

Perspective



Direct Seawater Electrolysis for Decentralised Hydrogen Production: Opportunities for the Blue Economy

Vasundhara Nettem and Nasir Mahmood *

School of Science, RMIT University, Melbourne, VIC 3001, Australia

* Correspondence: nasir.mahmood@rmit.edu.au

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Abstract: The blue economy is one of the most carbon-intensive sectors globally, with shipping alone emitting over 1000 Mt CO₂ annually. Decarbonising it needs a clean, energy-dense fuel, and green hydrogen has emerged as a leading option. However, existing electrolysis systems remain centralised, relying on freshwater and poorly suited to offshore conditions. Direct seawater electrolysis (DSE) resolves this by coupling offshore renewables with seawater to produce hydrogen directly at the point of demand. This eliminates the need for dedicated desalination, potentially reducing hydrogen production costs by up to 30%. Yet deployment is constrained by competing chlorine evolution, anodic corrosion, and cathodic hydroxide precipitation. In addition, scalable seawater electrolyser architectures remain underdeveloped. Advancing DSE requires integrating catalyst innovation with durable, environmentally robust system design. Here, we connect mechanistic strategies for mitigating cathodic precipitation with an ionically bonded heterostructure design principle for anodic OER-CER selectivity, and extend both to the underexplored challenges of intermittency and membrane durability. At scale, DSE could transform energy supply in the blue economy, enabling decentralised hydrogen production directly from seawater.

Keywords: direct seawater electrolysis; green hydrogen; blue economy; cathodic precipitation; ionic heterostructures; interface engineering

1. Introduction

Decarbonising hard-to-electrify sectors is one of the main challenges of the energy transition. Among these sectors, the blue economy, including shipping, offshore energy, and coastal industries, is a major contributor to global emissions. Shipping accounts for about 3% of global CO₂ emissions and could see emissions rise by up to 50% by mid-century without strong intervention. In response, the 2023 IMO greenhouse gas strategy targets net-zero shipping emissions by around 2050, with interim reductions of 20–30% by 2030 [1]. Coastal aquaculture adds a further ~261 Mt CO₂-eq annually, with output projected to grow 32% by 2030 [2]. Together, these pressures demand clean energy solutions that are energy-dense, transportable, and deployable in remote marine environments. Green hydrogen uniquely meets this need, producible from renewable sources, carbon-free in operation, and compatible with existing marine fuel infrastructure.

Conventional electrolysis is optimised for ultrapure freshwater, typically requiring 15–20 L of high-purity water and 50–55 kWh of electricity per kilogram of hydrogen [3]. In offshore settings, this freshwater must be supplied by desalination, adding capital cost, energy use and operational complexity. State-of-the-art reverse osmosis can provide freshwater at about US\$0.50–1.00 m⁻³, but it is an extra system layer that raises costs and pushes hydrogen prices above the ~US\$2 kg⁻¹ target [4,5]. In addition, most hydrogen production is centralised and land-based [6]. Supplying offshore users then requires transporting hydrogen, which adds cost, energy losses and infrastructure demands. Together, desalination dependence and centralised production make conventional



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electrolysis poorly suited to offshore deployment. Direct seawater electrolysis circumvents this bottleneck entirely, treating seawater not as a feedstock requiring pre-treatment, but as a direct input, co-located with the offshore renewables that power production (Figure 1). A 1 GW offshore wind farm co-located with DSE electrolyzers could, in principle, produce approximately 45,000 tonnes of hydrogen per year without consuming a single litre of fresh water [7].

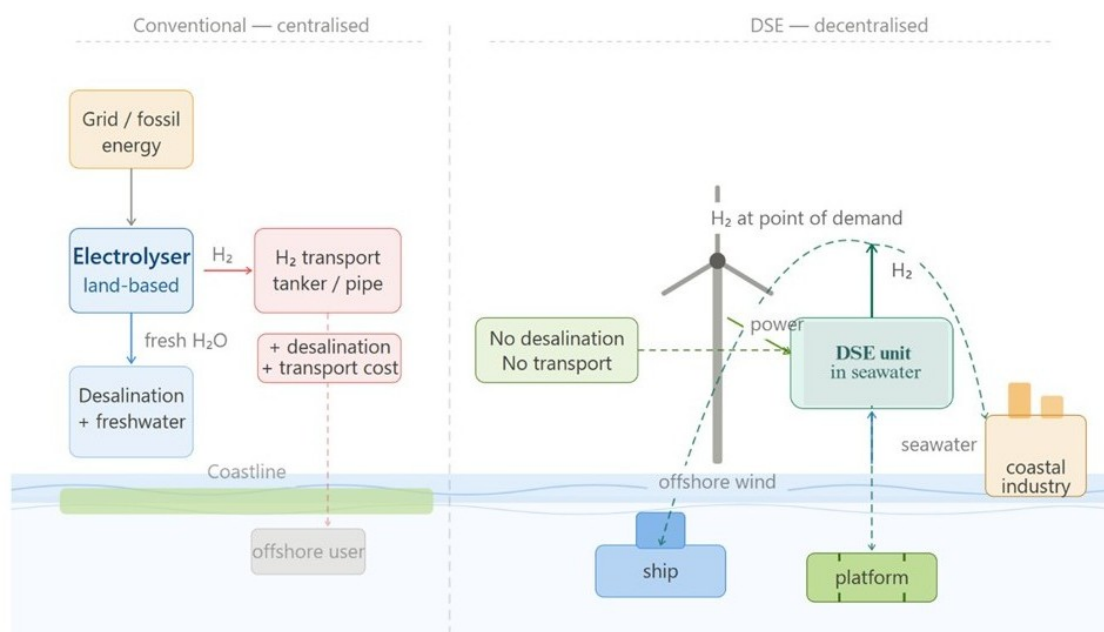


Figure 1. The DSE system concept, showing the centralised vs. decentralised hydrogen production mismatch and how DSE resolves it.

2. Cathodic Precipitation: Mechanisms and Mitigation

The practical DSE deployment exposes electrodes to a hostile, multi-component environment that challenges durability. Chloride ions, divalent cations (Mg^{2+} , Ca^{2+}), dissolved gases, microorganisms, and diurnal temperature fluctuations all conspire against electrode longevity. At the cathode, as water molecules approach and undergo reduction, protons are adsorbed on the electrode surface for HER, while hydroxide ions (OH^-) accumulate in the vicinity. When local pH rises above ~ 9.5 , Mg^{2+} and Ca^{2+} present in seawater at ~ 55 mM and ~ 10 mM, respectively, precipitate as insulating $\text{Mg}(\text{OH})_2$ and CaCO_3 deposits [8]. These insoluble hydroxides block active catalytic sites, increase internal resistance, and cause progressive voltage losses often within hours of operation above 100 mA cm^{-2} . To combat the issue, four mechanistically distinct mitigation strategies have emerged (Figure 2a). First, structural self-cleaning exploits H_2 bubble-driven shear forces to physically dislodge precipitates [9]. Honeycomb-type 3D cathode architectures create a microscopic bubble/precipitate traffic system releasing uniformly distributed small H_2 bubbles across the entire cathode surface to continuously repel $\text{Mg}^{2+}/\text{Ca}^{2+}$ deposits, enabling 1000-h stable operation at 1 A cm^{-2} . Second, interfacial pH management suppresses precipitation by maintaining locally acidic conditions at the cathode surface [8]. Lewis acid overlayers such as Cr_2O_3 on CoO_x capture in-situ generated OH^- , inhibiting both precipitate formation and chloride corrosion, with demonstrated stability exceeding 100 h at 500 mA cm^{-2} . Third, electrostatic repulsion exploits the positive charge of Mg^{2+} and Ca^{2+} , making the cathode surface positively charged to repel incoming divalent cations before they reach the electrode interface [10]. Proton sponge additives introduced at the cathode can alleviate precipitate contamination by modulating the local chemical microenvironment, though their effectiveness diminishes at high current densities. Fourth, surface passivation through polyanion coatings and protective shells physically shields active sites [11]. $\text{Cu}_2\text{S}@ \text{NiS}@ \text{Ni}/\text{NiMo}$ electrodes achieve 250 mV overpotential at 1000 mA cm^{-2} with durability exceeding 2000 h, the NiS layer providing sulphur-rich polyanion coatings that resist both Cl^- corrosion and $\text{Mg}^{2+}/\text{Ca}^{2+}$ precipitation simultaneously [12]. Despite this progress, each strategy involves trade-offs, structural architectures add fabrication complexity, electrostatic approaches lose efficacy at high current densities, and surface coatings risk delamination under prolonged marine operation.

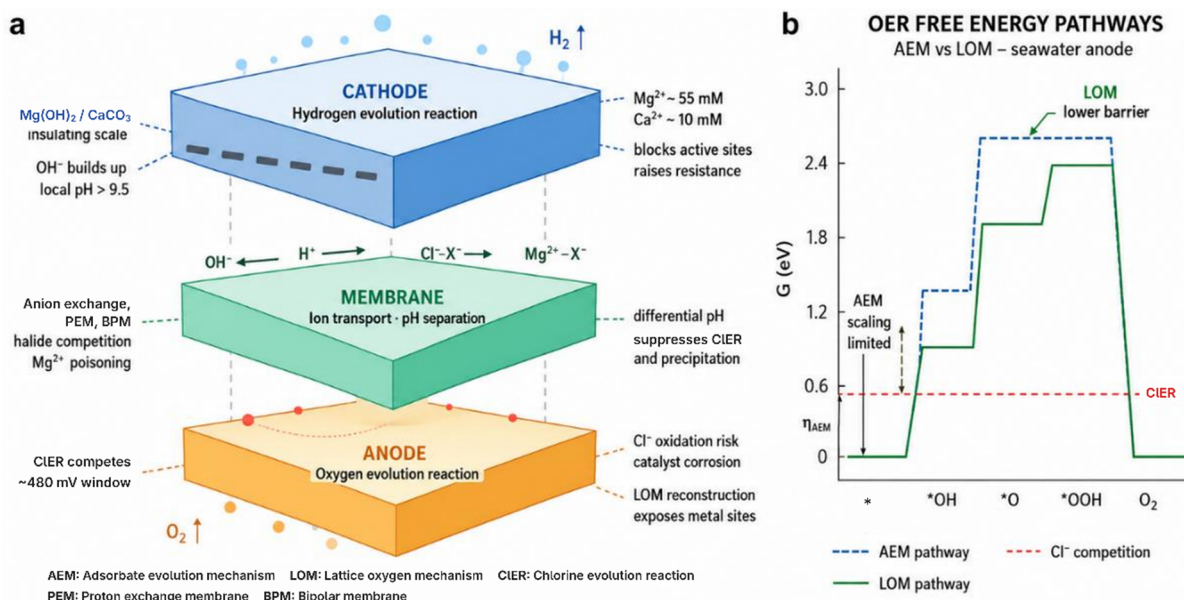


Figure 2. (a) An illustrative cross-section of a seawater electrolyser showing electrode challenges, (b) OER free energy for AEM and LOM pathways in seawater.

3. Anodic Selectivity: OER-CER Competition and Heterostructure Design

Similarly, the oxygen evolution reaction (OER) represents the principal kinetic and selectivity bottleneck in direct seawater electrolysis. In alkaline seawater, the chlorine evolution reaction (CIER) onset potential sits only 480 mV above the OER, meaning catalysts operating above this threshold risk generating toxic hypochlorite rather than oxygen [13]. This narrow thermodynamic window defines the central design constraint for seawater anodes. OER proceeds through two competing mechanisms the adsorbate evolution mechanism (AEM), involving four sequential proton-electron transfer steps constrained by universal scaling relationships, and the lattice oxygen mechanism (LOM), which breaks these scaling limitations through direct lattice oxygen participation in O-O bond formation [14] (Figure 2b). In seawater, however, the LOM pathway carries a durability penalty, surface reconstruction associated with LOM activity exposes vulnerable metal sites that accelerate chloride-induced corrosion, creating a fundamental tension between high OER activity and corrosion resistance in seawater anodes [15]. Our group has demonstrated that inorganic-organic hybrid heterostructures are a platform for simultaneous OER enhancement, CER suppression, and corrosion mitigation. In our MXene-MOF systems, ionic Fe-O-Co interfacial bonds redistribute charge density, stabilise active sites, and preferentially promote OH^- adsorption over Cl^- adsorption, thereby improving OER selectivity and long-term durability under ampere-level current densities. DFT calculations show substantially reduced chloride binding energies at the heterointerface relative to either parent phase [16]. Extending this principle, our boron-modified FeS_2/Ni -MOF heterostructure demonstrates that Fe-S-Ni ionic bonds induce directional charge redistribution at active sites. While boron-derived surface borate species locally enrich OH^- concentration and accelerate OER intermediate conversion, critically, in situ generated sulphate passivation layers provide a secondary electrostatic barrier that repels Cl^- and protects against anodic corrosion under prolonged operation, all validated by operando spectroscopy and DFT [17,18] (Figure 3a). In our $Co-MOF@WO_3 \cdot B_2O_3$ system, we demonstrated that replacing conventional van der Waals heterostructure contacts with ionic Co-O-W bonds creates efficient interfacial electron transfer pathways and structural robustness under corrosive seawater conditions. With boron serving a dual electronic and chemical role, modifying the WO_3 d-band structure to optimise OER intermediate binding. While B_2O_3 hydrolysis generates interfacial B-OH sites that preferentially coordinate OH^- and electrostatically repel Cl^- . DFT confirms that OH^- adsorption energy is significantly more favourable than Cl^- at this engineered interface [19]. Most recently, our Fe,B-doped $Ti_3C_2T_x$ MXene/N-doped nickel molybdenum oxide (FBT/NMO) 2D/2D heterointerface pushes this framework to its most quantitatively characterised expression. Strong interfacial electronic coupling redistributes electron density toward interfacial oxygen atoms, generating an electron-rich region of $-28.42e$ (Figure 3b). It simultaneously accelerates charge transfer kinetics and Sabatier-optimises the adsorption free energies of OH^* , O^* , and OOH^* intermediates, reducing the rate-limiting ΔG step well below either parent material. This translates directly into catalytic performance, across the full compositional series, FBT/NMO(50) delivers the highest current density at any given potential (Figure 3c), requiring overpotentials of only 239, 396, and 578 mV to reach 100, 500, and 1000 mA cm^{-2} , respectively. The lowest of any composition tested, and substantially below both parent materials (NMO:

370/636/843 mV; FBT: 257/426/618 mV) and commercial RuO₂ (363/585/792 mV) at the same current densities (Figure 3d). Simultaneously, in situ electrochemical reconstruction of Mo species into tetrahedral molybdate (MoO₄²⁻) creates a dynamically self-renewing, negatively charged surface layer that electrostatically repels Cl⁻ and suppresses CER throughout extended operation at ampere-level current densities for more than 1000 h [20] (Figure 3e). Collectively, our body of work across these four heterostructure systems, spanning MXene-MOF [16], sulfide-MOF [17,18], metal oxide-MOF [19], and 2D/2D MXene-oxide architectures [20], establishes a unifying design principle. That ionically bonded organic-inorganic interfaces, through the convergence of charge redistribution, preferential OH⁻ coordination, in situ passivation, and dynamic surface reconstruction, offer a viable and scalable route to resolving the OER-CER selectivity challenge in direct seawater electrolysis, shifting the field from conventional catalyst optimisation toward interface-controlled ion management and reaction selectivity engineering.

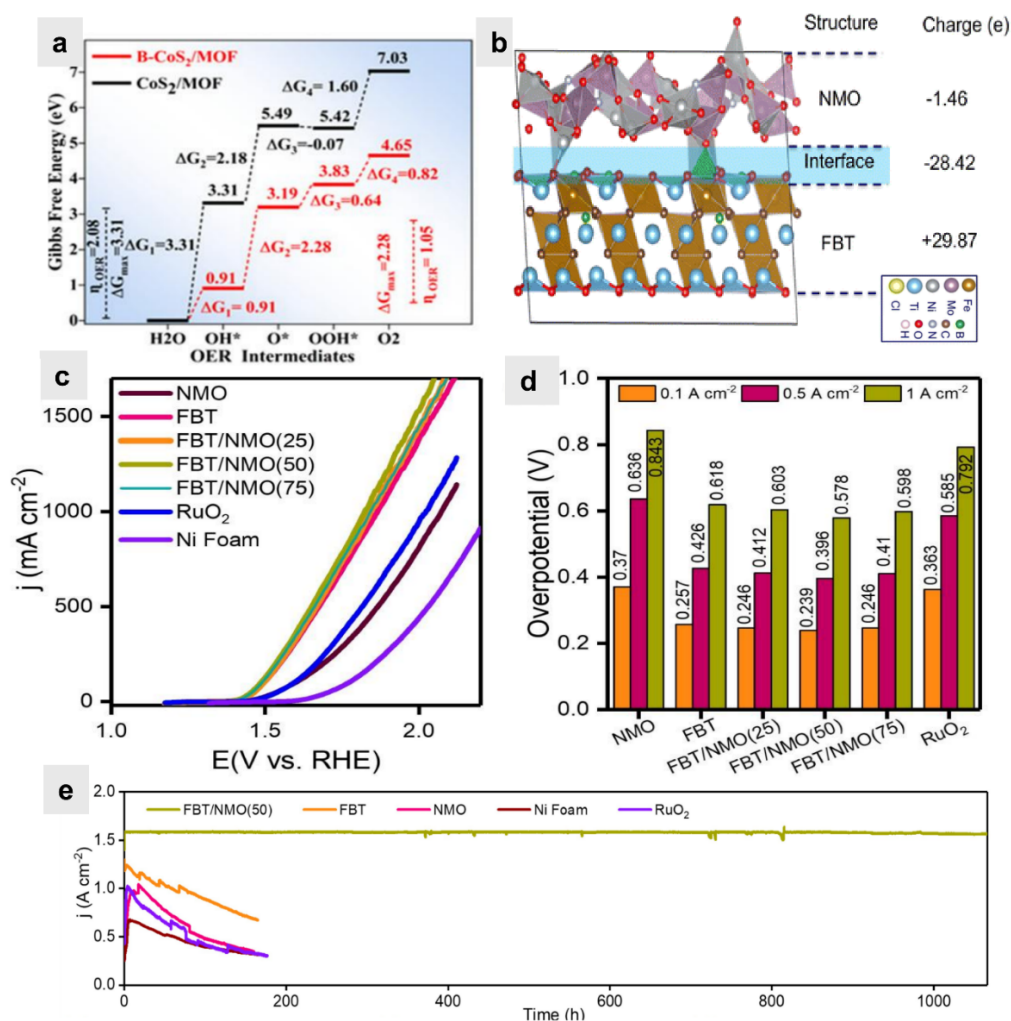


Figure 3. (a) Gibbs free energy diagram for OER using CoS₂/MOF and B-CoS₂/MOF catalysts; (b) Heterointerface of Fe, B-doped Ti₃C₂T_x MXene/N-doped nickel molybdenum oxide; (c) OER polarisation curves for NMO, FBT, FBT/NMO(25/50/75), RuO₂, and Ni foam; (d) Overpotential comparison across the same catalysts at 100, 500, and 1000 mA cm⁻²; (e) Long-term chronoamperometric stability, showing FBT/NMO(50) sustaining ~1.5 A cm⁻² for over 1000 h (Figures adapted with authors' permission).

4. Intermittency and Membrane Durability

Among these realistic deployment challenges, one failure mode has received insufficient attention. Offshore renewables are inherently intermittent, wind and wave power fluctuate on timescales from seconds to days [21]. During shutdown intervals, cathode potentials drift to oxidising values, converting active metal phosphide or nitride surfaces to electronically insulating oxide phases, while halide ions adsorb at now-unprotected metal sites. Sha et al. demonstrated that constructing an in-situ phosphate passivation layer on NiCoP–Cr₂O₃ cathodes can protect active sites against oxidation during shutdown and repel halide adsorption, achieving 10,000 h of stable intermittent operation at 0.5 A cm⁻², a benchmark that redefines the durability standard for the field [22]. Membranes represent

an equally critical and underexplored component in marine-compatible electrolyser design. In seawater environments, both anion exchange membranes (AEMs) and proton exchange membranes (PEMs) face degradation mechanisms absent in freshwater systems. Cl^- ions compete with OH^- for transport across AEMs, reducing ionic selectivity, lowering Faradaic efficiency, and accelerating polymer backbone degradation through halide-mediated oxidation. PEMs, meanwhile, suffer from cation poisoning as Mg^{2+} and Ca^{2+} displace proton-carrying sites within the sulfonated membrane. Bipolar membranes (BPMs) offer a partial solution, maintaining differential pH across the junction suppresses both precipitation and CIER simultaneously, but introduces voltage penalties that reduce overall system efficiency. Recent advances in composite membranes incorporating ionic sieving layers and anti-fouling coatings show promise, yet no membrane system has demonstrated stability beyond 1000 h under natural seawater conditions at industrial current densities. Membrane durability in real marine environments remains one of the most underdeveloped frontiers in DSE scale-up [23].

Beyond durability, three levers govern the practical Faradaic and energy efficiency of DSE systems: suppressing CER at the anode, since even minor hypochlorite generation diverts charge away from OER and can approach thermodynamic parity at high current density; minimising ohmic losses from precipitate fouling and membrane resistance, and matching electrolyser current density to the intermittent power profile of offshore renewables, keeping catalysts within their optimal Tafel regime rather than forcing operation outside it during power fluctuations. Closing these losses is what separates laboratory Faradaic efficiencies approaching 100% from the substantially lower system-level efficiencies typically reported for pilot-scale seawater electrolyzers.

5. Deployment Roadmap

Three deployment horizons define the trajectory from laboratory to ocean (Figure 4). In the near term (2025–2030), the priority is standardised testing under real seawater conditions. In the medium term (2030–2040), modular DSE systems targeting 1–100 m^2 electrode areas should integrate with offshore wind, aquaculture platforms, and marine vessels with a levelized hydrogen cost target below $\text{US\$3 kg}^{-1}$, requiring electrolyser capital costs under $\text{\$300 kW}^{-1}$ and operating lifetimes exceeding 50,000 h. In the long term (2040–2050), thousands of autonomous offshore electrolyzers could supply bunkering depots, zero-emission aquaculture, and coastal green ammonia production, a vision that demands advances not only in electrode science but in corrosion-resistant stack materials, remote monitoring, and marine regulatory frameworks.

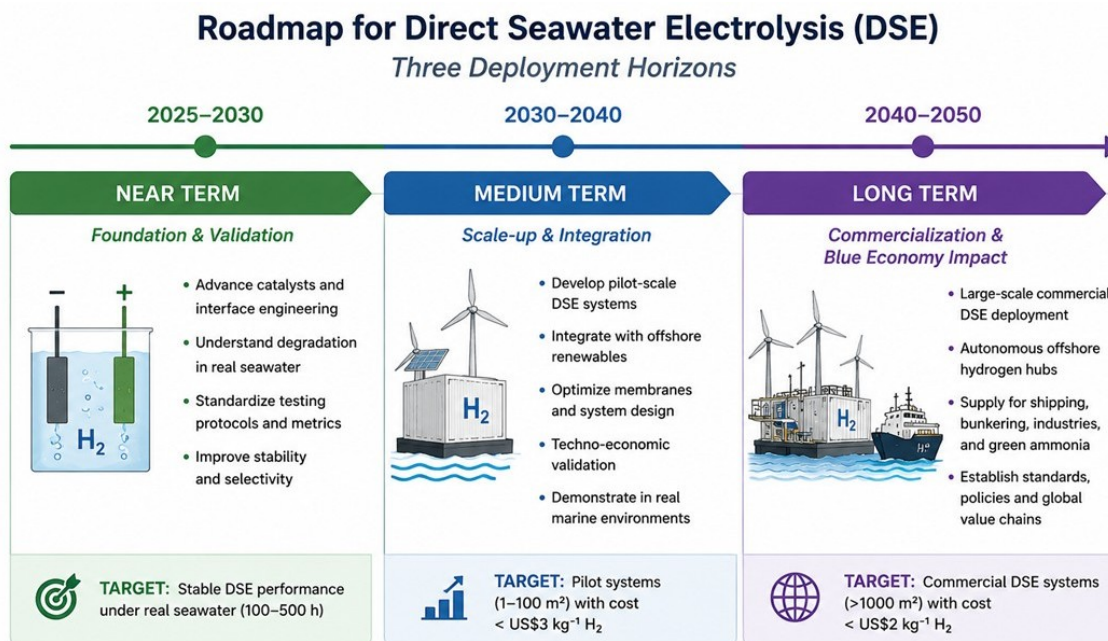


Figure 4. Deployment roadmap for direct seawater electrolysis across three horizons.

Techno-economic modelling supports the economic rationale for offshore-sited, decentralised production, direct coupling of electrolysis with offshore wind avoids the transmission losses and onshore infrastructure costs of centralised delivery, reducing the levelised cost of hydrogen (LCOH) from $\text{US\$3.86 kg}^{-1}$ (onshore-transmitted) to $\text{US\$2.09 kg}^{-1}$ (offshore-coupled) in techno-economic modelling of PEM systems [24]. Independently, offshore-sited, hydrogen-driven electrolysis has been shown to achieve an LCOH as low as $\text{\$2.7 kg}^{-1}$, undercutting both

onshore and in-turbine configurations by avoiding transmission losses and duplicated balance-of-plant [25]. These figures support the medium-term target of below US\$3 kg⁻¹ stated, provided electrolyser capital costs continue their projected decline toward US\$230–400 kW⁻¹ by 2030.

6. Conclusions

Direct seawater electrolysis (DSE) is not simply a way to bypass desalination; it enables a fundamentally different hydrogen infrastructure. The ocean provides both the water and, increasingly, the renewable energy needed for hydrogen production. The main challenge has been developing electrodes that can operate reliably in seawater. Encouragingly, progress has been rapid: stability has improved from tens to thousands of hours, cathodic precipitation is now manageable through interface design, and anodic oxygen selectivity has reached near-complete efficiency at practical current densities. Remaining issues, such as reproducibility in natural seawater, durability under intermittent operation, and the lack of marine-ready systems, are engineering challenges rather than fundamental limitations. The true advantage of DSE lies in reducing infrastructure complexity by enabling on-site hydrogen production. This is critical for the blue economy, where hydrogen must be generated directly at the point of use. Looking ahead, four research priorities will determine whether DSE moves from laboratory promise to offshore deployment: (i) validation under natural, biologically active seawater rather than synthetic electrolytes; (ii) catalyst and membrane designs explicitly tolerant of intermittent, renewables-driven operation; (iii) membrane systems demonstrated beyond 1000 h under industrial current densities in real seawater; and (iv) standardised testing protocols enabling direct comparison across the field, a gap noted throughout this Perspective. Addressing these will convert the current material-level gains into deployable offshore systems.

Author Contributions

V.N.: conceptualisation, investigation, visualisation, writing, original draft preparation; N.M.: conceptualisation, supervision, review and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

No new data were created in this study. Data shown in Figure 3 are reproduced from previously published work [16–20] and are available in those publications.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used OpenAI to generate a schematic illustration to improve readability. After using the tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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