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Integrated seawater hub: A nexus of sustainable water, energy, and resource generation

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HIGHLIGHTS

- Multipurpose SWRO facilities promoting resource and energy recovery, mitigating emissions
- Osmotic energy recovery from RO brine
- H_2 generation by direct seawater electrolysis
- Agricultural utilization of SWRO desalination product water and reject brine

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ABSTRACT

This review paper explores the potential for seawater desalination plants to operate as integrated hubs for addressing the increasing demand for water, energy, mineral resources, and foods, particularly in resource-scarce regions. The integrated seawater hub (ISH) utilizes seawater as a common input, provides multipurpose facilities that can cater to freshwater and agricultural requirements, brine processing for salt and minerals extraction, promotes energy recovery, and mitigates greenhouse gas emissions by employing renewable and alternative energy technologies, thereby bolstering sustainable development. Capitalizing on seawater, the most abundant resource on our planet, these plants can contribute significantly to the sustainability sector. This study delves into the essential aspects of integrating mainly the seawater reverse osmosis (SWRO) desalination process to create a portfolio of clean, sustainable water supplies, energy sources, and other valuable products. Furthermore, this paper seeks to offer a comprehensive analysis within a unified framework, incorporating various established technologies that demonstrate the multifaceted capabilities of desalination plants. This includes the delivery of a freshwater supply and effectively repurposing the brine, the primary liquid waste product from these facilities. Emphasizing the potential to achieve a circular economy centered on brine management, our review presents an environmentally friendly approach to urban development. The study also explores emerging research domains where seawater desalination plants utilize renewable energy sources like solar, wind, and biomass to produce clean water and green hydrogen. It suggests that further research and investment in the realm of integrated seawater resource hubs could yield significant benefits for both local communities and the wider global community.

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1. Introduction

Humanity faces significant challenges, including food, water, and energy security, along with climate change, desertification, and declining forests. Each issue carries potential solutions, but it is crucial that solving one does not exacerbate another. These interconnected challenges necessitate integrated solutions. One pressing issue is freshwater scarcity, amplified by global warming effects, which increase salinity in land and seawater, thereby limiting freshwater availability for domestic, agricultural, and industrial use. Desalination and sewage treatment have emerged as vital strategies to augment water supply beyond what the natural hydrological cycle offers [1]. Looking ahead, seawater, due to its vast availability, stands as a promising candidate for desalination to obtain freshwater.

Expanding the scope beyond freshwater scarcity, researchers are now leveraging seawater, the earth's most abundant chemical energy source, for emerging applications such as seawater greenhouse farming and mineral extraction from brine. The rising costs and environmental damage from fossil fuel consumption necessitate integrating renewable energy into industrial processes to reduce financial and environmental burdens. The feasibility of renewable resources like solar or wind energy, combined with seawater desalination plants, offers a promising approach to mitigating freshwater scarcity and promoting hydrogen generation for energy production or agricultural fumigation.

This paper introduces the novel conceptual design of the 'Integrated seawater hub' - an integrated approach to seawater utilities with significant implications for process economics and resource management. This model aims to improve the efficiency of SWRO plants in water recovery while unlocking new potential for energy and valuable element recovery from seawater or RO brine. It provides a versatile foundation for various applications, from improving the environmental sustainability of desalination plants to optimize energy usage and cost reduction.

Fig. 1 illustrates the proposed integrated seawater hub concept, which combines clean drinking water and agricultural water production, energy generation, and wastewater reclamation. The integrated seawater hub starts with the SWRO desalination plant, which intakes seawater directly from the sea, desalinates it, and distributes this freshwater to multiple endpoints, including the main city for drinking water purposes, the hydrogen production plant, and for seawater farming. Adjacent to the desalination plant and integrated with it are the wastewater (WW) treatment plant and the algae farming facility. The WW treatment plant intakes its wastewater from the adjoining SWRO plant (industrial WW) and domestic uses of the central city. Then, it uses the treated wastewater for algae farming to produce biofuel. Additionally, the salinity gradient between the treated wastewater and the SWRO wastewater brine has electrical power using pressure-retarded osmosis (PRO) and reverse electrodialysis (RED) plants. The generated electrical energy is directed to and stored in a power grid substation. The power grid substation also stores electricity generated from renewable energy resources like solar energy and wind energy. The stored power is later directed to aid in powering other industrial plants (i.e., hydrogen generation plant) or is used as an electricity source to the main city. The hydrogen generation plant uses treated water to produce hydrogen and supplies it for seawater farming. Also, it receives the algae farming facility's hydrogen byproduct, purifies, and re-distributes it. Moving on to the ammonia distribution line, this line is sourced from the fertilizers (ammonia) plant. It is either directed to the city as fertilizers-rich water or is used for fertigation purposes in greenhouses and concentrated solar power (CSP) seawater farming, in addition to its direct export using ships. Furthermore, the treated water is constantly monitored for mineral collection and re-distribution.

The ISH aims to provide sustainable solutions for water, energy, and resource generation in arid regions by using seawater as input for various processes and addressing environmental degradation challenges. The ISH concept is a highly efficient, sustainable, and environmentally friendly model aimed at minimizing the carbon footprint of seawater desalination. To our knowledge, no previous review has explored the innovative approach of utilizing valuable resources inherent in seawater using this concept. This paper provides the first

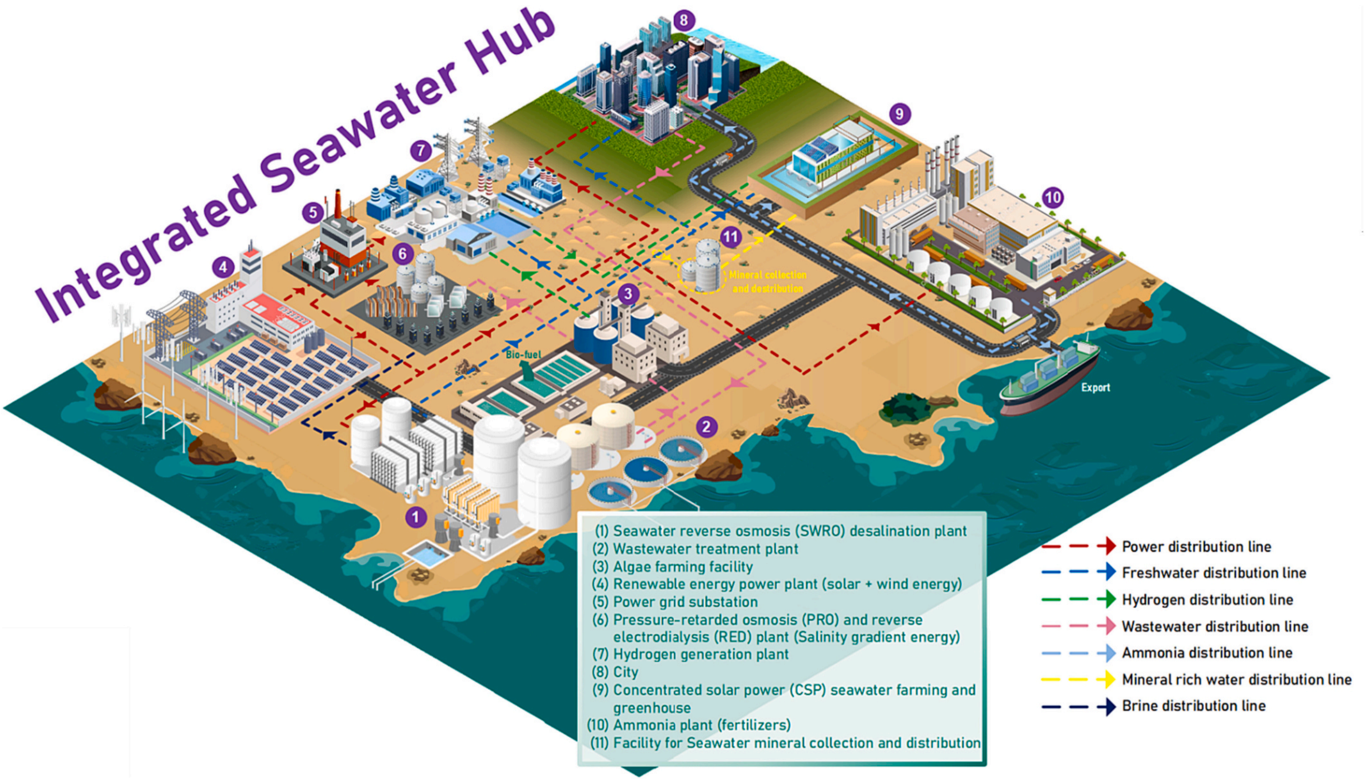


Fig. 1. Integrated seawater hub concept: the potential hub for the future by integrating water, resource recovery, energy, and agriculture.

analysis of a multipurpose seawater desalination plant's potential. This plant would integrate multiple energy-efficient processes, renewable energy sources, and cutting-edge technologies to treat seawater efficiently, yield potable water, and recover valuable resources and energy. The paper also explores the potential benefits of ISH for the water-energy-food (WEF) nexus, which is a framework to analyze the interdependencies and trade-offs among these resources. It will also highlight the opportunities and techno-economic challenges of implementing the ISH in arid regions and provide future research and development recommendations.

2. SWRO as a resource hub: solution to sustainability challenges

2.1. Desalination

Desalination, currently employed in over 150 countries, provides potable water to over 300 million people, catering to various demand segments [2]. As reported by the International Desalination Association (IDA), as of 2022, 22,757 desalination plants operated globally, producing 107.5 million cubic meters of water daily. The estimated CAPEX and OPEX for desalination in 2022 were 6466 and 10,752 million US dollars, respectively [3]. Fig. 2a depicts major techniques contributing to the desalination market, the viability of each relying on factors such as electricity cost, water quality, and regional technical resources. Fig. 2b provides a graphical representation of the number of seawater desalination methods as discussed in scientific literature. Membrane-based technologies have recently received more attention for their lower energy consumption, resource recovery efficacy, and relatively improved recovery rates in producing drinking water [4,5], and majority of newly commissioned desalination plants employed this technology. The global desalination capacity has seen an average annual increase of roughly 7.5 %, with membrane desalination contributing significantly to total capacity [6].

SWRO is widely used for desalination around the world, and roughly half of the water produced via RO desalination comes from seawater, with the balance primarily sourced from brackish, freshwater, and treated wastewater. The SWRO process involves pressurizing feedwater to overcome the solution's osmotic pressure (around 3–5 MPa for seawater) [7], driving it through a membrane that permits only water molecules. This method effectively filters colloidal or dissolved particles from the solution, resulting in brine concentrate and nearly pure water, and modern SWRO plants have reduced energy requirements to 3.0 kWh/m^3 for the entire process, significantly lower than the 5–10 kWh/m^3 needed for traditional methods [8,9]. However, some issues remain to be addressed in SWRO plants, such as the environmental impact of brine disposal and membrane fouling [10]. A resource hub is a concept that aims to utilize the brine from SWRO for extracting valuable minerals and compounds that can be used for various industrial and agricultural purposes. The resource hub concept offers several notable seawater reverse osmosis (SWRO) advantages. One key benefit is reduced energy consumption and greenhouse gas emissions associated with SWRO. Furthermore, the resource hub approach creates opportunities for SWRO plant to diversify revenue streams and explore new markets by extracting valuable products like sodium chloride, bromine, magnesium, potassium, lithium, and more from the brine. Fig. 3a illustrates desalination's significant environmental impact. Another critical issue of SWRO is the ecological impact of brine disposal, which can affect marine ecosystems and biodiversity due to its high salinity, temperature, and chemical composition [11]. The resource hub concept can mitigate the environmental and ecological concerns related to brine disposal by reducing the volume of brine discharged into the sea and reducing salinity and toxicity in the effluent, thus improving its potential for reuse. Another critical issue of SWRO is membrane fouling, which can reduce the performance and lifespan of the membranes and increase the operational and maintenance costs. The resource hub concept can improve the membrane performance by lowering the feed water's fouling potential and enhancing the membranes' cleaning efficiency. Recent years have seen a substantial reduction in specific energy consumption (SEC) in SWRO facilities attributed to improved membranes, more efficient pumps, hybrid/integrated systems, incorporating renewable energy sources, osmotic processes, and energy recovery devices (ERD) [10]. Energy usage comprises about 36 % of a seawater desalination plant's operational costs [12], and substantial capital costs arise from seawater pumping equipment and water intake pipelines. Incremental RO plant expansion to meet demand is feasible. Consequently, implementing SWRO as a resource hub can significantly enhance desalination's sustainability, efficiency, and profitability while fostering water security and economic development opportunities. Large-scale seawater desalination facilities boast high energy efficiency and minimal environmental impact [13]. RO desalination presents several advantages over thermal options, including adaptability to local conditions, lower CAPEX, and potentially significant CO_2 emission reduction [14,15]. Given its simple processing, cost-effective installation, and minimal chemical usage, RO technology represents the future

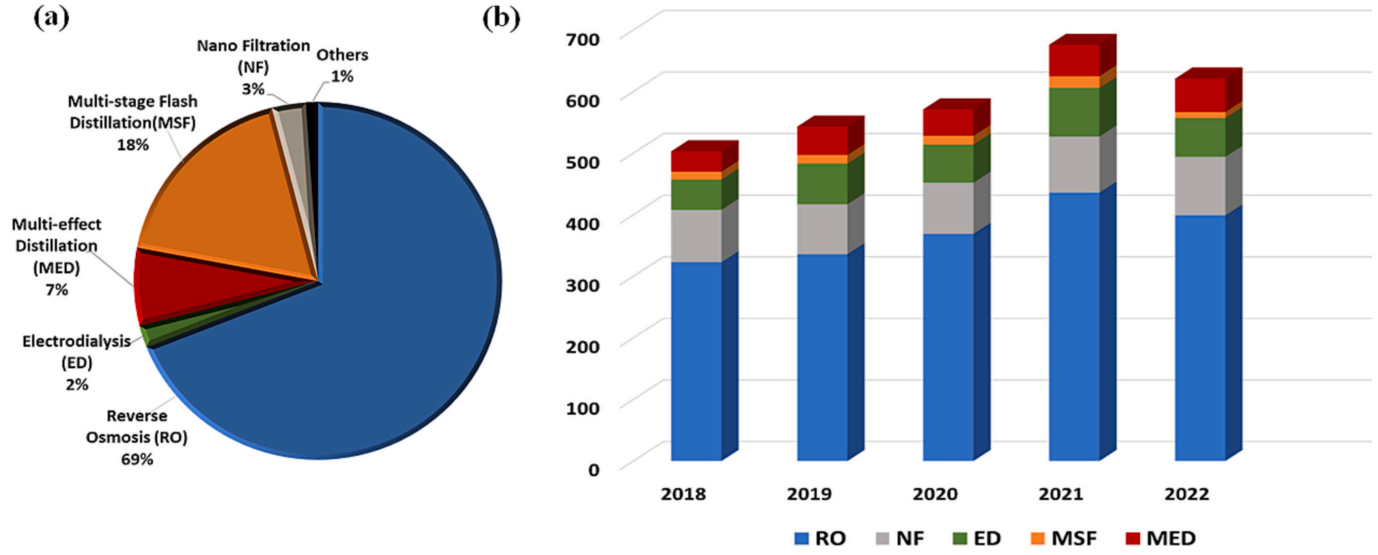


Fig. 2. (a) Contributions of various desalination methods worldwide (b) The number of papers published on the topic of "seawater desalination" by multiple approaches from the Web of Science database, March 2022.

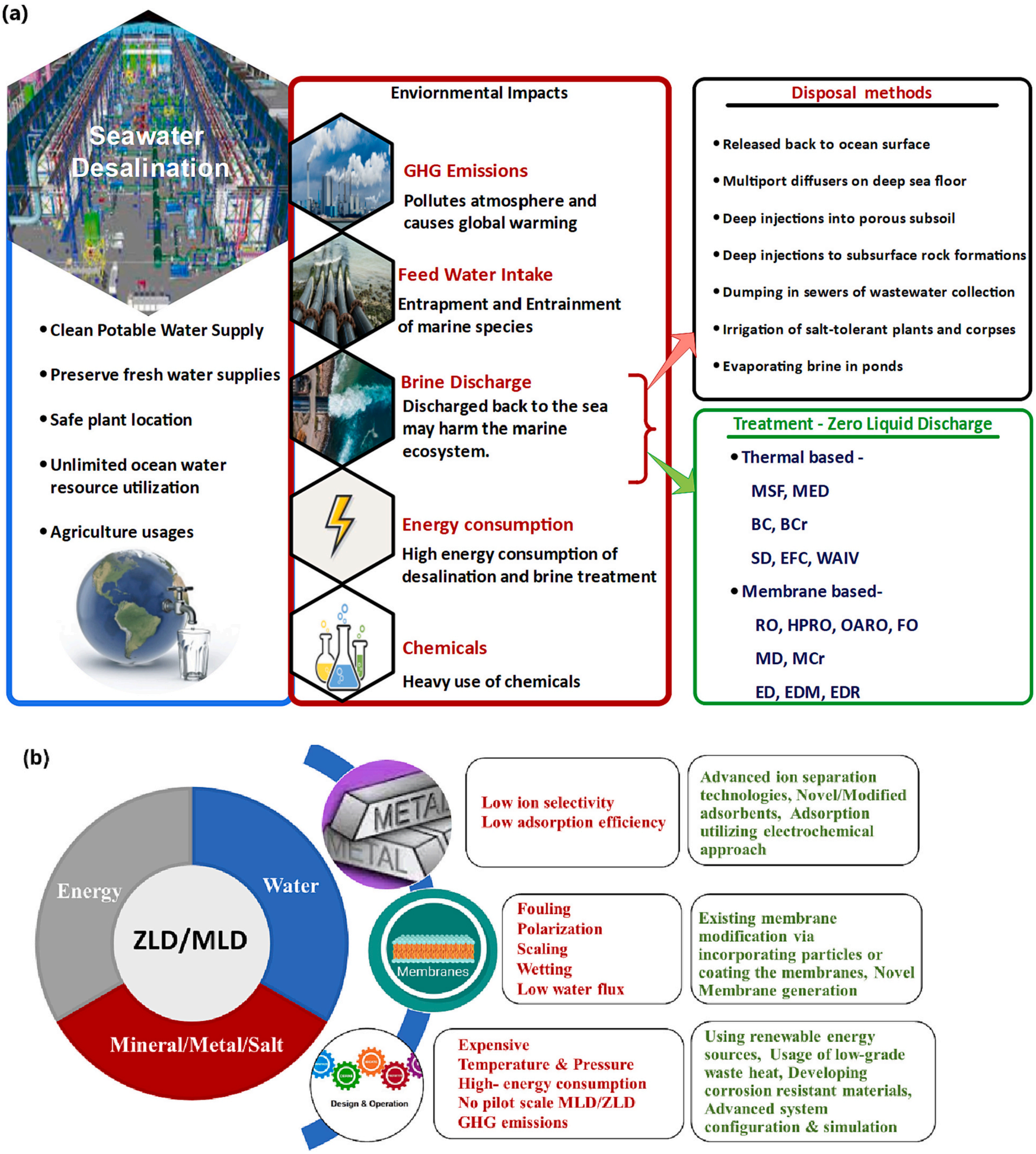


Fig. 3. (a) Advantages and impacts of desalination; Brine disposal methods and treatments. (b) Challenges and solutions of minimal and zero liquid discharge systems. Abbreviations: multi-stage flash (MSF), multi-effect distillation (MED), brine concentrator (BC), brine crystallizer (BCr), spray dryer (SD), eutectic freeze crystallization (EFC), wind-aided intensified evaporation (WAIV), Reverse osmosis (RO), high-pressure reverse osmosis (HPRO), osmotically assisted reverse osmosis (OARO), forward osmosis (FO), membrane distillation (MD), membrane crystallization (MCr), electrodialysis (ED), electrodialysis metathesis (EDM), electrodialysis reversal desalination (EDR).

Table 1
Characteristics of brine from various SWRO desalination plants [18].

TDS (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	HCO^{3-} (mg/L)	Ref.
50,200	625	2020	15,500	–	20,250	–	199	[19]
79,660	960	2867	25,237	782	41,890	6050	1829	[20]
55,000	879	1864	15,270	–	31,150	5264	432	[21]
70,488	790	2479	21,921	743	38,886	5316	173	[22]
68,967	845	2550	21,070	784	38,014	5342	274	[22]
80,028	891	2878	24,649	888	43,662	6745	315	[23]

of desalination and forms the foundation of the seawater hub concept.

2.2. *SWRO brine stream: waste-to-value management*

With over 3.5 million cubic meters of brine rejected daily, sustainable use and safe disposal are critical. Studies indicate that the brine outflow from desalination could increase salinity by an additional 2.24, 0.81, and 1.16 g/L in the Gulf, Mediterranean Sea, and Red Sea, respectively [16]. The constituents in the brine vary across desalination plants, as detailed in Table 1. Brine disposal can account for 5–33 % of a desalination plant's overall cost, making it a significant issue in the plant installation [17].

Past efforts in brine disposal have been limited, often paralleling wastewater disposal methods. Consequently, the exploration of repurposing to foster a circular economy through effective brine management is essential.

2.2.1. *Minimal and zero liquid discharge (MLD/ZLD) systems*

Effective brine management primarily aims to achieve ZLD, a water treatment approach aimed at total water recovery and conversion of residual matter into valuable salts, reducing the environmental footprint of desalination. ZLD systems, for instance, recycle, recover, and repurpose wastewater for industrial uses, diminishing brine production and waste disposal [24]. Despite the high cost, ZLD allows economic benefits by recovering usable minerals and salts from discharge. Various management methods have been devised in response to brine's environmental impact, predominantly focusing on disposal [25]. Additionally, several treatment techniques can be utilized to extract valuable resources from desalination brine. Fig. 3a and b highlight the primary brine management strategies, the challenges of implementing MLD/ZLD systems, and potential improvements.

Brine management, an evolving concept, presents an opportunity to extract metals from desalination plants. Thermal processes, while effective, are costly, energy-intensive, and contribute to greenhouse gas emissions. Alternative methods like RO, ED, FO, and MD are promising, but high costs necessitate regulatory incentives to lower energy consumption and incorporate renewable energy sources [26]. Recovered resources can be utilized in diverse applications such as agriculture, industrial processes, and energy production. Resource recovery can lessen the environmental impact of seawater desalination while providing an alternative source of valuable resources. Further research is needed to optimize resource recovery technologies and validate their economic viability. Effective SWRO brine management can enhance the sustainability of desalination plants.

3. Valuables from SWRO brine streams

3.1. *Resource recovery*

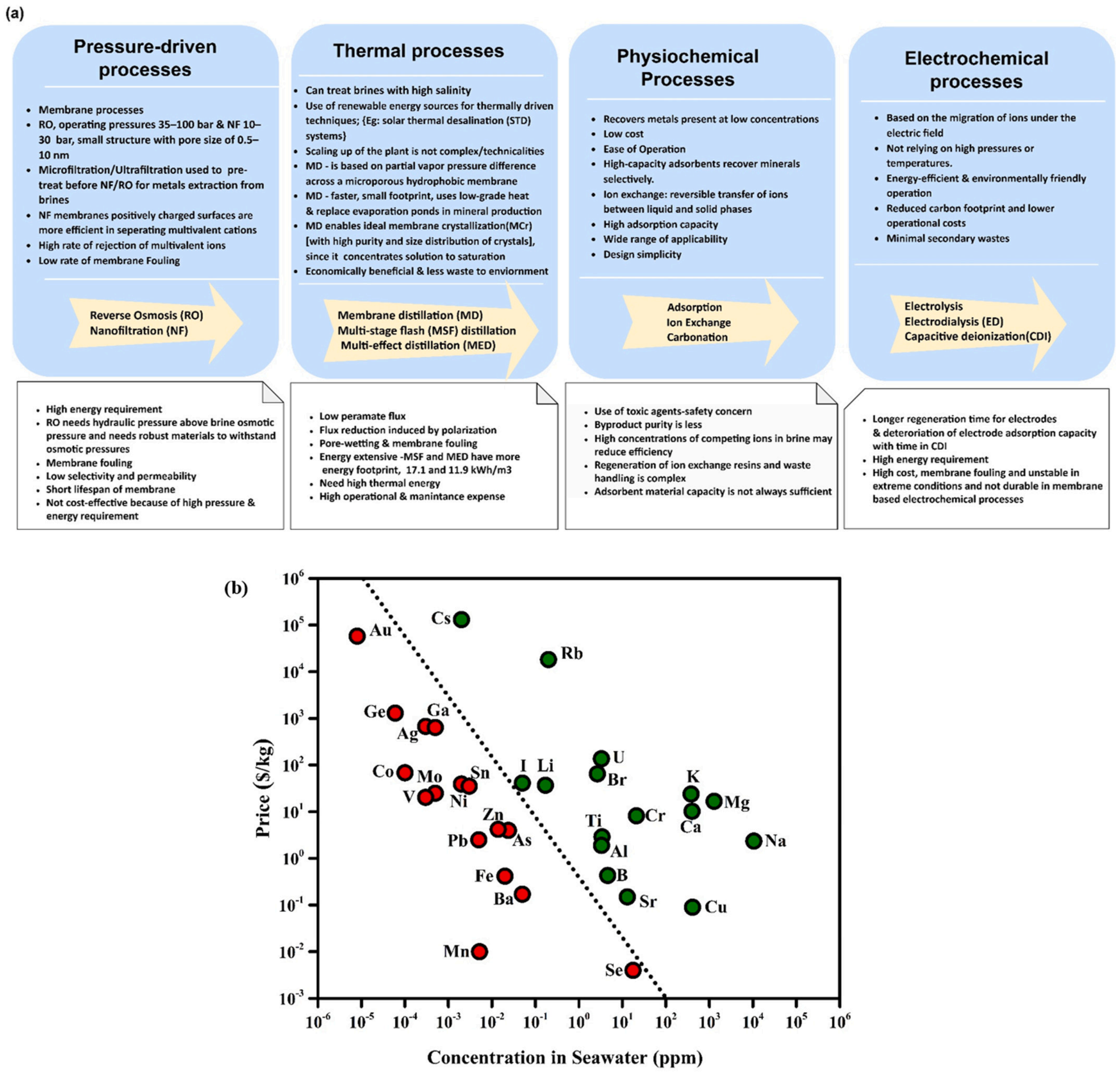
3.1.1. *Source of critical metals and elements*

Traditionally, seawater desalination is an energy-intensive process with considerable brine waste generation. The seawater hub concept shifts this perspective by emphasizing resource recovery from desalination to minimize environmental impact. As the concentration of discharge brine from desalination plants is usually double that of seawater [27], brine mining presents an effective method for resource extraction. This approach mitigates the environmental impact of brine disposal and could provide significant revenue streams from selling extracted commodities. Major seawater constituents, including Na, Mg, Ca, and K, can be economically extracted at scale using evaporation in solar ponds, precipitation, ion exchange, solvent extraction, and sorption. After salt extraction, residual minerals from seawater become considerably more concentrated, allowing for the recovery of critical elements like lithium, copper, and magnesium, essential for modern technologies like batteries, electronics, and alloys. In addition, SWRO brine is abundant in macronutrients such as nitrogen, phosphorus, and potassium, which are vital for plant growth. Organic matter and trace elements like boron can also be recovered from the brine, providing potential for biofuel production and materials like glass and ceramics.

Various techniques, including membrane technologies, forward osmosis, adsorption, and precipitation, can recover resources from desalination brine. High-performance RO and nanofiltration (NF) membranes show promise in desalination and resource recovery, ranging from high-value metals to dye molecules and nutrients like nitrogen and phosphorus [28]. Fig. 4a illustrates a classification based on the driving force employed, and it compares the pressure-driven, thermal, electro-driven, and other resource recovery methods from SWRO brine, highlighting their technological advantages and limitations. These techniques can be standalone or combined, contingent on the operational focus, to improve efficiency and reduce energy consumption in commercial scenarios. The economic viability of seawater or seawater brine mining primarily depends on the element price at the market, the concentration of elements in seawater, and extraction expenses. The basic screening of significant elements in seawater with economic gains is obtained from the log-log plot analysis as given in Fig. 4b. We have adopted the same analogy as used by Kumar et al. [29] to identify the potentially profitable distribution of elements for seawater brine mining. We revised the feasibility analysis using seawater element concentrations with updated 2022 market prices in the present study. The capital investment costs were not considered when performing the analysis, and the extraction cost ratio is assumed to be 1 for all elements. If the cost of the final product (element market value × element concentration in seawater) exceeds the cost of extraction, then that element is economically feasible for extraction and plotted a line that separates the 'economically viable' elements from the 'economically unfeasible'. The economic gains increased as the elements' concentration and market value increased. With increasing distance to the right of the separation line and further away from the horizontal axis toward the top, the economic benefit is anticipated to be more beneficial. If more practical and affordable extraction techniques/materials that are more cost-effective than mining them from lands can be identified, the elements in the feasible region on the right side of the plot could be desirable for extraction. It is also significant to note that seawater ion concentrations can vary widely depending on the geology, weather, and surface water runoff in each area. In such a scenario, Na, Ca, Mg, K, Li, I, Sr, Br, B, and U (and all the elements represented by green circles) would become potential targets for extraction.

Economic assessments are critical for evaluating the feasibility of methods or materials developed to extract various metals from seawater and to ascertain their competitiveness for production. Nevertheless, our economic analysis suggests more research is necessary for resource recovery from seawater to be cost-effective for most elements. Valuable metal ions like lithium (Li), uranium, rubidium (Rb), and cesium (Cs) occur in low concentrations (0.19–0.30) in seawater brine. Their selective separation from dominant ions and their precipitation and crystallization in a single-stage operation presents significant challenge.

3.1.1.1. Lithium. Lithium (Li) is a critical component of lithium-ion batteries (LIBs), which are widely used for energy storage in various applications because they offer advantages such as high energy density, high power density, and long life cycle [34]. Over the past 20 years, its demand has soared, especially from the electronic and automobile industries, leading to a 10-fold increase in the following [35]. Between 2020 and 2021, the demand for lithium rose by nearly 30 %, causing an extraordinary 300 % price hike, a trend projected to continue. The total lithium volume in seawater is estimated at approximately 230 Gt, surpassing terrestrial reserves [29]. Li extraction from concentrated brine is 30 % to 50 % less expensive than mined ores. High Li^{+}/Mg^{2+} solute-solute selectivity, improved water solute selectivity, and water permeability are necessary for this process [30]. Li extraction primarily relies on precipitation and ion exchange, involving the concentration of Li by



Pressure-driven processes

- Membrane processes
- RO, operating pressures 35–100 bar & NF 10–30 bar, small structure with pore size of 0.5–10 nm
- Microfiltration/Ultrafiltration used to pre-treat before NF/RO for metals extraction from brines
- NF membranes positively charged surfaces are more efficient in seperating multivalent cations
- High rate of rejection of multivalent ions
- Low rate of membrane Fouling

Reverse Osmosis (RO)
Nanofiltration (NF)

- High energy requirement
- RO needs hydraulic pressure above brine osmotic pressure and needs robust materials to withstand osmotic pressures
- Membrane fouling
- Low selectivity and permeability
- Short lifespan of membrane
- Not cost-effective because of high pressure & energy requirement

Thermal processes

- Can treat brines with high salinity
- Use of renewable energy sources for thermally driven techniques; {Eg: solar thermal desalination (STD) systems}
- Scaling up of the plant is not complex/technicalities
- MD - is based on partial vapor pressure difference across a microporous hydrophobic membrane
- MD - faster, small footprint, uses low-grade heat & replace evaporation ponds in mineral production
- MD enables ideal membrane crystallization(MCr) [with high purity and size distribution of crystals], since it concentrates solution to saturation
- Economically beneficial & less waste to envionrment

Membrane distillation (MD)
Multi-stage flash (MSF) distillation
Multi-effect distillation (MED)

- Low peramate flux
- Flux reduction induced by polarization
- Pore-wetting & membrane fouling
- Energy extensive -MSF and MED have more energy footprint, 17.1 and 11.9 kWh/m3
- Need high thermal energy
- High operational & manintance expense

Physiochemical Processes

- Recovers metals present at low concentrations
- Low cost
- Ease of Operation
- High-capacity adsorbents recover minerals selectively.
- Ion exchange: reversible transfer of ions between liquid and solid phases
- High adsorption capacity
- Wide range of applicability
- Design simplicity

Adsorption
Ion Exchange
Carbonation

- Use of toxic agents-safety concern
- Byproduct purity is less
- High concentrations of competing ions in brine may reduce efficiency
- Regeneration of ion exchange resins and waste handling is complex
- Adsorbent material capacity is not always sufficient

Electrochemical processes

- Based on the migration of ions under the electric field
- Not relying on high pressures or temperatures.
- Energy-efficient & environmentally friendly operation
- Reduced carbon footprint and lower operational costs
- Minimal secondary wastes

Electrolysis
Electrodialysis (ED)
Capacitive deionization(CDI)

- Longer regeneration time for electrodes & deterioration of electrode adsorption capacity with time in CDI
- High energy requirement
- High cost, membrane fouling and unstable in extreme conditions and not durable in membrane based electrochemical processes

Fig. 4. (a) Broad categorization of resource recovery techniques along with the advantages and challenges. (b) Analysis of average concentration of elements in seawater vs. Latest market prices for screening the economic feasibility of seawater mining. The costs were taken from the latest USGS Mineral Commodity Summaries 2022, [30] except for Na, K, Ca, and U [31]; Element concentrations in seawater were obtained from [32,33].

rejecting other monovalent ions such as Na^+ and K^+ and the removal of impurities like B.

Various materials have been used as lithium-ion sieves (LIS) to selectively adsorb Li^+ from water resources, such as $H_{1.6}Mn_{1.6}O_4$, $H_{1.33}Mn_{1.67}O_4$, MnO_2, and H_2TiO_3. These inorganic powders are often processed into composites for easy handling and reuse, with Li^+ capture and composite adsorbent regeneration performed via a moderate acid-stripping solution [36]. However, the powdery nature of LIS adsorbents can cause congestion and pressure drops in fixed-bed columns, slowing filtration rates. To tackle this, researchers are exploring adsorbents combined with electrochemical Li^+ recovery, offering broader ionic species recovery from various water sources by adjusting the electrodes and system configurations. In electrochemical resource recovery, ions migrate directionally under an electric field. While multiple ED stages enhance the purity of recovered brine components, they increase operational costs and energy consumption, requiring a balance between price and performance.

Guo et al. proposed a two-stage ED configuration for waste brine component separation [37]. In the first stage, monovalent cation/anion exchange membranes (MCEM and MAEM) are used to extract monovalent ions, such as Li, Na, and Cl, from brine. The mother liquid is transferred to stage 2 for further ion separation. By-products include lithium chloride, magnesium sulfate, sodium chloride, and potassium chloride, and under ideal circumstances, the Li recovery ratio was 76.45 %. Thermal-driven techniques, like membrane distillation crystallization (MDC), can extract other resourceful ions, like lithium and strontium, from brine in desalination plants [38]. However, MDC applications in large-scale industries are still developing due to low selectivity for Li^+ recovery in seawater brines with varying interference ions. Lithium production from brines by various techniques is given in Fig. 5a.

Utilizing various technologies, including solvent extraction, ion exchange, membrane processes, or adsorption, lithium can be extracted from SWRO brine [39]. These phases could change, though, depending on several variables, including scale, location, technology, and economics. Brine is rich in lithium chloride (LiCl), and subsequent treatments are required for battery applications. Removal of impurities such as sodium, magnesium, calcium, sulfate, and bromide from LiCl using selective precipitation, crystallization, or electrochemical methods is crucial. LiCl is the primary raw material to produce desired Li compounds or Li metal. Lithium carbonate (Li_2CO_3) and lithium hydroxide monohydrate ($LiOH.H_2O$) are the recommended primary minerals for battery-grade lithium [40]. The lithium recovery system reported that utilizing a k-MnO_2-Ag rechargeable battery can significantly recover lithium from brine with magnesium ions, which has an efficiency of 1.0 Wh per 1 mol of lithium [41]. Avdibegović et al. proposed a one-step solvometallurgical process that uses ethanol as a green solvent and $LiOH{\cdot}H_2O$ as a reagent to dissolve LiCl and precipitate $Mg(OH)_2$ selectively and $Ca(OH)_2$ from SWRO brine, resulting in a high-purity LiCl solution (>99.5 % Li) at room temperature [42]. Recently, Hu et al. [43] presented a one-step technique to electrochemically extract lithium from low-concentration solutions (such as brine, seawater, or discarded lithium-ion batteries) into a form that immediately produces commercial battery materials, skipping the expensive processes of lithium separation and purification. The Li extraction device and working mechanism by this approach are given in Fig. 5b. By this approach, Li was selectively extracted and processed to form battery cathodes, such as spinel $LiMn_2O_4$ and layered $LiNi_xMn_yCo_zO_2$. According to the techno-economic analysis, the prepared cathode materials provide economic advantages over commercial cathodes. Li-ion batteries are crucial to the overall decarbonization effort, therefore, the demonstration of a one-step Li extraction to a ready-to-use material could increase access to Li resources at a lower cost by removing processing steps.

Research is also being conducted on combining various techniques to enhance Li recovery efficiency. For example, incorporating high surface area nanofibers into Li-based adsorbents has shown high effectiveness in capturing Li from seawater. Additionally, due to advances in Li recovery from brine, most Li is now produced from brine concentrations ranging from 300 mg/dm^3 to 1600 mg/dm^3 [44]. These findings could enable practical, industrial Li recovery from seawater, with electrochemical systems providing a faster alternative to conventional methods. The extraction of lithium from seawater brine streams can help to build a circular economy that encourages the development of Li-ion batteries for EVs and solves intermittent issues of renewable energy sources. Furthermore, because seawater is an unlimited resource, this strategy is sustainable for supplying rising lithium demand.

3.1.1.2. Uranium.

Uranium recovery from seawater, which contains nearly 1000 times more uranium than conventional ore reserves, has the potential to sustain nuclear power as conventional reserves deplete. Despite the low concentration, desalination brine rejects, which has a significantly higher uranium concentration, present a feasible source for uranium recovery. Electrochemical methods using modified carbon electrodes show promise for uranium extraction from seawater [33]. Amidoxime is considered as a promising adsorbent for uranium extraction. A technique using irradiated and amidoximated low-cost polyacrylonitrile fibers as a uranium recovery agent has been reported successful [34]. The fibers display super adsorbent properties, offering a new method for absorbing uranium ions released into seawater. Their kinetics of saltwater absorption is relatively fast, achieving a swelling ratio of about 300 % within 5 min.

Wiechert et al. conducted 84-day adsorption experiments using amidoxime adsorbents to measure the concentration and adsorption of seven metal ions, including uranium, zinc, copper, iron, vanadium, calcium, and magnesium, in seawater and brine reject from desalination plants [45]. The results showed higher uranium adsorption in seawater than in brine due to competition from iron and vanadium. Minimizing the impact of competing ions is crucial to harness brine reject as a uranium resource. In a separate study, Wongsawaeng et al. [46] explored direct uranium recovery from rejected brine concentrate by submerging amidoxime adsorbents in continuously flowing discharged brine concentrate (Fig. 6a). They found that increased soaking time and higher flow rates improved uranium uptake. Adsorbent created by gamma irradiation demonstrated the highest uranium absorption at 1.39 mg/g with a brine flow rate of 20,000 L/h. For adsorbents with capacities of 1.39 and 2 mg/g, the estimated costs of uranium recovery at a large-scale SWRO plant were 406.81 and 338.95 USD/kg uranium, respectively. Although these exceed the current spot price of uranium

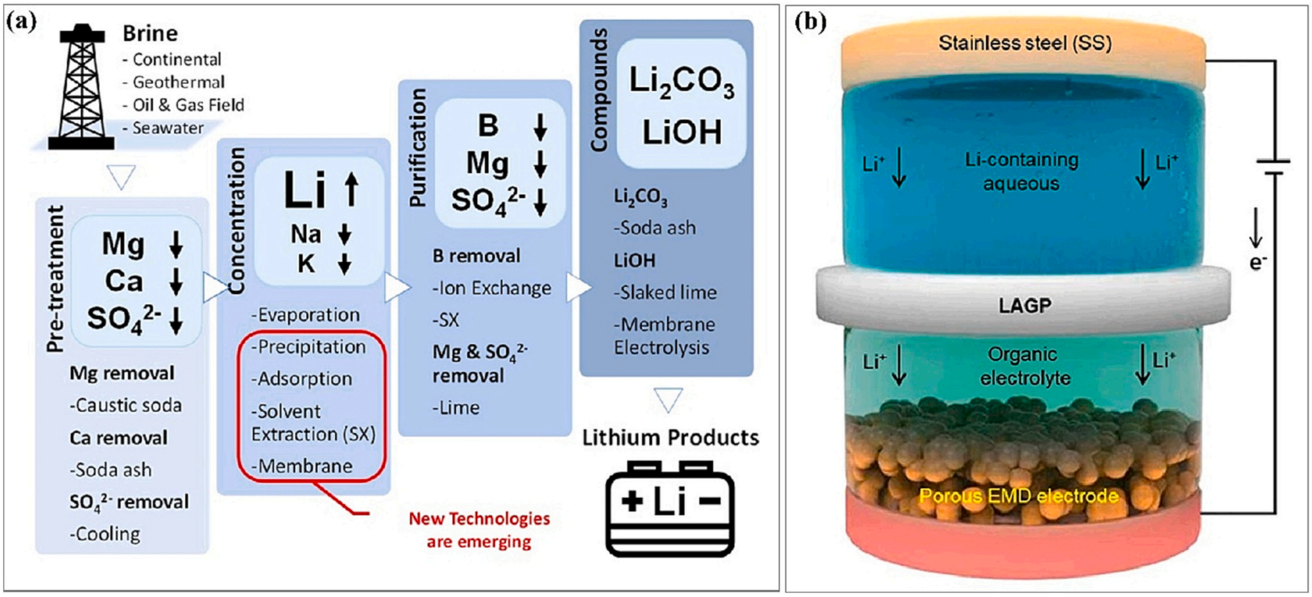


Fig. 5. (a) Li production process from brine sources [29]. (b) Schematic of the Li extraction device: the cathode and anode chambers are separated by a Li-ion-selective membrane [43].

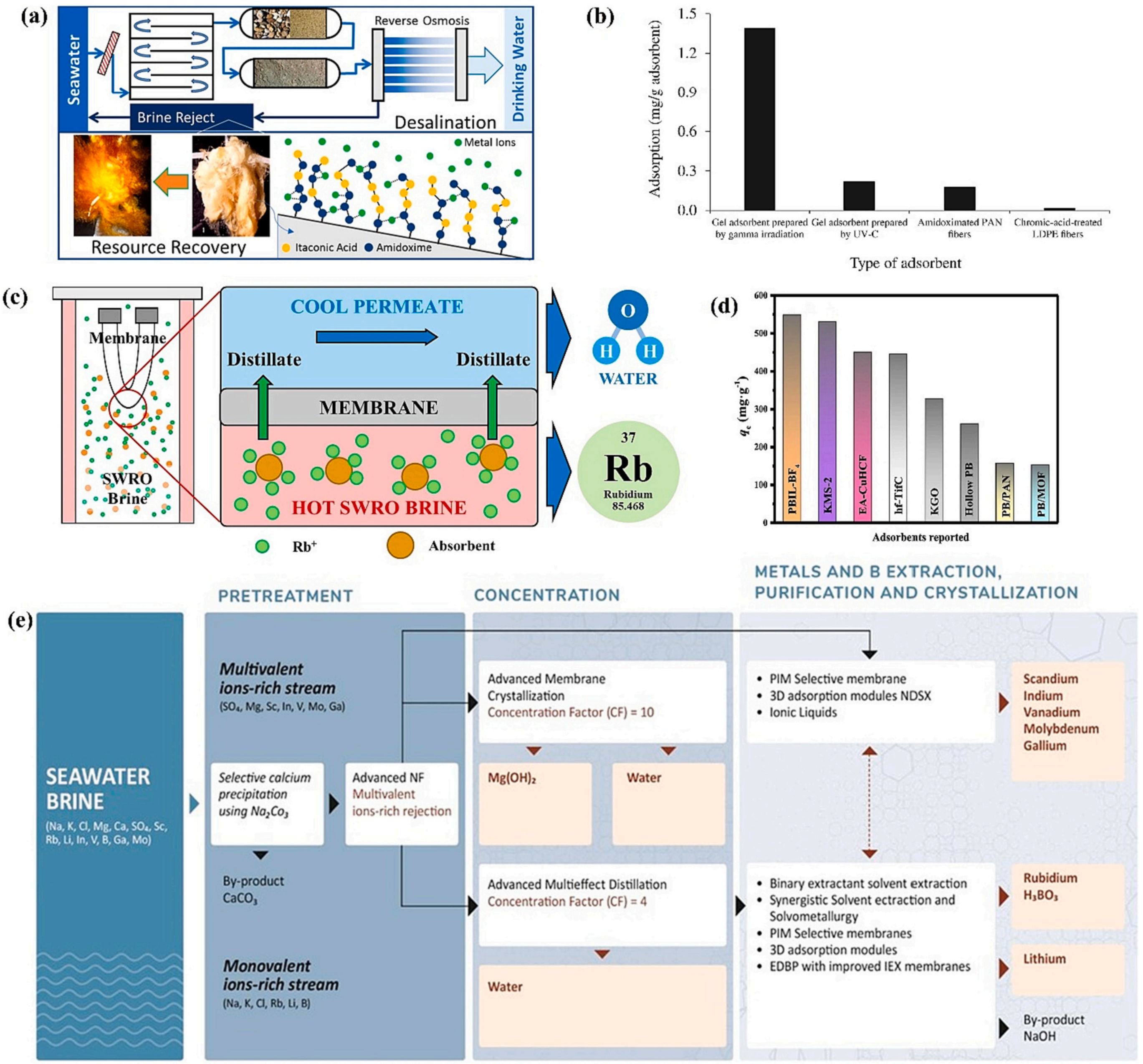


Fig. 6. (a) Uranium resource recovery using amidoxime functionalized adsorbent from desalination reject brine [45]; (b) Highest uranium adsorption from brine concentrate for each adsorbent (20,000 L/h flow rate) [46]. (c) Rubidium recovery by submerged membrane distillation-adsorption integrated system [49]. (d) A comparison of the adsorption capacity of various reported adsorbents for Cesium recovery [50]. (e) Scheme of process flow projected by the SEA4VALUE project for recovering metals by the multi-mineral modular brine mining process (MMBMP) [55].

(112 USD/kg as of March 2023 [47]), the use of more efficient adsorbents can reduce recovery costs. These findings highlight the need for further research to optimize uranium recovery from brine rejection. Integrating the adsorbent system with existing infrastructure can decrease deployment costs and mitigate biofouling risks by utilizing the desalination plant's filtration systems. This approach could potentially enable the recovery of other valuable minerals, such as lithium, magnesium, and vanadium.

3.1.1.3. Rubidium. Rubidium (Rb), a trace metal widely used in laser technology and fiber optic transmission, has a high market value [24]. Recovering Rb from SWRO brine could generate economic benefits and potentially offset brine treatment costs [30]. Rb can be extracted from seawater brine or simulated solutions using transition metal hexacyanoferrates (KMFC, M = Cu, Ni, Co, Fe). Due to the specific selectivity of these materials, adsorption techniques are primarily employed for Rb recovery. However, potassium ions in seawater often hamper Rb extraction efficiency. A potassium-based adsorbent (KCuFC) has been developed to address this issue. The unique Rb selectivity of KCuFC arises from its exchangeability with structural potassium in the ion-exchange adsorbent, attributable to their similar unhydrated ionic radii. An integrated MD-KCuFC (PAN) system was reported for simultaneous water recovery and Rb extraction from SWRO brine, enabling extended residence time for Rb sorption [48]. The system recovers 2.26 mg of Rb from 12 L of SWRO brine and achieves an additional 65 % water recovery. In a separate study, Choi et al. [49] examined an integrated submerged MD-KCuFC adsorption system, achieving a recovery ratio of 81 % and Rb extraction recovery ratio of 87 % using granular

KCuFC adsorbent in multiple cycle operations. Desorption using a 0.2 M NH_4Cl solution proved effective for Rb extraction and KCuFC reuse.

3.1.1.4. Cesium. The recovery of cesium from natural brine feedstocks, including seawater, has led to an increased focus on sorbents and ion exchangers due to the high purity of the recovered products, growing market demand, and the gradual depletion of high-grade cesium ores [50]. The organic ion exchanger $K_2CoFe(CN)_6$, initially designed for purifying high-salt concentrates at nuclear power stations, has proven efficient for trapping Cs from aqueous solutions [51]. Peterskvá et al. [52] explored the extraction of metals, including uranium, rubidium, cesium, and lithium, from RO brine at a facility at El Prat de Llobregat, Spain, using various sorbents. Among the tested materials, the hexacyanoferrate-based extractant, Cs-Treat, emerged as the most effective for both cesium and rubidium. The study revealed that salinity significantly impacts cesium sorption affinity onto Cs-Treat, with transition metal hexacyanoferrates-based sorbents showing selectivity for cesium [53].

The recovery of these metals/minerals from seawater or brine is primarily studied through adsorption/desorption and ion exchange processes [54]. Fig. 6a-d outlines various recovery techniques and adsorbents for key elements. Raffaele et al., as part of the SEA4VALUE project, assessed the feasibility of recovering elements like Li, B, Mg, Sc, V, Ga, Rb, Mo, and In from seawater desalination plant brines [55]. To achieve this, technological advancements like enhanced nanofiltration, membrane crystallization, advanced multi-effect distillation, and selective processes, such as adsorption and solvent extraction, are being developed (Fig. 6e). Various hybrid resource recovery methods from seawater and seawater brine are summarized in Table 2. Despite the reduced environmental impact of metal recovery compared to mining, further research is necessary to improve metal recovery efficiency and the feasibility of industrial integration.

3.2. Salt recovery and conversion to chemicals

Salt, a valuable resource recoverable from SWRO brine, can be obtained through thermal evaporation, membrane-based technologies,

Table 2
Integrated techniques for resource recovery from seawater/seawater brine.

Hybrid techniques	Feed solution	Cost	Recovery	Extracted products	Remarks	Ref.
RO, BC, BCr & WAIV	Seawater	US\$0.99/m^3 -US \$1.01/m^3	85.75 %–99.14 %	Water & mixed salt	The ZLD treatment system with WAIV crystallization presents lower cost and energy demands	[56]
NF, RO, BC & BCr	Seawater	US\$1.04/m^3 -US \$1.37/m^3	99.06 %–99.36 %	Water, NaCl & mixed salt	The profit gain varied from US\$181.44/day to US \$357.8/day. Each of the two ZLD treatment systems is lucrative.	[57]
MD & adsorption	Seawater	N/A	85 % (water) 59.9 %–97.5 % (Rb)	Water & rubidium	Feed flow rate: 0.8 L/ min; Feed composition: Na$^+$ (24,433–24,641 mg/L), Mg^{2+} (2741–2842 mg/L), K$^+$ (865–896 mg/L), Ca^{2+} (950–952 mg/L), Cl$^-$ (38,815–44,205 mg/L), SO$_4^{2-}$ (5499–5543 mg/L), Rb$^+$ (4.95–5.05 mg/L); Rubidium adsorption was improved when MD used in a continuous supply procedure.	[49]
ED & IEX	Seawater	N/A	76.45 % (LiCl)	Water & LiCl	Feed composition: Li$^+$ (0.14 g/L), Na$^+$ (20.81 g/L), K$^+$ (0.69 g/L), Mg^{2+} (2.25 g/L), Ca^{2+} (0.39 g/L), Cl$^-$ (37.32 g/L), SO$_4^{2-}$ (4.73 g/L), LiCl/MgCl$_2$/MgSO$_4$ ratio was 1:1.461:0.085; Energy demands: 0.66 kWh/(mol Li)	[49]
MD & RO	Seawater	N/A	65 % (water)	Water & rubidium	Feed flow rate: 100 mL Feed composition: Na$^+$(22,100 mg/L), Mg^{2+} (2570 mg/L), K$^+$ (783 mg/L), Ca^{2+} (894 mg/L), Cl$^-$ (41,400 mg/L), SO$_4^{2-}$ (8050 mg/L), Rb$^+$ (0.2 mg/L)	[48]
RO, MD & MCr	Seawater	€1.09/m^3	N/A	Water, CaCO$_3$, NaCl& KCl	The flux decreased from 3 L·m^{-2}·h^{-1} to 1 L·m^{-2}·h^{-1} during the 3-h procedure.	[58]
(1)RO-BC-BCr (2) NF-RO-BC (multiple)-BCr (multiple)	Seawater	US\$1.04/m^3 -US \$1.37/m^3	99.06–99.36 %	Freshwater, NaCl & Mixed salt	Feed flow rate: 100 m^3/ day Feed salinity: 38 g/L (Eastern Mediterranean water); The profit ranges from US\$181.44/ day to US\$357.8/ day - Both treatment systems are profitable	[57]
NF-MRC-MED-NTC	SWRO brine	Salt 0.99 \$/m^3 freshwater 1.01 \$/m^3	NaCl 97 %	Water and salts: Mg (OH)$_2$, Ca(OH)$_2$ and NaCl.	MLD process consists of: Nanofiltration NF (separation of bivalent from monovalent ions), (ii)Mg Reactive Crystallizer, MRC selective recovery of Mg and Ca, (iii)MED (freshwater production), (iv) NaCl Thermal Crystallizer NTC (NaCl recovery)	[59]
MD-MSF-Cr	SWRO brine	\$2.0/m^3	89 % water recovery rate, 35.97 kg/m^3 of Na$_2$SO$_4$.	Water and Na$_2$SO$_4$	The gained output ratio increased with the number of stages from 2.77 to 4.0, stabilizing at a flow rate of 700 L/h at 70 °C for 40 stages.	[60]
MED & TVC	Seawater brine	Variable	>90 %	Water & mixed salt	Brine treatment is lucrative. Waste-heat integration lowers the cost of treatment. Feed flow rate is 22.42 m^3/day; Feed brine salinity is 72,000 mg/L	[61]
NF, ED& EDBM	SWRO brine	–	>70 %	Water, HCl & NaOH	NF was used to concentrate and separate Ca-Mg from RO brine for phosphate recovery. EDBM was applied to produce HCl and NaOH as chemicals for desalination treatments.	[62]
MD, MCr	SWRO brine	–	Water (recovery 98.6 %), Mg (66.2 %), Li (73.8 %)	Water, Magnesium, Lithium	Employing MCr, it is possible to recover many different ions from seawater. It can recover NaCl, KCl, NiCl$_2$ also	[63]
MSED, BMED	SWRO brine	\$0.50/kg	~92 %	coarse salt	Operating at a current density of 10 mA/cm^2 and a 100 mS/cm feed conductivity by employing a BMED stack equipped with BP-1 membranes. It is appropriate and competitive for industrial applications.	[64]

and crystallization. It can be used in the chemical industry to produce chlorine and caustic soda and in the food industry for preservation. Electrodialysis metathesis (EDM) is a process that separates ions from SWRO brine into two high-solubility salt solutions containing Na^+ salts and Cl^- salts (Fig. 7a). It follows the metathesis reaction MX + NaCl → NaX + MCl, where NaCl is substituted by another solution [65]. Diluted recirculation to RO boosts water recovery, and crystallizers recover Na_2SO_4 and NaCl from concentrated solution after Ca^{2+} and Mg^{2+} precipitation. In a study by Kumar et al. [66], they proposed the integrated valorization of desalination brine through NaOH and HCl recovery. Using membrane-based processes, resources in SWRO brine, specifically NaCl, can be recovered as valuable chemical commodities

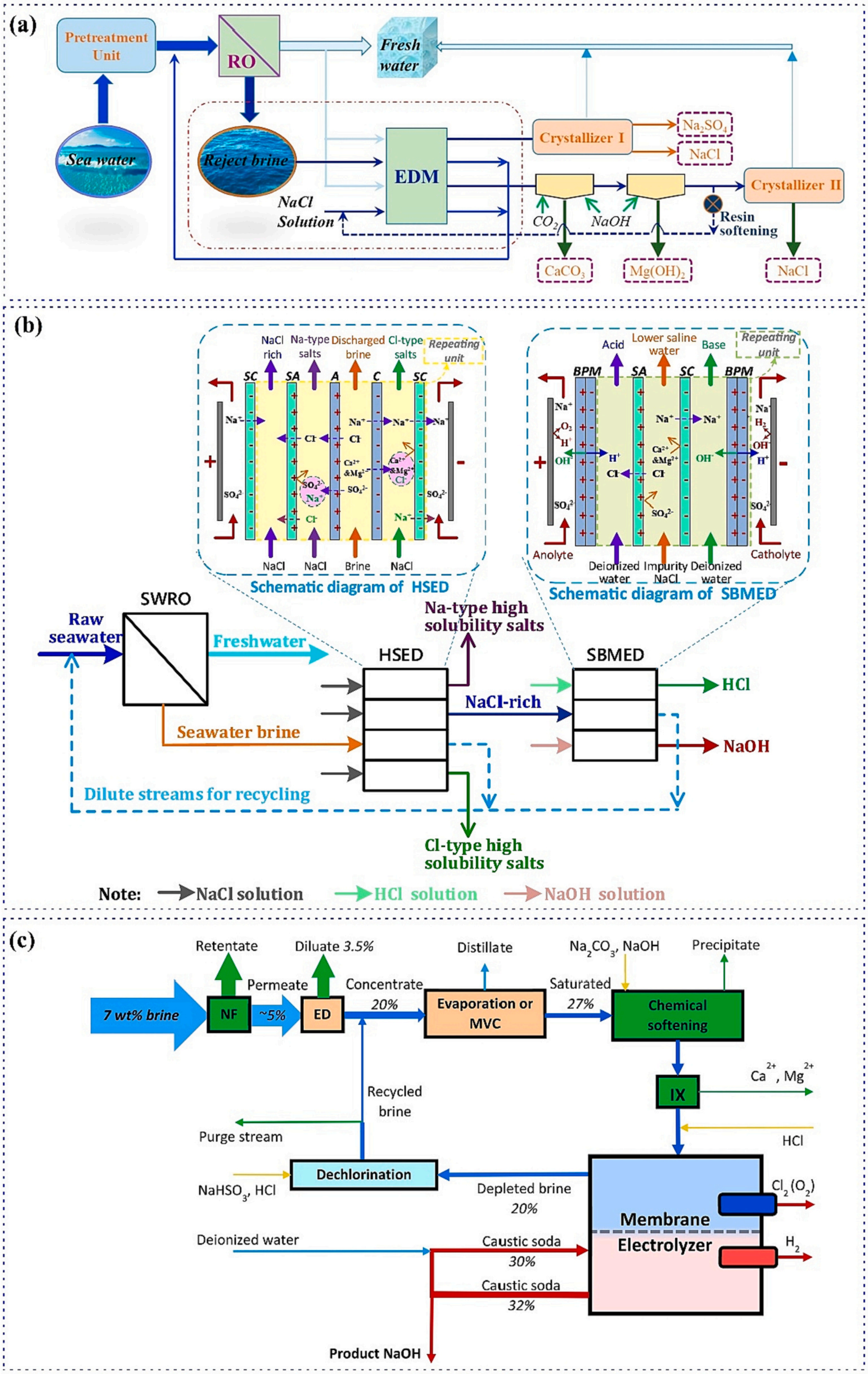


Fig. 7. (a) Process design for SWRO-EDM for water and salt recovery [65]. (b) Schematic illustration of seawater brine effluent valorization based on the novel hybrid ED system [67]. (c) Brine to NaOH system block flow diagram [68].

such as NaOH and HCl. This is achieved by pretreating the SWRO brine through nanofiltration, selective electrodialysis (SED), or electrodialysis (ED) and processing it by electrodialysis with bipolar membranes (BMED) to yield the desired products.

Producing NaOH and HCl from brine requires catalysts that enable H_2 gas generation through water reduction and selective O_2 production over chlorine gas within BMED conditions. NF, SED, and ED are distinct pretreatment techniques that enhance the BMED system. NF purifies brine to contain monovalent ions primarily, SED segregates monovalent and multivalent ions, and ED forms concentrated ionic salt streams. These methods provide various approaches to valorize SWRO brine. A forward-thinking strategy for brine valorization at a seawater desalination plant is integrating the water, chemical, and renewable energy industries. This strategy promotes sustainability and economic benefits by recycling brine, producing freshwater, NaOH, and HCl [66], and directly contributing to desalination, with H_2 gas as an energy source. Chen et al. proposed a novel hybrid SED (HSED) coupled with a selective BMED (SBMED) system, an innovative approach that simultaneously recovers Ca^{2+}, Mg^{2+}, and SO_4^{2-} when supplemented with NaCl (Fig. 7b) [67].

Du et al. developed a process for producing sodium hydroxide from seawater desalination brine using membrane chlor-alkali electrolysis [68]. As shown in Fig. 7c, this multi-step process involves nanofiltration, concentration, softening, dechlorination, and membrane electrolysis. Not only does this approach cut effluent output from a reverse osmosis facility by nearly 29 % and boost water recovery from 50 % to 57.5 %, but it also streamlines the typical procedures in the chlor-alkali and desalination sectors, including NaCl and NaOH concentration, transportation, and dilution. Additionally, this process can generate revenue from byproducts like hydrogen, chlorine, and sodium hypochlorite, which can largely offset operation costs. If applied to all brine from a large-scale SWRO facility (about 10,000 kt/year), the process could yield around 35,000 tons of saleable caustic soda. While the recovered acid and base fall short of commercial quality standards, their onsite usage at the desalination plant is feasible despite high energy demands currently posing a hurdle for market entry. Further research is crucial to enhance the quality of recovered chemicals, advance the selectivity of membranes, streamline the process, assess post-concentration systems, and upscale technology.

4. Source of energy management and generation (durable and affordable technology)

Continued research into energy-saving strategies has enabled the recovery of about half of the energy used in seawater desalination. The most energy-demanding part of the SWRO plant is the RO process, consuming 2 kWh/m^3, while the remaining stages, like seawater intake, pre-filtration, permeate treatment, and distribution consume 0.45, 0.24, 0.4, and 0.22 kWh/m^3, respectively [69]. Several adopted strategies to decrease the specific energy consumption in SWRO plants include using ERDs. A comparative analysis depicts the effectiveness of various ERD types in reducing SEC. Additionally, SWRO brines can be valorized through energy recovery by harnessing salinity gradient power technologies [70], capitalizing on the brine's high salt concentration and osmotic pressure.

4.1. Energy recovery devices

The high osmotic pressure of saline feed water necessitates high-pressure pumping, resulting in a highly compressed saline concentrate stream. The centrifugal-type ERDs in SWRO plants, such as turbines, can convert the hydraulic energy of the concentrated brine stream into mechanical energy to drive a piston or pump [71]. Currently, the most efficient ERD option is the pressure exchanger (PX), directly transferring the pressure from the brine to the feed stream, offering 95–97 % efficiency. The type of ERD used in SWRO plants depends on the system's size, efficiency, and cost [10,72,73]. The energy recovered by the ERDs either assists the feed pump or directly drives part of the feed flow, reducing the energy demand on high-pressure pumps (HPPs) [74]. As shown in Table 3, ERDs can cut SEC by up to 60 % in the SWRO process [10], with ERD's capital expenditure (CAPEX) representing just 1 % of the total plant costs [69]. Piston-driven ERDs, though less compact and modular due to the need for control actuators and valves, have higher purchase and maintenance costs than pressure exchanger devices [74]. Its popularity in SWRO facilities is due to its compact size, stability, modular design, and effectiveness at recovery rates of up to 50 % [72].

Table 3
Efficiency and specific energy consumption of the ERD.

ERD's	ERD efficiency	SEC
Turbine	75 %	> 6kWh/m^3
Pelton Wheel	85 %	3.5–5.9 kWh/m^3
Piston driven ERD	95–97 %	3.5–4.6 kWh/m^3
Rotary driven ERD	95–97 %	3–5.3 kWh/m^3

4.2. Osmotic energy recovery (RO-PRO, RED)

RO technology demands significant energy input to derive freshwater from seawater. Incorporating efficient energy recovery systems can reduce both the costs and energy consumption of SWRO plants. Hybrid systems pairing RO with either pressure retarded osmosis (PRO) or Reverse electrodialysis (RED) are potential solutions for SWRO desalination. These configurations introduce a more diluted waste stream into the process, thus effectively lowering the desalination system's overall energy consumption.

4.2.1. RO-PRO

The pressure retarded osmosis (PRO) process is the critical solution to significant challenges such as managing concentrated brine and energy consumption associated with SWRO. As a post-treatment step in existing desalination facilities, the membrane-based PRO process can convert the retentate's osmotic energy into hydraulic pressure, which is then harnessed for electricity generation in a turbine. This method, developed by Sidney Loeb in the 1970s, is a variant of FO and uses the chemical differences between liquids with varying salt concentrations to generate renewable energy [75]. High osmotic power is inherent in the highly saline RO concentrate. A semi-permeable barrier separates two solutions with differing osmotic and hydrostatic pressures. As water crosses the membrane from the low to higher osmotic side, countering the hydrostatic pressure gradient, an excess of diluted and hydrostatically compressed seawater is produced. This additional volume of water is used to generate power, utilizing energy recovery device [76,77] or a hydro-turbine [78] to harness the increase in osmotic pressure on the draw side. From an energy balance perspective, the energy required for high-pressure pumping (hydrostatic pressure) effectively serves the role of osmotic pressure. The RO-PRO hybrid system not only conserves energy but also dilutes RO concentrate back to seawater levels, mitigating the impact of discharge on marine ecosystems [79]. Theoretical studies conducted by Wan et al. highlight the energy-saving potential of this system over standalone RO, contingent on the availability of a dilute waste stream [80]. Fig. 8 compares the SEC of various SWRO processes: (1) SWRO alone, (2) SWRO with a pressure exchanger (SWRO+PX), and (3) SWRO with pressure exchangers and PRO (SWRO + PX + PRO). Notably, the integrated SWRO-PRO process demonstrates the lowest SEC. When SWRO operates at 25 % and 50 % recovery and brines are diluted to seawater levels, the SECs required to produce 1 m^3 of desalinated water can be reduced to 1.08 kWh and 1.14 kWh, respectively. This highlights the necessity of determining the ideal operating pressure for the PRO process to enhance its average power density and reduce the integrated SWRO-PRO process's SEC. While SWRO and PRO integration is possible, the development of new PRO membranes is imperative to

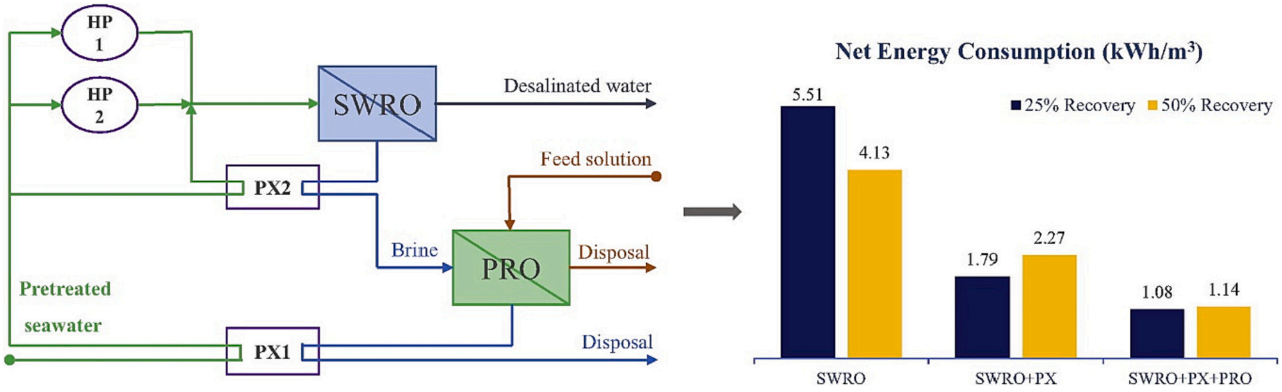


Fig. 8. Schematic of the integrated SWRO–PRO processes and the comparison of minimum SECs of SWRO, SWRO + PX, and SWRO + PX + PRO systems [80].

maintain the PRO system's ideal operating pressure and achieve the necessary high-water flux.

Beyond the RO-PRO hybrid, there are investigations into the feasibility of RO with both open and closed-loop configurations, as illustrated in Fig. 9a and b [81]. The RO with open-loop PRO (RO + oPRO) configuration captures osmotic energy using ERDs, reducing the RO's OPEX. However, increased CAPEX undermines its profitability. Conversely, the RO with closed-loop PRO (RO + cPRO) system recycles pressurized and diluted brine as seawater feed to RO while also capturing osmotic energy. This approach reduces both OPEX and CAPEX by eliminating the need for additional ERDs and downsizing the seawater intake, pre-treatment, and brine discharge units.

Touati et al. combined PRO, SWRO, and nanofiltration technologies to produce irrigation water, drinking water, and power [82]. In this configuration, the SWRO brine was used as the draw solution, with the nanofiltration concentrate serving as the feed for the PRO unit (Fig. 9c). Tests showed over 0.38 kWh/m^3 of the system's consumed energy was recovered, making the system economically viable when using \$5/m^2 membranes, and maintaining current PRO membrane performance. Higher membrane prices above \$15/m^2 would necessitate improvements in membrane performance. Li et al. noted that RO-PRO could reduce energy consumption compared to standalone RO, but at the cost of requiring larger membrane areas and operating at lower recovery rates [83]. They also noted the need for pre-treatment due to PRO's susceptibility to significant fouling [84,85]. While there are clear advantages to hybrid RO-PRO plants, the barriers to commercialization remain. Further pilot or operational scale research is needed to quantify and evaluate these benefits accurately.

4.2.2. RED

Reverse electrodialysis (RED), an innovative technology, can generate renewable, commercial-grade power from salinity gradients. Integrating RED with the SWRO desalination process, where SWRO brines are used as high-salinity feeds, reduces energy consumption during desalination [86,87]. This prospect has driven efforts toward commercializing desalination-RED hybrid plants. In RED, ions transverse through alternating cation and anion exchange membranes (CEMs and AEMs), arranged in a sequence of nearby high and low-concentration compartments (HCC and LCC) filled with saltwater and freshwater, respectively. The sequence generates a potential gradient, allowing selective ion transport across the membranes. The ionic flux is converted into electricity by an electrode connected to an external circuit [88]. Incorporating RED into desalination systems provides a cost-effective, fully renewable, and sustainable energy source [89]. The process emits no greenhouse gases, making it an ideal strategy for decarbonizing desalination. Additionally, RED can enhance power density and water recovery rate in desalination technologies while mitigating the environmental risks associated with brine discharge [90].

RED's energy recovery potential has been explored through integrated schemes, utilizing a third process to optimize water recovery or energy savings by employing desalination brines as concentrates. Investigations have focused on co-producing water and energy by integrating SWRO desalination with membrane capacitive deionization (MCDI) or direct contact membrane distillation (DCMD) alongside the RED system to increase desalination's energy efficiency [91,92]. Jang et al. [93] reported that various advantages could be obtained from integrating RO and RED systems, depending on configurations. If a solution from the RED process is used as a feed for the RO process, it can reduce the energy consumption of the RO process. Conversely, using concentrated water from the RO process as feed for the RED system can enhance the RED system's power density.

Fig. 10a presents the RO-RED scheme, where RO desalinates seawater, and RED receives the SWRO brine and secondary effluent, preventing seawater contamination by organic micropollutants. Despite RED generating more due to the higher concentration, the RO-RED configuration's overall energy balance might be less favorable. The model predicts energy consumption to be approximately 1 kWh/m^3 for RO-RED [86]. Complex schemes, such as RED pre- and post-treatment or brine recirculation (Fig. 10b), were assessed, but similar energy performances were projected.

Choi et al. [92] highlight the potential of a hybrid membrane capacitive deionization (MCDI)-RED system to enhance SWRO desalination's energy efficiency. Due to MCDI and RED's efficient integration, the energy efficiency of the RO-MCDI-RED hybrid system was markedly improved. Optimal operating conditions for the hybrid system involved applying 0.8 V on MCDI at 50 % and 80 % of water recovery for the first and the second pass RO, respectively. Compared to a conventional two-pass RO system with or without RED, the hybrid system reduced energy consumption by 39 % and 17 %, respectively. Tufa et al. [91] studied an integrated MD-RED design for energy-efficient seawater desalination (Fig. 10c), reporting up to 17 % reduction in electrical energy consumption for the hybrid system incorporating RED. The inclusion of an MD unit downstream of the RO brine led to a substantial enhancement of the water recovery factor, allowing the production of a highly concentrated brine that augments the electrical power generated by the RED unit.

The RED system, less susceptible to fouling, can maintain performance over extended periods. While RED's power density is lower than PRO, it can be improved by modifying the cell's design, membrane resistance, and length [70]. A clear advantage of RED over PRO is its ability to convert salinity gradient energy (SGE) into electricity directly, bypassing intermediate energy conversion stages (mechanical into electric). However, fewer studies have explored integrating SWRO with RED for energy recovery from brine than other energy recovery methods. The performance of the RED system and the hybrid system need further refinement and development to commercialize the RO-RED hybrid system.

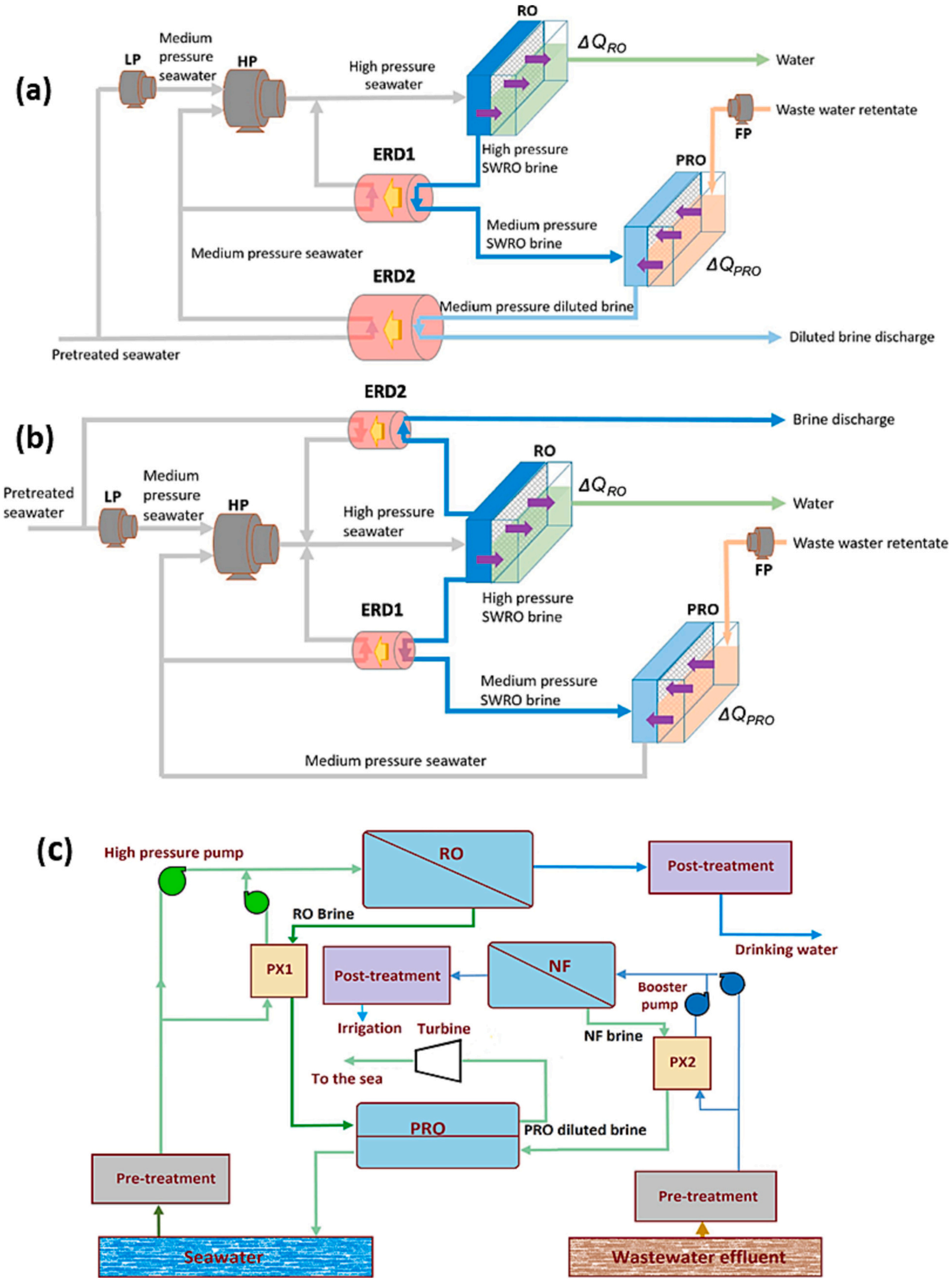


Fig. 9. (a) RO with open-loop PRO (RO + oPRO). (b) RO with closed-loop PRO (RO + cPRO) integrated process [81]. (c) Combined SWRO-PRO-NF for drinking water, energy, and water for irrigation production (Redrawn, [82]).

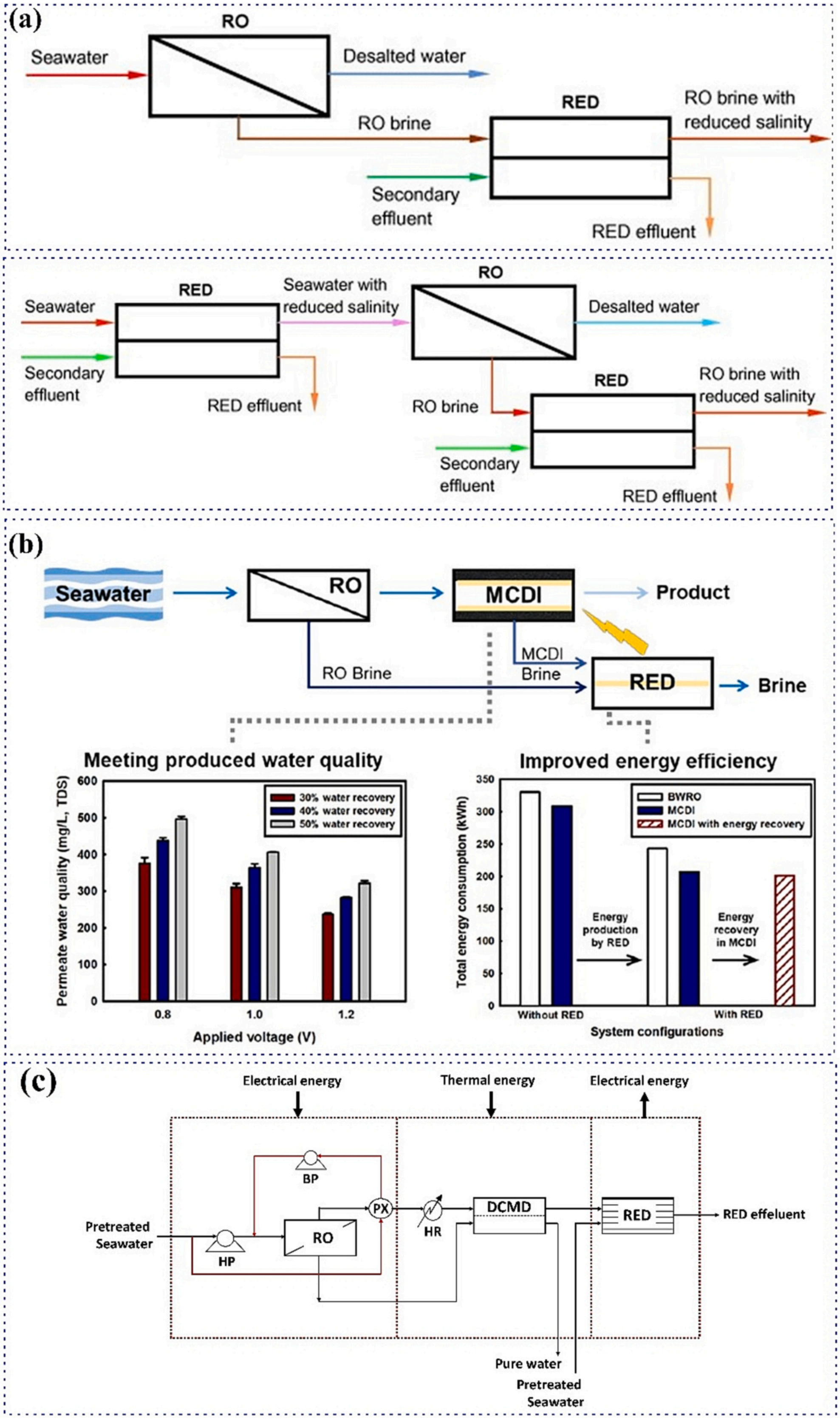


Fig. 10. Desalination systems with RED. (a) RED–RO hybrid processes: RO ⇒ RED mode and a complex arrangement RED ⇒ RO ⇒ RED mode [86]; Conceptual design of (b) novel RO-MCDI-RED [92] and (c) RO-DCMD-RED hybrid system for energy-efficient seawater desalination [91].

4.3. Renewable energy powered SWRO

As freshwater demands increase, and fossil fuel reliance becomes unsustainable, renewable energy becomes prominent in desalination applications. Transitioning from fossil fuel-powered desalination plants to those driven by renewable sources, such as wind or solar power, could significantly enhance sustainability and decrease carbon footprint, making renewable energy a likely future powerhouse for desalination. According to the International Renewable Energy Agency (IRENA), global renewable power generation capacity is 3064 GW in 2021. In which the solar photovoltaic (PV) capacity was 849 GW [94]. Integrating RO with renewable energy systems presents a solution for prospective seawater hubs' energy and water needs. Alkaisi et al. have outlined [95] the contribution of each renewable energy source to global desalination technology (Fig. 11a). Notably, the ocean serves as a potent resource hub for energy, offering a practical solution to power SWRO desalination plants. Fig. 11b illustrates the theoretical resource potential of ocean energy [96].

Solar energy, the most prevalent renewable source worldwide, has the potential to contribute toward global energy needs. Freshwater is scarce in the Middle East and North Africa (MENA) regions, while seawater and brackish water are abundant. Given their lower energy requirements, solar photovoltaic and membrane-based desalination technologies are becoming increasingly popular. Given that these countries receive 5–7 kWh of solar insolation per day, making solar energy emerges as a potential power source for desalination in these areas [97]. One of the main challenges in utilizing solar is its intermittent availability [98,99]. The plants often rely on hybrid systems that combine solar energy with other sources to meet their energy needs, ensuring consistent and reliable operations [100,101].

One of the major solar-powered desalination plants in the MENA region, Al Khafji desalination plant uses reverse-osmosis technologies, developed at King Abdulaziz City for Science and Technology, and is powered by electricity produced by solar photovoltaics. The capacity of the desalination plant is 60,000 m^3/day of clean water, with peak production of 90,000 m^3/day. The solar power plant provides 10 MW of electricity daily to operate the desalination plant [102]. A case study of this plant presents an example of the successful implementation of a renewable energy resource-powered desalination plant [103]. NEOM, the planned “smart city” initiative in Saudi Arabia, which in June 2022 announced a project with French energy company Veolia and Japanese trading company Itochu that will develop a reverse osmosis desalination facility entirely powered by renewable energy, expected to be completed in 2025, the plant will produce 500,000 m^3/day [104].

Indirect utilization of renewable energy for desalination, such as powering RO systems with wind-generated electricity, is an option. However, since energy conversion often results in energy loss, direct application of renewable energy is generally more efficient. When combined with desalination, wind technology is especially beneficial in coastal regions with high wind potential, as it can provide the electricity required for SWRO desalination plants. Cabrera et al. [105] recently proposed a method to design and operate flexible SWRO facilities powered by wind and wave energy. The approach uses statistical analysis to determine the capacity of single-stage SWRO modules, tailoring their power consumption to the anticipated energy output from renewable, optimizing resource usage, and maximizing freshwater production while minimizing costs. A case study in Gran Canaria, Spain, used mean, mode, and median output power values to determine the optimal layout for a wind and wave energy-driven desalination plant. The wave energy-powered desalination plant could produce an average of 1.51×10^5 m^3/year freshwater, albeit at a high specific cost of 8.3 €/m^3 due to the low maturity of wave energy converter (WEC) technology. In contrast, the wind-powered desalination plant produced an average of 3.96×10^5 m^3/year of freshwater at a competitive specific cost of 1.5 €/m^3 using the proposed method. Most wind-powered RO desalination currently operates on a smaller scale, for example, in Spain's Canary Islands (5–50 m^3/day for wind RO) and Fuerteventura Island (56 m^3/day for diesel-wind RO) [96].

Shahzad et al. [105] noted that PV-SWRO methods are currently the costliest, with prices ranging from \$11.7 to \$15.6/m^3. However, the appeal of renewable energy-powered systems is growing due to advancements enabling cost optimization per unit of desalinated water by combining multiple renewable energy systems [106]. Standalone desalination units powered solely by renewable energy are often insufficient to meet the electrical demands of RO plants [107]. When renewable energy sources are unavailable, hybrid power generation systems present a viable solution. Furthermore, energy storage devices can be integrated with renewable energy sources and hybrid approaches to ensure a steady electricity supply to the desalination units [108].

4.4. Hydrogen renewable energy: green hydrogen production

According to a 2022 International Energy Agency report, global hydrogen demand reached 94 million tonnes (Mt) in 2021 [109]. Several commercial hydrogen (H_2) production methods exist, with water electrolysis into hydrogen and oxygen powered by renewable energy emerging as a favored alternative to fossil fuels. This process, creating green hydrogen, is rapidly gaining traction worldwide for decarbonizing heavy industry, long-haul freight, shipping, and aviation, thereby promoting a circular carbon economy (Fig. 12a and b).

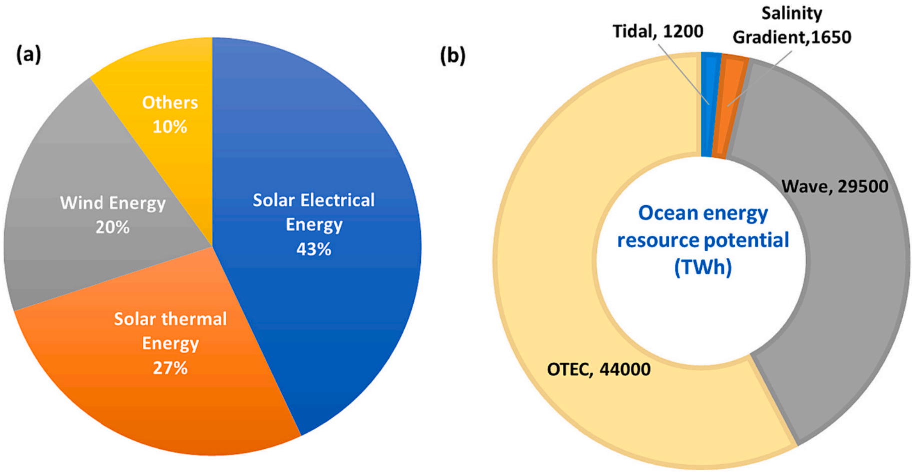


Fig. 11. (a) Percentage of renewable energy source to the RED systems (Redrawn, [95]). (b) Ocean energy resource potential (TWh) (Redrawn, [96]) (OTEC = ocean thermal energy conversion).

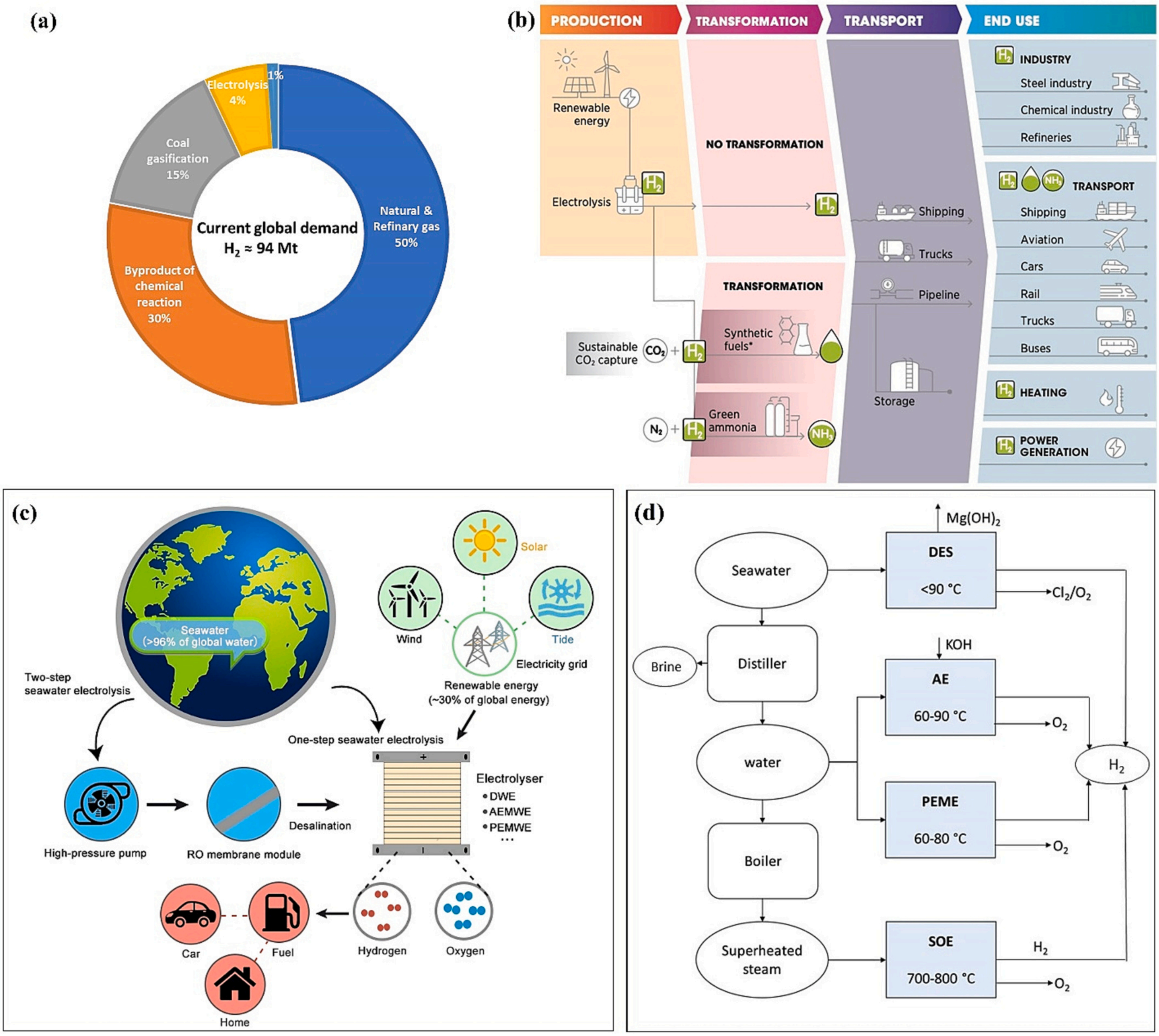


Fig. 12. (a) Global hydrogen demand and various sources for commercial hydrogen production. (b) Green hydrogen production, conversion, and end users across the energy system [Source: WEF, IRENA]. (c) Pathways to produce H_2 from seawater and renewable energy: Left:- Two-step seawater electrolysis, Right:- One-step direct seawater electrolysis [113]. (d) Block diagram of various electrolysis technologies applied to seawater [112].

Table 4
Reactions that take place in various seawater electrolysis cells.

Electrolysis	Anode	Cathode	Overall
DES	$2Cl^{-}_{(aq.)} \rightarrow Cl_{2(g)} + 2e^{-}$	$2H_2O + 2e^{-} \rightarrow H_{2(g)} + 2OH^{-}_{(aq.)}$	$2NaCl_{(aq.)} + 2H_2O_{(l)} \rightarrow Cl_{2(g)} + H_{2(g)} + 2NaOH_{(aq.)}$
AE	$2OH^{-}_{(aq.)} + \frac{1}{2}O_{2(g)} \rightarrow H_2O_{(l)} + 2e^{-}$	$2H_2O_{(l)} + 2e^{-} \rightarrow H_{2(g)} + 2OH^{-}_{(aq.)}$	$H_2O_{(l)} \rightarrow \frac{1}{2}O_{2(g)} + H_{2(g)}$
PEME	$H_2O_{(l)} \rightarrow \frac{1}{2}O_{2(g)} + 2H^{+}_{(aq.)} + 2e^{-}$	$2H^{+}_{(aq.)} + 2e^{-} \rightarrow H_{2(g)}$	$H_2O_{(l)} \rightarrow \frac{1}{2}O_{2(g)} + H_{2(g)}$
SOE	$O^{2-}_{(g)} \rightarrow \frac{1}{2}O_{2(g)} + 2e^{-}$	$H_2O_{(g)} + 2e^{-} \rightarrow H_{2(g)} + O^{2-}_{(g)}$	$H_2O_{(g)} \rightarrow \frac{1}{2}O_{2(g)} + H_{2(g)}$

Although oceans, comprising 96 % of the world's water and converting 71 % of Earth's surface, are a significant potential resource, seawater must be desalinated before electrolysis for hydrogen production due to the method's dependence on pure water [110,111]. While this H_2 production process is environmentally friendly and emits no carbon dioxide, it is expensive and energy intensive. Electrolysis is the most established when comparing selectivity, activity, and sustainability across various seawater splitting techniques. Researchers are exploring the use of seawater as an abundant source for hydrogen production by developing large-scale seawater electrolysis through direct (one-step) and indirect (two-step) approaches (Fig. 12c). The two-step method involves initial seawater pre-treatment using RO membranes, followed by water splitting through a conventional electrolyzer. Fig. 12d illustrates various electrolysis technologies suitable for seawater-based hydrogen production, such as direct electrolysis of seawater (DES), alkaline electrolysis (AE), proton exchange membrane electrolysis (PEME), and high-temperature solid oxide electrolysis (SOE) [112]. Table 4 provides the reactions occurring in these electrolysis cells at different temperatures.

4.4.1. H_2 generation by direct seawater electrolysis

Advancements in seawater electrolysis depend on developing corrosion-resistant electrodes that facilitate water splitting into hydrogen and oxygen, reducing the need for desalination. Dionigi et al. examined the complex electrochemistry of chloride oxidation, determining that it largely depends on factors like temperature, pH value, and applied potentials. Based on existing literature, they generated a Pourbaix diagram that includes the chemistry of chloride and oxygen, set at a temperature of 25 °C and seawater concentration of 0.5 M, as depicted in Fig. 13a [114]. Fig. 13b illustrates the maximum allowable overpotential for oxygen evolution reaction (OER) electrolyzer catalysts to enable 100 % selective water splitting. Chloride oxidation reactions in highly acidic and alkaline environments are presented by Eqs. (1), (2).

In highly acidic conditions, the chlorine evolution reaction (CLER) occurs:

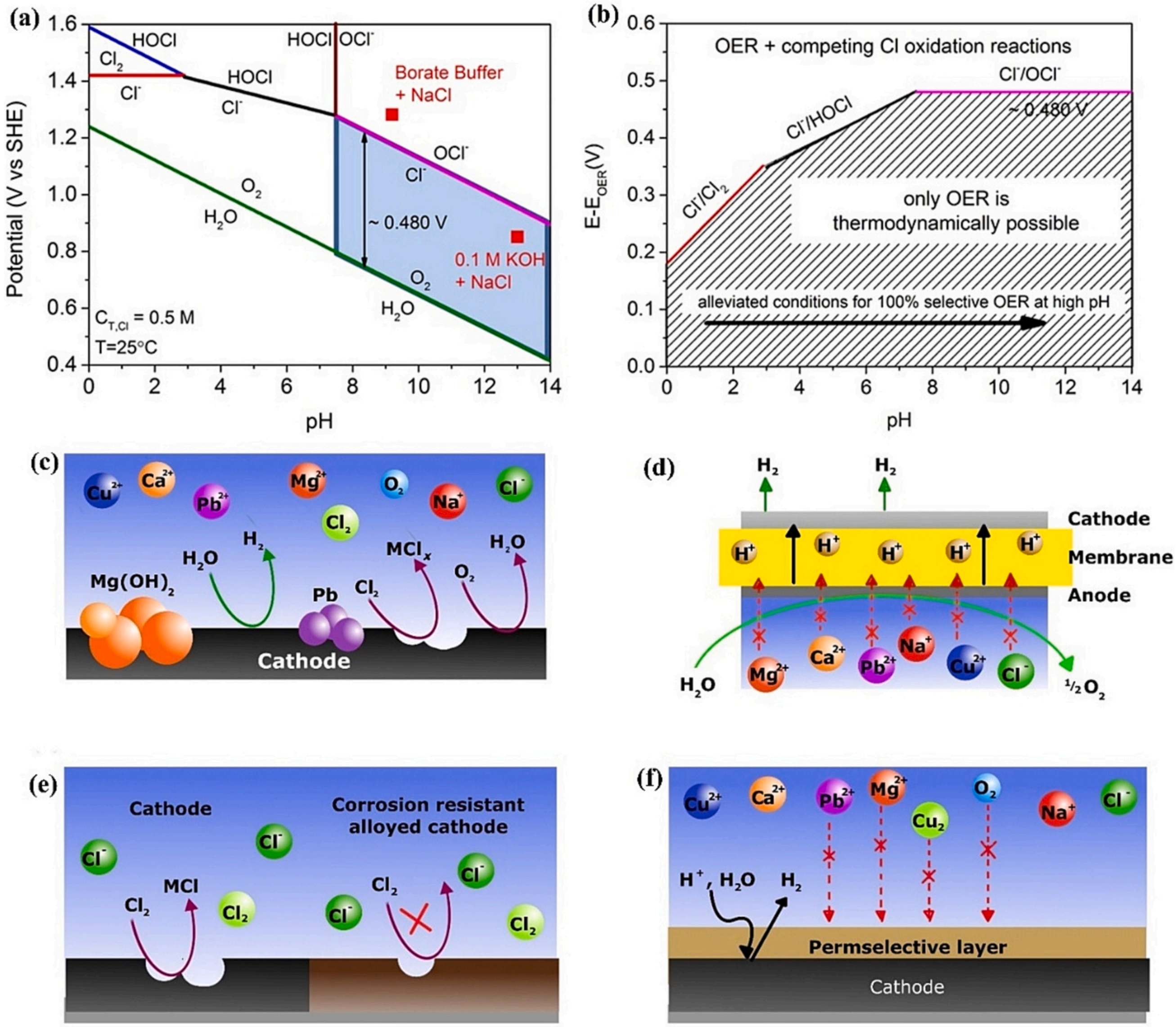


Fig. 13. (a) Pourbaix diagram for artificial seawater model. (b) alleviated conditions for selective OER in alkaline conditions (representation of E vs. pH for competing for OER and chloride (Cl^-) oxidation reactions) [114]; (c) Challenges with HER in seawater; Potential solutions to improve the long-term stability of HER. (d) Isolation of the catalyst layer to isolate the catalyst from the water supply using an appropriate membrane/engineering the reactor to avoid catalyst deactivation. (e) Designing inherent corrosion resistance/employing selective surface chemistry to maintain long-term stability. (f) Using permselective overlayer on top of the catalyst/membrane to protect the catalyst surface (Redrawn, [115]).

$$2\ Cl^{-} \rightarrow Cl_2 + 2e^{-}\ E_0 = 1.36V\ vs\ SHE\ at\ pH0 \quad (1)$$

In alkaline environments, hypochlorite formation occurs:

$$Cl^{-} + 2OH^{-} \rightarrow ClO^{-} + H_2O + 2e^{-}\ E_0 = 0.89V\ vs\ SHE\ at\ pH14 \quad (2)$$

The primary competition for OER includes hypochlorite production at high pH and the chlorine evolution reaction (ClER) at low pH. This analysis suggests that the ideal design requirement for achieving highly selective oxygen evolution from seawater oxidation is an overpotential $(\eta_{OER}) \leq 480\ mV\ at\ pH > 7.5$.

Feasible renewable H_2 generation from seawater can be achieved through strategies such as (i) developing semi-permeable membranes suitable for seawater electrolysis, (ii) applying corrosion-protective electrode coatings, (iii) mitigating corrosion with innovative floating-type platinum catalysts for ion recombination, and (iv) developing seawater electrolysis catalysts that remain active and selective amid pollutants like metal ions, chloride, and microorganisms. Tong et al.

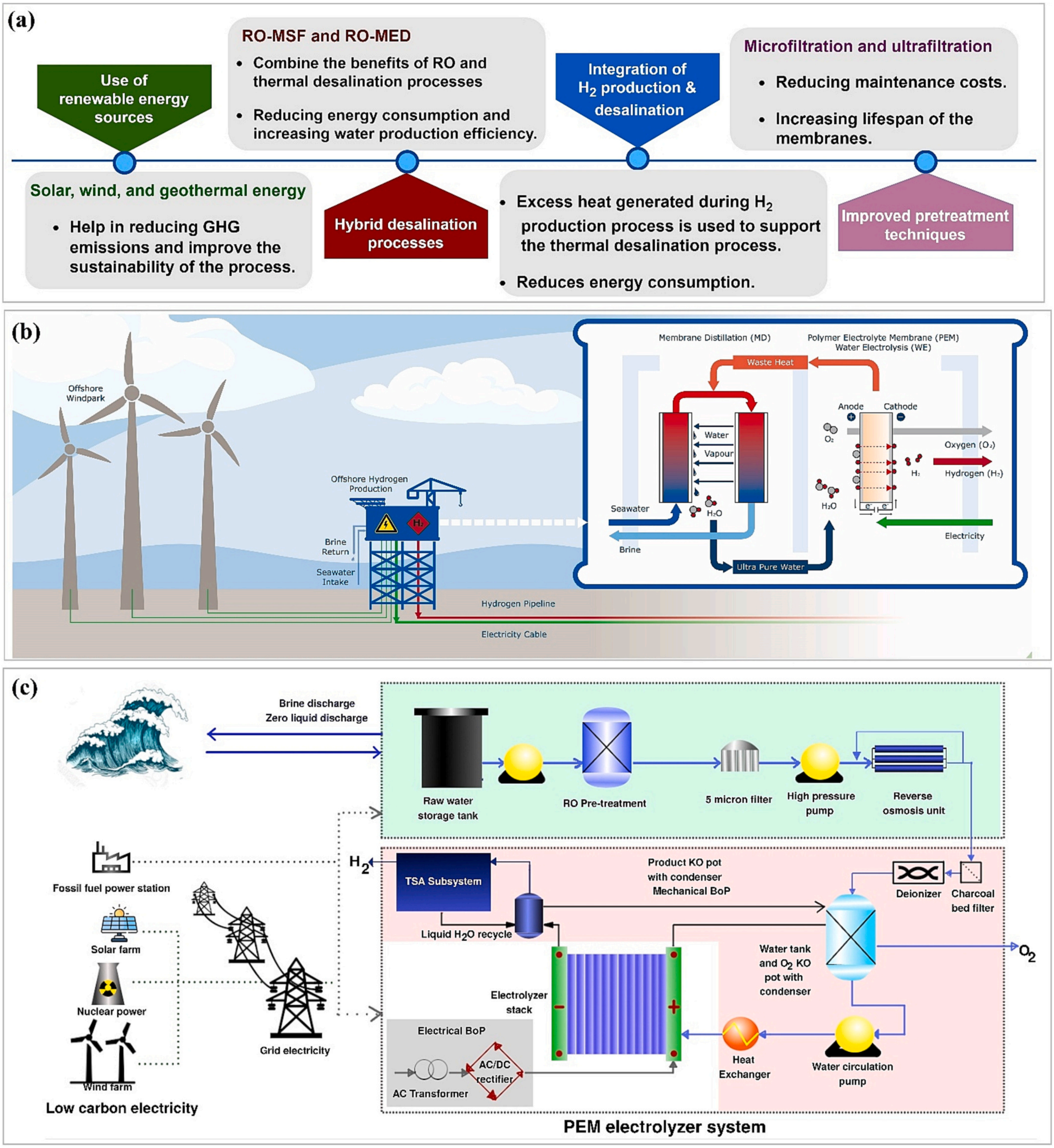


Fig. 14. (a) Various approaches for enhancing H_2 production through desalination. (b) Integration of membrane distillation and polymer electrolyte membrane water electrolysis [121]. (c) Grid-powered SWRO-PEM system for H_2 production (Redrawn, [122]).

[115] have delineated these primary challenges and potential solutions for hydrogen evolution reaction (HER) in seawater (Fig. 13c–f).

Current research on seawater electrolysis emphasizes the need for highly durable, corrosion-resistant electrocatalysts with improved activity, pH stability, and minimal electroreduction of high-valence ions [116,117]. To enhance the economic viability of seawater electrolysis, Shi et al. proposed a novel approach using commercially available RO membranes, which selectively transport favorable ions, unlike the conventionally used ion-exchange membranes [118]. They demonstrated a proof-of-concept design for direct seawater H_2 production using RO membranes with an inert anolyte, thereby preventing chlorine gas generation. Sun et al. devised a solution to overcome the challenges associated with seawater electrolysis, such as high electricity consumption and anode damage from chlorine chemistry. They implemented an effective technique that combines seawater reduction with thermodynamically favorable hydrazine oxidation [119]. This hybrid seawater splitting approach, paired with hydrazine degradation, outperformed commercial alkaline water electrolysis and the most sophisticated seawater electrolyzers, achieving chlorine-free hydrogen production at a lower electricity expense of 2.75 kWh per m^3 H_2 at 500 mA cm^{-2}. Incorporating hydrazine fuel cells or solar cells for sustainable hydrogen production allows for self-powered hybrid seawater electrolysis, paving the way for a carbon-neutral hydrogen economy by transforming ocean resources and eliminating hazardous pollutants. In a recent study, Xie et al. reported H_2 generation through membrane-based in-situ direct seawater electrolysis [120]. This system enables the direct electrolysis of seawater into hydrogen without prior desalination by combining electrochemistry and physical mechanics for phase change. This process effectively isolates the ions in seawater, generating hydrogen through in-situ electrolysis. The system performed continuously for over 3200 h at a current density of 250 $mAcm^{-2}$ without any malfunction under practical conditions. Notably, this procedure has no adverse effects and requires no additional energy. Advancements are underway as seawater exhibits the potential to become a “Zero-Emission fuel”.

Direct seawater electrolysis for green H_2 generation faces several critical challenges, including reduced electrocatalyst stability, shortened electrode lifespan due to side reactions, active reaction site obstruction, and corrosion from NaCl and other dissolved seawater salts. Impurities deposition, such as metal ions (like Pb^{2+}) electroreduction and hydroxide formation (such as $Mg(OH)_2$/$Ca(OH)_2$), can further degrade stability under cathodic reduction conditions. Since electrodes are often made from costly metals like platinum, this method has not been deemed economically viable for H_2 production. Even though much progress is happening in direct seawater electrolysis, it is considered an emerging and complex technology that demands specialized catalysts, membranes, and electrolyzers to handle seawater's inherent complexities, corrosiveness, and biofouling issues. Furthermore, as of now, cost-benefit analyses indicate that indirect seawater electrolysis is more favorable when compared to a one-step process. In view of all these factors, for the proposed integrated seawater resource hub, we suggest the desalinated seawater electrolysis for green hydrogen production since it is a well-established, practical, and cost-effective method that can utilize seawater directly as a feedstock without requiring time-consuming pre-treatment steps.

4.4.2. Seawater desalination - H_2 generation to improve sustainability

Hydrogen production from seawater can be more sustainable and reliable by leveraging advancements in desalination (Fig. 14a) followed by electrolysis powered by renewable energy. However, generating harmful chlorine gas from seawater chloride ions necessitates the development of sustainable technology for large-scale green hydrogen synthesis. Additional desalination techniques, such as RO and thermal methods like multi-stage flash (MSF) or multi-effect distillation (MED), can supplement this process. While RO delivers high-purity water suitable for fuel cell technology, thermal desalination is cost-effective for large-scale operations due to its lower energy needs and avoidance of high-pressure pumps required by RO, despite a higher chloride concentration in the product water.

Researchers from Wageningen and Hydrogen Energy have successfully demonstrated a hybrid system combining membrane distillation and polymer electrolyte membrane water electrolysis (MD-PEMWE), powered by renewable electricity [121], thereby realizing a “Seawater to Hydrogen (Sea2H2)” proof of concept (Fig. 14b). In another study, Khan et al. examined a system capable of producing 50 tons/day of H_2 through PEM water electrolysis, in tandem with a SWRO plant [122]. The grid, a mix of fossil and renewable sources, drives the system (Fig. 14c). The SWRO process separates salts from saline water using RO membranes with necessary pretreatment steps to manage (bio)fouling and scaling. RO membranes effectively remove over 99.8 % of total dissolved solids (TDS), and a two-pass RO system ensures high-purity water for the PEM electrolyzer. Such systems are particularly feasible in coastal regions with abundant seawater and high solar or wind energy levels. This approach is especially viable in areas with existing large-scale desalination facilities and easy access to seawater.

Set to debut in Saudi Arabia's net-zero emission megacity, NEOM, by 2026, the NEOM Green Hydrogen Company (NGHC) is slated to become the world's largest utility-scale, commercial, and water electrolysis-based green hydrogen production hub [123]. With nearly 4 gigawatts of combined onshore solar, wind, and energy storage, the facility will run exclusively on renewable energy. A large seawater desalination plant, paired with brine processing, forms the heart of the operation, aiming for over 60 % recovery, high efficiency, and cost savings. The facility will mitigate around 5 million metric tonnes of carbon emissions annually. Producing 600 t of green hydrogen and nitrogen daily via water electrolysis and air separation, the hub also plans to export up to 1.2 million tonnes of green ammonia annually, transferred directly to tanker ships located near key global shipping channels and distribution points (Fig. 15).

Ginsberg et al. explored the synergistic potential of desalination and hydrogen production via electrolysis when powered by solar energy [124]. Fig. 16a shows the levelized costs of water (LCOW) in terms of capital expenditure (CAPEX), operational expenditure (OPEX), and energy costs. The Integration of renewable energy, desalination, and electrolysis assumes the necessity of seawater as a feedstock for hydrogen generation and heat production during the electrolysis process (Fig. 16b). The increase in waste heat with high current density operation in electrolysis suggests the potential to utilize this heat in thermal desalination when coupled with desalination units. Fig. 16c shows the correlation between current density and efficiency (higher heating value) in the PEM electrolyzer. Fig. 16d and e illustrate the current-voltage (I-V) curves, corresponding efficiencies, and heat generation per kg of hydrogen for a 10 MW PEM electrolyzer (rated capacity at 1.7 A cm^{-2}) operating at 60 °C. Optimizing the electrolyzer operation and harnessing heat energy for thermal power desalination could reduce the cost of hydrogen production through water electrolysis to \$2/kg (H_2), rendering it comparable to hydrogen produced via steam methane reforming (SMR).

Lee et al. proposed a combination of hybrid desalination and water electrolysis to generate hydrogen and pure water with a 4 MW plant capacity [125]. Electricity produced from the desalination process powers high-temperature steam electrolysis using a solid oxide electrolysis cell (SOEC) and an alkaline electrolysis cell (AEC), reducing electricity costs and hydrogen production expenses. The levelized costs were \$1.08–1.86 per ton for pure water, \$1.75–5.32 (SOEC), and \$0.63–2.35 (AEC) per kg for hydrogen, a significant decrease. Process simulation and optimization confirmed the electrical coupling of hydrogen production and desalination, resulting in a \$2.33 and \$4.34 reduction per kg of hydrogen compared to previous reports. Despite the increased pure water production costs due to electricity supply for water electrolysis, the lower hydrogen production cost compensated for the loss, thus presenting this novel approach as a viable alternative for

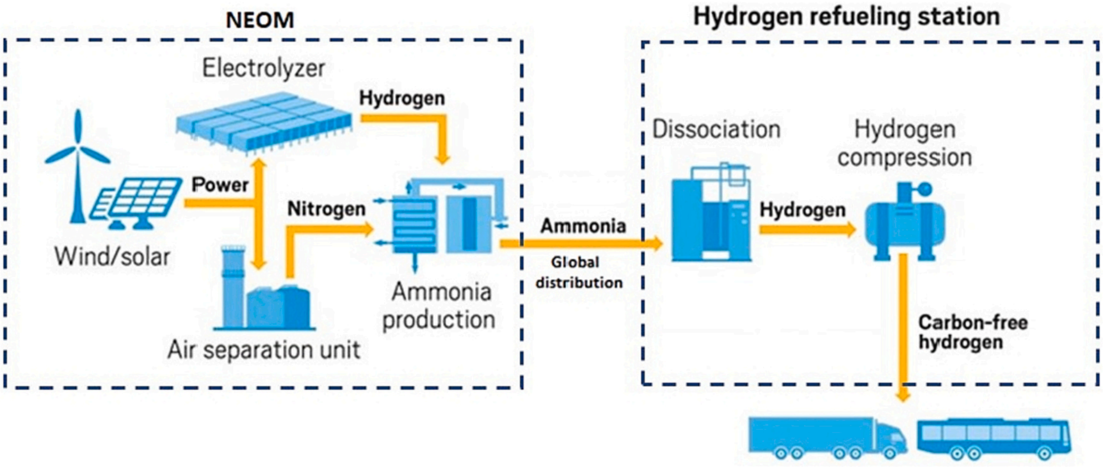


Fig. 15. Schematic of the green-H_2-based ammonia production facility run on renewable energy in NGHC.

decentralized hydrogen production.

Hausmann et al. examined the competitiveness of a direct seawater splitting (DSS) scenario compared to a two-step method for freshwater and green hydrogen production [126]. Their evaluation considered factors such as thermodynamic requirements, energy consumption, device complexity, size, capital costs, and freshwater and green hydrogen prices (Fig. 16f). The study concluded that seawater purification costs were minor relative to water splitting. Concurrently, Khan et al. critically reviewed direct seawater electrolysis for hydrogen production, considering energy, cost, and environmental impacts [122]. They also investigated a two-stage SWRO combined with a PEM water electrolysis technique and found that SWRO's infrastructure and OPEX were negligible compared to commercial water electrolysis energy needs (Fig. 16g). Notably, SWRO desalinated water prices have been decreasing alongside an increase in the global installed capacity of RO. Their analysis showed that the one-step seawater electrolysis process only offered modest energy, economic, and environmental benefits, suggesting a higher benefit from investments in technologies like SWRO and PEM coupling systems over direct processing.

Economic evaluations for the two-step hydrogen production process, primarily involving RO desalination plants, are steering research toward cost optimization to lower associated desalination expenses [127]. Significant interest lies in the electrolysis of offshore saline water for hydrogen production coupled with electricity from wind or solar power plants. The current electrolysis process for hydrogen production demands highly pure water, a viable resource. However, the abundant availability of seawater could potentially make the electrolysis procedure commercially viable.

5. Agriculture

Agriculture is the largest global water consumer, accounting for 70 % of usage, followed by industrial (21 %) and domestic needs [128]. In arid coastal regions like Somalia and Kenya, limited access to irrigation water severely restricts food production. Around 8.7 million cubic meters of desalinated water are used globally for irrigation. Critical factors in agricultural desalination include cost-effective methods, yields sufficient to offset expenses, and minimizing the environmental impact of desalinated water irrigation [128]. Seawater's high salinity, with a TDS range of 35,000 to 45,000 ppm, requires careful handling [129], and using it for irrigation without precautions to remove salts can increase soil salinity. The additional water needed for leaching depends on the irrigation water's salinity and the crop's salt tolerance. Diaz et al. noted increased soil salinity and boron levels when irrigating with desalinated seawater, potentially affecting moderately tolerant crops' productivity [130]. Therefore, developing a water treatment system that effectively removes pollutants and significantly desalinates water is critical. Table 5 provides the range of values for parameters of water quality for irrigation.

Birnhack et al. identified key quality parameters for desalinated water used in agricultural and municipal applications, including electrical conductivity (EC), concentrations of Cl, Na^+, B, Ca^{2+}, Mg^{2+}, and SO_4^{2-}, alkalinity, the calcium carbonate precipitation potential (CCPP), and pH [132]. They found that minerals like Ca^{2+}, Mg^{2+}, and SO_4^{2-} in desalinated water function as additional fertilizers. The salinity of desalinated water, especially NaCl concentration, influences the EC value. Optimizing production costs can also enhance the use of desalinated water in agriculture.

5.1. Seawater greenhouses (SWGH)

Seawater greenhouses (SWGH) leverage two abundant resources - seawater and sunlight - to create optimal conditions for crop growth in arid, hot regions where water scarcity threatens food security and prompts migration. Crops typically grown in conventional greenhouses, like tomatoes, cucumbers, lettuce, peppers, strawberries, and herbs, can also be cultivated in SWGH. This innovative system harnesses water vapor from evaporating salt water for cooling and humidification. Temperature differences between sun-heated surfaces and cold seawater drive the system's humidification and dehumidification. The SWGH produces its water supply through solar distillation, reducing plant transpiration loss and creating an efficient environment. Local climatic data is used in modeling and simulation to predict greenhouse performance and inform design. This resulting environment reduces evapotranspiration by up to 90 %, enhancing growth conditions and significantly decreasing irrigation needs met through desalination. Fig. 17a depicts the critical properties of SWGH.

LightWorks Ltd. in the UK introduced the SWGH concept in 1991, with a pilot project launching in Tenerife, the Canary Islands, the following year. The successful pilot verified the SWGH concept and highlighted its potential for arid regions. In 2000, a second SWGH was constructed on Al-Aryam Island in Abu Dhabi, UAE, with a design tailored for extreme Middle Eastern climates and locally sourced materials, featuring a robust steel frame similar to a multi-span polytunnel. In 2004, the third SWGH pilot was established near Muscat, Oman, in collaboration with Sultan Qaboos University; this project demonstrated the technology's effectiveness under extreme desert conditions, showcasing its ability to rehabilitate salt-damaged land using the Oasis Effect for soil hydration rather than relying on groundwater resources.

In 2010, the first commercial SWGH project was launched in Port Augusta, Australia, incorporating solar PV and RO desalination techniques for increased efficiency and cost-effectiveness. With the

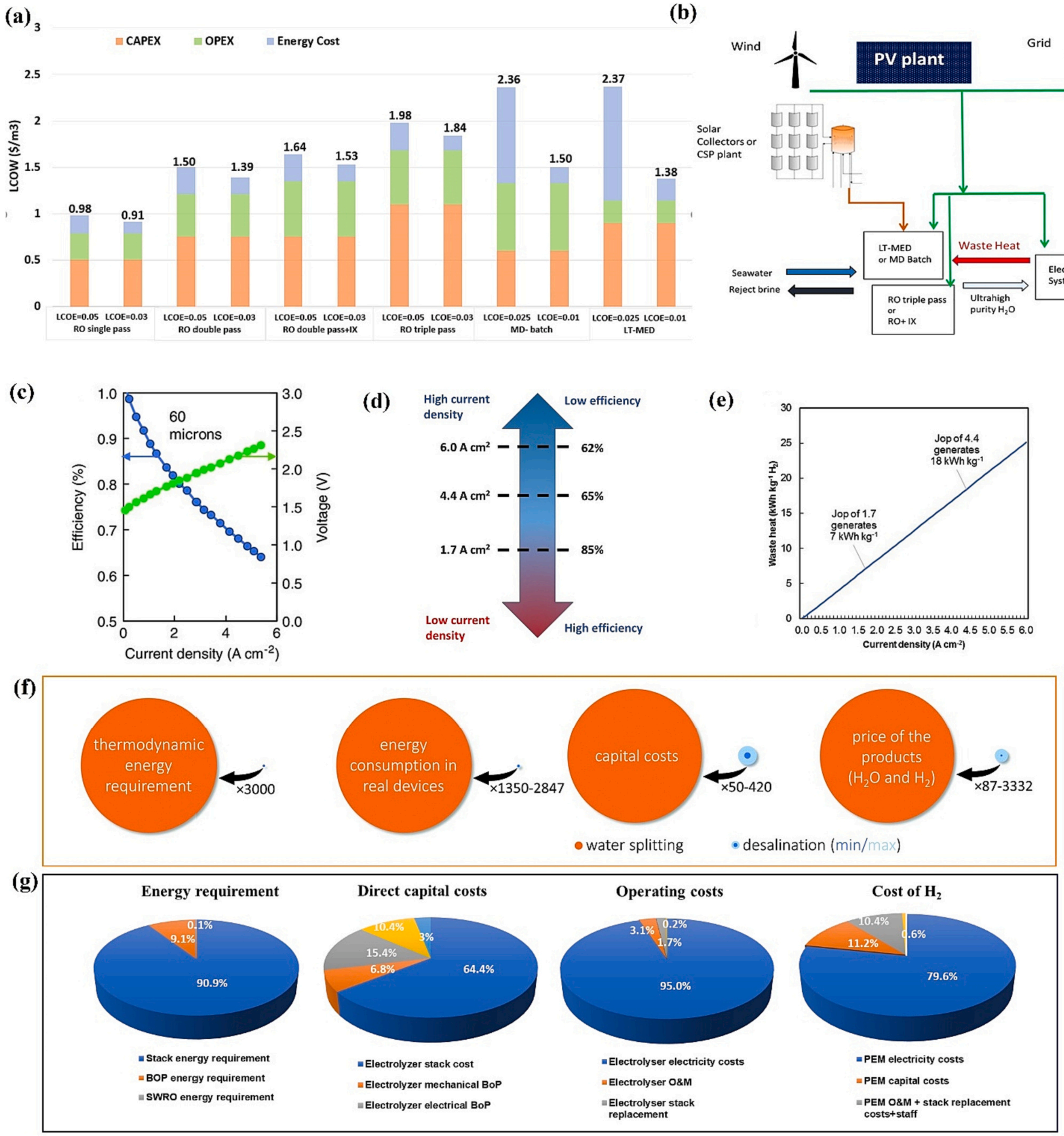


Fig. 16. (a) LCOW breakdown of different desalination technologies at a medium (2000 m^3 day^{-1}) capacity (levelized cost of electricity, LCOE for MD-batch and LT-MED is 0.05 \$ m^{-3}) (Redrawn) (b) Integrated solar-/wind-powered plant for producing freshwater and hydrogen from water desalination and electrolysis. (c) The tradeoff between electrolyzer current density and efficiency. (d) Current-voltage (I-V) and corresponding efficiency curves based on experimental I-V curves (Redrawn). (e) heat generation per kg of hydrogen production [124]. (f) Comparison of water splitting and water desalination [126]. (g) Partition of the cost comparison involving energy requirement, capital cost, and the operating cost of H_2 of electrolysis plant based on SWRO-PEM with 50 tons H_2/day capacity (Redrawn from [122]).

escalating global water scarcity and drought conditions, SWGH has found unique commercial potential, leading to an expansion of this project to 20 ha. In 2017, another SWGH was established in Berbera, Somaliland, a region marked by severe food insecurity. This project used advanced modeling techniques and a shade net design, utilizing core evaporative cooling components developed in earlier projects [133]. Like those depicted in Fig. 17b in Oman, these solar-powered greenhouses employ seawater piped into wells to create optimal growing conditions through a novel desalination process.

Given the potential for brine discharges to contaminate aquifers and oceans, it's recommended to employ evaporative coolers in SWGHs to decrease brine volume, facilitating the growth of high-value plants and sea salt production. Paton and Davis examined using brine for cooling and salt production within wind-driven SWGHs [134]. Fig. 17c illustrates the desalination brine valorization process, where a moistened evaporative cooling pad is used for brine passage, aiding salt production. This method further concentrated the brine before directing it to a series of evaporation ponds for salt extraction.

Table 5
Guidelines for interpretations of water quality for irrigation (FAO Standards) [131].

Potential irrigation problems		Degree of restriction on use		
		None	Slight-moderate	Severe
Salinity	EC_w ($dS\ m^{-1}$)	<0.7	0.7–3.0	>3.0
	TDS (mg/L)	<450	450–2000	>2000
Infiltration	SAR = 0–3 and EC_w =	>0.7	0.7–0.2	<0.2
	SAR = 3–6 and EC_w =	>1.2	1.2–0.3	<0.3
	SAR = 6–12 and EC_w =	>1.9	1.9–0.5	<0.5
	SAR = 12–20 and EC_w =	>2.9	2.9–1.3	<1.3
	SAR = 20–40 and EC_w =	>5.0	5.0–2.9	<2.9
Specific ion toxicity	Sodium (Na)			
	Surface irrigation (SAR)	<3	3–9	>9
	Sprinkler irrigation (meq L^{-1})	<3	>3	
	Chloride (Cl)			
	Surface irrigation (meq L^{-1})	<4	4–10	>10
	Sprinkler irrigation (meq L^{-1})	<3	>3	
	Boron (B) mg/L	<0.7	0.7–3.0	>3.0
Miscellaneous effects (on susceptible crops)	Nitrate (NO_3-N) (mg L^{-1})	<5	5–30	>30
	Bicarbonate(HCO_3) (overhead sprinkling only) (meq L^{-1})	<1.5	1.5–8.5	>8.5
pH	Normal range 6.5–8.4			

5.2. Agricultural utilization of SWRO desalination product water and reject brine

The RO method, while beneficial, has limitations in agricultural applications. These include inadequate nutrient, boron, or chloride levels in desalinated water, high-volume brine discharge, soil alteration due to excess sodium, and substantial energy consumption [135]. Seawater membrane-based desalination addresses these limitations, satisfying the rising demand for irrigation water for fertigation. Countries like Spain, which has one of Europe's most agriculturally productive regions, have successfully implemented seawater desalination for irrigation [136]. Brackish water reverse osmosis (BWRO) and SWRO are the preferred agricultural desalination technologies. With superior

Table 6
Water-quality parameters after desalination for agriculture [138].

Parameter	Recommended value
EC(dS/m)	<0.3
$[Cl^-]$ (mg/L)	<20
$[Na^+]$ (mg/L)	<20
$[Ca^{2+}]$ (mg/L)	32–48*
$[Mg^{2+}]$ (mg/L)	12–18
$[SO_4^{2-}$-S] (mg/L)	>30
[B] (mg/L)	0.2–0.3
Alkalinity (mg/L as $CaCO_3$)	>80*
CCPP (mg/L as $CaCO_3$)	3–10*
pH	<8.5*

* Value based on the Israeli recommendations for desalinated water, 2007.

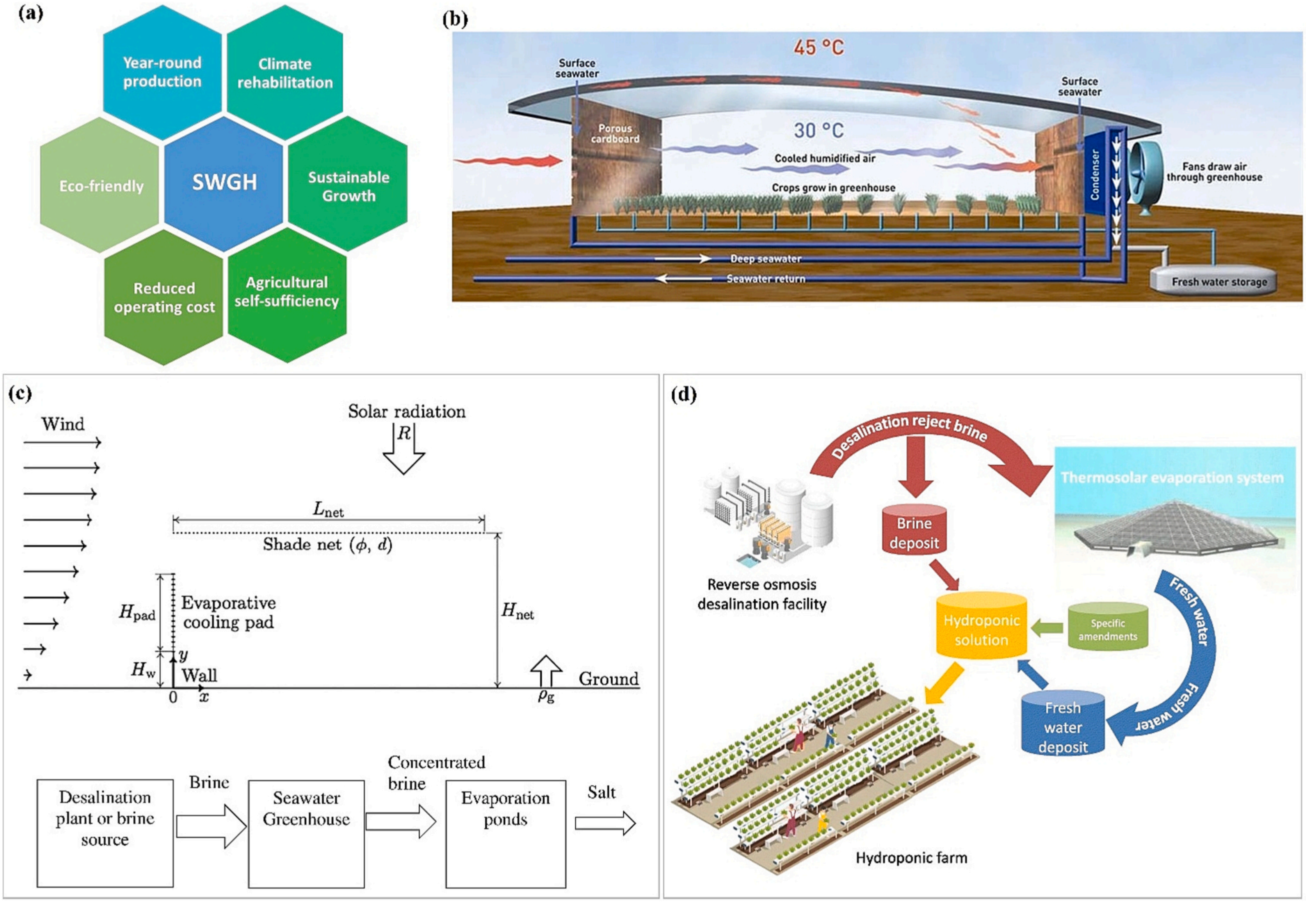


Fig. 17. (a) Seawater Greenhouse Properties. (b) SWGH in Oman (Photo credit: Seawater Greenhouse Ltd.). (c) Basic concept of seawater greenhouse for brine utilization: Seawater greenhouse with wind approaching from the left and the Flow diagram for the utilization of desalination brine in SWGH [134]. (d) Schematic of the utilization of brine from SWRO plant in a hydroponic farm [140].

water quality, lower energy requirements, and reduced water costs, SWRO has emerged as the dominant process [136,137]. Countries like Spain and Australia depend on SWRO to meet agricultural irrigation needs. Building on Israeli experience, Yermiyahu et al. [138] proposed water quality parameters for agricultural use (Table 6).

Proper management is critical when using rejected brine for agriculture due to its high salinity, which could cause soil salinization or desertification if mishandled. Limitations such as low TDS levels and the absence of harmful substances, which meet national health requirements, are prerequisites for its agricultural use. Many plants process brine stream effluent into liquid fertilizers, typically utilizing an ion exchange technique to regulate sodium and hardness levels [139]. Proper brine management can positively impact the public and ecological perceptions of desalination. Studies on brines from several SWRO plants reveal high nutrient content, suggesting their suitability for agriculture. Minerals from rejected brine serve as consistent, reliable sources for hydroponic cultivation [140] (Fig. 17d). Essential plant minerals like Ca^{2+}, K^{+}, and Mg^{2+}, derived from dissolved inorganic salts, are vital for plant growth and crop production [141]. Utilizing rejected brine is an effective method to obtain macronutrients, reducing the cost of mineral nutrient solutions by 20 % and mitigating productivity losses from high Na^{+} levels in commercial crops [142].

5.3. *Potential use of algae for agriculture*

5.3.1. *Algae utilization*

Algae, ubiquitous microscopic photosynthetic organisms found in various water bodies, can sometimes pose challenges due to harmful algal blooms (HABs) that cause RO membrane fouling, reduced throughputs, and additional pre-treatment steps [143]. However, we aim to explore the potential of microalgae as a seawater-based resource for value-added biomaterials or as a biotechnological tool for desalination and brine bioremediation.

5.3.2. *Agriculture: algae as a seawater-based crop*

Current agricultural systems primarily rely on freshwater and arable land for food and feed crop production. However, cultivating marine microalgae presents a promising alternative, as it can be grown on nonarable land using saline or seawater, efficiently utilize fertilizers, and achieve higher oil and protein yields than traditional crops [144]. The resultant biomass offers diverse applications, such as food, feed, biofuels, pharmaceuticals, and chemicals [145].

Microalgae production is a straightforward process, requiring sunlight, (sea) water, fertilizer, and CO_2. Given the vast biodiversity of microalgae, physiochemical parameters (i.e., temperature, salinity, light intensity) and resulting biomass productivities and compositions can vary significantly [146]. Typically, algae cultivation systems are terrestrial, employing either an open raceway pond or a closed photobioreactor (PBR) design [147]. This concept of land-based mariculture, the large-scale cultivation of marine microalgae in arid coastal areas, has gained interest over the past decades. Further research is required to enhance economic feasibility and promote widespread commercial adoption [144]. Aspects such as nutrient utilization from natural seawater, temperature regulation using seawater, and harnessing wave energy for mixing can play a vital role in these developments [148,149]. The case study of *Chlorella* sp. illustrates the use of bicarbonate-supplemented seawater in a floating photobioreactor on the ocean to optimize marine microalgae production (Fig. 18a).

Marine Eutrophication – increasing levels of nutrients such as nitrogen and phosphorus – is a global concern causing undesirable changes in natural environments [150]. Yet, this issue can be reframed as an opportunity by utilizing these nutrients for controlled algae cultivation. For instance, Kim et al. successfully cultivated *Tetraselmis.* sp. using natural seawater and available nutrients within a semi-permeable membrane PBR [148]. This concept of a semi-permeable PBR can be further integrated into floating PBR systems deployed directly on the (sea)water surface [151]. Such systems resolve culture temperature control concerns, as the surrounding water's high heat capacity yields stable temperatures, eliminating the need for active thermal regulation and associated costs [152].

Moreover, wave energy can be directly translated to hydrodynamic culture mixing, constituting 29–52 % of the total production costs in conventional land-based systems [153,154]. Through innovative wave energy utilization, studies by Zhu et al. and Kim et al. showed how different wave conditions, mooring systems, and the introduction of partitions impact hydrodynamic performance and algal culture mixing in floating PBRs [155,156]. These studies validate utilizing ocean resources as an alternative seawater hub, producing algae biomass for food, feed, and fuel applications.

5.3.3. *Algae cultivation on brine*

Brine disposal remains a significant challenge for the desalination industry due to increased salinity and concentrated nutrients such as nitrogen and phosphorus [157]. Algae-based bioremediation presents an additional solution for managing brine [158], leveraging the biodiversity of algae, including strains that thrive in high-salinity environments. Studies by Nadi et al. and Zarzo et al. demonstrated the efficacy of such strains in pollutant removal from desalination brines, with *Scenedesmus* sp. and *Tetraselmis suecica* removing up to 63 % of TDS and 45 % of nitrates, respectively [159,160]. Zhu et al. combined brine cultivation with floating PBRs for *Dunaliella salina* [161], a strain known to increase the production of high-value metabolite β-carotene under high salinities, enhancing the economic prospects for biomass valorization [162,163]. Fig. 18b illustrates the circular bioeconomy perspective of using RO brine from seawater to cultivate *Dunaliella salina* and produce valuable β-carotene as a bioproduct.

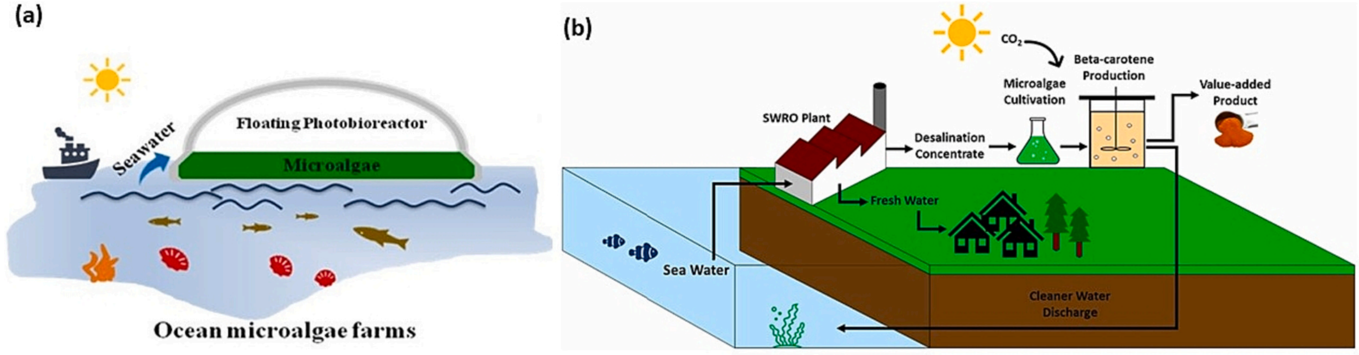


Fig. 18. (a) Marine microalgae production in floating photobioreactor on the ocean [149]. (b) The circular bio-economy perspective of SWRO brine usage for *Dunaliella salina* based β-carotene byproduct [163].

5.3.4. Algae-based desalination

One of the latest developments in seawater-based algae processing involves using algae for desalination [164]. Certain halophilic algae species can intracellularly accumulate salts through biosorption and bioaccumulation, potentially reducing extracellular salinity with lower energy demands than conventional desalination processes. Ghobashy et al. examined the desalination capacity of *Scenedesmus arcuatus*, *Chlorella vulgaris*, and *Spirulina maxima,* achieving removal rates of up to 48.9 % for TDS from natural seawater [165]. Similar studies have found that several *Scenedesmus* sp. strains could remove up to 97 % of TDS from water with salinities similar to seawater (30–40 g/L TDS) [159,166,167]. When coupled with carbon capture, this process could lessen carbon footprints, and the biomass produced could be valorized for economic viability. Although in its nascent stages, algae's potential as a sustainable desalination technology holds promises for future applications.

6. Challenges and prospects for sustainable scaling-up

An SWRO seawater hub is a complex system that combines various technologies and processes to generate freshwater and other valuable products from seawater. We must confront technical and economic challenges to implement such an integrated hub successfully. Integrating these diverse processes necessitates meticulous design, optimization, and coordination to ensure the system's compatibility, reliability, and flexibility. Additionally, the performance and availability of these processes are influenced by seawater quality and quantity variations due to location, season, and climate. This system's primary technical challenges and opportunities pertain to optimizing membrane performance, reducing energy consumption, and finding ways to make the most of the brine stream. Achieving these objectives demands careful attention to the design, operation, and maintenance of the SWRO hub and innovative solutions for energy and resource recovery. It's important to acknowledge the potential of renewable energy sources, such as solar power, in desalination. Still, it must also recognize the limitations and the necessity for comprehensive energy management strategies to address the intermittent solar energy availability in the MENA regions and beyond.

Furthermore, the production of multiple products and services through the SWRO hub may necessitate various market conditions, regulatory frameworks, standards, and infrastructure, which could present challenges and uncertainties during development and deployment. Lastly, it's worth noting that the capital and operating costs associated with an SWRO-integrated seawater hub may exceed those of traditional SWRO desalination due to the system's complexity, novelty, and scale. However, these challenges can vary significantly based on location, scale, technology, and economic considerations.

From a sustainability perspective, the proposed integrated seawater hub based on SWRO presents viable solutions for meeting water demand, energy recovery, and resource availability. It utilizes renewable sources (i.e., seawater), promoting cycles of use and recovery that minimize waste. However, the high energy requirements and possible impacts on marine environments must also be considered. The seawater hub's resource recovery technique also acts as an alternate and sustainable means of manufacturing metals and minerals, as opposed to traditional land mining and extraction processes, which consume enormous amounts of water while adding to air, water, and soil pollution. Various strategies, like energy recovery devices and renewable energy, are being applied to enhance ISH sustainability. The scalability of the hub depends primarily on technological advancements and economic factors. It represents a promising avenue for expanding water supply, energy recovery, and agricultural applications, especially in water-scarce regions. The sustainability and scalability of the ISH depend on the local conditions, the water demand, the availability of resources, and the integration of processes. However, scaling up operations often involves substantial financial investment and sophisticated infrastructures, potentially limiting its applicability in resource-limited settings. The SWRO hub can offer a viable and beneficial option for water supply and resource management by addressing these aspects.

7. Outlook and conclusion

The integrated resource management model within the integrated seawater hub is proposed in the present work. The concept of a seawater hub signifies a substantial stride toward sustainable and environmentally conscious seawater desalination solutions. It holds the potential to transform seawater treatment and ensure a consistent freshwater supply for communities globally. This proposed model embodies a closed-loop system, aiming to minimize the environmental footprint of seawater desalination while guaranteeing a continuous freshwater supply. A circular economy centered around sustainable brine management can diminish production costs and open secondary income streams from desalination plants worldwide. To realize this vision, developing and implementing eco-friendly, cost-effective brine treatment methods and high-quality membrane designs for valuable metal extraction from the rejected desalination brine is essential.

Furthermore, the seawater hub's resource recovery could reduce waste and recover valuable resources for various industries. It can curtail reliance on fossil fuels by prioritizing energy recovery and harnessing renewable resources. This approach promotes sustainable resource management and enhances energy security, thereby mitigating resource depletion. Harvesting osmotic energy from brine can improve sustainability and maximize the benefits of brine mining by efficiently utilizing the brine. A thorough examination of power systems, desalination units, and site topography is necessary to check the viability of using renewable energy (particularly solar energy) as the primary energy source for seawater-based resource hubs. Accelerating the development of renewable energy-powered desalination facilities with multiple functionalities is highly advised, especially in the MENA region, which has a sizeable percentage of the global desalination capacity and abundant solar energy resources. In addition to lowering carbon emissions and carbon footprints in these high-emission nations, such an endeavor will also improve the environment and the availability of clean water and energy in the decades to come.

Detailed and comprehensive modeling and optimization of the ISH system by assessing its components and considering the life cycle are necessary. More experimental and pilot studies are needed to validate the performance and feasibility of the ISH technologies and processes. Constructing the seawater hub involves creating a sophisticated pipeline network to transport feed water to the plant. Although the intricate systems designed to extract multiple valuables through brine management increase overall complexity, technological advancements target operational improvement via full automation. Artificial intelligence (AI), still in its early stages in the desalination industry, could significantly enhance monitoring, risk identification, process control, maintenance prediction, operation optimization, reducing energy and chemical consumption costs. It can also develop predictive models for water usage, sensor-based monitoring systems, and real-time smart alarms for issue detection and response. Integrating AI with emerging technologies like the Internet of Things (IoT) could further sophisticate water resource management systems. In conclusion, seawater factories could address some of the most pressing global challenges, such as water scarcity, energy insecurity, and resource depletion.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dong Suk han reports financial support was provided by Qatar National Research Fund. Ho Kyong Shon serves as an Editor-In-Chief for the Desalination journal, while the editorial handling and review of this manuscript were overseen by a different Editor-In-Chief.

Data availability

Data will be made available on request.

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