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Progress on smart integrated systems of seawater purification and electrolysis

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Water electrolysis powered by renewable energy could provide green hydrogen energy that has significant potential to build a near-zero-emission society. In addition to factors such as catalyst, membrane, and electrolyzer technology, the quality of water is coherently related to the efficiency of water electrolysis, which has garnered intense research interest recently. Impure water (represented by seawater) splitting is expected to enable broader access to water feedstocks and reduce capital costs, but it is currently facing huge operational challenges. To date, ultrapure water electrolysis with or without buffer ions has remained the most practical solution. The purification process is achieved through energy-intensive reverse osmosis technology traditionally, resulting in high capital costs and large ancillary facilities. In very recent years, researchers have been dedicated to integrating seawater purification and electrolysis into a single unit considering its significant advantages in hydrogen production efficiency, stability, energy consumption, cost, and system complexity. This minireview first highlights the progress in the smart integrated systems, then critically discusses their shortcomings, and finally provides perspectives for guiding future developments. The smart integrated systems are expected to provide a more flexible solution for green hydrogen production.

Broader context

The long-term stable operation of water electrolysis devices for green hydrogen production necessitates the utilization of high-quality water. Naturally distributed water sources like seawater possess a plethora of impurities which renders them unsuitable for direct application in water electrolysers. Hence, the purification of water remains a necessary step before the direct electrolysis of unpurified water, such as the direct electrolysis of seawater, can be achieved. However, a conventional two-step electrolysis strategy, involving water purification followed by electrolysis, presents several drawbacks including the need for additional energy inputs, heightened engineering complexities, and increased maintenance expenditure. Recent progress has seen the emergence of a single system intelligently integrating seawater purification and electro-splitting. Such smart integrated systems have the potential to mitigate the detrimental impacts posed by seawater constituents whilst circumventing the challenges associated with introducing supplementary purification units. This minireview provides an overview of the recent progress in the smart integrated system of seawater purification and electrolysis, with critical insights and pertinent perspectives proposed. It is anticipated that this minireview could offer a guide for future research in seawater electrolysis and sustainable hydrogen production.

1 Introduction

Water electrolysis powered by renewable energy sources including solar, wind, geothermal, and marine could provide green hydrogen energy that has significant potential to build a near-zero-emission society.[1–3] As an alternative to freshwater electrolysis, electro-splitting seawater into hydrogen energy could mitigate the freshwater crisis and save system costs, thus attracting a wide range of interest from researchers all over the world.[4–6] Research on seawater electrolysis dates back to 1975 (Fig. 1a).[7–16] However, it is only in the past two years that the research on seawater electrolysis has ushered in explosive growth (Fig. 1b). The complexity of the chemical and biological components is the major challenge in seawater electrolysis research.[17,18] The 3.5 wt% salts containing various metallic elements within seawater would bring about many drastic competitive side reactions, while the biological species tend to form insoluble precipitates and cause block hazards to catalysts and electrolysers.[19–21]

Currently, there are two major leading strategies in the deployment of seawater electrolysis, *i.e.*, direct seawater electrolysis (DSE) technology and two-step seawater electrolysis (TSSE) technology (as can be seen in Fig. 2a and b).[22,23] DSE directly

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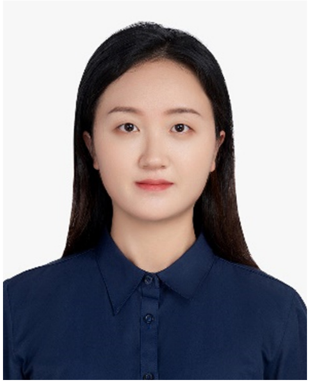
employs natural seawater as a feedstock for electrolysis. With no need for an additional purification process, DSE offers a significant cost advantage and factory distribution flexibility. However, DSE implementation remains extremely challenging at the current stage, as the existing active catalysts, membranes, and electrolysers may not meet the critical needs for DSE.[24] For instance, chlorine evolution reaction (CER) that has long been regarded as the biggest obstacle for DSE, will compete with anodic OER, and the produced chlorine gas will corrode electrolytic cell components such as bipolar plates.[25] In TSSE technology seawater is firstly pre-purified (typically by a reverse osmosis technology under high pressure), and then subjected to electro-splitting.[26] Although a favorable electrochemical performance similar to pure water electrolysis can be achieved by eliminating interferential species in seawater with the pre-purification step, the purification unit in this two-step technology requires additional energy supplies and advanced membrane technologies.[27,28] Besides, the independent chambers required for the purification process would possibly incur extra system engineering challenges, increase maintenance costs, and occupy more space.[29] Although previous analysis has confirmed that the specific energy consumption of seawater purification costs only a small fraction of the overall cost of hydrogen production (0.05–0.14%), given that water electrolysis is an energy-intensive process and that its future requirements will be on a large scale, any energy-saving measures will provide substantial economic benefits.[30]

Over the past few years, researchers have attempted to overcome the challenges associated with DSE and TSSE.[31,32] Recently, integrating seawater purification and electro-splitting into a single system (named as ISPE technology) has emerged as a highly advanced and promising alternative to DSE and TSSE (Fig. 2c). With the capability of achieving purification in the ISPE system itself, problems of DSE such as low efficiency, poor stability, severe corrosion issues, and impurity interference can be largely avoided. Additionally, existing freshwater electrolysis technologies, from catalysts to membranes and electrolyzers, are also suitable for the ISPE system. On the other hand, unlike TSSE, the ISPE without additional purification units can reduce the capital costs and technical challenges derived from an extra energy supply. These advantages give ISPE tremendous potential to make a substantial contribution to establishing a decarbonized society.

Considering the increasing demand for green hydrogen, the increasing shortage of freshwater resources, and the significant breakthrough of ISPE, it is now essential to systematically summarize and review ISPE to provide support and guidance for its future development. In this mini review, we summarize several effective and attractive cases for intelligently constructing ISPE systems and critically evaluated their advantages and disadvantages, with pertinent perspectives outlined at the end.



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2 Strategies of ISPE

2.1 Forward osmosis-water splitting strategy

Reverse osmosis technology is currently the leading desalination technology on the market and has been extensively used to purify seawater for electrolysis.[33] The defects such as relatively high cost and being energy-intensive, however, have posed enormous challenges in its practical application in seawater electrolysis.[34] Realizing these limitations, some have attempted to adopt alternative technologies to achieve seawater purification.[35,36] Forward osmosis as a physical phenomenon, refers to the water molecules spontaneously transported through a selectively semi-permeable membrane under the driving force of osmotic pressure difference,

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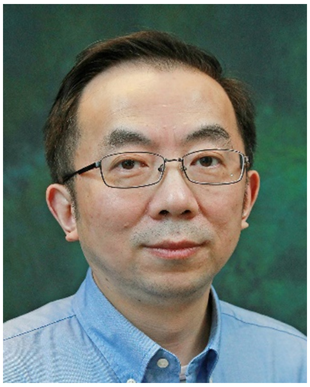

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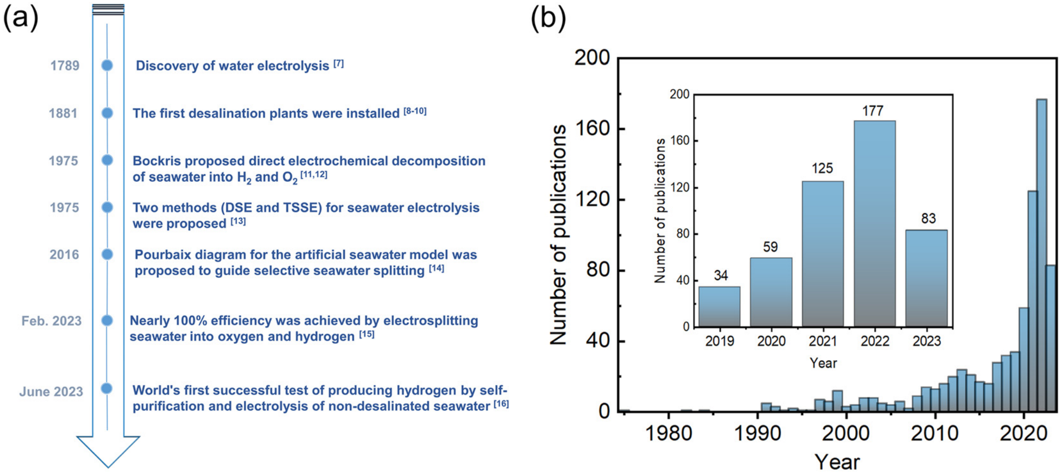

Fig. 1 (a) A brief timeline of seawater electrolysis development.[7–16] (b) Publications on seawater electrolysis since the year 1975, which was searched for based on the key phrase "seawater electrolysis" in the Web of Science database on 21st May 2023.

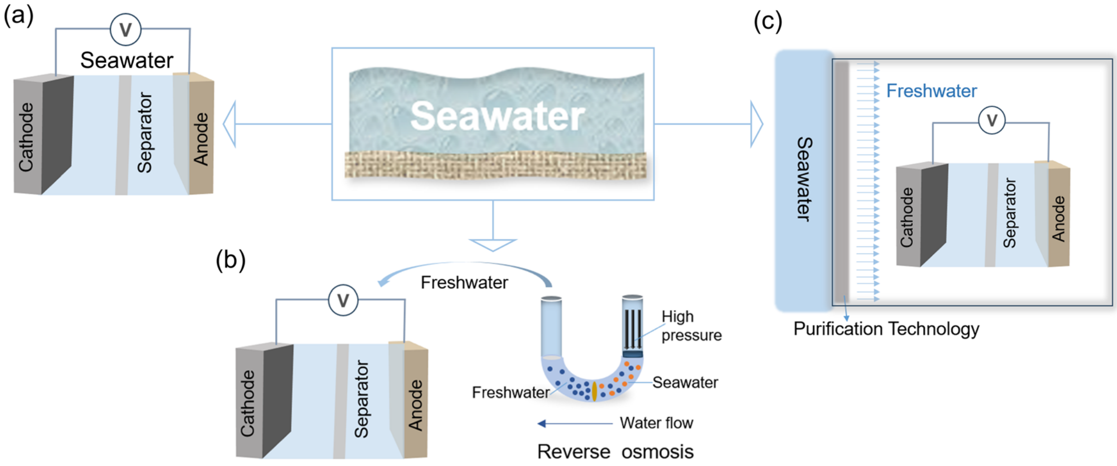

Fig. 2 Three technologies for seawater electrolysis. (a) Direct seawater electrolysis (DSE) technology. (b) Two-step seawater electrolysis (TSSE) technology. (c) Integrated seawater purification and electro-splitting (ISPE) technology.

opposite to the reverse osmosis technology that is driven by external pressures.[37] The spontaneous nature of forward osmosis signifies no additional force and energy, which could significantly reduce the costs and efforts of the system.

The advantages of forward osmosis can be further amplified when integrated with seawater electrolysis. For instance, in a report in 2021, Nocera's group ingeniously designed a system that employs a forward osmosis principle to purify saltwater and then feeds into water electrolysis, and was named the forward osmosis-water splitting (FOWS) system.[38] In this system, driven by differential concentrations, water molecules in 0.6 M NaCl solution (as an alternative to seawater) were spontaneously transported to the specially designed electrolyte, *i.e.*, a more concentrated 0.8 M NaPi solution, through the cellulose acetate membrane, achieving self-purification. The penetrated water in the electrolyte would then be consumed by water splitting to maintain the concentration difference, thus realizing the integration of purification and water splitting (Fig. 3a). It's worth noting that the penetration rate and the electrolysis consumption rate of water need to be balanced to ensure a differential concentration. The 0.8 M NaPi electrolyte offers at least three advantages. Firstly, since both pure water and seawater are unbuffered, the pH values would fluctuate during the electro-splitting process, seriously affecting the electrolytic efficiency and stability. The NaPi solution acts as a buffer to stabilize the pH of the electrolyte (especially at the interface between electrode and electrolyte) and avoids the formation of carbonate and hydroxide precipitates, thus improving the efficiency and stability of water electrolysis. Secondly, the neutral property of NaPi solution (pH = 7) could avoid severe corrosion issues (such as in the cases of acidic and alkaline electrolytes), which is favorable for electrolyser components. Lastly, phosphate is stable under the working voltages of water electrolysis. The cellulose acetate membrane is a commonly used forward osmosis membrane, with advantages of favorable hydrophilicity, low cost, and acceptable physical strength. However, the cellulose acetate membrane could

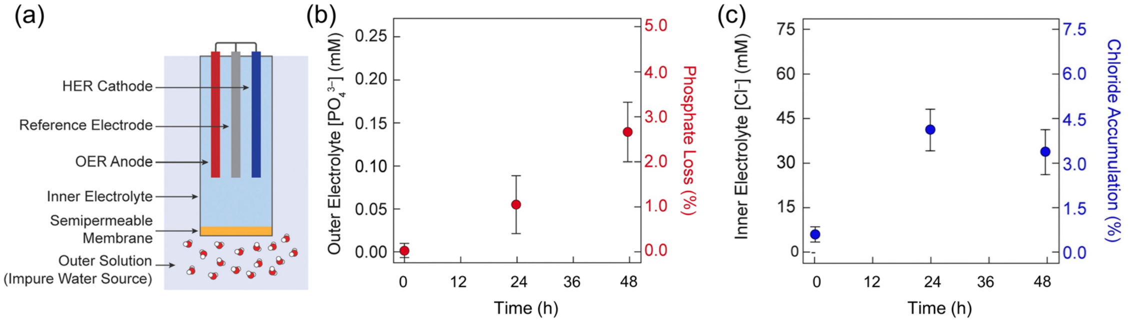

Fig. 3 (a) Schematic diagram of the forward osmosis-water splitting electrolyser. (b) Quantification of Pi ions in outer solution over 48 h of operation. (c) Quantification of Cl$^-$ in inner electrolyte solution over 48 h of operation. Reproduced with permission from ref. 38. Copyright 2021 National Academy of Sciences.

only exhibit optimal performance at pH 4–6. When the pH value of the solution is higher than 6 or lower than 4, the membrane tends to hydrolyze and the pores within the membrane will expand, resulting in ion exchange problems. Therefore, it is not surprising to find that in this study, Pi and Cl$^-$ leached from the electrolyte and external solution, respectively (Fig. 3b and c). The authors have noticed the membrane issue in their following research.[39] In the following reports, the external solution, *i.e.*, 0.6 M NaCl solution, was replaced by real seawater, while the inner electrolyte remains unchanged. After 5 days of operation, except for Pi and Cl$^-$ leakage, small amounts of Mg^{2+} and Ca^{2+} also accumulated in the cathode surface in the forms of carbonates and hydroxides. Although negligible in the short time, long-term salt ion crossover will significantly impact the electrochemical performance. Therefore, as realized by the authors, the membrane employed in the studies is defective, and the type and selectivity are of great significance for the FOWS system. The cell performance of the FOWS system, which requires a cell voltage of $\sim$2.8 V to deliver 250 mA, is comparable to the that of DSE and conventional water electrolyser under neutral pH values, suggesting its significant potential in practical hydrogen production.[40,41]

2.2 Vapor-fed-water splitting strategy

Although seawater consists of complex substances, the vapor over the ocean basically excludes various ions, organic matter, and biological species. Globally, the atmospheric relative humidity (RH) near the sea surface is constant, with slight seasonal variations.[42] Marine water vapor, owing to its relatively pure composition and abundance, if technically supported, can be used as an ideal water source for electrolytic hydrogen production.

Fortunately, a previous study has demonstrated that only feeding water vapor for electrolysis is experimentally feasible.[43] Spurgeon *et al.* operated a proton exchange membrane water electrolyzer (PEMWE) with vapor feedstock rather than a traditional liquid electrolyte and probed the current–voltage behavior under different RH values.[44] With argon (Ar) as a gas carrier of water vapor in both the cathode and anode, the PEMWE required a lower voltage than the electrolyser with liquid water to deliver the current density $<$40 mA cm^{-2}, while at $>$40 mA cm^{-2}, the performance of PEMWE was restricted mainly by the mass flux of water.[44] Besides, the relative humidity (RH) of the Ar gas carrier plays a crucial role in influencing the performance of the electrolyzer, as a decreased RH can lead to severe membrane dehydration, thus affecting its efficiency.[44] In addition, in the cathode, the O_2 gas in marine vapor could be reduced and compete with the hydrogen evolution reaction (HER) since it is thermodynamically more favorable, reducing the energy efficiency.[44]

Therefore, in their following study, the researchers input dry N_2 into the cathode to avoid the competition with side reactions and introduced seawater vapor at the near ocean surface to the anode of the PEMWE (Fig. 4a).[45] Operated under the marine vapor feeding, the activity of the electrolyser was increased with increasing flow rate and RH value. With 30% of RH, the

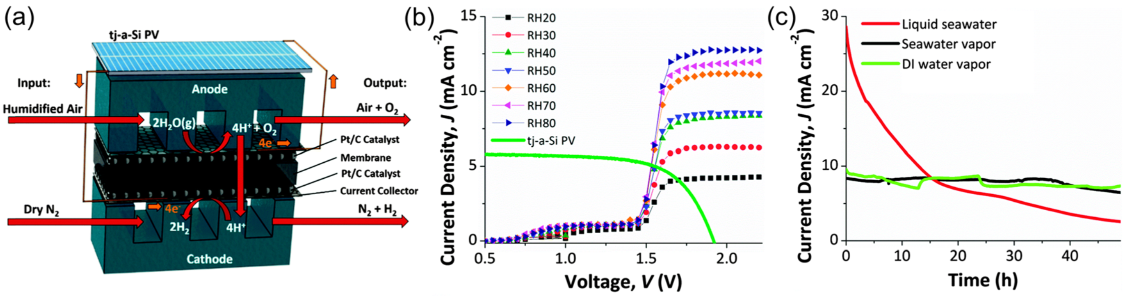

Fig. 4 (a) Schematic diagram of the vapor-fed water electrolyser. (b) The relationship between the relative humidity fed for the anode and the J–V curves. (c) Stability tests of the vapor-fed water electrolyser. The RH and flow rate for both seawater vapor and DI water vapor are 80% and 20 sccm, respectively. Reproduced with permission from ref. 45. Copyright 2016 Royal Society of Chemistry.

electrolyser could still reach a current density of >5 mA cm^{-2} at 1.5 V, suggesting the outstanding tolerance capability in water content within the vapor (Fig. 4b). The electrolyser with the seawater vapor (80% of RH) fed anode and dry N_2 fed cathode is much more stable than the electrolyser fed by liquid seawater at the constant cell voltage of 1.6 V (Fig. 4c). Initially, when utilizing marine vapor, the electrolyzer displays lower activity in comparison to the electrolyzer supplied with liquid seawater. However, over time, the current density of the electrolyzer receiving liquid seawater as a feedstock experiences a significant decline. After 15 minutes, it reaches the same value as the marine-vapor electrolyzer and continues to decrease thereafter. In contrast, the electrolyser fed with marine vapor suggested superior stability owing to the avoidance of damage from impure ions and precipitated species. Compared with an electrolyser with liquid electrolyte, the membrane of the electrolyser fed by marine vapor shows better stability because it could mitigate membrane damage by the concentrated solution. However, in terms of practical hydrogen production, the cell performance achieved by the vapor-fed seawater electrolysis strategy at room temperature, operating at 2.0 V to deliver a current density below 100 mA cm^{-2}, is far from satisfactory. As a sharp comparison, recent studies evidence that DSE has made significant progress in cell performance owing to the advances in efficient catalyst design and electrode modification.[15,46,47] Certain investigations on DSE have demonstrated their ability to sustain a current density of 400–1000 mA cm^{-2} at 2.0 V under room temperature.[15,46,47] Consequently, it is evident that the vapor-fed seawater electrolysis strategy has considerable room for further improvement.

2.3 Self-driven purification-water splitting strategy

If the technical and economic costs are reduced, seawater purification would significantly pave the way for seawater electrolysis development. Xie, Shao and co-workers recently proposed a novel integrated self-purifying water electrolysis model without any external purification unit.[48] By adopting a waterproof and breathable membrane of hydrophobic porous polytetrafluoroethylene (PTFE) as well as a self-dampening electrolyte (SDE), a scalable, side reaction/corrosion alleviated and highly efficient electrolyser capable of self-purification can be achieved (Fig. 5a). The special membrane allows water vapor to diffuse spontaneously under the vapor pressure difference between the seawater and the SDE and permit water migration, but resist the migration of ions and the corrosion from seawater. The migrated water vapor will re-liquefy through the absorption within SDE to provide sustained freshwater for electrocatalytic hydrogen generation. Then the freshwater consumption will result in a vapor pressure difference to facilitate the vapor diffusion from seawater to maintain the dynamic balance, enabling a stable and persistent water supply (Fig. 5b and c). The proof-of-concept electrolyser delivered excellent performance under both laboratory- and industrial-scale tests, which can be attributed to highly efficient hetero-ion resistance efficiency and sufficient water vapor diffusion channel through the PTFE membrane, as well as favorable ionic conductivity of SDE. This kind of design could enable the application of

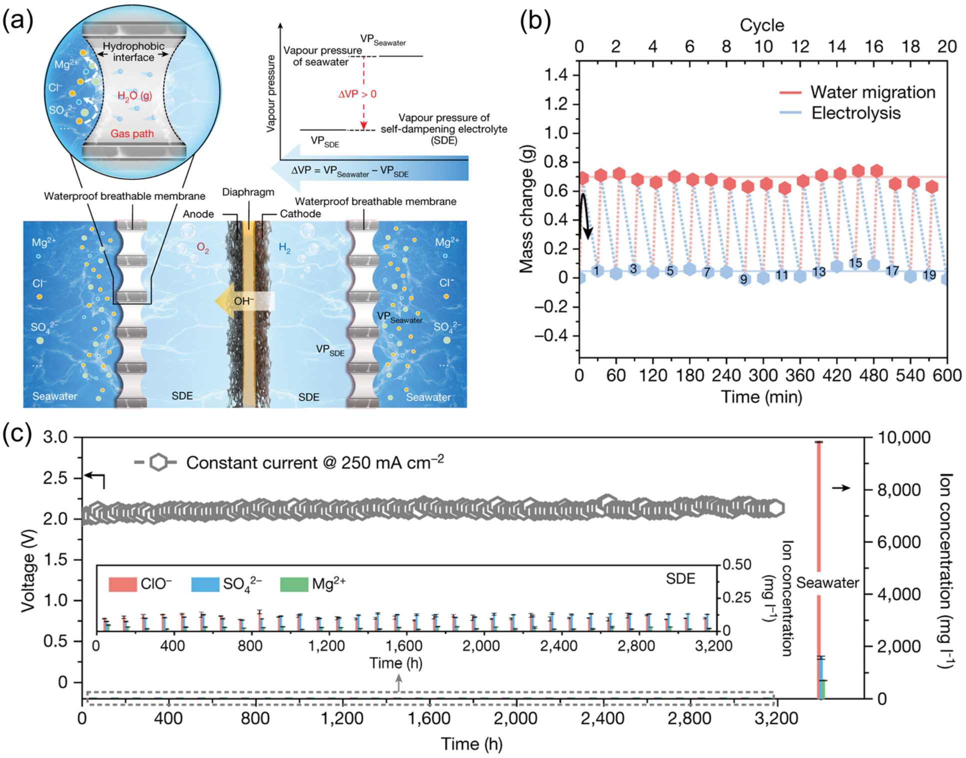

Fig. 5 (a) Schematic diagram of the self-driven purification seawater electrolyser. (b) Static equilibrium test of water migration and electrolysis. (c) Stability test of the scaled-up electrolyser. Reproduced with permission from ref. 48. Copyright 2022 Springer Nature.

well-developed freshwater catalysts, avoid the competitive CER, prohibit the core components of the electrolyser (catalysts, anode, cathode, and membrane) from corrosion, and result in no need for additional purification processes. More notably, the developed electrolyser can be extended to other impure water electrocatalysis. In addition, the electrolyser could support 250 mA cm^{-2} at a cell voltage of 2 V, surpassing some DSE electrolysers.[40,41] Therefore, it is a significant advancement in water electrolysis development.

It has been observed that although PEM and anion exchange membranes (AEM) were used in some parts of this work, the majority of electrochemical data was obtained based on a porous diaphragm (Fig. 5a). Note that utilizing a porous diaphragm usually leads to a reduced purity of the produced hydrogen gas at the cathode and to a pronounced crossover toward the anode, which, in turn, lowers the overall efficiency of hydrogen production.

2.4 Bipolar membrane-water splitting strategy

Bipolar membrane (BPM) is an emerging ion exchange membrane consisting of a cation-exchange layer (CEL) that only allows the transfer of cations and an anion-exchange layer (AEL) that only allows the transfer of anions.[49,50] BPM has been extensively employed in CO_2 reduction, electrodialysis, acid–base synthesis, and water electrolysis.[51–53] Compared with monopolar membranes, BPM offers several distinct advantages. The different ionic selectivities of CEL and AEL not only give BPM the ability to easily couple two different reactions, but also dispel the influence of opposite ions on a single reaction.[54] Besides, the reduction in electrolyte ion crossover allows easy collection and separation of products/reactants. In 2022, Chung and co-workers utilized BPM for the first time in seawater electrolysis to produce hydrogen.[55] Since then, several studies that integrate BPM and seawater electrolysis have been reported.[56,57]

For instance, Jaramillo and co-workers have elaborately employed BMP to design an asymmetric BPM water electrolyser (BPMWE) for seawater electrolysis and achieved long-term high-current hydrogen production.[57] The BPMWE was fabricated by a catalyst layer sandwiched between an AEL-attached anode and a CEL-attached cathode, with DI water and 0.5 M NaCl solution fed anode and cathode, respectively (Fig. 6a). The CEL layer can hinder the membrane crossover transfer of cathodic Cl^-, preventing it from competing with the anodic OER and affecting the overall efficiency of the electrolyzer. The cation Na^+ was transported from the cathode to CEL and catalyst layer, which was then blocked by the Donnan exclusion effect of AEL (Fig. 6b). Thereout, the exquisite application of BPM realized purification of saline water by mitigating the transmission of

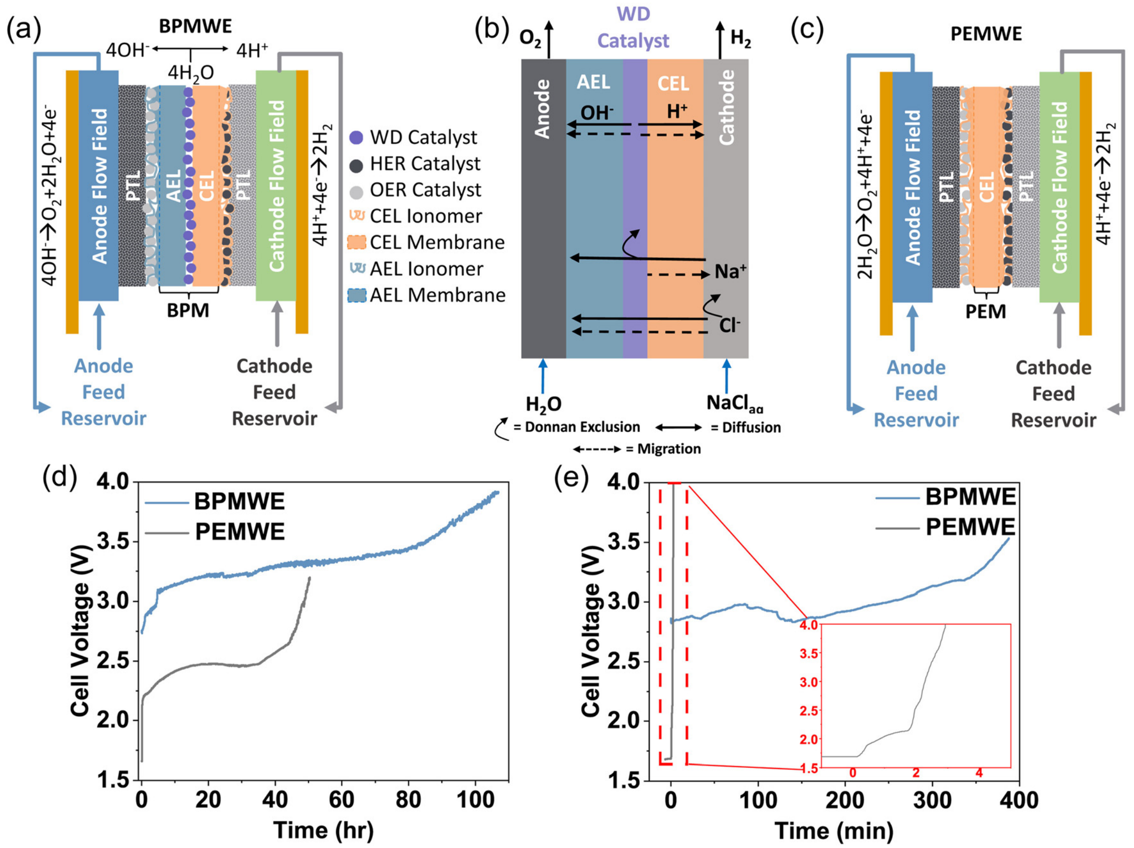

Fig. 6 (a) Schematic diagram of the BPMWE. (b) Ion-transport dynamics in BPMWE. (c) Schematic diagram of the PEMWE. (d) Stability of BPMWE and monopolar water electrolyzer that fed seawater for cathodes and DI water for anodes. (e) Stability of BPMWE and monopolar water electrolyzer that fed seawater for both electrodes. Reproduced with permission from ref. 57. Copyright 2023 Elsevier.

undesirable ion crossovers. For comparison, the authors also assembled a conventional PEMWE as shown in Fig. 6c. Compared with the monopolar PEMWE, BPMWE with impure water feed avoided competitive CER and achieved significantly enhanced stability (Fig. 6d). Inspired by the significant improvement, the authors then introduced real seawater to feed both the anode and cathode of BPMWE. The stability test, unfortunately, shows that the cell voltage substantially increased within a short range of time (Fig. 6e), signifying its inability in practical overall seawater electrolysis. As the U.S. Department of Energy (DOE) raised in the report of Technical Targets for PEM Electrolyzer, a PEM electrolyser should reach a lifetime of more than 40 000 h by 2022. The reason for the failure of introducing real seawater for both electrodes is that in the anode, the Cl^- within seawater could easily transport across the AEL and competitively oxidize in the catalyst layer to produce corrosive OCl^- species, which significantly affects the efficiency and durability of the system. This highlights the limitation of BPM for full seawater electrolysis. Other soluble and insoluble impurities within seawater can also contribute substantially to the dissatisfactory stability. Besides, as reported previously, one of the prominent problems with BPM is that the utilization of two pieces of membranes will result in a significant increase in internal resistance, which is why BPMWE requires a much higher operation voltage than monopolar electrolysers.[58,59] While the BPMWE strategy opens a new avenue for seawater electrolysis, it still has two drawbacks which need further addressing. First, a high cell voltage (>3 V) is needed to sustain a small current density of 250 mA cm^{-2}, far exceeding the cell voltages reported in existing studies for achieving the same current density under similar conditions.[40,41] In addition, a large mass loading of noble metal catalysts (6.25 mg cm^{-2}) was used. As per the Technical Targets for PEM Electrolyzer report issued by the U.S. DOE, this value exceeds four-fold the target loading value of noble metal materials (0.5 mg cm^{-2}) for PEM electrolyzers in 2026.

3 Conclusion and outlook

3.1 Conclusion

Seawater electrolysis can provide practical solutions for both large-scale renewable energy generation and freshwater conservation. Compared with the current popular DSE and TSSE, ISPE is an emerging and efficient technology. With the capability of simultaneously purifying and electro-catalyzing saline water, ISPE could circumvent the detrimental effects of seawater components, while eliminating the challenges of introducing additional purification units. As suggested above, ISPE can be implemented in various configurations, signifying its high structure tolerance. However, it is precisely these structural differences that result in significant variations in several key parameters among these strategies. Based on the corresponding references, Fig. 7 presents a comprehensive comparison of the introduced strategies in terms of current density, faradaic efficiency, stability, energy consumption, and cost. Out of these strategies, self-driven purification technology is the most promising one, exhibiting superior electrochemical characteristics and the lowest cost. The most remarkable achievement of this strategy lies in its stable operation of 3200 hours at a current density of 250 mA cm^{-2}, far exceeding other strategies. The forward osmosis strategy demonstrates inferior performance compared to self-driven purification technology, yet it is still highly promising. Both the vapor-fed strategy and the bipolar membrane strategy yielded unsatisfactory current density and stability while necessitating high energy consumption and cost, rendering them less appealing for practical application.

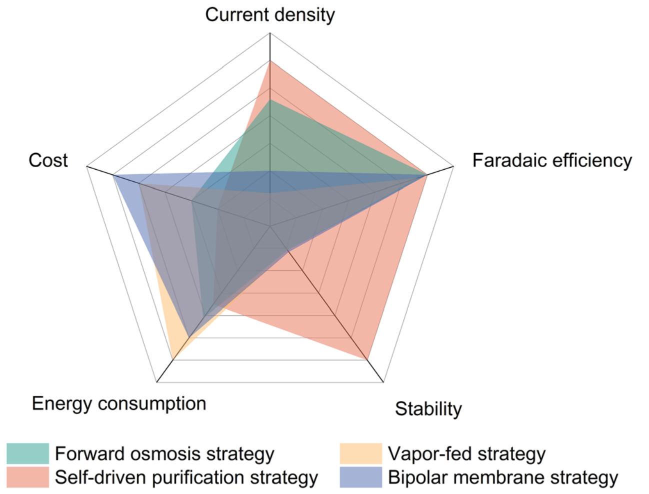

Fig. 7 Radar map for comparisons of the critical evaluation parameters of different ISPE strategies.

3.2 Outlook

As an emerging technology, there are some critical aspects that necessitate intensive research for ISPE to become practical and viable on a large scale.

3.2.1 Matching in purification rate and electrolysis rate. One key issue is how to ensure that the speed of the purified seawater can match the rate of electrolysis, particularly in long-term high-current production scenarios. The steady-state balance between seawater purification rate and electrolysis rate constitutes the fundamental basis for ISPE to operate smoothly and continuously. While the reported cases satisfy this prerequisite in laboratory settings, their adequacy under industrial-scale production conditions remains unvalidated. One approach to overcoming this challenge involves enhancing the seawater purification rate. This can be achieved by augmenting the ratio of seawater desalination units to electrolysis units, optimizing seawater purification units, or devising more effective integration strategies. Furthermore, exerting control over the rate of electrolysis to match the purification rate is also desirable.

3.2.2 Advancing in membranes. ISPE imposes intricate requirements concerning the types and properties of the membranes. Irrespective of the type of ISPE systems, the characteristics of membrane substantially determine the efficiency and performance of ISPE. For instance, in the self-driven purification-water splitting strategy, the polytetrafluoroethylene (PTFE) membrane functioned as a seawater purification unit, allowing the diffusion of water vapor while impeding the migration of ions and other impurities. Meanwhile, the diaphragm within the electrolyser unit served to separate the two electrodes and the resulting gas products. Given its critical role in ISPE, advancements in membrane technology may greatly expedite the progress of ISPE. Recent research has demonstrated the positive impact of membrane innovations on (sea)water electrolysis.[47] For example, water electrolyzers based on the emerging AEMs not only enable the utilization of catalysts that are not reliant on precious metals, but also achieve electrocatalytic activity comparable to that exhibited by PEMWE.[60,61] Consequently, membrane innovation holds considerable potential in driving the advancement of ISPE systems.

3.2.3 Developing new integrating strategies. Developing innovative and more effective strategies for ISPE is crucial to propel its further progress. There are several technologies that hold significant potential and advantages as ISPE strategies. For instance, solid oxide electrolysis cell (SOEC) technology typically dissociates H_2O into H_2 and O_2 at temperatures as high as 600 to 800 °C. The high temperature applied during start-up and operation processes could evaporate seawater into water vapor, which is then supplied to SOEC for hydrogen production, achieving simultaneous self-purification and electrolysis.[62] Coupling interfacial-solar stream and water electrolysis could provide another perspective for ISPE. The interfacial-solar stream is more efficient than natural vapor (strategy 2.2) in collecting water resources, thus providing a faster evaporation rate to match a more efficient electrolyzer.[63,64] If a flow-electrode capacitive deionization device capable of deionizing seawater by capacitive adsorption can be effectively integrated with an electrolyzer to form a single operating unit, it also has the potential to serve as an innovative ISPE system.[65]

3.2.4 Attaching importance to flexibility. Flexibility, whether in water sources, device sizes, or applications, is a potentially great advantage of ISPE that has not been extensively recognized by researchers. For example, since ISPE can realize self-purification, other impure water such as industrial sewage and wastewater may serve as water sources to generate hydrogen, which highlights the water source flexibility of SDE. Besides, without the requirement of additional purification units, ISPE can be assembled in desirable sizes to meet diverse needs, such as providing fuel for houses or vehicles, manifesting its scale and application flexibility. With the advancement of science and technology, the production and usage costs of electricity are expected to decrease gradually, which we believe will greatly promote the development of ISPE.

3.2.5 Achieving large-scale deployment in real marine environments. The successful implementation of ISPE systems at the laboratory scale has sparked interest among researchers to further investigate their potential for large-scale utilization in real marine environments for extended durations. However, the complex marine conditions and natural environmental factors introduce significant challenges for the practical, long-term deployment of ISPE systems. For instance, the intermittent nature of sunlight can lead to an unstable electricity supply for the electrolyzer, consequently resulting in fluctuations in electrolyzer efficiency. Additionally, ocean currents can induce varied pressure differences, posing damage to cell components such as purification membranes in ISPE systems. Moreover, it is essential to consider the environmental issues associated with the deployment of ISPE systems. For example, the membranes used in ISPE systems may degrade over time, contributing to plastic debris in the ocean and exacerbating pollution. Therefore, substantial research efforts are indispensable to achieve the practical implementation of ISPE systems in authentic marine environments.

Conflicts of interest

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

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