Offshore green hydrogen production from wind energy: Critical review and perspective

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A B S T R A C T

Hydrogen is envisaged to play a major role in decarbonizing our future energy systems. Hydrogen is ideal for storing renewable energy over longer durations, strengthening energy security. It can be used to provide electricity, renewable heat, power long-haul transport, shipping, and aviation, and in decarbonizing several industrial processes. The cost of green hydrogen produced from renewable via electrolysis is dominated by the cost of electricity used. Operating electrolyzers only during periods of low electricity prices will limit production capacity and underutilize high investment costs in electrolyzer plants. Hydrogen production from deep offshore wind energy is a promising solution to unlock affordable electrolytic hydrogen at scale. Deep offshore locations can result in an increased capacity factor of generated wind power to 60–70%, 4–5 times that of onshore locations. Dedicated wind farms for electrolysis can use the majority >80% of the produced energy to generate economical hydrogen. In some scenarios, hydrogen can be the optimal carrier to transport the generated energy onshore. This review discusses the opportunities and challenges in offshore hydrogen production using electrolysis from wind energy and seawater. This includes the impact of site selection, size of the electrolyzer, and direct use of seawater without deionization. The review compares overall electrolysis system efficiency, cost, and lifetime when operating with direct seawater feed and deionized water feed using reverse osmosis and flash evaporation systems. In the short to medium term, it is advised to install a reverse osmosis plant with an ion exchanger to feed the electrolysis instead of using seawater directly.

1. Introduction

The ongoing climate crisis has accelerated the need to move away from fossil fuels as the primary fuel source (which currently accounts for ~ 80% of the energy produced worldwide [1] and move towards more sustainable, abundant, green, and renewable fuel sources. Among such alternative fuels, hydrogen (H_2) is an attractive option because when it is combined with oxygen gas (O_2) within a fuel cell it can generate electricity without emitting any environmentally harmful greenhouse gases [2,3].

Also, green H_2 is one of the most promising clean and sustainable energy carriers for the decarbonization of the modern world with zero pollution field [4] and has a higher energy density (142 MJ kg^{-1}) than fossil fuels (ca. 50 MJ kg^{-1}) [5,6]. The UK government intends to achieve net zero emissions by 2050 with potential funding to decarbonize the key UK industrial sectors and provide energy for power and heating.

The UK government's initial H_2 Strategy was to achieve a low-carbon H_2 production capacity of 5 GW by 2030, but the government has doubled the ambition up to 10 GW by 2030, of which half would be the electrolytic method [5,7]. Scotland is playing an important role in the development of the H_2 economy, with the potential to produce industrial-scale quantities of H_2 from the onshore and offshore wind resources and energy systems. Further, the Scottish Government suggests it could deliver 21–126 TWh of H_2 per year by 2045, with up to 96 TWh of H_2 for export to European countries [8]. Large-scale floating offshore wind farms coupled with electrolyzers for the generation of H_2 are seen as an important decarbonization option in the coming decades [9]. It is projected that the levelized cost of energy (LCoE) for offshore wind in the European Union (EU) will range from 35.02 to 61.28 € MWh^{-1} with transmission (factoring in a 4% weighted average cost of capital (WACC)), and from 26.27 to 43.78 € MWh^{-1} without transmission, by the year 2030 [10].

A study conducted by Durakovic et al. [11] has shown that the

Abbreviations

AEM	anion exchange membrane
AEMWE	anion exchange membrane water electrolyzer
ASR	area-specific resistivity
AWE	alkaline water electrolyzer
BCM	billion cubic meters
Ca	circa (approximately)
CAPEX	capital expenditures
CCM	catalyst coated membrane
ClER	chloride evolution reaction
EU	European Union
FLNG	floating liquefied natural gas
FPSO	floating production storage and offloading
FSRU	floating storage and regasification unit
GDL	gas diffusion layer
HER	hydrogen evolution reaction
HHV	higher heating value
LCOE	levelized cost of energy
LCOH	levelized cost of hydrogen
LHV	lower heating value
MEA	membrane-electrode assembly
OER	oxygen evolution reaction
OPEX	operational expenditures
OWH	offshore wind-to-hydrogen
PEM	proton exchange membrane
PEMWE	proton exchange membrane water electrolyzer
pH	potential hydrogen
PTFE	polytetrafluoroethylene
SC	salt caverns
SWRO	seawater reverse osmosis
SSP	subsea processing
SWE	seawater electrolysis
TLP	tension legs platform
UGS	underground gas storage
WACC	weighted average cost of capital

implementation of H_2 in offshore wind projects in the European North Sea region could have a considerable effect (increment by up to 50%) on the development of the grid in both Europe and the North Sea. Further, the offshore energy hub serves as an important power transmission asset and is central to unlocking the North Sea's offshore wind potential [12, 13]. Offshore locations have high wind speeds (7–10 m s^{-1}) and are more consistent, producing more renewable electricity than onshore [14–16] with ~23.0% (in 2021) of renewable electricity produced from wind power onshore in the UK [12,17]. The challenge with offshore wind power is the transportation of the electricity onshore through power cables due to the sea conditions and corrosion, which lead to additional investment costs and high losses of electricity (3–5% for a single cable) and increases the overall production cost from offshore [18]. Considering that gas transport in pipeline results in much smaller energy loss than power transport, therefore, the generation of H_2 from offshore wind farms has a great potential depending on the distance from shore and pipe installation costs since the cost of transmitting H_2 is relatively low over the long distances. Therefore, direct generation of green H_2 from offshore facilities has the potential to significantly reduce production costs compared to onshore production [19]. However, it has more challenges when compared to onshore windfarms, such as corrosion, environmental emissions (e.g., brine and heat), erosion, biofouling, lightning, grid connections, storage of green energy, maintenance cost, and transport to onshore usages [20,21]. The preferred method of generating H_2 is water electrolysis since it can be coupled to renewable energy sources which elicits in the production of sustainable carbon-free fuels.

Current methods of water electrolysis (alkaline water electrolysis, anion exchange water electrolysis, and proton exchange membrane water electrolysis) which are used onshore depend on the purification of freshwater as a feed, which is both scarce (less than 1% of available Earth's water) and unevenly distributed globally. A major advantage of operating in a strong alkaline environment (pH $\geq$ 14) over that of neutral and acidic is that it allows the use of noble metal-free catalysts for the anode and cathode electrodes which significantly reduces the cost of the electrolyzer [22,23].

The use of seawater (close to neutral pH), given its vast availability and economic viability, is seen as a potential path to energy sustainability when paired with renewable electricity for hydrogen production. However, pre-treatment to remove solids, organic matter, and dissolved salts from seawater is necessary to prevent issues such as fouling, corrosion, unwanted chemical reactions, damage to membranes and electrodes, and salt build-up in the electrolyzer [24–27]. Key challenges include the formation of chlorine and hypochlorite from chlorine (Cl_2)

evolution reactions (occurring at about 1.72 V in alkaline mediums), which severely corrode electrolyzer components. Furthermore, reactions involving metal chlorination, contamination from various ions (like SO_4^{2-}, Br^-, F^-, Na^+, Mg^{2+}, Ca^{2+}, K^+, Sr^{2+}, Cu^{2+}, Cd^{2+}, $HCO3^-$, and CO_3^{2-}), and the creation of insoluble Mg/Ca hydroxide on electrode surfaces can compromise the long-term stability of seawater electrolyzers. Soluble dissolved salts (e.g., $FeCl_3$) can also precipitate with increase pH at the cathode (under current flow) as $Fe(OH)_3$ causing electrode and membrane fouling. Microorganisms and sediments mainly can result in membrane fouling and blockage of electrode and transport layer pores. To overcome these issues, the electrocatalytic surface area must be increased, and the system should be capable of performing both hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) efficiently for prolonged seawater electrolysis operations [24–26, 28]. Alternatively, the purification and separation process needs to be implemented.

Until now, only a few studies have been reported with electrolysis of direct seawater. They reported that OER potential (i.e., 1.23 V) should be lower than the potential (1.72 V) of hypochlorite/Cl_2 formation. The main challenges of using seawater for electrolysis come from complex seawater components, including ion species, microorganisms, and sediments. Moreover, the composition of seawater can vary based on seasonal changes and geographic location, which may affect the chemical and physical properties of seawater.

Recently, there has been increasing global interest in direct seawater electrolysis. Yu and colleagues developed highly stable, non-precious NiMoN and NiMoN@NiFeN as effective catalysts for HER and OER, respectively. These materials maintained consistent performance at 100 and 500 mA cm^{-2} in a mixture of 1 M KOH and natural seawater [29]. Similarly, Wen and the team introduced $Ir_1/Ni_{1.6}Mn_{1.4}O_4$ as a selective OER catalyst in a large-scale setup using 6.0 M KOH mixed with natural seawater. This catalyst achieved an impressive 500 mA cm^{-2} at 1.64 V with 60 °C, outperforming the standard IrO_2//Pt–C combination [30]. However, when using seawater alone (without an alkaline solution) there are very limited reports of effective and stable earth-abundant oxygen evolution electrocatalysts. Consequently, there is a growing interest in exploring other non-noble, affordable, and corrosion-resistant transition metal catalysts to enhance the slow OER process, ultimately improving the efficiency and selectivity of direct seawater electrolysis.

To this end, this review will provide a critical in-depth examination of the opportunities and challenges in offshore hydrogen production using electrolysis from wind energy and seawater directly or indirectly after purification.

2. offshore wind opportunities

2.1. Challenges of the offshore environment

Due to the benefits of environmental protection, offshore wind-to-H_2 (OWH) projects are receiving increased attention [31]. OWH systems use renewable energy instead of coal or natural gas to produce H_2, which results in cleaner and reduced carbon emissions. When compared to previous offshore wind power projects, OWH systems significantly lessen the volatility pressure brought on by the grid connection of renewable energy [32] and offer a workable alternative for the efficient usage of plentiful offshore wind energy. This EMS was designed using project data and was tested through numerical simulations. Additionally, OWH systems may be able to use existing natural gas pipelines to transport energy rather than having to construct new electricity transmission facilities, which helps to reduce overall investment [33]. Estimated average investment costs and specific costs for energy transport by hydrogen pipelines were shown to be lower than those for High Voltage DC lines for deep offshore locations [34].

There are many barriers to deploying OWH systems. The primary challenge is related to economics. OWH systems rely on high capital (CAPEX) and operational (OPEX) expenditures. CAPEX is attributed to the wind farm, electrolysis systems, and pipelines depending on where the systems are located. This is alongside the undesirable environmental setting which amplifies construction costs. In terms of OPEX, OWH systems need vessels for their maintenance procedures which is costly. Also, the components have a shorter service life than onshore systems stemming from long-term water erosion. Moreover, high-speed winds can cause the leading-edge erosion phenomenon of wind turbines. Finally, the business model to which an OWH system fits in with the rest of the supply chain, namely, demand, market caps, etc., must also be addressed. On this scope, the levelized cost of energy (LCOE) is coined as a yardstick to compare the different available technologies. The LCOE relates the costs of the system to its electrical output. Also, the levelized cost of H_2 (LCOH) pinpoints the least market price to gain a 10% annual rate of return in the system's lifetime [19]. In other literature, the LCOH over the lifetime of the system is expressed as:

$$LCOH = \frac{CAPEX + OPEX}{Mass\ of\ produced\ hydrogen\ (annual)} \quad (1)$$

The second issue is the technical side of OWH systems. In designing OWH systems, attention should be paid to the undesirable and variable offshore environment, namely, the waves, the wind, and the topography of the seabed. These settings complicate the technical specifications and relevant construction process for either fixed or floating scenarios. In the design stage, the components must be targeted at being operated maintenance-free for a long period, owing to the high cost of offshore maintenance. The produced H_2 can be transferred onshore using pipelines or stored in containers which could thereafter be transported onshore or used up in situ by other marine vessels, therefore the H_2 supply and demand scenarios must also be planned meticulously.

Third, there are environmental obstacles that need to be addressed. These include the effect on wildlife species both under the sea and above the sea. Bergström et al. [35] identified the positive side to underwater systems which were habitat gain and fisheries exclusion, while the acoustic disturbances and electromagnetic fields were penned as the negative influences.

2.2. Selection of offshore platform

Choosing a suitable offshore platform will depend on the state of the sea and seabed, the local winds, the size of the wind turbine, the depth of the harbors, the production facilities, and the cost and availability of materials and equipment. Micallef and Rezaeiha [36] reviewed the relevant literature on floating offshore wind turbines. Specifically, the research threads (Fig. 1a) on this subject were stratified into hydrodynamics, aerodynamics, aeroelasticity, structures, control, materials, and manufacturing and installation research themes. Also, they added that the literature identified the surging and pitching motions as the dominant critical motions relevant to floating offshore wind turbines (Fig. 1b).

The location of the offshore plant is a substantial factor that will affect the design of the facility. Weather conditions, wind speed, wave height, and water depth will all need to be considered when identifying the best location for the facility. The platform needs to be designed to be
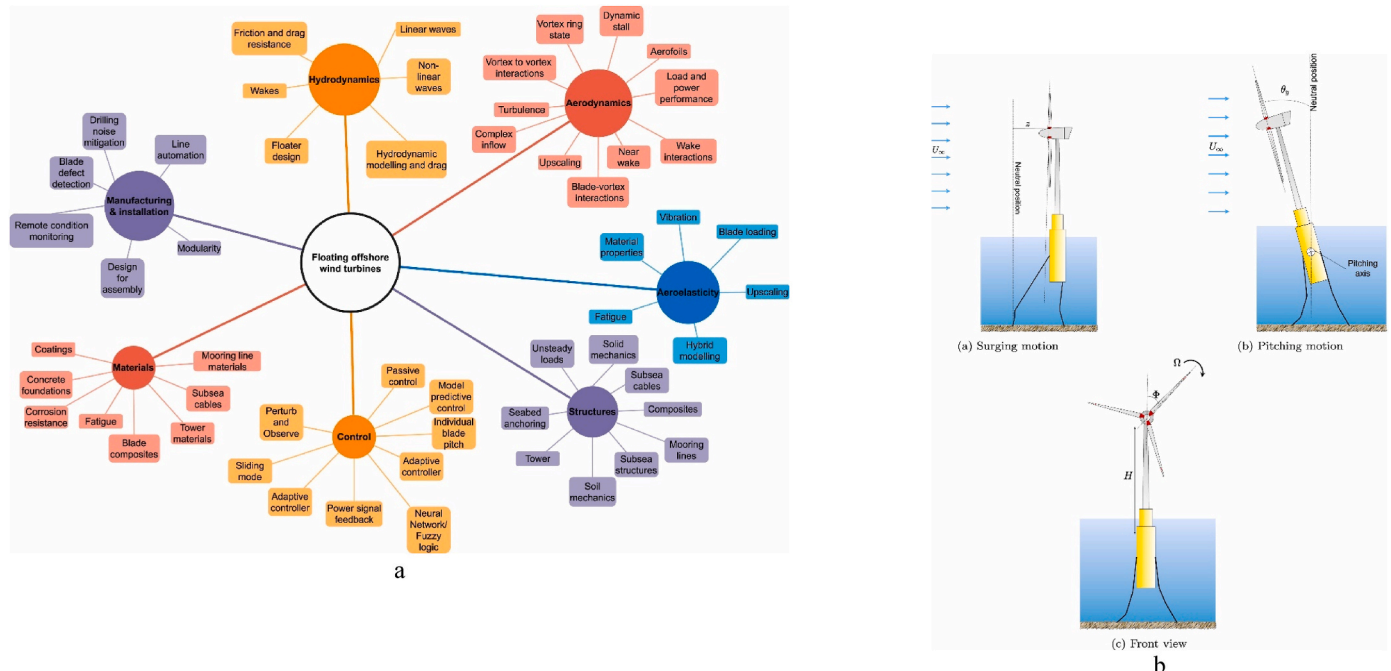

Fig. 1. **(a)** Research threads and **(b)** dominant motions relevant to floating offshore wind turbines [36], *reproduced with permission from Elsevier.*

readily accessible for maintenance and repair, which necessitates the presence of apposite access points, walkways, and other relevant infrastructure. Finally, all applicable international, national, and local laws and regulations pertaining to offshore H_2 and marine operations must be taken into consideration when designing the plant. The harsh marine environment includes corrosion, extreme temperature changes, and saltwater.

There are currently four different offshore platforms for wind turbines; barge, semi-submersible, spar, and tension legs platform (TLP) [37]. Approximately 80% of the world's offshore wind resources are located in waters deeper than 60 m, whereby fixed wind turbines are not practical. Ibrahim et al. [9] emphasized large-scale floating OWH systems and proposed three coupling scenarios, namely, centralized onshore, decentralized offshore, and centralized offshore electrolysis solutions, and concluded that for the centralized onshore, the alkaline electrolysis is favorable (lower CAPEX but slower response time), while proton exchange membrane (PEM) electrolyzer is a more adept solution relevant to its compactness and operational capability (faster dynamic response but more expensive and less sustainable due to use of IrO_2 and Pt) for the decentralized offshore. Finally, either alkaline or PEM electrolysis can be used for centralized offshore, which necessitates a more in-depth analysis for the decision as the optimal solution is very dependent on wind dynamics. The variables that they considered were choosing the electrolysis method, the platform, and the means for energy transmission. Wu et al. [38] implemented a two-stage location decision-making framework for identifying coupled wind power and H_2 storage systems. They employed the fuzzy entropy method for calculating the criteria evaluation weight. They concluded that TOPSIS and VIKOR methods should be employed to find optimal site locations for coupling wind and H_2 projects.

3. offshore wind-to-hydrogen

3.1. Direct seawater electrolysis

Present water electrolysis solutions count on ultrapure water. Owing to the plentiful reserves and rational economic viability, the seawater conversion to H_2 driven by electrical power from renewable sources is potentially a favorable prospect for sustainability. There are two main avenues for green H_2 production through the electrolysis of seawater. As shown in Fig. 2, these are the two-step method, whereby seawater is primarily desalinated via reverse osmosis, followed by additional purification via ion exchanger or capacitive desalination and thereafter introduced to the electrolyzer, and the second in which electrolysis is carried out after a simple pre-treatment to remove solids, organic and biological matters without significant desalination.

The electrolysis of seawater is a challenging process, primarily due to the complexity of its constituents, which include sediment, microbes, and various ionic species. Fouling by seawater electrolysis is affected mainly by sediment and microbes, which can be eliminated through pre-treatment. However, other ions cannot be removed by pre-treatment. With the present knowledge, three main challenges should be addressed for SWE [39]. Firstly, electrode deactivation is brought on by the deposition of metal cations, particularly heavy metals, on the cathode surface. Secondly, the OER will be hampered by the Cl^- ions, and the produced Cl_2 and other pH-dependent products (e.g., hypochlorite) can severely damage the electrolyzer components as per the well-known chlor-alkali industry. Cl_2 is toxic and will require transport to onshore making its production unfavorable on offshore wind farms. Thirdly, since there are few buffer ions in seawater, the pH cannot be incessantly maintained at large current densities, resulting in cations, namely, Mg^{2+} and Ca^{2+}, precipitating on the surface of the cathode as hydroxides [40]. The pH gradient in the anode and cathode will incur additional energy
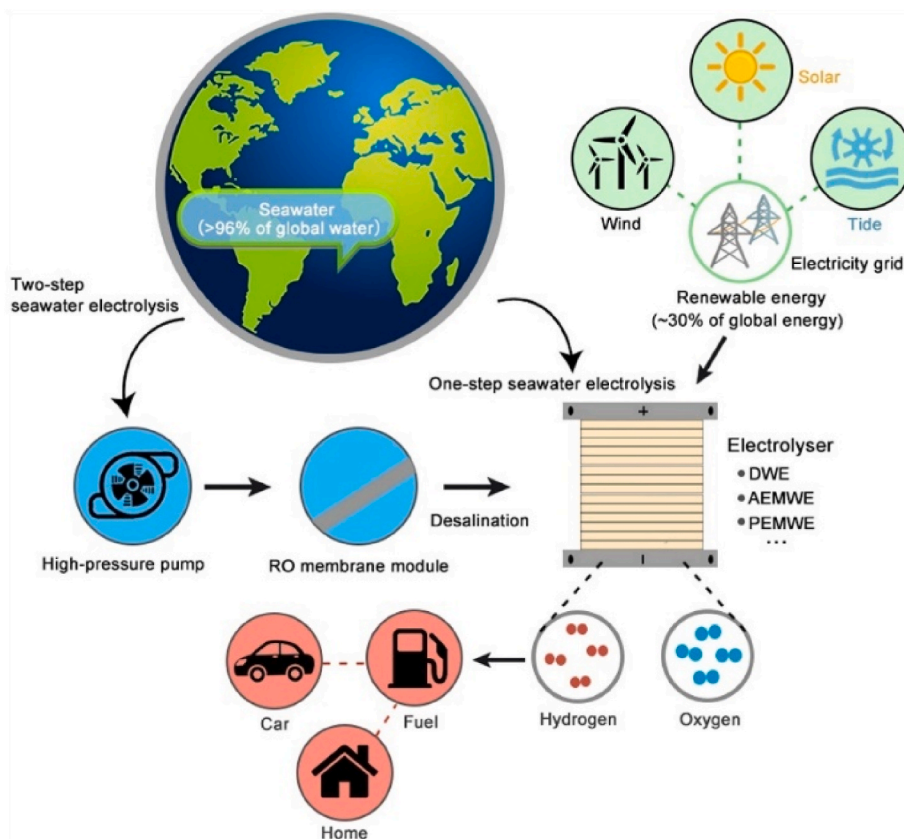

Fig. 2. Main avenues for green H_2 production through electrolysis of seawater [39]. *Reproduced with permission from Elsevier.*

loss lowering the electrical efficiency of H$_2$ production.

A membrane-based seawater electrolyzer was recently developed by Xie et al. [41] to produce H$_2$, which effectively resolved side reactions and corrosion issues. The researchers utilized a water migration mechanism based on liquid-gas-liquid phase transition for *in-situ* purification of seawater. They exploited the water vapor pressure difference between seawater and alkaline solutions which drives water vapor migration from seawater to alkaline electrolytes. They introduced a porous hydrophobic polytetrafluoroethylene (PTFE)-based membrane to allow water vapor transport but to block liquid water and ions transport between the alkaline and seawater electrolytes. They asserted that the new configuration was an efficient and scalable means for direct electrolysis of seawater, with a minor increment in operational costs. However, small ions migration from seawater to the alkaline solution was detected after 72 h, and the current density was capped at 0.4 A cm^{-2} (resulting in higher CAPEX costs) and required a cell voltage of 2.2 V which can result in higher energy cost/OPEX (67% electrical efficiency based on H$_2$ higher heating value (HHV)).

3.2. Anion exchange membrane water electrolyzer

Anion exchange membrane water electrolyzer (AEMWE) uses a solid electrolyte membrane (similar to PEM) that conducts hydroxide ions (similar to AWE) when fully hydrated and hence can operate at a differential pressure of 20–30 barg [4,42]. AEMWE has dynamics faster than AWE but slightly slower than PEMWE with a start-up from cold in the range of 5–10 min and ramp-up from 20% to 100% in 2–4 s and a minimum operating load of 5% of maximum capacity. AEMWE can therefore address the challenges of scaling up faced by both PEMWE (IrO$_2$) and alkaline water electrolyzer (AWE) (slow response time and high minimum load). However, AEMWE is not yet a mature technology with a lifetime of stack of about 5000–1000 h (system lifetime is much longer but will require stack replacement). Other challenges include higher energy use ca. 59 (54–65) kWh.kg$_{H2}^{-1}$. This is in part due to higher membrane resistance (mobility of hydrated hydroxide ion is 0.57 of that of the hydrated proton) and lower activity of the non-precious metal catalyst in less concentrated alkaline solutions. The other cause of higher energy consumption in comparison to PEMWE/AWE is the current small size of available commercial systems (2.5 kW/0.3 m^2 electrode area) increasing the contribution of the balance of plant energy consumption to the overall energy consumption. AEMWE operates at a higher current density than AWE (range of 0.1–1 A cm^{-2}) but lower than PEMWE because their area-specific resistance (ASR) is between the two as will be discussed below and in more detail in section 3.5.3. The currently higher alkaline concentrations limit the lifetime of the current commercial AEM membrane due to the chemical instability of the cationic head group (quaternary ammonium-based) in high pH at elevated temperatures (>50 °C). Other commercial AEMs with improved alkaline stability struggle to meet the conductivity or ASR (<0.08 Ω cm^{-2}) required to achieve good efficiency.

Operating AEM in seawater or NaCl environment will mean that AEM will conduct Cl$^-$ ions instead of OH$^-$ ions due to the significantly higher concentration of the former over the latter. This will address issues with the chemical stability of the headgroup mitigating one of the main challenges around the long-life use of AEM in electrolyzers. However, this comes with an increase of ASR by a factor of ca. 2.6 due to the slower mobility of Cl$^-$ in comparison to OH$^-$ (see section 3.5.3), as well as introducing challenges for electrocatalysis and stability discussed further in sections 3.5.1 and 3.5.3. This means that direct seawater electrolysis using AEM (Cl$^-$ conduction) will need to operate in a current range similar to that of AWE (0.1–0.5 A cm^{-2}) instead of that of OH$^-$ conducting AEM due to an increase of ASR when operating in NaCl environment. Other electrolyzers based on membrane-less/undivided cells are still under R&D and are discussed in a study by Niblett et al. [43].

3.3. Electrolyzer integration with offshore wind

There are three main electrolyzer configurations to couple the electrolyzers with wind power depicted in Fig. 3:

- **Onshore**: The electricity generated by the wind power plant is collected and transmitted to shore, where an electrolyzer produces H$_2$ (Fig. 3a).
- **Offshore**: The electricity generated by all wind power plants is transmitted to offshore substations in centralized and decentralized configurations. H$_2$ is produced by the electrolyzer using desalinated seawater, compressed, and transported to shore via pipeline (Fig. 3b).
- **In-turbine**: The electrolyzer, integrated with desalination units, is placed inside or adjacent to the wind power plant. The H$_2$ produced is compressed and transported through pipelines (Fig. 3c).

The merits and limitations of each configuration, best practices of installation of windmills, challenges, ongoing installations, recent updates, material development failure conditions, as well as global locations with wind speed dynamics, water depth, and seabed conditions, are discussed in another dedicated review by Claudio et al. [44].

Electrolysis-based H$_2$ production has a unique potential to provide seasonal flexibility to the power system, which cannot be effectively offered by any other resource [45]. This can play a significant role in balancing power systems with high shares of solar and wind, not only instantaneously and intra-day, but also across seasons. To achieve such benefits, electrolyzers must be designed not to operate at full capacity throughout the year, but rather use electricity when green and affordable. This requires the electrolyzers to be sufficiently oversized to avoid utilizing non-renewable or prohibitively expensive electricity to meet H$_2$ demand. Alkaline electrolyzers have demonstrated successful testing for primary control reserves in Germany, showing practical comparability to PEM electrolyzers in terms of speed. Manufacturers such as ITM Power and Siemens typically guarantee electricity consumption to ramp up and down in a few seconds, which primarily depends on the rectification system [45]. As mentioned earlier, electrolyzers can operate at partial loads as low as 5%, which can be sustained for long periods. However, operating at such low loads may result in significant efficiency losses due to the rectifier's characteristics. Additionally, PEM electrolyzers have the advantage of a cold startup in less than 5 min and can be shut down within seconds. Large-scale electrolyzers can help reduce critical peak loads by decreasing their electricity demand or interrupting their operation altogether. Nevertheless, there is an economic incentive to operate the electrolyzer for as many hours as possible to minimize the contribution of the investment cost to the total cost.

However, if we are considering the case where H$_2$ production is in deep or far offshore locations where connections to the electricity grid are not viable, then new optimizations are required to maximize the use of electricity while maintaining the lowest cost of H$_2$ production. For instance, studies have demonstrated that a Solar Farm in California achieves an optimal ratio of electrolyzer to solar power of 60% in cases where it operates independently from the electricity grid (such as in offshore, off-grid, or isolated situations). This setup enables the production of hydrogen at a cost that is $2 per kilogram lower compared to scenarios where hydrogen production is separated both temporally and geographically from photovoltaic (PV) power generation (e.g., onshore hydrogen production connected to the electricity grid and PV systems that are grid-connected). While increasing the electrolyzer size increases H$_2$ production and thereby reduces the PV capital cost components, the electrolyzer cost increases and reduced utilization of the electrolyzer far outweighs the other changes when its capacity increases from 60% to 100% of solar farm-rated power. In other words, because the capacity factor of solar in that case study was 24.3%, the capacity factor for an electrolyzer at the same rated power of PV (100%) would be also 24.3%, while the capacity factor for an electrolyzer at 60% PV-rated power
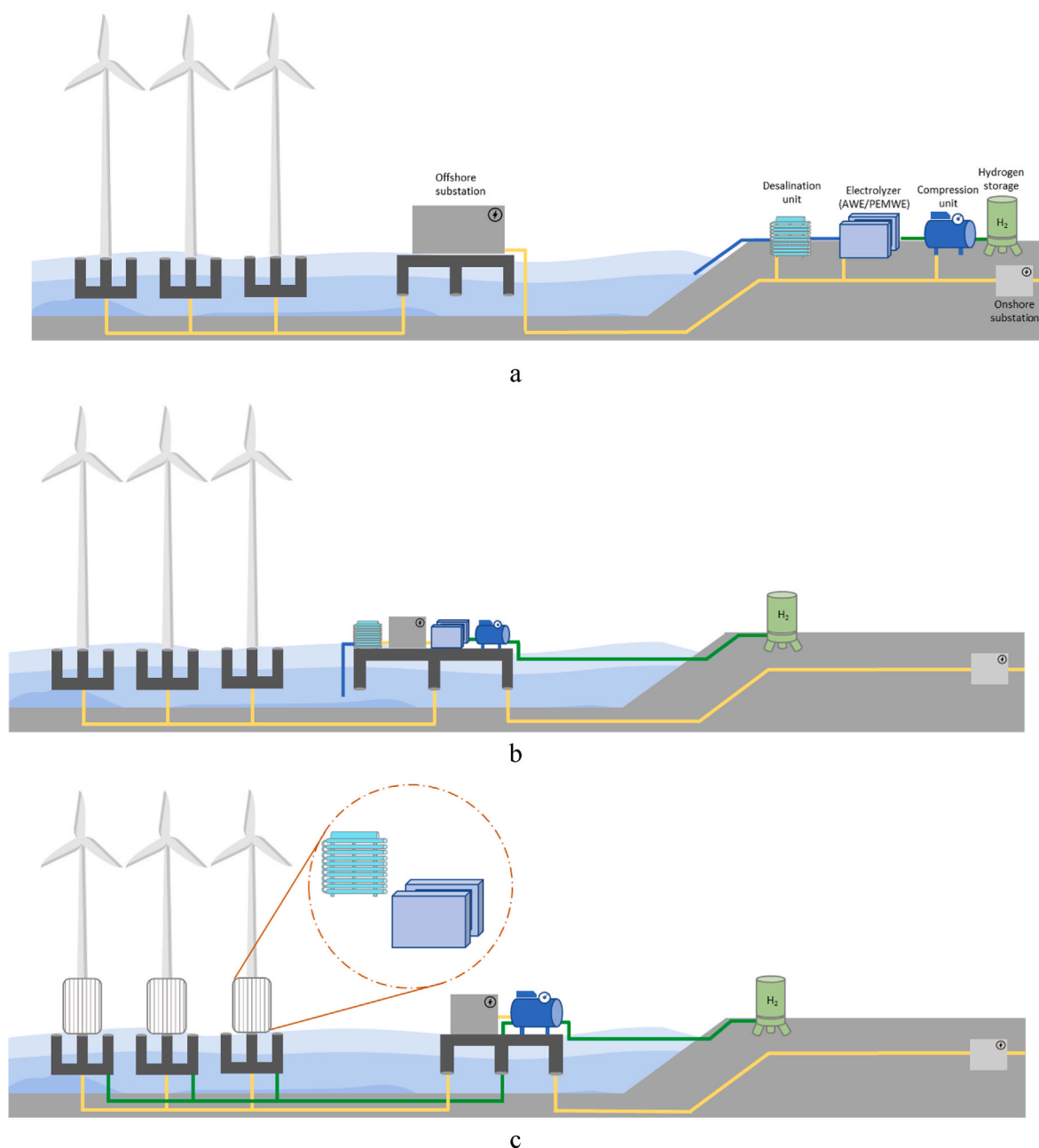
Fig. 3. Three different electrolyzer placements (yellow: electrical power lines; green: H$_2$; blue: seawater).

would be 31.6%. With the increase in capacity factor in deep offshore locations (e.g., from wind), the optimum electrolyzer size will also increase by >60% of rated renewable power. A study conducted very recently examined the optimization of coupling far offshore wind with an electrolyzer, taking into account system dynamics. A case study was conducted at a 200 km distance with 64 wind turbines, a single unit capacity of 6.33 MW, and a total installed capacity of 405.12 MW [46]. The optimal time-power-efficiency electrolyzer capacity was 336.1 MW or 83% of installed capacity for an average wind resource of 11 m s^{-1} and Weibull distribution parameters with a shape parameter of 2. The dynamics of the electrolyzer, minimal load, and size of the electrolyzer stack as well as the connections and control of the system will play a key role in overall integration performance. Some solutions are emerging based on hybrid systems (e.g., coupling alkaline and PEM electrolyzers) to balance costs and response time, coupling energy storage (batteries or supercapacitors) with alkaline electrolyzers to improve response time, or combining energy storage and electrolyzer in the same unit (e.g.,

alkaline water electrolyzers). There is a need for more research on the integration options and control to understand the impact of these solutions and their resulting dynamics on system costs, efficiency, and lifetime and consequently the cost of the produced H$_2$.

Offshore wind has the potential to both support resilient decarbonization and function as a renewable energy source for green hydrogen production. There is a need to use hydrogen directly to decarbonize heating, and transport, and hard-to-electrify industries. Over 70% of the cost of electrolytic hydrogen is electricity cost. The key is to capitalize on higher capacity factor from deep offshore locations to produce cheaper wind energy which can consequently be used to produce cheaper hydrogen. The conversion to hydrogen will allow long-term storage of energy as well as allow the utilization of increased capacity factor of generated wind power in deep offshore locations to 60–70%, 4–5 times that of onshore locations.

With increased distance from shore, the economic viability of electrical cables becomes narrow, making it uneconomical to transfer the

electricity from offshore wind farms to the shore. Therefore, other means of energy vectors shall be addressed to transfer this electrical energy. One means is converting this electrical energy to hydrogen and transferring it to the shore via either pipelines (which are much cheaper than electrical cables) or storage tanks (such as compressed hydrogen, liquefied hydrogen, LCOH, metal hydrides, etc.). A techno-economic evaluation of offshore wind-to-hydrogen scenarios conducted in the UK by Giampieri et al. [47] showed that compressed hydrogen produced offshore is the most cost-effective scenario and stated that the economic feasibility is greatly affected by the storage period and the offshore wind farm distance to the shore. Also, the high annual capacity factor of offshore wind farms makes the use of offshore wind for hydrogen production advantageous as well and can help with affordable hydrogen production [48]. Additionally, through modeling appeared to lower the cost of producing hydrogen, techno-economic cost model analysis, showed that with the scaling of offshore wind farms, the long-term outlook for the LCoH declined towards £2/kg of hydrogen for fixed bottom offshore wind turbines [49]. On this thread, Table 1 represents global efforts and projects on offshore wind to green hydrogen production.

Table 1
Global efforts on offshore wind to green hydrogen production.

Company/project	Year deployed (or estimated)	Country	Details/capacity	Ref.
European Clean Hydrogen Partnership program - The Hydrogen Offshore Production for Europe (HOPE)	2026	Belgium	10 MW 4 tons/day of green hydrogen	[50]
Lhyfe/Sealhyfe	2022	France	1MW-0.5 ton/day Connected to SEM-REV powerhub — the first European floating wind farm	[51]
OceanREFuel Project	2021	UK	Funded by the Engineering and Physical Sciences Research Council (EPSRC), Ocean REFuel is a five-year research program aimed at converting Ocean Renewable Energy to liquid and gaseous fuels.	[52]
Siemens Energy and Siemens Gamesa - H2Mare	2021	Germany	3*5 MW electrolyzers - Also considering converting hydrogen to methane, methanol, liquid hydrocarbons and ammonia	[53]
AquaVentus (SUB-PROJECTS: AquaPrimus, AquaDuctus, AND AquaSector)	2020	Germany	10 GW by 2035	[54]
NortH2 - a consortium consisting of RWE, Equinor, Eneco, and Shell	2020	Netherlands	Planning to for 4 GW of green hydrogen offshore by 2030 and 10 GW + by 2040	[55]

3.4. Other challenges

The process of producing green hydrogen from offshore wind turbines has similar challenges to other chemical processes in the offshore environment. Floating production storage and offloading (FPSO) units are deployed for offshore oil production, whereby crude oil is produced, stored, and offloaded to tankers for transportation to refineries. Floating liquefied natural gas (FLNG) unit is a technology that enables the extraction, liquefaction, and storage of natural gas on offshore floating facilities. These units are remarkably useful for unlocking gas resources in subsea gas fields that may be economically or environmentally challenging to develop using traditional onshore facilities [9]. The development and implementation of FPSOs and FLNG entail considerable upfront capital costs. Similarly, manufacturing capacity and capital might limit the rapid scale-up and installation of integrated offshore wind-driven hydrogen production farms.

The engineering, design, construction, and installation of mooring systems and processing facilities can be challenging in harsh weather conditions, such as storms, high waves, and strong currents. The limitation on space for FLNG is a challenge since the amount of feed gas that can be reserved for floating liquefaction is limited [56]. However, this is not an issue for offshore hydrogen systems, given the high power density and relatively small footprint of electrolyzer systems in the range of 70–150 m2 MW^{-1} and 35–50 m^2 MW^{-1} for 20 MW alkaline and PEM electrolysis systems, respectively.

High priority is given to protecting the environment and the safety of personnel. Emergency response plans and strong safety precautions are necessary due to the possibility of fires, leaks, and other mishaps. FLNG plants are exposed to safety concerns due to harsh environmental conditions, and they can be more expensive than onshore facilities due to the need for specially designed equipment and processes.

The corrosive marine environment poses a substantial threat to the integrity of FPSO structures. Similarly, all components in an FLNG facility need to be rated for marine service, which adds to the costs. Effective corrosion protection measures, such as coatings and cathodic protection systems, are essential to ensure the long-term reliability of the structure. Similar measures are needed to protect the water treatment and electrolyzer system, some of these should be enclosed and protected from the harsh offshore environment. Additional measures are also needed for the safe disposal of concentrated brine and other waste from the system.

Recent research has looked at new ways to deal with the high salt levels in brine waste resulting from seawater electrolysis either from direct electrolysis of seawater or from upstream purification steps (e.g., reverse osmosis). Various solutions are emerging form simple dilution of concentrated brine with seawater prior to discharge, to couple with other chemicals production such as chlorine, sodium hydroxide, soda ash and sodium bicarbonate that is carried out in traditional chlor-alkali process or brine treatment plant using waste alkali for CO_2 capture process [57]. This process not only purifies the brine but also recovers valuable materials such as magnesium hydroxide, calcium carbonate, chlorine, bromine, and hydrogen gas. Further technologies for brine management such as pressure retarded osmosis, membrane-based technologies, thermal-based technologies, and microbial desalination cell technology, are discussed also [58]. Energy management strategy (EMS) model featuring a 15 MW wind turbine integrated with hydrogen production and storage facilities and direct air capture units [59]. The designed system can capture a significant amount of CO_2if prioritized with a capture rate of 38.7–69.1 t-CO_2/day or track the external hydrogen demand that ranges from 1995 to 3565 kg/day if prioritized. Additional research is needed to account for full system OPEX and CAPEX costs to assess the viability of the various proposed solutions in terms of overall process efficiency and produced hydrogen costs trade-offs with additional revenues from other process products sales. The addition of other processes to the electrolysis process will require additional capital costs of equipment and the need for transport

infrastructure to bring produced chemicals to shore (e.g., Cl_2) or facilities to store the captured CO_2 (e.g., as sodium carbonates). Considerations should also be given to the global demand for these products and the required volumes in relation to the demand for green hydrogen.

Floating storage and regasification (FSRU) are designed for the storage and regasification of LNG. They can be used to supply LNG to areas with a demand for natural gas needless for a traditional onshore LNG terminal [60]. Similarly, ship movements can have an impact on the LNG process, which lowers the cryogenic process's performance [61]. When mounting the electrolysis system on a floating platform, considerations should be made to the impact of the platform on various equipment performance, lifetime, and maintenance schedules. This area is currently not well researched and future directions should study it in detail.

In subsea processing (SSP) produced fluids are handled and treated to mitigate flow assurance issues before reaching the platform or onshore [62]. Accessing and maintaining subsea and far offshore equipment is very challenging owing to the depth and distance from the shore of the installations and the high cost of sending specialized teams to carry out the repairs. Ensuring the reliability of the processing systems and developing effective maintenance strategies are critical for minimizing downtime, especially where access to offshore systems can be hindered by harsh weather. Implementing reliable control systems for operations is complex, involving managing robust communication, power supply, and control functions in the harsh environment [63]. These challenges are also applicable to offshore hydrogen production plants including water treatment (filtration desalination deionization) and electrolysis systems (electrolyzer, heat management, power conversion, gas purification, and compression).

3.5. Challenges presented with direct electrolysis of seawater

The composition of seawater versus freshwater offers challenges that need to be overcome to achieve efficient SWE. Seawater contains species such as microorganisms, sediment as well as various complex ions which result in various challenges when considering using seawater for direct electrolysis. Filtration is required to remove microorganisms and sediment as these would both cause complications in electrolyzer systems such as blockages and fouling of equipment. However, simple filtration does not remove the ions that are dissolved into the seawater and therefore, these ions should be considered when discussing direct seawater electrolysis [39], while these compositions vary geographically the species with the highest weight % are consistent, these various species are highlighted in Table 2.

Of the species described above, all <1 wt% are considered to be not present enough in such an amount as to be considered problematic when discussing seawater electrolysis. The metal cations present (K^+, Mg^{2+}, and Ca^{2+}) can be deposited onto the cathode surface when reduction potentials are applied, this can lead to the deactivation of this electrode and thus lower the efficiency of the system [65]. Whilst sodium is the cation present in the greatest wt. %, the reduction potential of this metal is very low (-2.7 V) so therefore, is not a concern for cathodic

Table 2
Concentration and salt mass percentage of various salt species that are found universally in seawater [64].

Species	Concentration (mg.l^{-1})	Salt weight percentage (wt.%)
Chlorine	18,980	55.0
Sodium	10,556	30.6
Sulfate	2649	7.7
Magnesium	1272	3.7
Calcium	400	1.2
Potassium	280	1.1
Bicarbonate	140	0.4
Bromide	65	0.2
Strontium	13	0.1

deposition.

The anodic challenges faced when trying to carry out OER are due to the presence of the various anions within seawater namely the chloride anion (~3.5 wt% of seawater [66]). The oxidation of this anion to form chlorine gas, the chlorine evolution reaction (ClER) or pH-dependent soluble species (e.g., hypochlorite) shown in Eq. (2), CIER is in direct competition with the OER at the anode [65]:

$$Cl^-(aq) + 2OH^-(aq) \rightarrow ClO^-(aq) + H_2O(1) + 2e^- : 0.89\ V_{SHE} \quad (2)$$
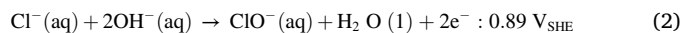
The OER requires a minimum electrical potential of 1.23 V vs SHE whereas the ClER requires a minimum of 1.36 V vs SHE [65]. This suggests that, thermodynamically, the OER should be the preferred reaction. However due to OER being a four-electron process, whereas ClER is a two-electron process, the OER is kinetically challenging when compared to kinetically faster ClER. The complex intermediates involved in the OER can also be attributed to the slow kinetics of the reaction [67]. Whilst there are other anions present in seawater, the bicarbonate and bromide anions are present in such a small amount, that they are usually deemed insignificant. The sulfate anion, however, is present in an amount that cannot be disregarded. Its oxidation potential, however, is high (>2 V) and therefore, is not a competitive reaction with OER. Various anion adsorption including sulfates can adsorb on the electrocatalyst surface affecting its activity. This however is very dependent on concentration, temperature and type and structure of electrocatalyst and will need further research. The presence of sulfate anions however helps to improve the conductivity of the solution and thus can help improve the performance of the electrolyzer overall.

Dissolved oxygen in seawater is at a similar level to that in fresh water. While the limited impact is expected at the cathode under operation from the hydrogen-oxygen combination reaction, under off cycles the oxygen will increase the electrolyzer cathode potential, particularly, if the cathode catalyst is active for the OER. The increase of cathode potential to oxidative potentials on off cycles and subsequent decrease to reducing potentials under HER might affect the lifetime of the catalyst if happens frequently. This issue is similar to the effect of hydrogen cross over to the anode electrode on the anode catalyst during the off period bringing the potential of metal oxide at the anode down to reducing potentials.

While the electrolyzer can operate for a short period at high cell voltage to produce oxychloride species to aid with the oxidation of organic matter and disinfection, these species might have detrimental effects on the membrane and electrocatalyst if not selected appropriately.

Due to these issues, methods by which it is possible to be selective toward the OER have been investigated [68]. Increasing the pH above 7 enables the difference between the thermodynamic potentials to be maximized (Fig. 4). Due to this, it could be desirable to operate in mild alkaline conditions. It should be noted that at higher pHs (>7) hypochlorite is evolved in SWE rather than chlorine gas. If the system is operated under alkaline conditions, different OER reactions should be considered as shown in Eq. (3):

$$4OH^- \rightleftharpoons O_2 + 2H_2O + 4e^- \quad (3)$$

However, this requires operation in a mixture of seawater and alkaline or buffer solution which is not practical. Another way to help achieve OER selectivity is to implement Cl^- blocking layers. It has been shown that MnO_2 helps to prevent chloride anions from reaching the electrode surface but still allows hydroxyl ions through [70].

The main method in which to be selective towards OER over ClER is to employ a catalyst that is selective towards this desired reaction. Importantly, these catalysts and their support or substrate they are deposited on should also have long-term stability in the highly corrosive seawater environment. This is particularly challenging in the oxidative environment of the anode where all metals will become oxidized due to the high potential used. While some metals are stable due to protection from the metal oxide passivating layer, the stability of that layer is very
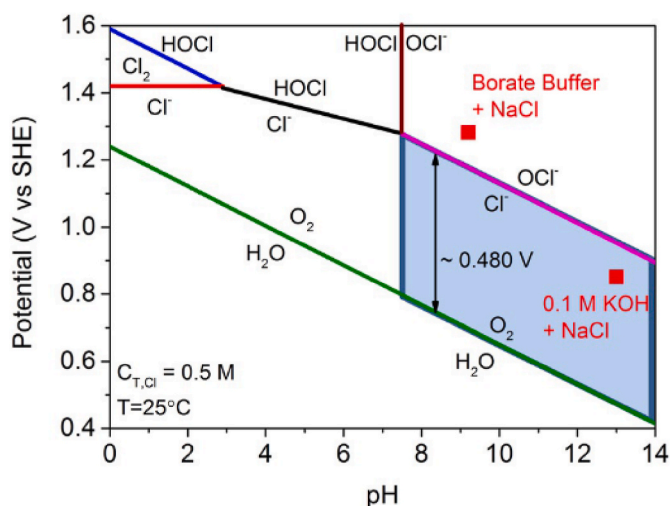
Fig. 4. Pourbaix diagram depicting the change in equilibrium potential as a result of the change in pH of both OER and ClER reactions. Carried out in a 0.5 M NaCl solution with NiFe LDH anodes. Potentials are registered as vs SHE [69], *Reproduced with permission from Chemistry Europe.*

limited in a chloride environment in most metal oxides resulting in the formation of soluble metal chloride salts and ligands. For example, Gold is stable in both acidic and alkaline environments under OER potentials forming a thin layer of gold oxide. However, in brine, gold dissolution is seen under OER due to the formation of gold chloride. Titanium and Tantalum are used as substrates to deposit the RuO_2 electrocatalyst in chlor-alkali electrolyzer anodes. The RuO_2 coating not only catalyzes the ClER but also protects the Titanium from oxidation and dissolution.

3.5.1. Electrocatalysts for oxygen evolution in seawater electrolysis

One of the earliest attempts to selectively produce O_2 was carried out by Bennett in 1980 [71], where a MnO_2 coating was used to achieve an OER selectivity of 99%, however, the catalyst required high over-potentials to be applied (low electrical efficiency of H_2 production) which is energetically unfavorable.

Since then, there have been numerous studies on the development of electrocatalysts for the OER in a NaCl environment. One class of catalysts that have been used is metal oxides like IrO_2 [72] and RuO_2 [73]
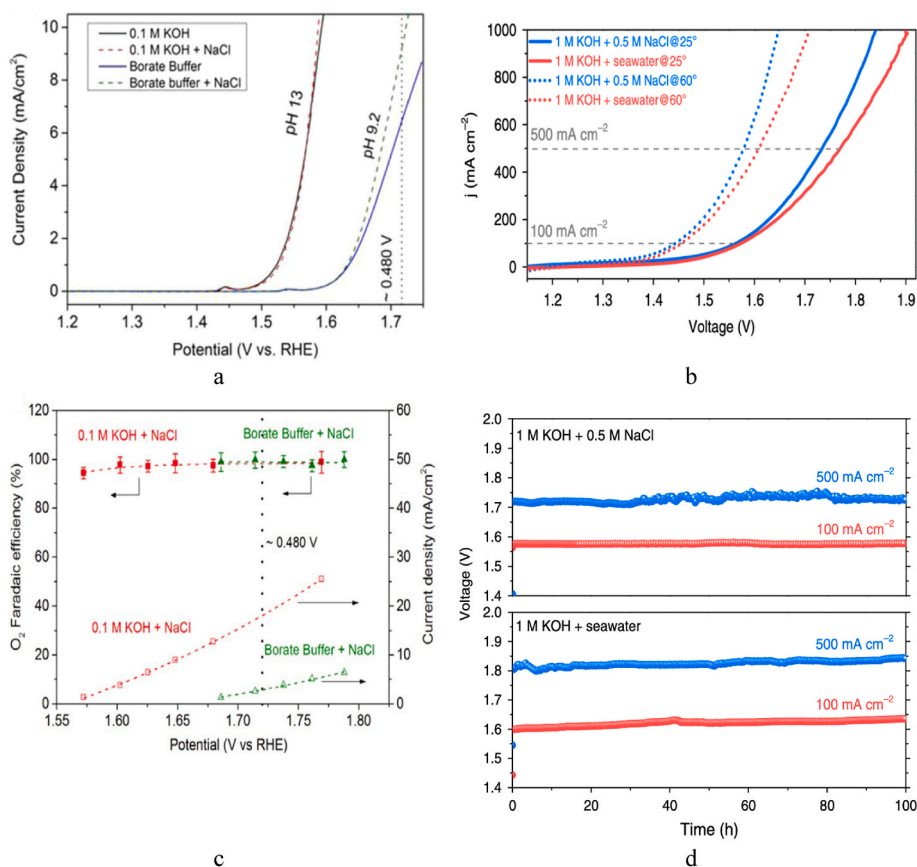
which are considered the most active electrocatalysts for OER [29] but equally active for ClER as they demonstrate little selectivity towards OER. Moreover, these materials are costly, so non-precious metals (first-row transition metals), which are easier to source due to being more abundant (thus making them more sustainable), should be considered as alternatives to make these electrolyzers viable at an industrial scale provided sufficient stability in seawater under OER can be achieved.

A key element that should be considered thoroughly, especially when dealing with direct SWE is the stability and longevity of the electrocatalyst and its support. If the electrocatalysts are not stable over a long period (as given in the catalyst durability in Table 3) they will constantly need replacement and as mentioned earlier in this review, this is undesirable, therefore, all catalysts must show resistance to corrosion by Cl^- under OER and should be able to maintain high current densities for a long period. These catalysts should also be examined for selectivity at pH below 7 where anode pH will decrease upon current flow due to OER which can be very challenging.

Heteroatom-doped metal alloys are reported to produce reasonable overpotentials at high current densities NiMoN@NiFeN (Fig. 5) [29], by achieving an overpotential of 277 mV @ 100 mA cm^{-2} however this was tested in alkaline conditions (1 M KOH) or a mixture of seawater with an alkaline solution. Metal layered-double hydroxides (LDHs), NiFe-LDH grown on nickel foam, were reported to offer low overpotentials when operating at high current densities offering better overpotentials than the doped composite materials (NiMoN@NiFeN). However, its demonstrated selectivity towards OER with an efficiency of 97.8% was reported in an alkaline seawater environment (0.1 M KOH) [69].

As discussed above, the saline water and alkaline solution mixture is unrealistic since:

- It is not possible to operate the electrolysis process continuously as accumulated salts from seawater need removal and hence the continuous source of alkaline needs to be added to the electrolyte mixture if fresh seawater solution is continuously added.
- Increasing OH^- concentration (increasing pH) in seawater/NaOH solutions will favor OER over ClER both kinetically and thermodynamically showing higher selectivity that is not attainable in seawater-alone solutions.
- Material stability is higher in higher pH environments due to the competitive adsorption of Cl^- and OH^- on metal and metal oxide surfaces. Under OER the surface of metal oxides, carbides, sulfides,

Table 3
Various electrocatalysts used in seawater electrocatalysts.

Catalyst	electrolyte	OER (mV)	Tafel slope	Cell voltage (V)	Durability (h)	Ref.
MoN–CO₂N	1 M KOH + Seawater	357 @ 100 mA cm^{-2}		1.70 @ 100 mA cm^{-2}	62	[74]
Mo-CoP$_x$/NF	1 M KOH + Seawater	–	–	1.61 @ 10 mA cm^{-2}	100	[75]
Fe–Ni(OH)₂/Ni₃S₂	1 M KOH + Seawater	269 @ 10 mA cm^{-2}	46 mV dec^{-1}	–	27	[76]
MnO$_x$/IrO$_x$	Acidic saline water	300 @ 5 mA cm^{-2}	43 mV dec^{-1}		–	[77]
Ag/NiFe LDH	1 M KOH + Seawater	217 @10 mA cm^{-2}	–	–	1000	[78]
NiFeOOH(S,Se)	1 M KOH + Seawater	239 @ 100 mA cm^{-2}	–	–	96	[79]
IrO₂@MnO₂/rGO	1 M KOH + Seawater	–	–	1.64 @ 10 mA cm^{-2}	16	[80]
NiMoN@NiFeN	1 M KOH + Seawater	307 @ 100 mA cm^{-2}	-	1.774 @ 100 mA cm^{-2}	100	[29]
3D bifunctional CoSe(Co₉Se₈)	Buffer solution + Seawater	-	–	1.8 @ 10 mA cm^{-2}	–	[81]
NiIr-LDH	1 M KOH + Seawater	361 @ 500 mA cm^{-2}	78.8 mV dec-1		650	[82]
Ru MOF CoFe nanoarrays@CC	1 M KOH + Seawater	–	–	1.54 @ 10 mA cm^{-2}	50	[83]
MnOx/NiFe-LDH/NF	1 M KOH + Seawater	276 @ 100 mA cm^{-2}	77.0 mV dece-1	–	50	[84]
NCFPO/C NPs	0.1 M KOH + Seawater	285 @ 10 mA cm^{-2}	–	–	100	[85]
Co–Fe LDH	Stimulated Seawater	530 @ 10 mA cm^{-2}	–	–	–	[86]
Se_NiFe–LDH	1 M KOH + 1 M NaCl	320 @ 20 mA cm^{-2}	–	1.58 @ 10 mA cm^{-2}	180	[87]
NiFe/NiS$_x$–Ni	1 M KOH + Seawater	890 @ 400 mA cm^{-2}	–	–	1000	[88]
GO@Fe@Ni–Co@NF	1 M KOH + 0.5 M NaCl and seawater	246 @ 50 mA cm^{-2}	–	1.94 @ 500 mA cm^{-2}	378	[89]
NiO$_x$–FeO$_x$@g–C₃N₄	1 M KOH + 0.5 M NaCl (Mimic Seawater)	192 @10 mA cm^{-2}	53 mV dece^{-1}	–	100	[90]
1D-Cu@Co-CoO/Rh	1 M KOH + 0.5 M NaCl (Mimic Seawater)	260 @10 mA cm^{-2}	–	1.60 @ 10 mA cm^{-2}		[91]
FTO/NiO	0.5 M NaCl +1.0 M KOH.	340 @ 10 mA cm^{-2}	–	–	8	[92]

Fig. 5. (a) Linear sweep voltammetry of NiFe-LDH in various electrolytes depicting the effect of the addition of Cl⁻ anions to the system [69], *reproduced with permission from Chemistry Europe,* **(b)** linear sweep voltammetry of NiMoN@NiFeN showing the various current densities and the effect of using real seawater vs artificial (0.5 M NaCl) seawater conditions [29], *reproduced with permission from Nature* **(c)** Comparison of faradaic efficiency and current density of NiFe-LDH in alkaline saline conditions and saline conditions with buffer present [69], *reproduced with permission from Chemistry Europe* **(d)** Stability analysis of NiMoN@NiFeN in both artificial and real seawater recorded at both 500 and 100 mA cm⁻² [29], *reproduced with permission from Nature.*

and phosphides are known to restructure in alkaline pH to form a more active layer of metal oxyhydroxides [93]. This will lead to higher activity and stability in an alkaline/NaCl mixture in comparison to NaCl alone where soluble metal chloride and Cl⁻ based complexes are formed. Similarly, in acidic media, IrO_2 is known to reconstruct to form more active IrO_xH_y.

Selectivity towards OER over ClER can be achieved by limiting the anode overpotential below 1.7 V vs RHE (Fig. 4) which is the minimum potential required for ClER (under conditions where the pH > 7.5). However, as discussed above this will limit the current density of the electrolyzer to >0.5 A cm⁻² which would result in higher capital costs. Importantly, as mentioned above upon current flow the pH of the anode will decrease rapidly below 7, significantly reducing the available gap of 0.48V between ClER and OER (e.g., to ca. 0.4 V at pH 5).

There is very limited literature reported on the use of organometallic complexes as catalysts for OER in SWE. One reported case, however, involved the use of iridium catalysts with different ligands attached through different headgroups to assess how different heteroatoms could affect the OER activity, selectivity, and stability of the catalyst [94]. Those complexes containing N heteroatoms appeared to exhibit the best performance of the catalysts described with some able to achieve an overpotential of 243 mV and 248 mV at a current density of 10 mA cm⁻². However, very limited stability was tests of up to 2 h shown Whilst only one of the catalysts within that work was tested for selectivity, it showed chlorine evolution still occurred when tested with synthetic seawater.

The majority of reported OER electrocatalysts in the literature that

exhibit promising activity, stability, or selectivity towards OER in seawater were tested in alkalinized seawater (a mixture of seawater and alkaline solution), some of which are shown in Table 3. As discussed above, these tests are not indicative of seawater alone or NaCl performance which will be significantly worse. Other studies have tested in acidified chloride solutions $KHSO_4/KCl$ [77]. To improve the selectivity of IrO_2 towards OER over ClER a blocking layer of additional metal oxide (e.g., MnO_2 based) or polymeric layer (proton or anion exchange electrolyte or hydrophobic layer of PTFE) is added on the IrO_2 surface to reduce adjacent Cl⁻ concentration. This is reported to improve selectivity and in some cases above 99% (potential dependent). However, the blocking layer also limits the current density and requires significant overpotential e.g. cell voltage was 3.2 V higher than that of the alkaline system at 0.1 A cm⁻² [95]. This translates to a cell voltage of ca. 4.8 V or electrical efficiency of ca. 30% based on the H_2 HHV. Very recently there has been some progress on reported activity OER (and HER) in seawater (without supporting alkaline solution). A cell potential of 1.9 V at 50 mA cm⁻² in seawater was reported (OER Potential of ca. 1.6 V RHE at 50 mA cm⁻²) [96] on nitrogen-doped $NiMo_3P$ mixed with carbon black. Current densities of 0.1 and 0.5 A cm⁻² were reported on Ru-CoOₓ at 1.83 and 2.2 V, respectively [97]. Selectivity data was reported at low overpotentials e.g. below the minimum required for ClER and hence were 100% selective towards OER. It would have been useful to report selectivity at practical current densities in the range of >0.1 A cm⁻². The stability of catalysts (and their supports) however, requires significant improvement for practical application of above 50,000 h.

Even in alkalinized seawater, the reported catalyst's maximum durability is only 1000 h (Ag/NiFe LDH and NiFe/NiSₓ–Ni). Not all

selectivity values are available throughout the literature so it is not possible to say if these electrocatalyst materials would meet the requirements of selectivity towards OER over ClER.

Therefore, catalysts with greater stability as well as being able to maintain low overpotentials at a constant current density are still required. This is essential as it minimizes the need for maintenance onboard offshore wind platforms and for a reduction in operating, overhaul, and capital costs. There is now wide consensus on the mechanism of OER in neutral pH, while some consider the more facile alkaline mechanism at pH of 7 and higher similar to that of seawater, the lack of buffer in direct seawater will result in rapid drop/acidification of the anode electrode environment upon current flow. Direct peroxide formation via anodic oxidation can occur at 1.76V (RHE) and OH radicals at 2.73 V (RHE). It was shown that decreasing the pH from 12.5 to 6.7 resulted in an increase of OH radical production by 50 folds during OER at TiO_2 [98]. If a similar scenario occurs in the seawater environment it will have a significant impact on the system lifetime due to rapid degradation caused by OH^- radicals attack.

Therefore, the outlook of the research in this field is firstly, to continue researching non-platinum group materials to help keep the capital and maintenance cost of any electrolyzers down to assist in the economic feasibility of offshore electrolysis. Also, the research should continue to analyze selective, stable, and active catalysts for OER in seawater electrolysis.

Literature results for seawater electrolysis (usually mimicking seawater by using 0.5 M NaCl solution) are reported with KOH added into the electrolyte as well, the presence of this base aids in the stability and selectivity of these catalysts as the excess OH^- ions lead to a driving force in the equilibrium for electrochemically producing O_2 from water and can help protect the catalytic surface from corrosive chlorine chemistry. However, this result means that in order to replicate the results on an industrial scale, KOH would need to be added to the electrolytes. This is not feasible on offshore locations as it would involve having to constantly resupply the KOH in the solution and it would be consumed in the process of electrolysis.

Therefore, catalysts and systems should be tested utilizing neutral saline water or neutral 0.5 M NaCl solutions so that catalysts can be uncovered which can lead to lower overpotentials at high current densities which also achieve high faradaic efficiencies for OER vs ClER.

3.5.2. Electrocatalysts for hydrogen evolution in seawater electrolysis

The other reaction that occurs within SWE is the H_2 evolution reaction (HER). As discussed above, if no buffer is used the local pH in the cathode electrode will increase with the increase in current density so HER can take place via the alkaline mechanism, the appropriate equation for this is shown as:

$$4H_2O + 4e^- \rightleftharpoons 2H_2 + 4OH^- \quad E^0 = -0.83\ V_{RHE} \quad (4)$$
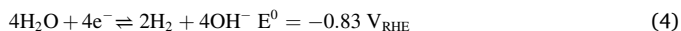
HER in alkaline media is slower than that of acidic media which is reflected by higher Tafel slope and lower exchange current density. Fundamentally this is because the water-splitting reaction takes place at the cathode in alkaline media as opposed to the anode in acidic. The catalysts for HER reaction in SWE are a more mature technology than the OER catalyst as some of these developed for alkaline and acidic HER can be used. This is largely due to the reducing environment allowing a larger choice of materials and the ability to use highly conductive metals or metals supported on carbon rather than oxides [99]. The prevalent issue with the cathodic reaction is the possible deposition of metal oxides/hydroxide/carbonates present in seawater on the cathode from the pH increase (as discussed earlier) causing failures in the efficiency of the electrode.

The promising catalysts in this area are those based on noble metals such as those based on Pt, Ru, and Ir. Pt/C and a ruthenium/cobalt catalyst (Ru-Cox) are reported to have an overpotential of −250 and −150 mV, respectively when operating at 100 mA cm^{-2} [97].

However, catalysts that are stable and do not contain precious metals are desirable for offshore settings as stability reduces the need for maintenance and the lack of noble metals increases the economic viability of the systems and reduces the cost of replacing the catalyst. Earth, abundant and non-noble metals have been investigated for their catalytic HER ability. For example, one such class of these catalysts is transition metal phosphides which have shown a good ability for HER. Xu et al. showed that a C–Co_2P catalyst could achieve overpotentials as low as 30 mV at 10 mA cm^{-2} showing the promise of non-noble catalysts [100]. N–$NiMo_3P$ and Ni-SN@C are reported for HER with the former [96] achieving −310 mV at 100 mA cm^{-2} in seawater, while the latter achieving a small overpotential of −23 and −180 mV at 10 and 100 mA cm^{-2}, respectively, and a Tafel slope of 41 mV dec^{-1} albeit in alkalinized NaCl solution [101].

However, the long-term stability of this catalyst in seawater is still lacking. Studies under more realistic and aggressive conditions required for integration with wind power conditions are lacking but are particularly important. For example, under open circuit conditions (less reducing) and under O_2-containing solutions (from permeation) as well as intermittent operations.

In summary, HER in seawater will be more energetically demanding than that in acidic media or PEMWE. In alkaline electrolysis this is also the case, this is balanced by faster and the ability to use a nonprecious metal catalyst for OER. However, in direct seawater, both HER is more challenging than PEM and OER is more challenging than alkaline and still requires precious metal catalysts like PEMWE but with the additional challenge of the selectivity requirement of OER over ClER. However, as discussed above to maintain efficiency> 82% of direct seawater systems need to operate below 0.5 A cm^{-2} due to high ASR >0.16 Ω cm^{-2} (see also next section). The limitation of cell voltage below 1.8 V and current density below 0.5 A cm^{-2} will reduce the demand on OER catalyst to be selective for OER as anode potential can be lower than that required for ClER (pH dependent) and reduce the pH gradient in the cell. However, this will increase the capital cost of the system. So the economic viability of direct seawater electrolysis will be dictated by the costs of electrode and electrocatalyst materials that meet the stability and activity targets discussed above.

3.5.3. Membranes for seawater electrolyzer

In general, the performance and durability of membrane-based water electrolyzers are effectively influenced by the ionic conductivity and mechanical stability of membranes. Seawater contains a significant amount of dissolved salts and hence has good ionic 30–60 mS cm^{-1} at ambient conditions. OH^- and H^+ concentrations in seawater (pH 7–8.2) are significantly (>3 orders of magnitude) lower than those of Na^+ and Cl^-. This means that the majority of charge carriers will be Na^+ and Cl^- with a transference number of ca. 0.37 for Na^+ and 0.63 for Cl^- in 0.65 M NaCl. A significant number of studies of seawater electrolysis have been performed in undivided cells (membrane-less). In comparison, alkaline electrolyzers use concentrated 30%wt KOH ca. 7 M with conductivity 0.65 S cm^{-1} at ambient temperature. This is an order of magnitude higher than that of seawater. These conductivities will result in ASR of ca. 3 and 0.3 Ω cm^{-2} for seawater and 30%wt KOH, respectively in an undivided cell with a spacing of 2 mm gap. This equates to voltage loss at 0.5 A cm^{-2} of 1.5 V and 0.15 V, respectively. As discussed above, such huge additional energy loss (voltage of 1.5 V) will make the process very inefficient. One solution to improve this is to allow electrolysis to increase the concentration of NaCl from ca. 0.65 M to a maximum of 6 M (close to the solubility limit at room temperature) by running the electrolyzer at low conversion. In other words, using electrolysis to increase the concentration of seawater inside the electrolyzer and maintaining afterward around that target value. This will result in improved conductivity by a factor of at least 7. However, risks of precipitation of other less soluble salts which can block the electrodes and pumping system should be mitigated.

H^+ and OH^- have diffusion coefficients in water at 20 °C of 7.1 ×

10^{-5} and 4.2×10^{-5} cm^2 s^{-1}, respectively. Considering the same 2 mm separation with a 1 mm distance from the electrode to the flow channel and starting seawater with pH 7, running a current density of 0.5 A cm^{-2} will result in an increase in cathode pH to 12.4 and a decrease of anode potential to 2.1 or pH gradient of 10 requiring additional cell voltage of 0.587 V at room temperature. However, operation on an undivided cell can create issues in terms of mixing of produced O_2 and H_2 gases which can have safety and purity implications. The use of porous membranes such as Zirfon Pearl (0.5 mm, 50% porosity) can reduce the gas cross-over and mixing. ASR of 0.3 Ω cm^{-2} is reported with 30% KOH at room temperature or conductivity of 0.163 S cm^{-1}. This is a quarter of that of 30%wt KOH solution which considering a porosity of 50% suggests a tortuosity of 2. This means that an ASR of 3 Ω cm^{-2} can be estimated for seawater operating cells with 0.5 mm Zirfon Pearl membrane which is impractical.

Other studies used (i) PEM water electrolyzer or (ii) AEM water electrolyzer as membrane separators with alkalinized seawater, synthetic seawater, or seawater. Smaller studies also looked at using a bipolar membrane (PEM-AEM) to achieve water dissociation into OH$^-$ and H$^+$ however these have limited maximum current density (due to water diffusion/delamination) below 200 mA cm^{-2}. Fully hydrated PEM (e.g., Nafion 0.91 mmol g^{-1}) has conductivity ca. 0.06 S cm^{-1} at room temperature. Similarly, AEM can achieve similar conductivity by using a higher ion exchange capacity (1.8–2.4 mmol g^{-1}).

It should be noted that in seawater PEM will be converted to Na$^+$ form while AEM to Cl$^-$ form due to the high concentration of Na$^+$ and Cl$^-$ in the electrolyte in comparison to H$^+$ and OH$^-$. H$^+$ has ca. 7 times higher relative mobility to Na$^+$ while OH$^-$ has 2.61 times higher relative mobility than Cl$^-$. A significant increase in membrane AEM or PEM resistivity will therefore occur. However, upon an increase in current flow due to the change in local pH adjacent to the anode/cathode, the ionomer/membrane will have a mixed content of Na$^+$/H$^+$ (PEM) and OH$^-$/Cl$^-$ (AEM). This is similar to the regeneration of the AEM membrane from carbonate/bicarbonates upon current flow in an AEM fuel cell or electrolyzer. The difference in the seawater case is that Na$^+$ and Cl$^-$ have a concentration of 0.5–0.7 M while even upon current flow if the cathode pH is increased to 10 and the anode decreased to 3, OH$^-$ and H$^+$ concentration will remain significantly (>2 orders of magnitude) lower than those of Na$^+$ and Cl$^-$. This means that the majority of charge carriers will be Na$^+$ and Cl$^-$. When using PEM >90% (permselectivity) of charge will be carried by Na$^+$ while in AEM by Cl$^-$. So, when using PEM or AEM NaOH will be at the cathode and HCl will accumulate at the cathode. The formed pH gradient will incur additional energy loss of 59 mV/pH at standard conditions as discussed above. Taking into account a current density of at least 0.5 A cm^{-2} and membrane ASR in the range of 80 mΩ cm^{-2} (PEM) –120 mΩ cm^{-2} (AEM), the exchange to Na$^+$ will cause an increase in ASR to 560 mΩ cm^{-2} (PEM) and 313 mΩ cm^{-2} (AEM) resulting in additional energy loss (from higher resistivity) of 240 mV and 96.5 mV, respectively. Other cations (K$^+$, Mg^{2+}, Ca^{2+}) and anions (HCO$_3^-$, CO$_3^{2-}$) will also exchange and have much lower mobility. They can also deposit on membranes causing fouling in addition to fouling from other organic and biological contaminants increasing further the resistivity and reducing lifetime [102–112]. It can be concluded that if a solid or polymer electrolyte membrane needs to be used for direct seawater electrolysis AEM will have an advantage over PEM due to faster mobility of Cl$^-$ over Na$^+$ and improved stability of AEM in Cl$^-$ environment over OH$^-$ ASR of AEM or membrane-less direct seawater electrolysis cell can be lowered by operating system under higher NaCl concentrations than that of pristine seawater, bringing ASR to a range of 0.2–0.3 Ω cm^{-2} in par with that of current AWE membranes. This means direct seawater electrolysis can be viable if the operating current density remains below 0.5 A cm^{-2}.

3.5.4. Energetics and feasibility of direct seawater electrolysis

One of the best-reported electrolyzers' performances under direct seawater electrolysis is 2.2 V at 0.5 A cm^{-2} (with most of the other reported values significantly higher than that as discussed above). This translates to an electrical efficiency of ca. 67% (based on an H_2 HHV of 39.4 kWh kg$_{H2}^{-1}$) or 59.3 kWh kg$_{H2}^{-1}$. PEM and alkaline electrolysis operate in the range of 1.56–1.7 V at 0.5 A cm^{-2} or 95-87% electrical efficiency translating to 41.5–45.3 kWh kg$_{H2}^{-1}$. Additionally, 7–15 kWh kg$_{H2}^{-1}$ is required for the balance of plant, purification, and power conversion bringing the total of the system to 48–60 kWh kg$_{H2}^{-1}$. With the latter accounting for most of the additional energy losses. In summary, direct seawater electrolysis will currently incur additional energy losses of at least 14 kWh kg$_{H2}^{-1}$.

To put this in perspective, desalination of water using Multistage flash evaporators requires ca. 24–240 Wh L^{-1} of produced water (sufficient to meet PEMWE or AWE requirement) or 2.14 kWh kg$_{H2}^{-1}$. Desalination of water using reverse osmosis (RO) requires pressure between 30 and 70 barg depending on water salinity producing water with dissolved solids in the range of 500–100 ppm which will require further treatments to drop to the required 0.5 ppm level. Seawater RO requires energy in the range of 3.5–4.5 kWh m^{-3}. Considering 4.2 Wh L^{-1} of produced water or 0.038 kWh kg$_{H2}^{-1}$. A membrane capacitive deionization and electrodialysis system can also be used to desalinate the water. Additional energy in both cases is needed to bring the water quality to 0.5 ppm from ca. 100 ppm. If water deionizers are used these will require 0.5–1 M acid and base solutions to regenerate the water deionizer mixed ion exchange bed once depleted.

The concentrated acid and base for regeneration can be stored offshore and replenished annually or can be obtained using electrodialysis of concentrated brine solution from the RO waste stream. To produce 0.5–1 M using an electrodialysis system a cell unit of anion/cation/bipolar membranes is required to separate the brine acid and base streams. The energy consumptions are dominated by anion/cation/bipolar membrane transport losses with total resistivity in the order of 40 Ω cm^{-2} and 1 V additional potential across the bipolar membrane with current efficiency in the range of 70–40% depending on the acid, base, and brine solution concentration (losses from counter ion permeation through the membrane) in the current range of 20–50 mA cm^{-2}. This translates to energy consumption to generate acid and base to regenerate ion exchange bed of 0.28 Wh L^{-1} water used (from 100 to 0.5 ppm) or 0.003 kWh kg$_{H2}^{-1}$ (considering the current density of 50 mA cm^{-2}, cell voltage of 3 V, and current efficiency of 50%).

In summary, currently, the argument for direct seawater electrolysis is weak considering the additional 0.5V required or an additional 14 kWh kg$_{H2}^{-1}$. This is one to three orders of magnitude higher than that required to desalinate the water to 0.5 ppm for PEM or alkaline electrolyzers by RO with mixed bed deionization 0.04 kWh kg$_{H2}^{-1}$ or for multistage flash evaporation 2.14 kWh kg$_{H2}^{-1}$. The footprint and weight of the RO system are relatively small. For example, for a 15 MW electrolyzer system, a Lenntech RO system with a capacity of 10 m^3 h^{-1} and energy demand of 11–22 kW (water salinity dependent) is required with a plant footprint of 3.5 m^2. In comparison, to supply the same water using a multi-stage flash evaporator, a Wartsila system will require energy of 1.85 MW with a footprint of 20 m^2 and weight of 32 tons.

In other words, direct seawater electrolysis needs to operate within 2 mV of that of alkaline/PEM electrolyzers at a current density >0.5 A cm^{-2} to have similar energy consumption to that of water purification by RO, the energy requirements as summarized and shown in Fig. 6 and Table 4. This will be very challenging to achieve, particularly considering that a system lifetime of 60,000–90,000 h also should be maintained. Reports in the literature [113] on 116 MW electrolyzer systems showed that an RO system to desalinate seawater would require 0.1% of electrolyzer total power or 0.2% of operating costs in agreement with the three orders of magnitude discussed above. The capital cost of the reserves osmosis system accounted for 3% of total electrolyzer system costs.
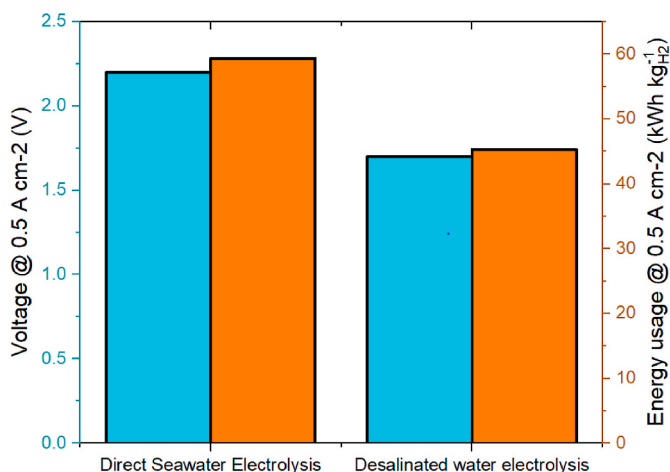
Fig. 6. Energetic comparison of direct seawater electrolysis versus electrolysis of pre-desalinated water, comparing both the voltage required to achieve current densities of 0.5 A cm^{-2} as well as this converted to an energy usage value.

Table 4
Additional energy costs to achieve desalination of seawater for use as an electrolyte in electrolysis.

Method of desalination	Additional energy cost (kWh.kg$_{H2}^{-1}$)
Multistage flash evaporation	2.14
Reverse osmosis	0.038

4. Conclusions and outlook

Production of H$_2$ in far offshore locations can unlock affordable green hydrogen by exploiting economies of scale and higher capacity factors. The design is complex, where factors such as marine challenges, energy and transport costs, harsh operating conditions, and safety, need to be considered.

Developing cutting-edge technologies for electrolysis and maintaining offshore platforms in harsh environments are major challenges. The considerable expense of deploying and running offshore platforms is another significant obstacle. This can be solved by pursuing economies of scale, creating new funding models, and finding ways to cut expenses, including the employment of modular designs and off-the-shelf components. Environmental challenges can be addressed by applying impact assessments and mitigation measures to reduce the impact of offshore platforms. Relevant national and international regulations can be addressed by communicating with regulatory agencies to ensure compliance with all relevant laws and regulations and staying informed about any changes to the regulatory environment.

In terms of the currently available commercial technologies for large-scale electrolysis >2 MW systems both PEMWE and AWE electrolyzers can be operated in offshore locations as their size and weight can easily be incorporated in floating wind turbine platforms or on separate dedicated platforms. There are concerns around the availability and cost of IrO$_2$ required for PEMWE as global efforts seek to install rapid electrochemical H$_2$ production of 100s of GW globally. AWE, on the other hand, will require improved control and other integration solutions (e. g., hybridization and storage) to allow for improved coupling of faster wind power generation dynamics with slower AWE response time, particularly around starting the AWE system from the cold. AEMWE has the potential to overcome the limitations faced by both AWE and PEMWE, however, there is still a need for significant R&D to achieve the required lifetime, scalability, and efficiency target.

There is still also a need for significant research to allow the optimization of the integration of electrolyzers in far/deep offshore locations with no or limited connection to the electrical grid. This includes the distribution of electrolyzers in the offshore location, their size, and power control as well as the development of hybrid systems to improve response time and the trade-off between overall energy efficiency and investment costs.

In the short to mid term, H$_2$ production using offshore locations needs to be done via the desalination of seawater to a purity level of 0.5 ppm of total dissolved solids. This can be done using RO and ion exchange or multistage flash evaporation, with the former having a much lower energy requirement in the order of 0.1% of total electrolysis system energy requirements as well as lower plant weight and footprint suitable for offshore platforms. The argument for direct seawater electrolysis, therefore, is currently weak. This is due to challenges with impurities that can foul electrodes and membranes as well as strong corrosivity of seawater due to high Cl$^-$ concentration both of which can limit system lifetime. Direct seawater electrolysis will also incur significant additional energy (>10% of total electrolysis system energy requirement) loss due to lower electrolyte conductivity, and pH gradient between anode and cathode upon current flow due to low OH$^-$ and H$^+$ concentrations in seawater. The low OH$^-$ and H$^+$ concentrations in seawater result in more sluggish OER in comparison to AWE and HER in comparison to PEMWE which requires yet additional energy losses (overpotential) to reach the same current densities. Finally, the very high selectivity of anode electrocatalyst towards OER over chlorine evolution needs to be met while simultaneously maintaining high activity towards OER and a long lifetime. There are currently no known materials to satisfy all these requirements. Some performance improvement has been reported by the development of new materials or the use of blocking layers as well as improvement in the fundamental understanding of OER. However, a significant amount of research is still needed to elucidate the complex processes and mechanisms taking place during OER in seawater.

In the long term, there is a potential to operate seawater electrolysis to allow for increased seawater concentration inside the electrolyzer allowing for improved conductivity. This can be achieved using undivided cells with laminar flow to divert the H$_2$ and O$_2$ gases to stop them from mixing or with the AEM membrane. The limitation of cell voltage below 1.8V and current density below 0.5 A cm^{-2} will reduce the pH gradient in the cell and the demand on OER catalyst to be selective towards OER only as ClER will be limited or not thermodynamically possible at such low OER overpotentials (<0.3 V). However, this will increase the capital cost of the system. So, the economic viability of direct seawater electrolysis will be dictated by the costs of electrode and electrocatalyst materials that meet the stability >50,000h and activity of 0.5 A cm^{-2} below 0.3 V of overpotential.

For direct seawater electrolysis, future research should focus on (a) electrocatalyst design and development of corrosion-resistant anode electrode materials and efficient electrocatalysts that can withstand the harsh seawater environment, while promoting the OER and HER and minimizing CIER, (b) improving electrode and cell design to reduce developed pH gradient between anode and cathode at high current densities and associated additional energy loss.

On a system level, there is a need to study different integration options in terms of health and safety, system cost and performance, and ease of access for maintenance. There is also a need for studies to understand the influence of floating platform movement dynamics on the various equipment in the water treatment and electrolysis system in terms of performance, lifetime, and maintenance schedules.

While electrolysis in seawater electrolysis alkaline mixture can improve stability, selectivity, and activity of OER electrocatalyst, separation and engineering solutions are needed to separate the accumulated salts and impurities from seawater from fouling the electrode and flow system. Some ions might still need to be removed to stop reacting with OH$^-$ forming precipitate and reduction in electrolyte alkalinity. Research in semi-permeable membranes can allow for more efficient and durable water purification such as in reverse osmosis, or in new systems including forward osmosis where the osmotic pressure between the

concentrated alkaline electrolytes in electrolyzer (acting as draw solute) and seawater can be exploited to drive the process.

In summary, desalination coupled with electrolysis technology presents a more viable and immediately implementable solution for hydrogen production from seawater. This approach, particularly the integration of seawater reverse osmosis (SWRO) with water electrolyzers, holds greater promise and practicality compared to direct seawater electrolysis.

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.

Data availability

No data was used for the research described in the article.

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