panthalassa	United States	Wave Energy	Prototyping stage	Developing the next generation buoy designed to convert wave energy into hydrogen [142].
EMEC Hydrogen Plant	Orkney, Scotland	Tidal Energy	Integrated with tidal converters	Produces hydrogen from tidal energy, demonstrating the full value chain from production to storage [142].
FORWARD2030	EMEC, Orkney, Scotland	Tidal Energy	2.030 MW by 2030	Integrates a tidal stream turbine with a hydrogen production facility to generate green hydrogen [142].
Namibia Wave Project	Namibia	Wave Energy	Not specified	Collaboration between AW-Energy Oy and Kaoko Green Energy Solutions for desalination and hydrogen production using wave energy [142].
FlexH2 Project	Netherlands	Offshore Wind	Not specified	Aims to develop and demonstrate technology for scaling up offshore wind to green hydrogen production [142].
Hokkaido Hydrogen Plant	Hokkaido, Japan	Offshore Wind	550 tons/year	Japan's largest hydrogen plant powered by offshore wind, set to supply various applications including vehicles and data centers [142].

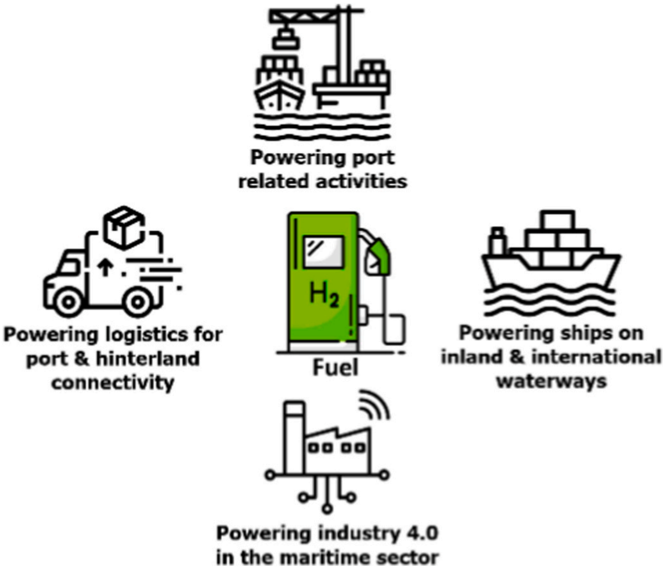


Fig. 19. overview of the various applications of hydrogen as a fuel in the maritime sector, reproduced with permission from Ref. [167].

environmental, and economic challenges. Technically, while the feasibility of marine energy-hydrogen systems is well-established, improving efficiency, reducing energy losses, and scaling up production remain critical challenges. Innovative solutions—such as advanced electrolyzer designs, hybrid systems combining different renewable sources, and efficient energy storage—are essential to optimize performance and expand deployment. Environmentally, this integration offers the potential to reduce carbon emissions and ecological footprints compared to traditional energy systems. However, the large-scale deployment of marine technologies must be accompanied by robust environmental safeguards, including impact assessments, adaptive management strategies, and comprehensive monitoring, to protect marine ecosystems and biodiversity. Economically, high production costs continue to hinder the widespread adoption of green hydrogen. Reducing costs through advancements in technology, economies of scale, and operational efficiencies is crucial. Policy interventions, such as subsidies, carbon pricing, and tax incentives, will play a pivotal role in fostering market competitiveness. Additionally, strategic investments in infrastructure and international collaborations will accelerate progress and lower costs. To overcome these challenges, a holistic approach is required—one that integrates technological innovation, environmental stewardship, and strong economic policies. By addressing these barriers with targeted investments, ambitious policies, and collaborative efforts, marine energy-hydrogen systems can become a cornerstone of global energy solutions, delivering long-term environmental and economic benefits while ensuring a sustainable future for all.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT in order to improve the readability and intended message of specific paragraphs. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no conflicts of interest regarding the publication of this manuscript titled " Marine Renewable Energy for Hydrogen Production: Advancing Towards a Sustainable Future

Through Technological, Economic, and Environmental Frontiers " in the Journal of Renewable and Sustainable Energy Reviews.

Data availability

Data will be made available on request.

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