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Review article

Feasibility analysis of green hydrogen production from oceanic energy

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ABSTRACT

Oceanic energy, such as offshore wind energy and various marine energy sources, holds significant potential for generating green hydrogen through water electrolysis. Offshore-generated hydrogen has the potential to be transported through standard pipelines and stored in diverse forms. This aids in mitigating the variability of renewable energy sources in power generation and, consequently, holds the capacity to reshape the framework of electrical systems. This research provides a comprehensive review of the existing state of investigation and technological advancement in the domain of offshore wind energy and other marine energy sources for generating green hydrogen. The primary focus is on technical, economic, and environmental issues. The technology's optimal features have been pinpointed to achieve the utmost capacity for hydrogen production, providing insights for potential enhancements that can propel research and development efforts forward.

The objective of this study is to furnish valuable information to energy companies by presenting multiple avenues for technological progress. Concurrently, it strives to expand its technical and economic outlook within the clean fuel energy sector. This analysis delivers insights into the best operating conditions for an offshore wind farm, the most suitable electrolyzer for marine environments and the most economical storage medium. The green hydrogen production process from marine systems has been found to be feasible and to possess a reduced ecological footprint compared to grey hydrogen production.

1. Introduction

Environmental sustainability and energy conservation are globally shared challenges [1]. An alternative to tackle these challenges is the continuous development of sustainable energy systems and their integration into existing production processes [2]. With the assistance of incentives and government programs, the production of electricity from renewable sources has been consistently on the rise [3]. This transition has led to significant structural changes in energy systems.

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Abbreviations

€	Euro
AE	Alkaline electrolysis
c	The scale coefficient
CAPEX	Capital expenditures
CF	The capacity factor
CCS	Carbon Capture and Storage
CO	Carbon monoxide
CO_2	Carbon dioxide
DES	Direct electrolysis seawater
DPBP	Discounted recovery period
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt hour
H_2	Hydrogen
η_{el}	Efficiency of the electrolyzer
HHV_{H2}	The higher heating value of hydrogen
IRR	Internal rate of return
k	The wind shape coefficient
kg	Kilogram
km	Kilometer
kW	Kilowatt
LCA	Life Cycle Assessment
LCOE	The levelized cost of energy
$LOCH_2$	Levelized cost of hydrogen
LOHC	Liquid organic hydrogen carriers
m	Meter
M_{H2}	Hydrogen mass
MW	Megawatt
NOx	Nitrous oxides
NPV	Net present value
O&M	Operation and maintenance
OPEX	Operation and maintenance expenditures
OTEC	Ocean thermal energy conversion
OWF	Offshore wind farms
OWT	Offshore Wind Turbine
PEME	Proton exchange membrane electrolysis
P_r	The rated electrical output power of the generator
s	Second
SOE	Solid oxide electrolysis
SWOT	Strengths, weaknesses, opportunities, threats
TEC	Tidal energy converter
TWh	Terawatt hour
USD	Dollars
V_{cin}	The initial shear rate
V_{cout}	The final shear rate
V_r	The wind speed
W	Yearly energy production of the turbine
WEC	Wave energy converter
Wh	Watt hour
y	Year

Solar and wind energy are the primary sources of energy utilized globally. However, with the increasing demand for energy by humanity, it would be desirable to use all available renewable sources. Considering that over half of the world's population resides in coastal regions, harnessing energy from the oceans is imperative. Marine energy sources, including ocean currents, thermal and seawater salinity gradients, tides, and waves, have the potential to offer a global installed capacity of up to 300 GW by 2050 [4]. Additionally, there exists an annual worldwide potential of 800 TWh exclusively from ocean currents. The electricity produced by oceanic energy tends to fluctuate and be intermittent, and at the same time, there are multiple grid failures that make the power supply

Table 1
Comparison of the parameters covered in this study with the available reviews.

Reference	Year of publication	Number of articles reviewed for the production of H_2 with renewable energies	Number of articles reviewed for H_2 production with onshore wind energy	Number of articles reviewed for H_2 production with hybrid oceanic energy systems	Number of articles reviewed for H_2 production with marine energy: wind + waves +currents	Environmental analysis or Life Cycle Assessment	Technical-economic studies	Review of operating conditions	Storage, distribution and use
[13]	2016	–	–	5	–		✓	✓	✓
[14]	2017	–	–	6	–	✓	✓	✓	✓
[12]	2017	97	–	–	–	✓			✓
[23]	2018	30	9	–	2	✓	✓		
[15]	2018	–	5	44	–		✓		✓
[26]	2019	170	–	–	–	✓	✓	✓	
[28]	2019	10	–	–	–	✓	✓		✓
[27]	2019	27	–	–	–	✓	✓		
[16]	2019	–	23	–	–			✓	✓
[17]	2019	–	–	–	11		✓	✓	✓
[24]	2020	40	–	–	–			✓	✓
[32]	2021	50+	–	–	–		✓		✓
[18]	2021		10	1	4		✓	✓	✓
[29]	2021	160		–	9		✓	✓	✓
[33]	2023	–	–	–	21	✓	✓		✓
This study	2023	–	–	6	44	✓	✓	✓	✓

inefficient.

Currently, the intermittency of renewable energy has an important economic impact, as electrical system operators resort to costly backup generation to manage large-scale intermittency [5]. An alternative is the implementation of energy-storage systems [6]. In this context, the production of hydrogen through water electrolysis interconnected with renewable energies could become achievable.

The options for hydrogen production can be classified into various categories, identified by colours: green, blue, grey, brown, black, turquoise, yellow, pink, orange, and white. For this study, green hydrogen specifically refers to hydrogen produced through electrolysis using electrical energy derived from renewable sources [7]. Please refer to Annex 1 for a detailed overview of the other hydrogen colours.

The integration of electrolysis with renewable energies is very beneficial since it allows the storage of electrical energy that is produced in excess in the form of green hydrogen, which can then be converted into electricity through a fuel cell, with conversion efficiencies of up to 65% [8]. The fuel cells generate high-quality energy, as both voltage and current are regulated and steady. Furthermore, the generated electricity can be integrated into the electric grid to reduce the intermittency and the gap between electricity demand and supply.

Additionally, green hydrogen offers numerous advantages, including being a clean fuel (as its combustion does not produce greenhouse gases, GHGs), providing high added value for industrial applications, offering various storage methods (such as gaseous, liquid, or in the form of metal hydrides), enabling long-distance transportation, easy conversion to other energy forms, and boasting higher and lower heating values surpassing those of conventional fossil fuels [9]. Green hydrogen can replace fossil fuels used in different industrial, chemical and transport sectors, contributing to reducing the global carbon footprint [10]. The drawback is that the majority of green hydrogen production methods are not technologically mature, resulting in elevated production expenses and low efficiency. The price of hydrogen for offshore wind energy converters must be on the order of 3 €/kg to be economically viable [11].

The challenges to developing a green hydrogen economy include achieving technical, economic, and social feasibility, cost reduction, and the implementation of infrastructure for distribution, disposal, and use. In this regard, in-depth analyses are essential to assess the technical and environmental sustainability of green hydrogen energy systems [12]. In this work, we explore the feasibility of hydrogen production from water electrolysis using electricity generated from oceanic energies, such as offshore wind energy and other marine energies.

The development of renewable projects in marine ecosystems generates environmental impacts that must be quantified and measured to make the best decisions and avoid damaging the environment as much as possible. Furthermore, it is important to develop optimized renewable projects to maximize hydrogen production and to obtain a deep understanding of potential enhancements that can drive forward research and development efforts.

Economic feasibility is also of upmost importance due to the enormous amount of capital required for the development of an electricity generation project and to comply with governmental and industrial interests. Environmental, technical, and economic feasibility studies are therefore needed to evaluate the potential of green hydrogen projects to aid decision making and provide confidence and financial certainty.

Green hydrogen production by onshore wind power has been recently reviewed by several authors [12–16], focusing mostly on reviewing the general H_2 production pathways by gasification, steam reforming, photosynthesis, electrolysis, thermochemical cycles, photoelectrochemistry, and biochemical, photonic, electrothermal, photoelectric, and photobiochemical processes. A few studies [17–20] have dealt with H_2 produced by marine energies.

Hybrid energy systems with green hydrogen production have been reviewed in onshore conditions from wind and photovoltaic energy [13–15], in which only one review [14] presents an environmental analysis. The different forms of storage, distribution and use of onshore-produced hydrogen have also been reviewed [15,16,18,21–24]. The main questions answered in these reviews are focused on the environmental sustainability [9,12,23,25–27], economic profitability [9,15,23,26–29], and technical feasibility [9,13–15,18,23,27–29] of green hydrogen production technologies. The consensus reached in previous works is that solar energy and onshore wind are the preferred renewable energies to produce green hydrogen, since they have a consolidated industry and their infrastructures are very well deployed with large-capacity farms around the world; therefore, their use significantly reduces capital and operating costs.

The production of hydrogen from marine energies has also been reviewed by several authors [17,18,23,29–33], although they did not address the storage and distribution of H_2 or environmental analysis, except [33]. Thus, to our knowledge, there is no comprehensive literature review on green hydrogen production through marine energy systems.

This work presents a comprehensive review of electrolytic H_2 production through marine sources, both wind and marine, considering the analysis of four criteria: operating conditions of energy and hydrogen production, analysis of the technical conditions of transport and storage, economic feasibility, and environmental assessment. The objective is to provide significant insights for the future development of technology to produce green hydrogen and reveal its potential to generate and store energy in the sea. In addition, challenges and prospects facing the H_2 industry are identified, hoping to create new scientific and technical insights.

An in-depth review of 50 research articles that were published during the period 2000–2023 led us to identify the potentialities and efficiencies in the production of energy and green hydrogen. To explore the state of the art on green hydrogen, a comparison of the scope of this work with the relevant studies on green hydrogen published in the last 5 years is presented in Table 1.

This work is divided into three sections: methodology, results, and conclusions. The results include a comprehensive review of oceanic energy resources, characteristics of marine farms for hydrogen production, technical and economic aspects, and a review of environmental assessments of marine projects for the generation of green hydrogen. Finally, conclusions are drawn to highlight optimal study paths and prominent technologies that can lead to more efficient, cost-effective, and sustainable H_2 sourcing.

2. Research methodology

An electronic search was carried out on Google Scholar, CONRICyT, Science Direct, Emerald, IOP, Oxford, ACS Publications, EBSCO, Springer, and Wiley. Different combinations of keywords were used, such as hydrogen production, green hydrogen, marine energies, offshore wind energy, and electrolysis. Articles published in international journals or in outstanding conference proceedings from 2000 to 2023 were first selected, resulting in a total of 598 articles. Second, papers from the disciplines of sciences, environmental sciences, applied sciences, ecology, economics, physics, engineering, meteorology and climatology, oceanography and chemistry were selected, reducing the number of articles to 258. Each article was then skimmed, and the relevance of the study in question was assessed. All articles that were found to be irrelevant to the production of green hydrogen from marine energies were neglected. Finally, 50 articles were selected for a comprehensive review. They were classified into 4 groups: (1) study cases [34–46], (2) technical-economic evaluations [17,19,20,47–61], (3) environmental analysis or life cycle assessment (LCA) [62] and (4) design and evaluation of system performance [30,63–76]. Fig. 1 illustrates the article classification scheme and the number of articles selected in each group.

3. Results

3.1. Ocean energy potential

The energy found in the ocean can be classified into two types: offshore wind and marine energy, which can also be subclassified according to the types of driving force, flow control and storage, as shown in Fig. 2.

Offshore wind power is created by the kinetic energy of the wind, which is produced by the irregular heating of the atmosphere due to solar radiation, the rotation of the Earth, and the irregularities of the Earth's surface [77]. Marine energy (ocean energy or hydrokinetic energy) is produced from kinetic energy that is created by the movement of ocean water, as well as from salinity and temperature differences within seawater [78], and it covers the wave energy converter (WEC), tidal current, tidal energy converter (TEC), also called tidal range, oceanothermic gradient or ocean thermal energy conversion (OTEC), underwater current, river current and salinity gradient. The technologies of saline gradient, OTEC and TEC have the advantage of controlling their water flows and hence the ability to control energy flows, and there is no need to store their energy [79]. The technologies of WEC, tidal current, underwater current and river current have the drawback of having intermittent water flows since marine resources are not constant throughout the day.

3.1.1. Offshore wind power generation capacity

Onshore and offshore wind farms (OWFs) are based on the same technology, but the advantage of the latter is its superior wind speed and steadiness, resulting in higher electricity generation [14]. In addition, the vast extension of the sea makes the installation of large offshore wind farms possible.

Offshore wind reaches a potential generally above 4000 h per year of effective generation with average speeds greater than 8 m/s (28.8 km/h) [80]. This translates into more than a 40% capacity factor. The potential of wind energy near the coast (<90 km) in the lower atmosphere and in waters of intermediate depth (<200 m) has been estimated as 180 000 TWh/y [11]. By 2022, the global offshore wind power generation capacity was recorded at 62.623 GW, and the energy output currently in onshore wind farms is 836.233 GW [81].

The conditions that determine that a region has a greater offshore wind potential are the differences in atmospheric pressure, in absorption of solar energy between the different geoastronomical zones of the Earth, in air temperature, and consequently the difference in air density, and the rotational movement of the Earth itself. The greater the difference between these variables is, the greater the generation of wind in that area.

The countries that are in the northern temperate zones (United Kingdom, Netherlands, Denmark, Norway, Germany, Poland,

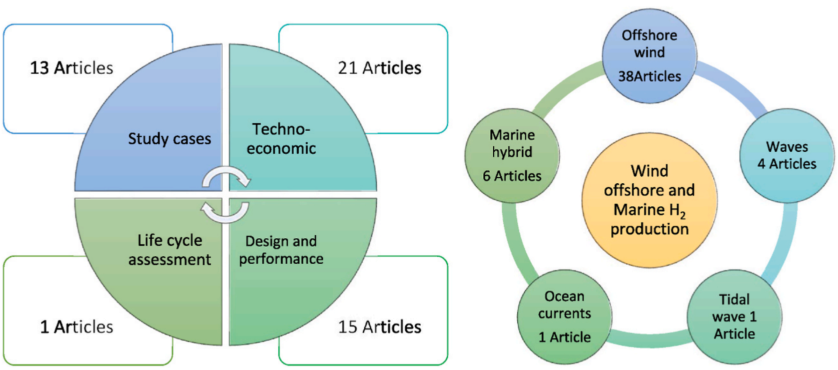


Fig. 1. Classification scheme of the articles reviewed.

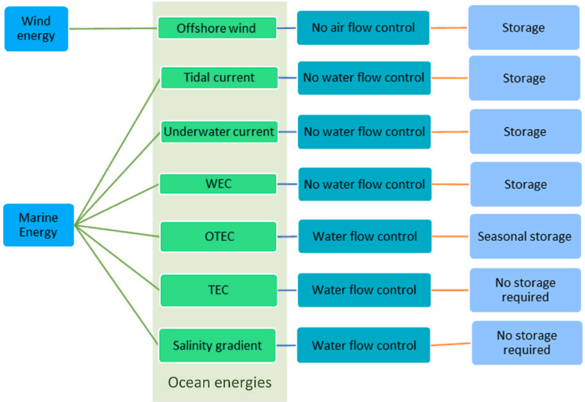


Fig. 2. Types of marine energy and offshore wind power.

Russia, etc.) and the southern temperate zone (Chile, Argentina, Australia, etc.) have great potential to generate offshore wind energy because they are located between the Arctic intertropical-polar or equatorial-polar Antarctic zones. The average annual speeds of these marine areas are greater than 10 m/s at a height of 100 m [82]. Thus, most offshore wind farms are installed in the North Sea, where the surrounding countries have led the technology since its implementation in the 1990s.

The countries with the highest offshore wind power generation capacity in 2022 were China (30.46 GW), the United Kingdom (13.928 GW), Germany (8.129 GW), the Netherlands (2.571 GW), Denmark (2.306 GW) and Belgium (2.262 GW) [80]. Fig. 3 shows the main offshore wind power generating countries, where the aforementioned countries stand out, and a mini graph is also presented where the increasing trend in global power generation reported until 2022 is distinguished.

The United Kingdom (1470 TWh/month), the United States (1079 TWh/month), Sweden (860 TWh/month) and Argentina (840 TWh/month), followed by Australia and New Zealand (600 TWh/month), have been identified as countries with the highest potential to produce energy using a 10 MW offshore wind turbine (OWT). This assessment considers factors such as resource availability, structural survivability, energy transport and logistics activities [83].

3.1.2. Marine power generation capacity

The ocean covers approximately 70% of the Earth's surface, so the wave energy generated in the oceans has great potential to produce electricity [84]. represent an extensive reservoir of untapped energy, offering immense potential that can be harnessed by many coastal nations. Marine energies are described below.

Tidal current. Surface ocean currents' kinetic energy propels turbines, which possess bidirectional capabilities and are linked to electric generators [85]. Turbines have the flexibility to be installed either on the seabed or as floating structures. Among the devices capitalizing on tidal currents are cross-flow turbines, vertical-axis turbines, helical screw devices, oscillating hydrofoils, and horizontal-axis turbines. The velocity of surface currents has a maximum of 2 m/s [86].

Underwater current. Similar to tidal current technology, the turbine is anchored to the seabed from 40 to 100 m deep to take advantage of underwater currents [87]. These turbines do not generate noise or visual pollution because they are submerged.

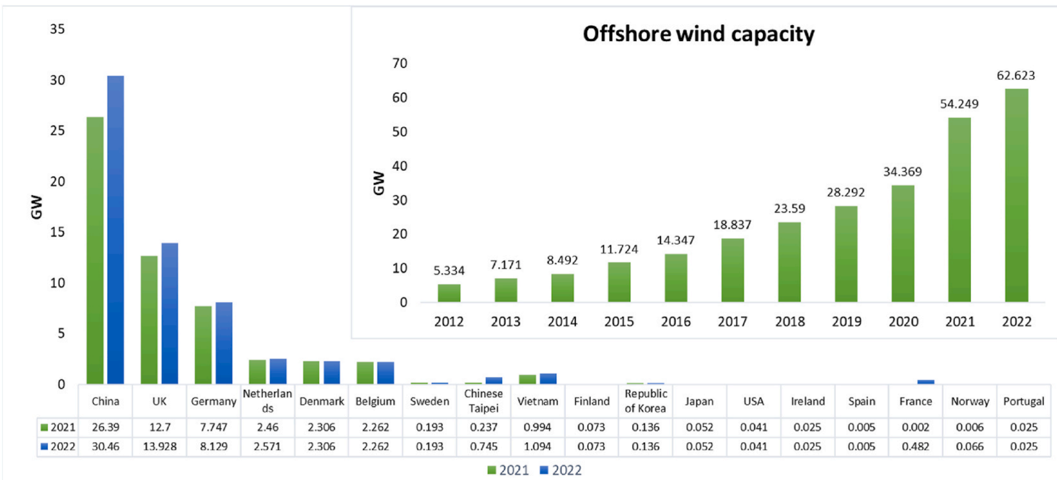


Fig. 3. Global offshore wind power capacity. Based on IRENA, 2023 [81].

WEC. Wave undulations or motion arise from the interplay between the wind and the ocean's surface, and the undulations have a sequence that adds up to produce the characteristic period of the waves [88]. West-facing coasts have the best wave resources due to their high latitudes (over 40°). The kinetic energy of waves can be found in the churning motion or the rising and falling of the waves. According to its physical principles, there are different devices that take advantage of wave energy:

- The wave-activated body uses the movement that waves give to a body, which transmits mechanical energy to a system such as turbines or electrical converters that convert it into electrical energy [88,89] (e.g., attenuators, oscillating wave converters, point absorbers).
- Overtoppings are breakwater barriers installed on the coast, and the water that overflows the breakwater barrier is stored in a tank and then passes through a hydraulic turbine [90].
- The oscillating water column takes advantage of the variation in the periodic level of the waves in a chamber of water and air introduced into the sea; when the air mass is compressed by the variations in undulation, the air drives a turbogenerator that generates electrical energy [87,88]. The chamber can be secured within a land-based structure or positioned atop a floating buoy.

OTEC. The differences (often exceeding 20°C) between the ocean's surface and its deep waters (approximately 1000 m) are harnessed for continuous electricity generation [86]. This process is conducted via the Rankine thermodynamic cycle. There are three categories of cycles: hybrid cycle, combining open and closed cycles to generate both electricity and potable water; open cycle, utilizing seawater as fuel; and closed cycle, employing a working fluid with a low boiling point (ammonia) [91].

TEC. Tidal energy is the power produced due to the variation in elevation between high and low tides, a result of the moon's gravitational influence [92]. To take advantage of height changes in sea level, tidal dams are used to collect water behind some dikes when the water level is high (5 m or more); later, when the tide is low, a gravity flow is created, enabling water to course through turbines [93]. Electrical generators harness the converted potential energy of stored water and transform it into electricity. This technology occurs in estuaries, closed bays, artificial lagoons and reservoirs.

Salinity gradient. The interaction between water masses of different salinity is exploited through the potential that arises from the ionic exchange between fresh and saltwater ions or from the interaction between saline and hypersaline water [86]. The global salinity difference arises from the movements of underwater and surface currents [94]. There are several methods to generate energy from salinity gradients, including reverse electrodialysis and pressure retarded osmosis. The salinity gradient attains its peak potential at the estuaries of large rivers.

Currently, almost all technologies that tap into ocean energy are regarded as being in the initial stages of development, encompassing both conceptual and demonstration phases [88].

The theoretical potential of tidal currents and TEC has been estimated at 1800 TWh/y, WEC at a theoretical potential of 29 500 TWh/y, the salinity gradient at a theoretical global potential of 1650 TWh/y, and OTEC at an estimated world potential of 44 000 TWh/y [76,77,93]. According to Our World in Data [95], the total world energy consumption for 2021 was 167,781 TWh, so the energy potential of all marine energies would be enough to supply 45.87% of the annual world demand.

In 2022, the global capacity of marine power generation was 0.523 GW, a majority of which is derived from tidal range (0.495 GW) alongside a minor fraction from tidal currents (0.011 GW) and waves (0.002 GW). The countries with the highest contributions to marine energy were the Republic of Korea (0.256 GW), France (0.211 GW), the United Kingdom (0.022 GW) and Canada (0.021 GW) [81]. In both Brazil and New Zealand, the wave energy potential has been estimated as 372 TWh/month and 286 TWh/month, respectively [83].

3.1.3. Marine hybrid potential

A hybrid marine energy system involves integrating a marine energy source with other renewable resources, such as solar or wind. This combined system can be linked to the grid or function autonomously (off-grid). The development and implementation of hybrid systems require high solar and wind potential, as well as optimal accessibility to the marine areas of the region.

The utilization of hybrid marine systems presents numerous benefits, such as reduced environmental pollution, enhanced efficiency, and improved reliability [70]. Farahani et al. [61] forecasted that a hybrid system made up of an offshore wind farm and photovoltaic panels could generate a total of 23610 MWh/y in the near future.

The locations that present a maximum probability of 81% for the combined use of offshore wind and wave energies are mainly New Zealand, the southeast coast of South America, the European region of the Atlantic Ocean, South Australia and the coast of Morocco, as well as Canada, the United States and small regions of the Pacific Ocean off Central America [82]. The methodology used to estimate such a probability considered data on the availability of resources, structural survival, logistics activities and energy transport. This data series was mapped in spatial and temporal resolutions (e.g., charting extreme oceanic conditions concerning structural resilience), giving temporal parameter percentages and estimation of extractable power as results. New Zealand and Brazil have been identified as the regions with the greatest attainable energy potential because of the combination of offshore wind energy and wave energy, with more than 345 TWh/month each [83]. To determine the extractable power, areas with a probability greater than 60% were used, considering the power curves of the NREL-5MW and DTU-10MW wind devices and a WEC power matrix adapted from Roberson et al. [96].

Thus, the implementation of hybrid energy systems that can take advantage of multiple renewable resources, such as solar, wind and marine energy, is recommended to satisfy the energy demand, while hybrid systems coupled to hydrogen production could compensate for imbalances between energy production and consumption.

3.1.4. Electrolytic hydrogen production from marine resources

An alternative to storing energy from ocean energy sources is to convert it to hydrogen through electrolysis, thereby storing ocean energy in hydrogen form. Coupling green hydrogen production with ocean energy can be done either by offshore centralized electrolysis or onshore electrolysis.

The proportion of electrolysis in worldwide hydrogen production is approximately 4%. Electrolytic hydrogen can be produced by four technologies: alkaline electrolysis (AE), proton exchange membrane electrolysis (PEME), high-temperature solid oxide electrolysis (SOE) [9], and direct electrolysis seawater (DES). The first three technologies are more suitable for producing green hydrogen from marine resources, and their main characteristics are shown in Table 5.

The most frequently employed electrolysers to produce green hydrogen through marine energy and offshore wind are PEME and AE, with 55% and 26% preferences, respectively, as shown in Fig. 4. This is mainly due to their technological maturity and their higher efficiencies.

The most important characteristics of an electrolyzer to obtain a higher yield of green hydrogen are a long useful life, good efficiency, low constant deterioration, and good integration with the intermittency of renewable energies [39].

PEME and AE are the most appropriate electrolysis technologies for generating green hydrogen in the marine setting. These can be incorporated into an offshore platform, from which hydrogen can be transported to land via tanker or pipeline. There is also the possibility of using fuel cells to convert green hydrogen into electricity and transmit it to the mainland through cables. Another option is to install electrolysers on the coast. The choice between the two options will rely on the distance between the marine farm and the coast.

Comparing AE and PEME technologies, the advantages of AE are a higher resistance to impurities in the feed water, a longer nominal useful life, and a more mature technology, while its disadvantage is a slow response to power intermittence. PEME is the most suitable to support the integration of marine intermittent energy due to its fast response to the energy input; it also includes electrodes that allow higher densities of electric current, a membrane that deteriorates rapidly, electrodes that suffer greater corrosion and a short useful life [59,70,76,100]. AE reports the highest efficiencies in different case studies for offshore scenarios, higher than 72% (Fig. 5). PEME commonly presents efficiencies of ca. 66%, although Dinh et al. [36] reported an efficiency of 93%. An efficiency of 60–70% was reported by Barakat et al. [70] for a PEME within a hybrid hydrogen power generation system.

DES technology could be a viable option if it demonstrates efficient management of water impurities or if advancements in water treatment methods make them more cost-effective and efficient [58,101]. However, DES technology for offshore hydrogen production has been found to be unsuitable for generating green hydrogen in the sea [76]. This is attributed to challenges such as low power density operations, restricted electrolysis of only a minor portion of water interacting with the electrode, concerns related to corrosion and contamination, and the production of chlorine rather than oxygen at the anode and hydrogen at the cathode [102]. Thus, a primary obstacle has revolved around developing stable and active anode catalysts that enable selective oxygen evolution over chlorine. Moreover, DES demands approximately 160% more specific energy compared to low-temperature electrolysis for hydrogen production. The specific energy needed for direct electrolysis of seawater is 452 MJ/kgH_2, while low-temperature electrolysis requires 174.6 MJ/kgH_2 [71]. Significant research advances have been made in the use of seawater for electrolysis [71,76,101,103,104], which will undoubtedly emerge as the most sustainable method to produce green hydrogen in the future. Despite the resources and endeavors dedicated to the advancement of this technology, the direct division of seawater is far from being commercialized. Currently, the best technical and economical option is to purify seawater and use conventional electrolysis.

Producing green hydrogen from seawater holds the promise of decreasing the global water footprint. Approximately 97.5% of the water on Earth is found in the oceans and seas, and only 2.5% is fresh water [105]. This seawater can undergo purification processes, such as desalination through methods such as reverse osmosis, distillation, freezing, hydrate formation, electrodialysis reversal, multistage flash, and vapour compression [105–107]. Once purified, it can be used in electrolysers. Ocean energies have easy access to seawater, making them a viable option for incorporating desalination plants into the electrolytic production of green hydrogen [108].

Reverse osmosis technology is the most mature and can remove up to 99% of salts (ions) and particles [107]. It applies high pressure to water to push it through a semipermeable reverse osmosis membrane, which requires higher pressure and higher salt concentration (overcoming osmotic pressure). The goal is to remove salt and larger particles from the water. The water that passes

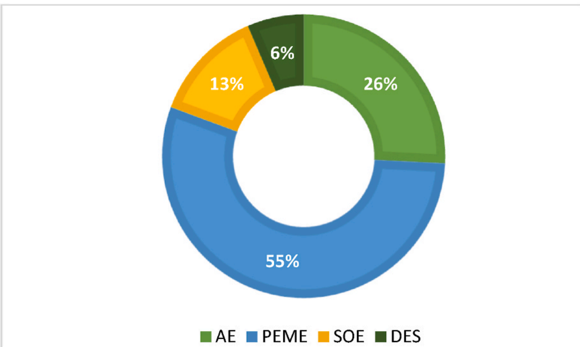


Fig. 4. Electrolyzers are most commonly used to produce green hydrogen with marine energy [17,19,20,31,47–76].

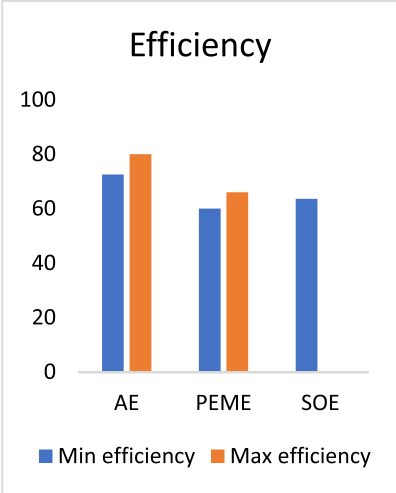


Fig. 5. Efficiencies of electrolysers reported in previous works for marine scenarios.

through the membrane is called the permeate, and currently, the equipment can recover up to 50% of the water fed [106]. In addition, RO consumes less energy than other desalination methods, approximately 3–5 kWh for every 1000 kg of clean water produced. Depending on the stoichiometry of the reaction, 9–10 kg of clean water is required for every 1 kg of H_2 [106].

Although the energy (which is negligible compared to the energy consumption of the electrolysers) and the economic cost of hydrogen production would increase (approximately $0.01/kg of additional H_2) [107], this coupling to obtain clean water may be feasible.

On the other hand, it is necessary to posttreat the brine after reverse osmosis, as it has the potential to adversely affect marine ecosystems. Currently, methods such as zero liquid discharge and the exploration of high-pressure reverse osmosis to desalinate brines with high concentrations, among others, are being investigated. Another alternative that can be considered is to use brine to add value and not reintroduce it into the marine environment.

Table 2
Relevant factors to consider in site selection for ocean energy development. Based on [109].

Category	Relevant Factors	
	Negative	Positive
Environmental	Fishing capacity Protected areas Species migration routes	No noise pollution No visual impact
Location	Long distance to railroad Long distance to power lines Long distance to substations Long distance to urban areas Long distance to main roads Site accessibility	Short distance to ports The closer the farm is, the better.
Economic	High total investment High construction cost No government support Marine transit	Low manpower Low O&M
Meteorological		High wind speed, wind density and no wind turbulence Many effective hours of wind and energy marine Current speed and high current density Wave periodicity High tidal range
Orographic	Great sea depth	No sea floor slope Geographical direction/orientation No seawater roughness Plant elevation
Society	No public acceptance	Electricity demand Employment generation Local development

Table 3
Types of foundations for offshore wind turbines [112–119].

	Suitable for water depth	Suitable seabed conditions	Weight	Composition	Advantages	Disadvantages
Bottom-fixed						
Gravity based	≥42 m	Clayey, sandy and rocky soil	1500- 4500 Ton	Large structures or shell structures constructed from reinforced or prestressed concrete with steel reinforcement	Do not produce a considerable level of noise and vibration.	The extensive dredging and seabed preparation will impact water quality and disrupt the ecosystem of the seabed.
Monopolite	≥60 m	Hard to semihard soil	1000-2000 Ton	One single steel tube pile	No seabed preparation or scour protection required	Construction noise that occurs during pile driving (210 underwater dB).
Tripile	30–50 m		400 Ton/each pile	Comprise of three piles that uphold a central transition piece positioned above sea level.	Their stiffness exceeds that of monopiles.	These structures are relatively weighty, and their cost is impacted by the significant quantity of steel and the manufacturing process,
Tripod	≥60 m		700 Ton (without piles)	Lattice structure with three steel legs that supports a central steel column	Has good stability and overall stiffness. The foundation costs less than intricate jackets.	he complexity of installation primarily stems from the expansive footprint. Tripods possess complex primary joints that heighten the potential for fatigue-induced failures. Not suitable for less than 8 m depth
High-rise pile cap	24 m	Sand and bedrock seabed	3000 Ton	Tall pile caps are generally made from concrete or a blend of steel and concrete.	Low cost, simple operation, high efficiency, and high security	No major harm
Jacket	50–70 m	Not suitable for dense sand, hard clay and weathered rock soils.		Steel lattice tower with three or four legs	No preparation needed for the seabed.	The underwater noise resulting from pile driving can impact marine life and might not be viable in areas with deep water or a shallow rock layer at the surface.
Suction bucket	≥35 m	Sandy or clayey soils	+270 Ton	Steel−concrete composite structure	The technique has no environmental impact on the offshore seabed and is recyclable. It possesses a great capability for anti-overturning moments and features adaptability to soft ground. It requires less offshore equipment, making installation and removal easy.	No major harm
Floating foundations						
Spar	≥200 m	Ocean surface	5000–10,000 Ton for a 2–5 MW	A circular cylinder that is weighted down using water, metal, or concrete in its lower compartments.	spars are well-matched for activities in deep waters and demanding environmental conditions.	The small waterline area leads to a relatively high roll and pitch motion response, a large installation size, manufacturing challenges, inconvenience in mobility, and increased costs
Tension-leg-platform	≥100 m	Ocean surface		Compatible platform tied vertically with tendons and has excess buoyancy	Strong stability and minimal dynamic response to wave forces	Complexities in anchoring systems and of installations.
Semisubmersible or barge	≥100 m	Ocean surface		Made up of three or four separate and interconnected columns	Can set up and initiated close to the shore, and then transported by floating it to the offshore location. Easier	The utilization of braces impacts fatigue life and affects the design. The large structure size leads to

(continued on next page)

Table 3 (*continued*)

	Suitable for water depth	Suitable seabed conditions	Weight	Composition	Advantages	Disadvantages
					installation and decommissioning compared to other floating concepts. Provides hydrodynamic stability and enhanced structural rigidity to endure wave loads.	significant wave loads and motion responses.

3.2. Technical aspects

The key aspects to consider when developing a green hydrogen production project using ocean energy include the selection of the site, the evaluation of the resource, the installation characteristics of the marine farm, the operative characteristics of the energy generation, and the conditions of transport and storage of hydrogen. The conditions and technical characteristics most frequently found in the reviewed studies are described below. The factor that affects all the mentioned aspects is the distance since it is influenced by the type of installation, the type of foundation, the storage method, and the most suitable transport for hydrogen. Furthermore, the distance is directly correlated to the speed of offshore wind, and it also affects the cost of energy and hydrogen.

3.2.1. Site selection for ocean energy projects and installation characteristics

The effectiveness of an energy system relies on the geographical attributes of a region, where key aspects encompass the potential of natural resources, proximity to grid interconnection, ocean depth, accessibility, economic activities, settlement structures and energy infrastructure. Site selection for marine farms must consider an assessment of these factors, as they impact the environment, economics, and feasibility of marine energy generation throughout the life of the farm.

Rediske et al. [109] classified several important factors for site selection in onshore wind projects into six categories: environmental, location, economic, meteorological, orographic and social. The most recurrent factors examined were those that had an impact on society, such as distance to noise pollution, public acceptance, and urban areas.

Rediske et al. [109] also proposed a procedure for selecting the site for onshore wind projects. Adapting their methodology to offshore projects, site selection for a marine energy project could be performed in three different stages: 1) selection of candidate sites according to their marine potential; 2) exclusion of inappropriate sites according to marine transit or areas of fishing use, protected areas, and species migration routes; and 3) prioritization of optimal areas for installing marine farms considering relevant restrictive or positive factors (see Table 2). Restrictive factors are those that limit or slow down the implementation of an ocean energy project, while positive factors are those that favor or do not affect the implementation of an ocean energy project. Factors that are not relevant in ocean projects are land rent, land use, agricultural capacity, urban areas, land area protection, land slope, watercourses and streams, soil roughness, geological suitability, and stroboscopic effects.

In the selection of favorable sites for the implementation of marine energy production as well as for the design of equipment, it is also important to evaluate extreme environmental conditions, as they affect the durability of the structures utilized for harnessing marine resources [83], port access, water depth, ease of fabrication, turbine or device integration, cost and performance.

Ocean depth also has an important influence on the viability of an offshore project. The deeper the sea location is, the more expensive and longer it takes to construct the farm. Wind turbine foundations are therefore selected based on the depth of the sea.

The structures used to fix the OWT are categorized into two primary groups: bottom-fixed and floating foundations. A brief overview is provided in Table 3. Bottom-fixed types include gravity-based, Monopolite, bottom-fixed gravity-based, Monopolite, Tripile, Tripod, suction bucket, jacket, and high-rise pile cap. In a floating foundation, the base of the wind tower is kept in one place with the help of long cables that are attached to the seabed (e.g., Spar, Tension-leg-platform, and Semisubmersible), and the water depths can be 200–300 m. For water depths greater than 100 m, floating structures become the most economically favorable option [110,111]. According to a recent report by the Global Wind Energy Council [112], floating offshore wind has the greatest potential because the vast majority of the global offshore wind technical potential lies in deeper waters. Thus, offshore wind farms installed in deeper water locations seem more promising than those in shallow water.

Castro-Santos et al. [111] carried out an economic comparison of three different categories of floating offshore wind platforms, semisubmersible platforms, tension leg platforms (TLPs) and masts, to be installed in deep waters in Galicia, Spain. The best economic alternative was the semisubmersible platform. The results of the semisubmersible platform were an internal rate of return (IRR) from 9.54% to 14.23%, a net present value (NPV) from 191.69 MW to 366.79 MW, a levelized cost of energy (LCOE) of 75.11 €/MWh and a discounted recovery period (DPBP) of 7–9 years. These results indicated the good economic viability of a farm made of 21 OWTs with 5.075 MW of power.

Other floating concepts are currently being developed that combine the benefits of established floating designs and are suitable for implementation in water depths ranging from 10 to 1000 m, for example, the TetraSpar floater, which features a simple tetrahedral structure with one keel.

Regarding offshore operation and maintenance activities, the accessibility of the site is also a key element for its selection, as it comprises a substantial portion of the overall project costs due to the significant expenses in the logistics involved. One of the limitations of the usability of areas with high marine energy resources is the lack of nearby port services and, on the other hand, the accessibility conditions since they reduce the suitability in midlatitude areas, where there is a high energy density and, consequently, most adverse oceanic weather circumstances [120].

Several models have been developed for site selection, including those based on statistical tests. The following have been used in the literature: Multicriteria decision making [121]: this model is used to implement a geographic information system to select ideal locations for wind farms; Geographic Information Systems [122]: deals with choosing the spatial suitability of solar and wind farm sites based on socioenvironmental, economic, and technical outlooks; Statistical methods, System Advisor Model [123]: it is employed to compute the capacity factor for the most favorable localities within the study area at various elevations; Anderson Petersen of Double Data Envelopment Analysis [124]: these models help to choose optimal locations according to social and value criteria; Principal Component Analysis [125]: it is used to give an integrated mathematical approach for optimizing the siting of wind power farms and sensitivity analysis.

3.2.2. Technical characteristics of marine farms for energy and green hydrogen production

The amount of oceanic resources that can be exploited to produce green hydrogen depends on the current state of marine technology evolution. The capability of offshore farms to produce green hydrogen depends on six characteristics: capacity factor, wind or current speeds, capacity, distance from the farm to the coast, total energy generated, and percent of energy used to produce hydrogen. The ideal green hydrogen production through offshore wind energy can be determined from the following equation [126]:

$$M_{H2} = \frac{\eta_{el} W}{HHV_{H2}} \quad \left(KgH_2/_y \right) \tag{1}$$

where:

$$W = CFP_r(8760) \quad \left(Wh/_y \right) \tag{2}$$

$$CF = \frac{exp\left[-(V_{cin}/c)^k \right] - exp\left[-(V_r/c)^k \right]}{(V_r/c)^k - (V_{cin}/c)^k} - exp\left[-\left(\frac{V_{cout}}{c} \right)^k \right] \tag{3}$$

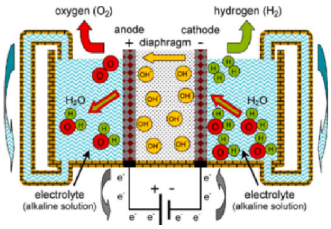
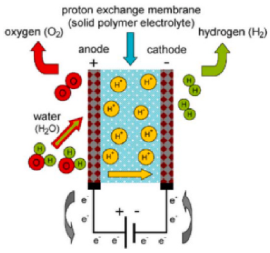
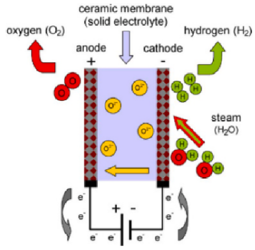
where M_{H2} is the quantity of hydrogen mass generated, η_{el} is the efficiency of the electrolyzer, W is the yearly energy production of the turbine in Wh/y, HHV_{H2} is the higher heating value in kWh/kg of hydrogen (39.4 kWh/kg), CF is the capacity factor defined as the ratio between the average power output and the rated output power of the generator, P_r refers to the electrical output power rating of the generator in W, V_r indicates the wind speed, V_{cin} is the initial shear rate, V_{cout} is the final shear rate, c is the scale coefficient and k is the wind shape coefficient.

The main technical parameters that determine the amount of energy that can be obtained from a turbine are the device efficiency and the capacity factor [127]. Several authors, as shown in Table 4, have projected offshore farms based on these factors. The capacity factor for offshore wind turbines ranges from 40 to 60%. The maximum capacity factor reported is 64%, which implies that as the

Table 4
Characteristics of marine farms for hydrogen production.

Ref	Marine energy resource for H_2 production	Capacity factor	Wind speed or currents	Capacity (Nominal power output)	Distance from the farm to the coast	Total energy generated by the marine farm	% Of energy used to produce H_2
[34]	Offshore wind		7 m/s	1.2 MW	20 km		
[58]	Offshore wind			100 MW		331.68 GWh/y	5 al 75% (50% on average)
[59]	Offshore wind	36%		1000 MW			35%
[38]	Onshore wind and Wave	50%	6–7 m/s Wind and 5–7 kW/m wave	4.25 MW VAWT and 8.6 MW WEC		8.5 GWh/y Wind and 10.5 GWh/y WEC	
[39]	Offshore wind	56%		72 MW			
[60]	Onshore wind and offshore wind		6.5–7.5 m/s	1.3 MW and 2.5 MW	30 m and 60 m		
[70]	Ocean currents		3.2 m/s	1.5 MW			
[72]	Onshore wind and offshore wind		14 m/s	Total 89.92 GW: 70.9 GW onshore and 19.02 offshore	22 km–74 km		22%
[17]	Offshore wind			300 MW total, 5 MW OWT		50 GWh/week	
[75]	Tidal range		1 m/s	1.245 MW			
[44]	Offshore wind		5.5–7.5 m/s	8 MW		21.024 GW/year	40%
[47]	Offshore wind		12.5 m/s	504 MW	14.5 km		
[36]	Offshore wind	40%	8.13 m/s	101.3 MW			
[49]	Offshore wind	44–64%			5–500 km		

Table 5
Electrolysis technologies for hydrogen production characteristics [49,97–99].

Characteristics	Type of electrolyzers		
	AE	PEME	SOE
			
Electrolyte	A caustic aqueous solution of NaOH (15–20% w) KOH (30–35%w)	Acidic polymeric membrane: Solid polymeric Usually, Nafion®	Ceramic Y_2O_2–ZrO_2, $Sc_2O_3ZrO_2$ MgO–ZrO_2, CaO–ZrO_2
Semi reactions (anode)	$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$ $2H_2O \rightarrow O_2 + 2H_2$	$H_2O \rightarrow {}^1/_2 O_2 + 2H^+ + 2e^-$	$2O_2^- \rightarrow O_2 + 4e^-$
Semi reactions (cathode)	$4H_2O \rightarrow 4H^+ + 4OH^-$ $4H^+ + 4e^- \rightarrow 2H_2$	$2H^+ + 2e^- \rightarrow H_2$	$2H_2O + 4e^- \rightarrow 2O_2^- + 2H_2$
Electrodes/Catalysts	Anode: Ni, Fe/Ni Alloys, metal oxides. Cathode: Steel + Ni/NiCo	Anode: Graphite PTFE + Ti/Ru2, IrO2 Cathode: Graphite + Pt/Pt	Anode: Ceramic (Mn, La, Cr)/Ni Cathode: Zr + Ni/CeOx
Current state	Commercially mature	High cost, low capacity, short life, compact design.	Highest efficiency
T (°C) in cell	60–80	50–80	650–1000
P (bar) in cell	<30	<700	<30
Current density (A/cm^2)	0.2–0.8	0.6–2.0	0.3–1.0
Cell voltage (V)	1.8–2.4	1.8–2.2	0.95–1.3
Efficiency	62–82	67–82	90–95
System energy consumption (kWh/Nm^3H_2)	4.5–7.0	4.5–7.5	2.5–3.7
Cell area (m^2)	<4	<0.3	<0.01
Capacity of H_2 produced (Nm^3/h)	1–1500	1–230	1–40
Purity of H_2 generated (%)	99.8	99.999	99.9
System Life Time (h)	60000–90000	20000–60000	10000–40000
Cold start time (min)	<60	<20	>60
Rated load range (%)	10–110	0–160	20–100

system benefits from more hours of viable wind conditions, the capacity factor increases. Marine farms with floating wind turbines far from shore have higher capacity factor ranges than those close to shore [3]. Speeds greater than 7 m/s are reported for offshore wind and 3.2 m/s for currents, while capacities greater than 1000 MW have been obtained using offshore wind turbines. The distances between the coast and the offshore wind farm range from 12 km to 180 km. Usually, some installations have been carried out in shallow water (1–10 m depth) or with a depth of up to 45 m.

3.2.3. Storage and transportation of green hydrogen

3.2.3.1. Storage. The method used to store hydrogen depends on its physical state. As a gas, hydrogen can be stored in underground sites (salt caverns), pressurized gas tanks (steel tanks and composite tanks), and pipelines (dedicated and mixed with natural gas) [18,24,32]. For large-scale applications, storing hydrogen in salt caverns is considerably more cost-effective than using large battery storage systems [60]. Storage tanks that can store gas at a pressure of 700 bar are expensive because they require advanced materials, for example, carbon fibre, and therefore, they are not viable for large stationary applications [128].

Aquifers have been observed to be unsuitable for storing hydrogen because hydrogen molecules are very small, which causes large leaks in aquifers that are not well sealed, unlike salt caves [128].

As liquid hydrogen, it can be stored in hydrogen tanks and liquid ammonia and liquid organic hydrogen carriers (LOHC). Liquid hydrogen storage in cryogenic containers occupies a smaller storage volume compared to gas containers, but on the other hand, the liquefaction and compression of H_2 consumes large amounts of electrical energy (6–13 kWh/kg H_2), which corresponds to 30–36% of the energy of the fuel [11,128].

As solid hydrogen, small quantities of hydrogen can be stored within metal hydrides [117], which currently exist on a very small scale [129]. The use of metal hydrides to store H_2 can be reversible or irreversible. In reversible storage, metal alloys are used to improve the weight of the system and the temperature at which it is possible to recover the hydrogen and restore the hydride. In irreversible storage, the material engages in a chemical reaction with a different substance, for example water, resulting in the release of hydrogen from the hydride. As a result, the dehydrated mixed metal is not converted back into hydride.

Hydrogen storage is also achievable through adsorption onto solid surfaces, the hydrogen atoms will be attracted by the atoms of the nanomaterials, and then the hydrogen will be stored in the active center of the nanomaterial (hydrogen is adsorbed) [130]. Adsorption occurs by chemisorption or physisorption [131], the difference being the type of force that attracts hydrogen. In the physisorption process, the attraction is weak if cryogenic temperatures are not handled, and the attractive bonds are van der Waals forces (usually less than 10 kJ mol–1). In this process, the attraction is also more than a layer of atoms of the adsorbed solute [132]. In chemisorption, the bonds are very strong (the interaction energy is distributed within the range of kJ mol–1); here, the adsorbed atoms and molecules remain on the surface through valence forces of the same type (electrons are shared between the hydrogen and the surface of the nanomaterial), which generates a chemical bond that will have a high reactivity because the electronic structure is altered [133]. Only a monolayer of the adsorbed solute is formed. Then, hydrogen is released through chemical reactions under specific conditions. The Kubas interaction lies energetically between physisorption and chemisorption, with an enthalpy ranging from −20 to −70 kJ/mol H_2 and a binding energy between 0.1 and 0.8 eV [131].

Various material structures and synthetic approaches have been reported, providing a range of components, surface areas, pore sizes, and functionalities for hydrogen storage [134,135]. The main technologies are presented below:

Table 6
Current main methods of hydrogen storage. Based on [18,32,129,136].

Physical state of hydrogen	Storage method	Capacity	Storage conditions	Characteristics
Gaseous	Underground storage	300 thousand- 6 millions of kg H_2	200 bar 15 °C	- The gas remains pure - Commercially available - Affordable construction expenses - Minimal leakage rates - Swift withdrawal and injection rates - Harsh conditions for bacteria
	Steel tanks	80–1000 kg H_2	15 °C 300 bar 23 kg/m^3	- The best option for short distances - Are getting lighter and stronger - Commercially available - It needs an energy demand of 2.23 kW/kg H_2 for conversion to ambient conditions
	Composite tanks	5–3000 kg H_2	15 °C 700 bar 41 kg/m^3	- Made steel with glass fibre, carbon fibre or polymer liner such as High-Density Polyethylene - They demonstrate the ability to swiftly refuel vehicles within approximately 3–5 min, but come with high costs, weight, and pressure. - It needs an energy demand of 3 kW/kg H_2 for conversion to ambient conditions
	Pipelines	Up to 350 kg H_2/mile	Diameters of 25–30 cm 10–20 bar	- Hydrogen pipes are expensive due to the requirement for larger diameters, leak and compression tests. - There is ongoing exploration and testing regarding the incorporation of hydrogen into existing natural gas pipelines
Liquid	Liquid hydrogen tanks	1500–30000 kg H_2	1 bar −253 °C 70 kg/m^3	- Ideal for longer distances or with limitations of space - High purity - Bulk hydrogen storage is enabled by its greater density in comparison to gaseous alternatives - High initial investment associated with the cryogenic liquefaction plants - High energy consumption to liquefy the hydrogen (10 kW/kg H_2 for conversion on average) - Suggested for large-scale systems to minimize efficiency losses - Commercially available
	Liquid Organic Hydrogen Carrier, LOHC	200–5000 kg H_2		- They need a catalytic reactor to absorb hydrogen into an organic molecule. - Subsequently, another catalytic reactor is used to recover the hydrogen - To initiate the hydrogen release (dehydrogenation), temperatures ranging from 200 °C to 450 °C are essential.
	Liquid ammonia tanks	1000–10000000 kg H_2	25 °C 10–20 bar 122.4 kg/m^3	- Ammonia can be safely stored and transportedat low pressures. - Ammonia does not emit any CO_2 emissions during the process of dehydrogenation - High cost, complexity to produce ammonia and to recover hydrogen.
Solid	Metal hydrides	5–20 kg H_2		- Each 100 kg of metal can accommodate 5 kg of hydrogen storage. - To store approximately 5–7% of its capacity, the reaction demands temperatures in the vicinity of 2500°C. - Releasing hydrogen necessitates temperatures in the range of 120°C–200°C.

- Nanoporous carbon materials comprise carbon nanofibers, carbon nanotubes, and activated carbon.
- Covalent organic frameworks (COFs) are carbon-based crystalline nanoporous organic polymers that are built with strong covalent bonds.
- Porous aromatic frameworks (PAFs) possess a diamond-like tetrahedral configuration, incorporating numerous phenyl rings, and are typically created through irreversible cross-coupling reactions.
- Metal-organic frameworks (MOFs) are crystalline porous materials composed of groups of metal ions and organic ligands, e.g., MOFs, COFs, and PAFs [136].
- Nanoporous organic polymers: hypercrosslinked polymers, conjugated microporous polymers, and polymers of intrinsic microporosity [137].
- Nanoscale Hydrides: Typically, these hydrides consist of a metal cation and a hydrogen anion. Hydrides hold potential as materials for storage applications because of their high hydrogen densities and relatively elevated safety characteristics (low reactivity).

Table 6 presents the main hydrogen storage methods, storage capacity, operating conditions, and some relevant technical characteristics. Table 7 shows the type of technology used to store and transport the H_2 obtained from marine energies reported in the study cases. The type of storage is selected according to the final application, which requires an analysis between technical performance and profitability [138].

The most developed ways of storing hydrogen are as a compressed gas and as a cryogenic liquid [18]. Two other methods that are under development are storage through chemical substances (ammonia, hydrazine, MOFs, LOHCs, formic acid, hydrocarbon substances, etc.) and storage through physical interactions (carbon nanotubes, clarets, microspheres, and glass capillaries) [139].

The research conducted by Qureshi et al. indicates that compressed gas, liquid, and cryogenic storage options for H_2 are not suitable alternatives for mobile applications due to security concerns and excessive expenses. However, storage can be improved by using catalytic materials, doping, plasma interaction with metals, additive cold rolling, mechanical ball milling, and solid-state storage methods for example metal hydride alloying, complex metals, and carbon-based materials [136].

3.2.3.2. Transport. The transport of energy from the sea to the coast can be in the form of electricity or hydrogen. The distance of the marine farm from the coast is an important factor since it determines the effect on the economic viability of the system [30]. Calado and Castro [18] analysed two possible scenarios of energy transport for hydrogen production. According to their results, the best option is for the electrolyzer to be located onshore at a distance to the coast between 50 and 100 km. The advantage identified for the land-based electrolyzer was its increased flexibility for the operator, offering the choice to either sell electricity or produce hydrogen based on the most economically favorable option.

Thus, for short distances from the coast, the best option is to transmit energy from the sea through an electric cable to the coast to later transform it into hydrogen, and for distances greater than 1000 km and during periods of low electricity prices, the optimal approach involves converting energy into hydrogen and transporting it by ship. Moreover, when submarine pipelines rupture, repairing them can be more challenging and costly than repairing submarine cables. Similarly, the operation and maintenance (O&M) expenses for pipelines are typically greater than those for submarine cables [71]. Currently, there are H_2 detection devices in pipes that can operate at various temperatures, humid environments, and concentration levels [136]. These devices hold significant importance in ensuring the safety and acceptance necessary for the growth of the hydrogen economy.

Hydrogen liquefaction presents the lowest costs among all the studied ship transport routes [19]. However, hydrogen compression provides less energy loss than cryogenic liquefaction [140]. Compressed hydrogen transport is probably the best option provided that pipelines can withstand the brittleness and diffusivity of hydrogen. If stainless steel pipes suffer from embrittlement, transportation using LOHCs is likely the most auspicious alternative due to its suitability for hydrogen distribution and its lower cost compared to transportation with ammonia.

Table 8 summarizes the results mentioned. It is important to highlight that increasing the fuel cell to any of the scenarios will increase the cost of investment and operation, which will increase LCOE.

Table 7
Storage, transport, and final use of the green H_2 obtained from marine energies.

Study	Offshore resource	H_2 Storage	H_2 Transport	Final use of H_2
[63]	Wave	Batteries	–	Mobile transport
[43]	Offshore wind	–	Tanker truck or by a 100 bar pipeline.	Mobile transport
[61]	Offshore wind/FV	In salt caverns	–	Mobil transport, thermal demand, or electricity grid
[36]	Offshore wind	In salt caverns	–	Mobil transport
[49]	Offshore wind	–	Transport by ship or by pipe	Mobil transport, industrial scale, electricity, and heat
[50]	Marine energy and offshore wind	–	By ship LH_2 trucks, by pipeline and by submarine cables	Mobil transport, industrial scale, electricity and heat
[51]	Offshore wind	In tanks and salt caverns	By ship LH_2 trucks and existing oil tankers	Petrochemicals, Oil refining, and ammonia production

Table 8
Green hydrogen production and transport scenarios categorized by the distance from the farm to the coast.

	Transmission			Conversion	Transport	Disposal	Distance		
							Up to 10 km	50–100 km	Over 1000 km
Marine farm or marine hybrid	Submarine electric cable	Onshore transformer		Onshore hydrogen production platform		Storage and distribution for fuel cells, industrial market or as transportation fuel	The best choice		
	Submarine electric cable	Offshore transformer	Submarine electric cable	Onshore hydrogen production platform				The best choice	
	Submarine electric cable	Offshore transformer	Electric cable	Offshore hydrogen production platform	Hydrogen pipeline		Cheaper than with ship	Less economical than onshore electrolyzer	
	Submarine electric cable	Offshore transformer	Electric cable	Offshore hydrogen production platform	Tanker-ship with compressed hydrogen or liquefied hydrogen		Less economical than pipe.		The best choice

3.3. Economic aspects

3.3.1. Economic feasibility

To comprehensively analyse the economic viability of a marine system incorporating hydrogen production, several economic factors must be determined, such as the LCOE, levelized cost of hydrogen ($LOCH_2$), IRR, capital expenditures (CAPEX), operation and maintenance expenditures (OPEX), electricity rate, NPV and DPBP [111].

The economic viability of a renewable energy project can be initially evaluated through the LCOE, which is defined as the price at which the generated electricity must be sold for the system to reach a breakeven point by the end of its lifetime (€/MWh). The LCOE is the ratio of the annual cost of energy production and the annual electricity generated [141]; the lower the LCOE is, the better. Thus, the LCOE provides a comprehensive viewpoint encompassing both economic and technical aspects [142].

The LCOE of offshore wind farms has been calculated by several studies under different conditions (wind speed range, wind power, location, distance from the OWF to the coast, size of the marine turbine, etc.) yielding values of 83 €/MWh [71], 45.1–56.64 €/MWh [72], 38.1 €/MWh [47], 20–70 €/MWh [49], 51.4 €/MWh [50] and 75.11–89.43 €/MWh [111]. Through a comparative study of marine renewables, D'Amore-Domenech and Leo [71] found that offshore wind power has the lowest LCOE and the best short-term global growth prospects.

The main factors that have been shown to increase the LCOE were the high life cycle cost and the low energy produced by the farm. The greater the energy generated by the marine farm is, the lower the LCOE. The lowest values correspond to 20 €/MWh, while the highest values correspond to 89.43 €/MWh. The high uncertainty is associated with the risk in the development of technology and marine resources. In general, the economics of the OWF improve as the wind speed increases, as more energy can be produced [111].

The NPV of some distant maritime concepts with hydrogen production has also been estimated by several authors [36,47,72], who agree that it is necessary to achieve a 30% reduction in the total capital cost of hydrogen production for the hybrid system to be feasible and successful. They also concur that by 2030, the hydrogen production systems of offshore wind farms will be cost-effective at a hydrogen price of ca. 5 €/kg. For instance, Dinh et al. [36] analysed the feasibility of green hydrogen production with ocean energy composed of 16 OWTs of 6.33 MW and using PEME technology. They showed that it can be profitable in 2030 if the price of hydrogen remains at 5 €/kg. For the DPBP, the years can range from 8 to 16 years, depending on the hydrogen storage time. Shorter storage terms (2–7 days) are cheaper compared to longer storage periods (20–45 days) due to the significant capital expenditures involved in storage systems.

CAPEX is conditioned by the price of design, consent, production, acquisition, installation, and commissioning [141]. OPEX and LCOE have been shown to decrease exponentially as the size of the OWT increases, mainly because fewer units need to be installed and maintained while producing more expected power [143]. Conversely, with an increasing distance from shore, CAPEX has been shown to increase linearly, while OPEX and LCOE increase exponentially (see Fig. 6 (a) and (b) purple line) [52]. While an increase in sea depth does not affect OPEX, it does result in a nearly linear rise in CAPEX and LCOE due primarily to expenses related to foundations, support structures, and installation. (see green line in Fig. 6 (a) and (b)). Moreover, a rise in the overall wind farm capacity leads to a proportional rise in both OPEX and CAPEX (refer to Fig. 6 (c)). However, it exhibits a decreasing exponential trend in LCOE for the specific wind turbine rating, owing to increased energy generation and decreased costs per wind turbine [142].

Woznicki et al. [55] made a technoeconomic comparison of three scenarios: off-grid OWF with offshore electrolysis, grid-connected OWF with offshore electrolysis, and grid-connected OWF with onshore electrolysis. The lowest $LCOH_2$ (6.88 €/kg) was attributed to the first option, mainly due to the null H_2 transport costs. When transport costs were considered, the $LCOH_2$ increased by 7.9%.

Kim and Kim [60] argued that green hydrogen generated by onshore wind farms is a better option than that generated by offshore wind farms due to the high cost of capital needed for the latter, although the latter has a high wind potential. However, several techno-economic studies [20,43,69,144] have shown that, in the long term, hydrogen from offshore wind power may be feasible on the market for isolated consumers, for example, on islands.

3.3.2. Computer-aided economic evaluation of green hydrogen projects

The simulation of conceptual models can be used to evaluate the techno-economic feasibility of offshore wind farms. The simulation of grid-connected and off-grid supply systems with any combination of power sources can be carried out by a number of software

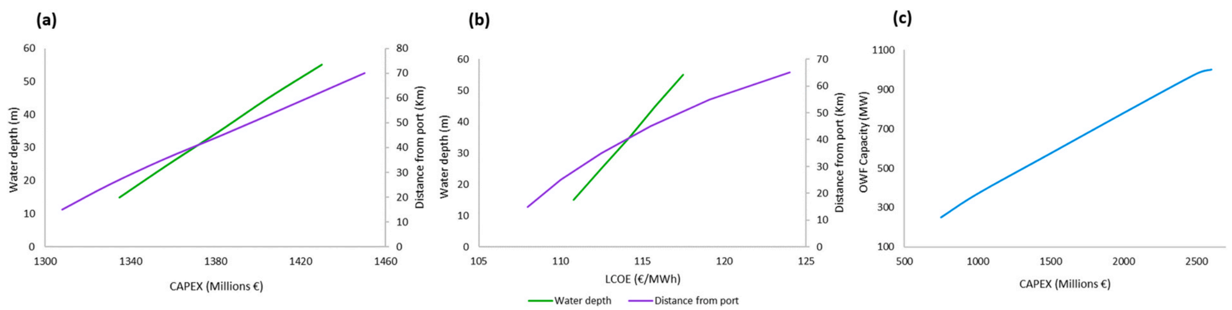


Fig. 6. (a) Behavior of CAPEX in relation to the distance from the port and water depth; (b) Behavior of LCOE in relation to the distance from the port and water depth; and (c) Behavior of CAPEX in relation to the capacity of the OWF. Data adapted from [143].

programs, such as HOMER Pro, HYBRID2, TRNSYS, HYDROGEMS, INSEL, ARES, RAPSIM, SOMES, SOLSIM, CARE and HOGA, which are useful for evaluating the feasibility and performing optimization and sensitivity tests of hybrid renewable energy systems [145]. For instance, HOMER Pro employs climate data for designated locations, diverse technological options, component prices, characteristics of the electrical grid, load demand data, and project lifetimes as inputs to model various system configurations. Following the provision of decision variable values as inputs, the HOMER Pro algorithm assesses each potential combination of resources and simulates all feasible setups capable of meeting the necessary system demand and constraints at each stage of the simulation process. HOMER Pro has been recently used [146,147] to optimize the initial costs and unit power cost of hybrid marine systems with hydrogen production.

Maximizing profits through the optimization of wind-hydrogen plant operations is contingent upon the technical and economic limitations of wind flow, transmission networks, and the installed capacities of wind and hydrogen facilities [55,66,148]. Relatively expensive wind and hydrogen infrastructure are other factors that affect the profitability of wind-hydrogen plants.

In their optimization study, Hou et al. [39] found that there is greater economic viability if green hydrogen is sold directly to consumers rather than being converted back into electricity and sold on electricity markets. It has been found that the best option for green hydrogen to be competitive is the fuel market for fuel cell vehicles. Conversely, for hydrogen to be competitive in large industries or in grid insertion, there must be cost reductions and support mechanisms, for example, a carbon tax of between 50 and 200 €/kg [11]. Another possibility to improve the NPV is the commercialization of the oxygen produced [49].

3.3.3. Hydrogen electrolysis and storage costs

The cost associated with hydrogen production via water electrolysis predominantly relies on factors such as the capital cost and efficiency of the electrolyzer, including the cost of electricity and the plant's capacity factor [11]. The production of green hydrogen has been found to be not profitable by Meier et al. [58], who evaluated two advanced electrolyzer technologies. They identified four aspects that must be met to reduce the cost of green hydrogen production: further electrolyzer technology development, large-scale production, reduction in component costs and improvement in technology efficiency.

Regarding the cost of investment, the most important characteristic is that it will be low today and in the coming years [71]. According to short- and long-term cost data for electrolysers [49,55,144], AE technology consistently outperforms PEME technology due to its lower costs and higher efficiency, even with its broader operating range (viz. Table 9). In the selection of the optimal electrolysis technology for the sustainable production of green hydrogen from seawater and marine energies, buyers or decision makers must consider economic, environmental, and social criteria. Using a two-layer optimization method (sequential quadratic programming and adaptive particle swarm optimization), AE-based technology was identified as the best economic option for integrating offshore wind farms with diverse hydrogen storage setups in Denmark [39].

The $LCOH_2$ has been found to be directly proportional to the distance of the marine farm from the coast; as the marine farm is located farther from the coast, the $LCOH_2$ increases [20] due to expensive power lines and losses during power transmission; for cases where hydrogen is transported from offshore platforms, more pipeline connections will be needed, implying higher costs. The resulting cost of green hydrogen obtained from marine energies (Table 10) is in the range of 3–5 €/kg with a production capacity of 90% in the electrolyzer, although there is potential to decrease the cost of the electrolyzer in the future. The production capacity of the electrolyzer also influences the cost of hydrogen; as the generation capacity increases, the cost of hydrogen production decreases. As stated by the Hydrogen Council [111], the electrolyzer should operate with a production capacity of at least 30% to reduce the cost of hydrogen production to 2.00–2.50 €/kg H_2, which can compete effectively with natural gas.

The form of storage, distribution and final use of green hydrogen are useful to determine its best added value. Table 11 shows the $LCOH_2$ of the different hydrogen storage methods according to the amount that needs to be stored. For large-scale hydrogen storage, salt caverns are the cheapest option, and liquefied hydrogen is the most expensive of all storage options.

According to Franco et al. [49], the use of gas pipelines to transport hydrogen has an $LCOH_2$ of 5.85 €/kgH_2 and has the potential to reach 2.2 €/kgH_2. If the distances from the OWF to the coast are greater than 150–250 km, it is cheaper to transport hydrogen by ship; if the distance is less, the most convenient transport is gas pipelines.

In summary, the reported costs of sea green hydrogen are well above the ideal cost proposed by the Hydrogen Council. This means that for the price of green hydrogen to decrease, it is necessary to reduce the costs of electricity generation. Hydrogen liquefaction offers the best characteristics for long distances between all ship transport routes studied (viz. Tables 6 and 8).

Table 9
Costs of the most commonly used electrolysers in marine applications.

Characteristics	Type of electrolyzers		
	AE	PEME	SOE
Investment cost (€/kWh)	946–1773	1655–2483	>2364
O&M cost (% of capital cost)	1.5	1.5	N/A
CAPEX (€/kWe)	450–1260 [49]	990–1620	2520–5040
OPEX (% of CAPEX)	1.5	1.5	–
CAPEX (€/kW) 2017	777.70–1458.19 [144]	1360.98–2041.47	
OPEX (% of CAPEX)	2	2	

Table 10
Level cost of hydrogen from OWFs and marine farms.

Ref	$LCOH_2$
[63]	23.44 €/kg PEME
	21.84 €/kg SOE
[59]	4 -13 €/kg H_2
[39]	2-9 €/kg H_2
[60]	8.9–10.1 $/kg H_2
[11]	4.4–5.5 €/kg (scenarios)
	5.11–2.34 €/kg (specifications)
[71]	4.25 €/kg
[55]	6.88 €/kg
	7.067 €/kg
	7.394 €/kg
[45]	0.90 €/kg H_2 at 50% electrolyzer production capacity
	5.50 €/kg H_2 at 10% electrolyzer production capacity
[47]	3.77 €/kgH_2
[36]	5-7 €/kg
[48]	5.35 €/kgH_2,
	with the potential to be 2.17 €/kgH_2
[49]	5.99 €/kgH_2,
	with the potential to be 2.61 €/kgH_2
[32]	3.62 €/kg
[18]	9.17 €/kg AE
	3.77–11.75 €/kg PEME
[52]	4.65–8.08 €/kg
[20]	13 €/kg

Table 11
Hydrogen storage costs. Based on [129].

Stored hydrogen scale	Type of deposit or conversion	$LCOH_2$/day
100 ton	Salt caves	0.23 €/kgH_2
	Rock caverns	0.71 €/kgH_2
	Depleted gas fields	1.9 €/kg H_2
	Convert hydrogen to ammonia	2.83 €/kgH_2
1 ton	Steel tanks	0.19 €/kgH_2
	Liquid hydrogen tanks	4.57 €/kg H_2

*To standardize the data, all costs are reported in €, considering the currency exchange rate of 1 USD to 1 € in 2022.

3.4. Environmental aspects

Green hydrogen production through electrolysis can be viewed as an efficient and environmentally friendly technology owing to its ability to achieve high energy conversion efficiencies (ranging from 65 to 86% in AE and PEME). In contrast to hydrogen production through steam methane reforming (SMR), it has been shown to result in 94% fewer greenhouse gas emissions [39,149].

According to a recent report from the International Energy Agency [150], 830 million metric tons of CO_2 could be avoided annually if the conventional method of producing hydrogen is changed to an electrolysis-based method, i.e., green hydrogen.

The environmental criterion is that the electrolyzer does not emit substances that affect the marine environment and workers. Barakat et al. [70] found that the cleanest option is PEME technology due its fast response and environmental safety, since AE presents possible electrolyte leaks that have the characteristic of being extremely caustic and imply a great danger for workers and the environment. In another study, d'Amore-Domenech et al. [76] analysed the performance of electrolysis technologies using marine renewable energies. They observed that DES has a very high degree of impact and a very high environmental risk (due to the use of chlorine and very caustic brine), AE has a medium degree of impact and a medium environmental risk (due to very caustic electrolyte spill), PEME has a low degree of impact and a very minimal environmental risk, and SOE has a low degree of environmental impact and a medium environmental risk (due to superheated steam).

Dutton [56] analysed the offshore wind energy used for electricity generation in the UK, omitting embodied energy in construction and other processes in this analysis. The results indicated that the generation of 1 GWh of electrical energy through water electrolysis (69% efficiency) for subsequent use in a conventional internal combustion engine rather than gasoline could lead to a reduction of 139 tons of CO_2 emissions. Alternatively, generating hydrogen (69% efficiency) via water electrolysis for a fuel cell electric vehicle, substituting for a gasoline vehicle, could result in a CO_2 emissions reduction of 268 tons.

Wulf and Kaltschmitt [62] performed an LCA of six different hydrogen production and supply pathways in Hamburg/Germany. Green hydrogen from renewable energy sources by electrolysis of water from surplus electricity from OWFs, hydrogen from methane, hydrogen from glycerol as a byproduct of biodiesel production, hydrogen from electrolysis with electricity extracted from electric mix, hydrogen by coal gasification and biomass gasification. The results showed that utilizing electricity extracted from the German grid's electricity mix for hydrogen production through electrolysis and generating hydrogen via coal gasification does not help reduce GHG emissions; however, a reduction in GHG emissions was achieved by supplying green hydrogen from OWFs and hydrogen obtained by biomass gasification (brown hydrogen).

Franzitta et al. [38] presented a feasibility study of two plants, one of 4.25 MW from wind resources and another 8.6 MW from sea waves, including the hydrogen storage and distribution for public transportation infrastructures in western Sicily and Pantelleria, Italy. The OWF and the wave farm were shown to be capable of producing enough hydrogen to replace the entire fleet of diesel-powered city buses with the same number of hydrogen vehicles. Utilizing hydrogen in the functioning of these vehicles was demonstrated to notably decrease the emission of particulate matter and GHG in both sites analysed, 1444 tons/CO_2 avoided and 22.85 tons/NOx avoided, respectively.

Seddiek [44] quantified prospective GHG emission reductions for the Port of Damietta, Egypt, using fuel cells and OWTs as a green energy concept, achieving reductions in CO_2, NOx and CO emissions of 32.18, 53.2 and 8.32 tons/year, respectively.

In the production and transportation of construction elements and their assembly and maintenance on a marine site, it has been found [89] that most of the environmental impact stems from structural components constructed with reinforced concrete. It was also found [88] that the functioning of underwater current power systems will lead to substantial mortality rates among pelagic organisms such as fish and marine mammals.

In a strengths, weaknesses, opportunities, threats, "SWOT" analysis, environmental security is considered a strength that promises the reduction of GHG emissions in a marine energy generation system compared to conventional energy generation. However, the profitability and high capacity factor (more than 45%) of the OWT is an important value among the energies that produce energy in the ocean. The opportunities are the advancement of the technological maturity of marine systems (offshore wind, tidal wave, submarine current, WEC, TEC, oscillating wave surge converter, etc.) that have been developed for the generation of clean energy and the generation of green hydrogen, as well as advances in the improvement of electrolysers in marine environments. Weaknesses include the high investment cost of marine systems, the production of green hydrogen and the dependence on tankers from the oil area to install or maintain the systems [33,151]. Another area of opportunity is when there are economic and social benefits of hydrogen production by marine means, for instance, derived from the concurrent generation of both electricity and potable water in coastal regions prone to drought. Finally, the main threat could be legal procedures that can stop or delay the development of marine projects for the generation of clean energy.

3.5. *Evaluation of green hydrogen production capacity*

To ascertain the best marine technology for green hydrogen production, the Elimination et Choix Traduisant la Realité (ELECTRE) method was used. Of the 50 articles reviewed, only 8 were found to have the necessary data to perform a multicriteria decision analysis. To choose the optimal solution, 4 selected criteria were drawn. In order of prioritization, the criteria were the amount of hydrogen obtained by the system, total investment cost, capacity factor, and time (hours) available for hydrogen production. The descriptions of the 8 selected systems are shown in Table 12.

The ELECTRE method shows that the best technologies to produce hydrogen in the marine environment are OWTs and ocean currents. High speeds, high capacity factors (40% and 56%, respectively) and investment costs (2.4 and 2.33 M€/MW, respectively) make them the best choice. OWT technology generates more hydrogen than all other systems, but it has a lower capacity factor than ocean current turbines, and the investment cost (€/MW) is the highest compared to all marine systems analysed.

Of the hydrogen production systems with onshore electrolysis, marine current and TEC technologies are the best option because of their low investment costs and high capacity factors (56% and 90%, respectively), as well as the flexibility of operation and maintenance in power generation and hydrogen production.

In terms of offshore centralized electrolysis hydrogen production systems, OWTs are found to be the best option, followed by WECs and marine hybrid systems. It should be noted that centralized marine electrolysis is the most expensive way to generate hydrogen but has better energy yields. Currently, hydrogen infrastructure is only possible with large investments and decentralized generation.

4. Conclusions

This work focused on the review of green hydrogen production through oceanic sources, both offshore wind and marine sources.

The best technical characteristics of a marine farm must have a capacity factor equal to or greater than 50%, as well as wind speeds greater than 7 m/s (for offshore wind farms), and the closer the oceanic farm is to the coast, the more economical and flexible it is for the operator and there are fewer energy losses. The most suitable electrolyzer for marine environments is currently the PEME due to its faster response time to intermittent energy from marine energies and because it has better environmental behaviour. Hydrogen production with ocean technologies is feasible and is a way to increase the reliability and quality of power.

The cost of the marine farm will be higher if it is far from the coast, the greater the depth of installation, and if the capacity of the farm is very large; in contrast, when the size of the turbines (for example, offshore wind) is higher, the CAPEX decreases because fewer units will be required to reach the desired capacity. The price of green hydrogen is conditioned by the CAPEX system, which provides marine renewable energy. Feasibility increases as the CAPEX of each technology becomes more affordable.

For short distances, the most economical option to transport H_2 is to transmit energy through an electric cable to the coast and then transform it into hydrogen. For distances greater than 1000 km, the transport of hydrogen by ship is the most economical option. Hydrogen liquefaction offers the best characteristics for long distances between all ship transport routes studied. For large amounts of hydrogen, the most economical storage is in salt caves.

Table 12
Characteristics of marine systems analysed.

Technology	System	Ref.	Power rating (MW)	Electricity generated by the Marine farm (MWh/y)	Energy available for hydrogen production (MWh/y)	Amount of H_2 obtained (kg/y)	Investment cost M€	ELECTRE method choice
OWT	Centralized offshore electrolysis	[57]	100	331680	328646.64	4105517	716.15	7
OWT	Centralized offshore electrolysis	[17]	600	5200000	5200000	92560000	2630	3
OWT	Not specified	[44]	15	21024 MW	26280	821250	35.937	1
WEC	Centralized offshore electrolysis	[63]	1	2955.4	2437.76	52320	5	5
Ocean currents	Onshore electrolysis	[70]	1.5	7391.25	7391.25	131564.25	3.5	2
Marine hybrid	Centralized offshore electrolysis	[40]	19.8	9871.936	8851.177	23902.24	40.2	8
Marine hybrid	Not specified	[38]	12.85	19000	17940	318588	59	5
TEC	Onshore electrolysis	[75]	1.245	9790.68	9790.68	174274.104	4.735	4

*To standardize the data, all costs are reported in €, considering the currency exchange rate of 1 USD to 1 € in 2022. Costs were estimated for ocean currents, WEC, and TEC systems from the references [37,148]. The amounts of hydrogen were also assumed with the following units: 11.1 Nm^3 of H_2 = 1 kg of H_2 and amount of energy consumed by the electrolyzer = 0.05618 MWh/kg of H_2.

When the price of hydrogen is between 5 and 13 €/kg, it follows that more profit can be made by selling hydrogen rather than producing electricity; thus, it becomes more favorable to use wind power to produce hydrogen rather than simply selling electricity.

In the implementation of marine renewable projects, 65% of the emissions of GHG come from the manufacturing and installation stages of the farm, but these environmental costs have long-term compensation since marine projects have a life of 20–50 years. The generation of green hydrogen does not produce significant pollution, and the use of green hydrogen can greatly reduce the environmental impact on future operations in the transport sector, oil refineries and, in general, industrial sectors.

Transitioning to a hydrogen economy presents fresh economic possibilities for nations and regions heavily reliant on fossil fuel exports for a considerable portion of their national income. Additionally, it can open avenues for new export prospects for countries with abundant renewable energy resources. This is because the costs of producing green hydrogen are decreasing, thanks to emerging electrolyzer technology that is projected to become more efficient, resistant, and cost-effective in the upcoming years.

This review analysed offshore wind power scenarios, offshore devices, and offshore hybrid systems. The different technologies used in this study have varying levels of maturity. Therefore, it is recommended that future work include analysis with more ocean energy technologies for green hydrogen production. Further development of marine systems that integrate hydrogen generation is necessary to ensure comprehensive reporting and analysis.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex 1

Table A1
Classification of hydrogen production by color [7,130,152–154].

Hydrogen classification	Description
Green	Hydrogen produced by electrolysis of water using electricity from renewable energy sources (such as wind, ocean, solar, hydropower, etc.) is generated with zero emissions of CO_2 into the atmosphere.
Blue	Hydrogen is derived from natural gas (through SMR process) with the reduction of CO_2 emissions through Carbon Capture and Storage (CCS) methods.
Grey	Hydrogen is derived from natural gas (through the SMR process) with CO_2 emissions.
Black	Hydrogen is produced from bituminous (black) coal through the gasification process, without reduction of CO_2 emissions using CCS methods.
Brown	Hydrogen is generated from lignite (brown) coal (through the gasification process) with CO_2 emissions.
Pink	Hydrogen is produced through water electrolysis, using electricity (and/or residual heat, with steam, adapted to an SMR) from nuclear power plants. It is also known as red or purple hydrogen.
Turquoise	Hydrogen is generated from the methane gas pyrolysis process, which does not generate CO_2 emissions since solid carbon is produced.
Yellow	Hydrogen is produced by the electrolysis of water using exclusively photovoltaic solar energy, resulting in "zero" CO_2 emissions into the atmosphere.
White	Geological hydrogen of natural origin is found in underground deposits and extracted through "fracking". Fracking is widely recognized as highly polluting to the environment.
Orange	Hydrogen is produced from biomass (materials of plant origin and/or organic waste). It is considered with a moderate environmental impact.
Mustard	Hydrogen is generated by electrolysis of water from the energy of the energy mix of the electrical network

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