# Green hydrogen from the ocean: Prospects and pitfalls

**Mai Gao,[1] Ming Ma,[2,3,*] and Zheng Xing[1,*]**

[1]School of Chemical Engineering and Technology, Sun Yat-sen University, Zhuhai 519082, China
[2]Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China
[3]One Healing Biotech Limited, Central Plaza, 18 Harbour Road, Wan Chai, Hong Kong SAR, China
*Correspondence: xingzh7@mail.sysu.edu.cn (Z. X.); mmskku@gmail.com (M. M.)

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It is anticipated that, over the coming decades, the dominant paradigm of global energy system will shift toward a renewable-based cycle centered on hydrogen energy combining wind and solar power. According to the data published by International Energy Agency (IEA), the global hydrogen production in 2024 surpassed 100 million tonnes (Mt), maintaining an average annual growth rate of 2.0-2.5% over the past four years. "Green hydrogen", that is, hydrogen produced from water electrolysis using renewable electricity sources (solar, wind, etc.), not only serves as a zero-carbon-emission fuel, but also represents an efficient medium for the storage and transportation of renewable energy. Nevertheless, "green hydrogen" only accounts for approximately 0.1% of the hydrogen market, with the vast majority of hydrogen still being produced from fossil fuels. Thus, to develop cost-effective production pathways for green hydrogen has become a hot topic.[1]

Recently, marine-based green hydrogen (MGH) technology, which integrates a front-end seawater desalination unit with an electrolyzer powered by marine renewable energy, has emerged as a transformative solution to potentially reshape the global energy landscape. Conventional green hydrogen technologies rely heavily on terrestrial freshwater resources for both reactants and cooling, intensifying competition for limited freshwater supplies. MGH systems employ membrane-based osmotic filtration to desalinate seawater and utilize electricity generated from offshore wind turbines or photovoltaic cells to drive proton exchange membrane electrolysis (PEME), enabling full-life-cycle zero-emission hydrogen production.[1-2]

## CURRENT STATUS OF MGH TECHNOLOGY

As the front-end subsystem of MGH systems, the seawater desalination unit is meant to keep supplying high purity freshwater to the downstream electrolyzer. After years of research, the state-of-the-art seawater desalination unit now often employs an integrated reverse osmosis (RO)/electrodeionization (EDI) configuration. In the RO stage, seawater undergoes primary filtration, flocculation, and other pretreatment processes to minimize the risk of physicochemical fouling and scaling on the reverse osmosis membrane (ROM) caused by insoluble particulates. Desalination and stream separation are subsequently achieved through the ROM, generating a brine stream that, upon meeting the relevant discharge standards, can be discharged directly into the deep ocean or further treated via dehydration and separation. The ROM, serving as the core RO component, is predominantly fabricated through interfacial cross-linking polymerization between aromatic polyamides and aromatic chlorides. This subassembly displays an anomalous behavior of isodense swelling upon seawater contact, which effectively promotes water permeation. Furthermore, crosslinking polymerization produces a high density of surface-exposed carboxyl groups together with

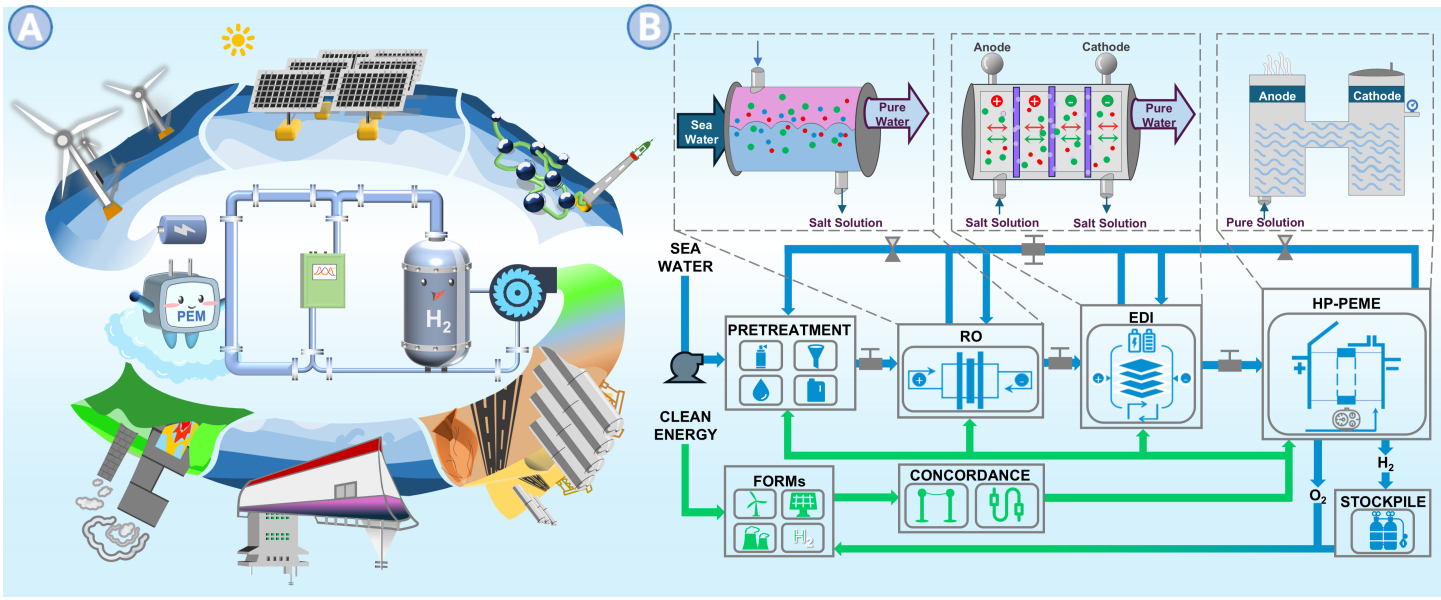


**Figure 1. (A) Fabrication and utilization of MGH; (B) Integrated dual circulation of energy and seawater within the RO/EDI/HP-PEME System.[1-2]**

other negatively charged moieties. These functional groups effectively repel hydrated ions such as $Na^+$ and $Cl^-$, only allowing water molecules to permeate via physical adsorption and hydrogen-bonded chain transfer.[3] Although RO can achieve a desalination rate of ≥ 99.5% for seawater, the permeate conductivity remains in the range of 400-1000 μS·cm$^{-1}$, which is markedly higher than the standard required for industrial PEME (1 μS·cm$^{-1}$). Therefore, secondary desalination of the RO-treated water is indispensable for MGH.

Originating from the stringent high-purity water demands of semiconductor and other precision industries, EDI has been increasingly integrated into seawater desalination systems since the early 21$^{st}$ century, significantly accelerating the development of MGH. During the EDI process, an applied external voltage utilizes ion-exchange resins as a conductive medium to drive the desalination of saline water and its separation into product water and concentrate streams. By leveraging these coupled separation and concentration mechanisms, the desalination compartment produces treated seawater with a conductivity of ≤0.1 μS·cm$^{-1}$. Such a process operates without acids or bases, and when powered by green electricity, EDI ensures a fully carbon-neutral desalination cycle.

Upon securing the desalinated water supply, electrolysis becomes the critical step for producing high-purity hydrogen. High-pressure PEME (HP-PEME) systems is a hydrogen production and processing system that, with additional energy input to overcome the pressure differential, utilizes a pressure-resistant proton exchange membrane (PEM) to achieve anode–cathode gas separation, while integrating high-pressure $H_2$ enrichment and delivery on the cathode side through pressure-resistant structural design. HP-PEME systems are widely recognized as the cutting-edge water electrolysis technology for green hydrogen production. The system also offers second-scale ramp-up capability, enabling effective mitigation of the inherent variability in offshore wind power output.[4] In collaboration with Kyoto University, Honda Motor Co., Ltd. has developed a 70 MPa single-cell PEME prototype, which demonstrated the feasibility of high-pressure operation under laboratory-scale conditions.

Currently, the integrated RO/EDI/HP-PEME system represents the most advanced MGH technology. Notably, Shanghai Sizhu patented a design combining two-stage RO, EDI, and wind-powered 70 MPa HP-PEME, projecting an annual hydrogen output of 0.16 Mt. In contrast, Xie et al. proposed a "direct electrolysis" technology for hydrogen production from seawater,[5] but which essentially relies on phase-change desalination rather than directly electrolyzing seawater. Since this approach does not fundamentally bypass the desalination process, achieving true direct electrolysis of seawater remains an unattainable goal.

## CHALLENGES AND PROSPECTS

**Water-salt selectivity rather than water permeability.** Although the RO/EDI/HP-PEME system has demonstrated feasibility under laboratory conditions, it faces significant challenges when applied to real seawater environments and scaled up for industrial deployment. For seawater desalination, the pursuit of higher efficiency and faster freshwater production has long remained a central objective. Nevertheless, even a fivefold increase in water permeability of state-of-the-art aromatic polyamide RO membranes only reduce energy consumption by ca. 3.7%. Thus, enhancing the water-salt selectivity of ROMs represents a more effective approach to achieving substantial improvements in overall system efficiency.

**Boron permeation and accumulation.** While RO/EDI processes effectively reduce seawater salinity, boron levels remain problematically high. This is because 98% of boron exists as neutral boric acid ($B(OH)_3$), whose molecular size (~0.26 nm) is nearly identical to water (~0.28 nm), preventing effective removal via physical adsorption or electrostatic interactions. With seawater concentrations (~4.5 $mg{\cdot}L^{-1}$) exceeding regulatory standards by tenfold, residual boron poses significant "Boron Risks". It causes biological toxicity and poisons HP-PEME catalysts by coordinating with Lewis acid sites, collectively increasing operational costs and health concerns. In the absence of pH adjustment, an advanced approach is to functionalize the ROM surface with aliphatic amines or polymers. By altering the high-flux pore architecture, this method achieves a substantial increase in boric acid selectivity with only a marginal compromise in permeability.

**Hydrogen permeation and back-diffusion in PEME.** PEMs, exemplified by perfluorosulfonic acid resins, are designed to efficiently conduct protons through nanoscale channels. However, in high-pressure acidic environment, proton and hydrogen gas transport exhibit partial coupling: $H_2$ rapidly diffuse by following the high-flux channels established by hydrated protons, creating a critical trade-off between proton conductivity and hydrogen permeability in the PEMs. Moreover, at the anode exhaust outlet, the $H_2$:$O_2$ concentration ratio may reach its peak, particularly under maximum electrical load conditions. In MGH systems, this could exceed the lower flammability limit of hydrogen, existing significant safety risks and affecting overall system efficiency. To address these issues without significantly increasing membrane thickness, a cutting-edge solution involves embedding Pt nanoparticles within the PEMs, which could facilitate the recombination of permeating $H_2$ and $O_2$ into water, thereby mitigating hydrogen crossover and reducing the partial pressure of the gas mixture in the anode chamber.

## CONCLUSION AND OUTLOOK

In summary, the RO/EDI/HP-PEME configuration represents the most feasible MGH strategy for the energy transition, despite near-term infrastructure and expertise challenges. Beyond technological innovation, overcoming these barriers requires the International Maritime Organization (IMO) to establish "Boron Sensitive Areas" modeled on the Particularly Sensitive Sea Area (PSSA) framework to geographically mitigate the Boron Risks via real-time monitoring. Furthermore, it is essential to refine the *International Code of Safety for Ships using Gases or other Low-flashpoint Fuels* (IGF Code) regulations concerning system pressure and materials for high-pressure mobile hydrogen storage systems.

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## AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

## DECLARATION OF INTERESTS

The authors declare no competing interests.