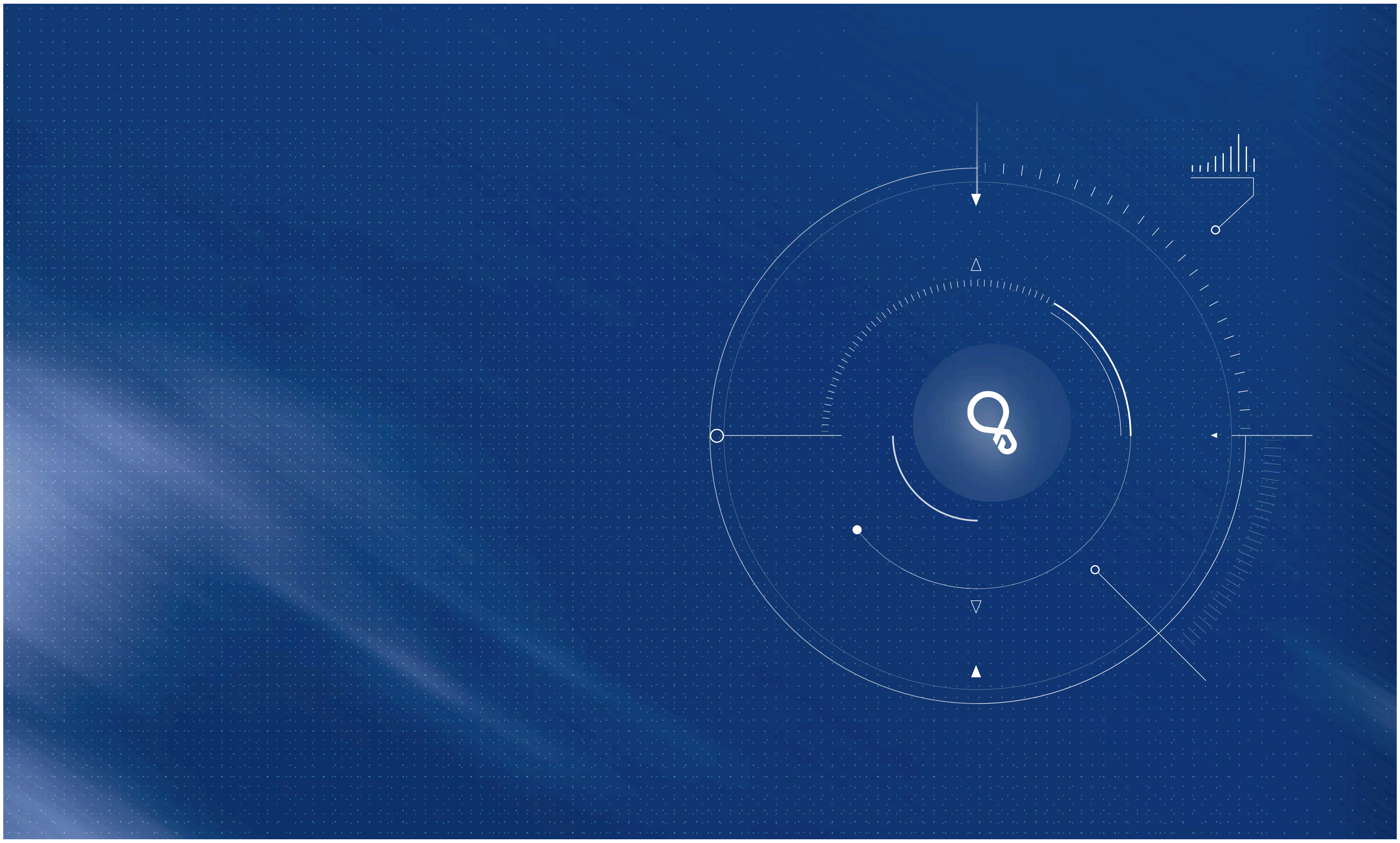
cypris

SEPTEMBER 2025



RESEARCH BRIEF

Low-Energy Desalination

Prepared By

Cypris Team

info@cypris.ai

Cypris Research Brief | For: Open Access
9/10/2025

Table of Contents

Executive Summary

This Research Brief aims to deliver a clear, evidence-based overview of today's low-energy desalination technologies to guide near-term decision-making. This report combines a review of scientific literature from 2015-2025 to examine the different specifications that different desalination approaches have, including but not limited to energy consumption, pretreatment and posttreatment burden, and temperature and operational constraints. This report compiles and normalizes measured system-level performance from real pilots/demos where available, maps technology readiness and commercialization gaps across approaches, compares each approach against a conventional reverse-osmosis baseline on energy, recovery, and operational robustness, and surfaces practical deployment constraints such as feedwater envelopes, pretreatment needs, and fouling sensitivity. This brief is tailored to inform technical experts and product development teams about the alternatives to traditional reverse osmosis in the low-energy desalination space.

Analyst Opinion

The low-energy desalination space is showing a clear shift towards reducing specific energy consumption whenever possible, as desalination is an energy intensive process. Although this Research Brief only qualifies <2 kWh/m^3 as "low-energy," a majority of large-scale systems have a system-level energy consumption above this level. It should be noted that the theoretical thermodynamic minimum specific energy for seawater desalination is 1.07 kWh/m^3 at 50% recovery and 35g/L salinity (seawater). The specific energy consumption of a real SWRO plant is approximately 3.5-4.5 kWh/m^3, including energy expended during pretreatment and posttreatment processes. [1] Brackish water desalination requires less energy consumption than seawater desalination and has a lower thermodynamic minimum energy due to having a lower salinity than seawater. It should be noted that the <2 kWh/m^3 threshold for "low-energy" has different implications for brackish water and seawater. A seawater desalination system with a system energy consumption near or below 2 kWh/m^3, would be considered highly efficient, as a desalination system with an energy consumption of 2 kWh/m^3 would currently be considered best-in-class. A brackish water desalination system with an energy consumption of 2 kWh/m^3, would be considered a moderate rate of energy consumption, as lower consumption can be achieved feasibly, especially at lower salinities.

Reverse osmosis is the most prevalent desalination method at-scale. To increase the system energy efficiency of a seawater desalination system reliably, the use of energy recovery devices such as pressure exchangers is recommended to capture and reuse the hydraulic pressure in the RO system to minimize energy losses of the system. Hybridizing the SWRO scheme with different mature or almost mature desalination approaches, such as FO or MD respectively, can potentially improve performance at high salinities, and the integration of renewable energy such as photovoltaic cells and solar heat collectors can drastically decrease the energy consumed by thermal processes. Integration of solar thermal energy for requirements such as the thermal energy required to operate membrane distillation, or the significant thermal energy consumed by the thermal distillation required for post-treatment recovery of the draw solution in forward osmosis could make the overall seawater desalination system much more efficient. At extremely high

---

[1] Kim et al., "A comprehensive review of energy consumption of seawater reverse osmosis desalination plants." *Applied Energy*. 2019

salinities, the osmotic pressure required to conduct reverse osmosis becomes extremely high, making it valuable to integrate a different approach that can desalinate brine using less energy.

For low salinity desalination (<5g/L) electrodialysis is a mature, highly efficient approach. However, above 5g/L of salinity, reverse osmosis remains the most efficient and mature means of desalination. While capacitive deionization shows promise for high recovery and energy efficient desalination below a salinity of 10g/L, the technology requires more development to improve its durability, stability, and scalability.

Research Methodology

In our research, we utilized the Cypris platform, and broader internet searches to identify relevant data. We surveyed peer-reviewed journals for experimental studies and data on energy-efficient desalination methods. Throughout this process, we refined our approach by adapting our keywords to synonyms and related terms to ensure comprehensive data collection within this sector. For our foundational query, we used Cypris' semantic searching functionality with the following search term: Low Energy Desalination.

Catalog of Low-Energy Desalination Technologies

Reverse osmosis (RO) desalination works by applying pressure to saline water to force it through a semipermeable membrane, separating pure water from salts and other impurities. In the natural process of osmosis, water moves from a region of low solute concentration to a region of high solute concentration across a membrane to balance concentrations. Reverse osmosis applies pressure greater than the osmotic pressure to push water molecules through a membrane, leaving dissolved solutes behind.[2] Desalination by means of RO is one of the most efficient and economically viable processes at scale. The efficiency of RO systems depends on multiple factors, such as operating parameters, membrane type, configuration, and feedwater characteristics. Higher salinity, in cases such as seawater reverse osmosis (SWRO) lead to higher osmotic pressure, which in turn leads to higher pressure and energy requirements to overcome the osmotic pressure. Although improvements in pressure pump technology and energy recovery devices have improved the energy efficiency of RO systems, RO systems still face the challenges of significant maintenance requirements due to membrane fouling as well as high energy consumption especially at higher salinities.[3] One study says If normalized salt passage has increased by 15%, or normalized permeate flow has decreased by 15%, it is time to clean the membranes.[4] Baseline levels of energy use for reverse osmosis range from 0.8-2.5 kWh/m^3 for brackish water, and 2.5-8.5 kWh/m^3 for seawater.[3] The following sections explore alternative methods to RO in the desalination space, as well as their energy performance, technical characteristics, and operating envelope. Typical recovery rates for RO are 35-50% for seawater desalination due to high fouling potential and increased salinity, and 60-80% for brackish water.[5] This research brief defines "low-energy" desalination approaches as those that demonstrate measured system-level energy consumption of <2 kWh/m^3 at pilot or demo scale.

Forward Osmosis

Forward Osmosis (FO) uses the differences in osmotic pressure across a semi-permeable membrane, between a concentrated extraction solution and the diluted feeding solution (such as seawater). Compared to RO, it uses moderate pressures in the natural direction of the osmotic flow, leading to a lower propensity for scale formation with very high permeate recoveries, which can reach 90%. FO has low specific energy consumption, between 0.25 and 1 kWh/m^3. However, the extraction solution requires post-treatment and recovery, which lead the system specific

---

[2] Sensorex. 2025."Understanding the Reverse Osmosis Desalination Process." *Sensorex*. Accessed September 9, 2025. https://sensorex.com/understanding-reverse-osmosis-desalination-process/

[3] Miranda et al., "Recent desalination technologies by hybridization and integration with reverse osmosis: a review" *Water*. 2021

[4] Puretec, 2025. "Reverse Osmosis – The Basics" *puretecwater.com*. Accessed September 10, 2025. https://puretecwater.com/resources/the-basics-of-reverse-osmosis/

[5] Eaiwater, 2025. "Optimizing Reverse Osmosis Recovery Rates and Membrane Health." *Eaiwater*. Accessed September 9, 2025. https://eaiwater.com/ro-recovery-rates/

energy consumption to be much higher (up to 21 kWh/m^3). The most used recovery method is thermal distillation that consumes significant energy amounts. Waste heat is generally used for this operation. Combination of technologies, including solar energy, can improve energy yields, and the environmental and economic indicators of the operation.[3] FO is very good for treating feeds ranging from brackish water to seawater, to more concentrated brines, as the higher salinity leads to greater natural osmotic pressure which the FO process exploits.[6] Although fouling is still an issue for FO, fouling has been observed to be more reversible than in RO, due to hydraulic compaction being lessened on the surface of FO membranes. Therefore, it is easier to clean the membrane surface in FO compared to RO.[7]

FO is a mature technology. In July 2018, the largest demonstration plant in operation, with a production of 500 m^3/d, was installed in the Zhoushan Islands of China. Although this technology is very promising, there are still barriers to overcome around costs of the membranes and use of the extraction solution requiring post-recovery treatments, thus making profitability economically unfeasible on a large scale. It is expected that the establishment of hybrid systems powered by renewable energies can overcome some of these barriers. Specific consumption of FO is around 1.95 kWh/m^3, and when using hybrid RO-FO systems this can be reduced to 1.83 kWh/m^3, while an FO-RO coupling manages to reduce it down to 1.47 kWh/m^3.

Membrane Distillation

Membrane distillation (MD) is acknowledged as an alternative membrane-based approach in the desalination industry and allows efficient operation at high salt concentrations. Contrary to the electricity/pressure-driven RO, water permeation in MD is driven by a thermal process with minor electrical energy consumption. The electric energy required for RO is estimated at 2.5–7.0 kWh per m^3 vs the 0.6–1.8 kWh per m^3 needed for MD. The main difference lies in the high pressure (20–100 bar) that the RO pumps need to overcome the osmotic pressure and allow water to permeate through the membrane at a reasonable rate. It is worth noting that pre-treatments to avoid fouling in RO are more complex, thus more expensive, than simple candle filters or the addition of biodegradable antiscalants that have been reported for MD. 90–98% of the total energy requirement in MD is thermal energy, but the low and wide temperature gradients (30–80 °C) needed to carry out desalinization by MD makes it possible to directly couple it with renewable sources of thermal energy such as solar collectors or waste heat.[8]

MD has low fouling and can handle a wide range of salinity, including brackish water and seawater. However, it also has low water recovery and high energy consumption if not coupled with the input of thermal energy. Without coupling for the input of thermal energy, membrane distillation energy consumption can range from 22-67 kWh/m^3.

Unlike MD, mature technologies such as RO have well-established guidelines and software on plant design, process control, and engineering developments, broadly available in the literature. Membrane performance in MD can be obtained experimentally or predicted by theoretical modeling. However, reported experimental results in the literature normally lack some of the required data to do a proper scale-up module design.[3] On the other hand, MD is found to be the

---

[6] Tian et al., "Forward osmosis membranes: the significant roles of selective layer." *PubMed, Membranes.* 2022

[7] Yu et al., "Forward osmosis membrane fouling and cleaning for wastewater reuse" *Journal of Water Reuse and Desalination*. 2016

[8] Ramos-Paredes et al., "Towards the technological maturity of membrane distillation: the MD module performance curve" *npj Clean Water*, 2023

most suitable when the input energy source is solar or waste heat, due to the energy intensive nature of the distillation process. Additionally, recent developments in membrane technology allow MD to run in compact modular configurations such as spiral configurations, making MD more promising to operate on a bigger scale.[9]

Electrodialysis

In electrodialysis (ED), the ions move through selective ion exchange membranes which only allow either cations or anions to pass through them. By alternating these membranes with spacers between them, it creates two separate streams: a desalinated stream and a concentrated salt stream.[10]

ED is much better suited for low salinity applications, as higher salinity leads to a lower recovery rate, and higher energy consumption. Specifically, for feed salinities of 1 and 3 g/L, ED has lower energy consumption than RO throughout the entire range of salt removals (20% to 90%), though the disparity between the SEC decreases as the salt removal and feed salinity are increased. For example, for a 1 g/L feed and 30% salt removal, ED utilizes 0.013 kWh/m^3 while RO requires more than 3-fold the energy (0.042 kWh/m^3. When salt removal is increased to 80%, however, this factor decreases to nearly 2-fold. Similarly, the energy consumption of RO and ED converges when assessing a 3 g/L feed salinity. For a salt removal of 80%, for instance, the SEC of ED is 0.29 kWh/ m^3, while that of RO is only 24% higher at 0.36 kW/ m^3.

Though ED requires less energy for the treatment of relatively low feed salinities, RO becomes the energetically superior technology as feed salinity is increased, particularly at high salt removals. When the feed salinity is increased to 5 g/L, for example, ED maintains lower SEC than RO up to 80% salt removal. However, further increasing the feed salinity to 10 g/L shifts this transition point to only 65% salt removal. Notably, for high feed salinities and salt removals, the magnitude of the SEC considerably grows, thereby also making the difference in the performance of RO and ED more substantial. For instance, in the case of 90% salt removal of a 10 g/L feed, the SEC of ED is 2.99 kWh/m^3 while that of RO is only 1.51 kWh/ m^3, a sizable difference of 1.48 kWh/ m^3. In contrast, for a 3 g/L feed, the maximum difference in the SEC of ED and RO is only 0.093 kWh/m^3.[11]

Electrodialysis reversal, or EDR also uses electricity to clean the electrodialysis cell by periodically reversing the flow of ions through the membrane. In normal electrodialysis, hardness scaling and fine organic material can accumulate on the membrane surface, leading to membrane fouling. But by reversing the flow of the applied direct current, salts and organics are driven back into solution and cleaned off the membrane surface. This self-cleaning procedure helps provide consistent, high recovery of desalinated water from brackish water feeds, and reduces membrane fouling compared to reverse osmosis. ED coupled with EDR leads to lower pretreatment requirements compared to RO, as well as more operational robustness due to the capability of self-cleaning. [10]

Capacitive Deionization

Capacitive Deionization (CDI) is a process system that removes charged species from water using an electrical potential difference (electrical driving force on the ions) between a pair of electrodes

---

[9] Ghaffour et al., "Desalination by membrane distillation" *Intech Open eBooks*. 2022

[10] Veolia, 2025. "Electrodialysis reversal (EDR)." *Watertechnologies.com.* Accessed September 9, 2025. https://www.watertechnologies.com/products/electrodialysis-reversal-edr

[11] Patel et al., "Energy consumption of brackish water desalination: identifying the sweet spots for electrodialysis and reverse osmosis" *ACS ES&T Engineering*. 2021

made often of porous carbon. One electrode which is positively charged adsorbs anions (negatively charged ions) and the other electrode which is negatively charged adsorbs cations (positively charged ions).[12]

The absence of hydraulic pressure means that fouling can be controlled in contrast to pressure-driven membrane processes, and operational expenses can be reduced. Additionally, a relatively low voltage is required (< 1.8 V) which means there are significant advantages in terms of low energy requirements with substantial water recovery. Compared with other desalination technologies, CDI is cost-efficient, environmentally friendly, high water recovery, easy to operate, and simple to regenerate. [13] In low-salinity feed streams, CDI uses less energy than other current processes (0.1-1.5. kWh/m^3).[14] However, as a desalination method, conventional CDI has not been found to be an energy-efficient method for the treatment of high-salinity solutions.[15]

A variant of CDI known as membrane CDI can attain high salt rejection and water recovery without an energy penalty,[13] but membrane fouling during lengthy operations prohibits MCDI from being scaled up and used in many applications.[14] Membrane CDI is also more expensive and complex. [14] CDI is still in the preliminary stages of research and development, and have not reached enough maturity for extensive use.[3]

Energy Recovery Devices

Use of Energy Recovery Devices (ERD) such as pressure exchangers has allowed a significant reduction in energy consumption of the RO thanks to the transfer of hydraulic energy from the brine to the feed, reducing energy consumption of high-pressure pumps. [3] In a typical SWRO system process, pressure exchanger devices and a high-pressure pump work in parallel to supply pressurized seawater to membranes. While the high-pressure pump consumes electricity, pressure exchange devices operate only on brine energy. By reducing the duty of the high-pressure pump by up to 60% compared to operation without energy recovery, pressure exchange technology reduces the energy required to desalinate by a similar percentage – up to 60%. Additionally, a SWRO process equipped with pressure exchange devices allows separate control of the high-pressure pump, providing plant operators with flexibility to cope with changing conditions and optimize plant performance. Pressure exchange devices on the market claim up to 98% efficiency, further reducing energy consumption and operating costs. [16] Albeit not an alternate approach to RO, using energy recovery devices in tandem with RO is one of the most feasible ways to reduce energy consumption of a large-scale desalination plant.

Batch and Semi-Batch Desalination

Batch and semi-batch desalination work by recirculating rejected brine back into the feed stream in RO configurations, enabling the reduction of the difference between pump pressure and osmotic pressure. Mathematical modeling confirms that batch RO can be more energy efficient than can continuous RO, especially at a higher recovery ratio. For seawater, at recovery ratios of 40%, 50%,

---

[12] Lenntech, 2025. "Capacitive Deionization (CDI)." *Lenntech*. Accessed September 9, 2025. https://www.lenntech.com/processes/capacitive-deionization-cdi-.htm

[13] Pang et al., "Advances and challenges in capacitive deionization: materials, architectures, and selective ion removal" *Desalination*. 2024

[14] Elewa et al., "A comparison of capacitive deionization and membrane capacitive deionization using novel fabricated ion exchange membranes" *MDPI, PubMed Central, PubMed, Materials*. 2023

[15] Qin et al., "Comparison of energy consumption in desalination by capacitive deionization and reverse osmosis" *Desalination*. 2019

[16] GWI, 2025. "PX Q400: Increased Efficiency in SWRO Desalination" *Globalwaterintel.com*. Accessed September 9, 2025. https://www.globalwaterintel.com/articles/px-q400-increased-efficiency-in-swro-desalination

and 60%, batch RO used respectively 17%, 23%, and 31% less energy than did continuous RO. For brackish water, at recovery ratios of 60%, 70%, and 80%, batch RO used respectively 9%, 19%, and 34% less energy than did continuous RO. [17] Another source conducted numerical modeling and concluded that, for seawater at 50% recovery, batch RO required 25% less energy than continuous RO. Additionally semi-batch RO demonstrated up to 37% energy savings for brackish water desalination at high water recovery, while batch RO demonstrated up to 64% energy savings.[18]

Hybridization with RO

Hybridization is a strategy that seeks to integrate multiple desalination approaches to reduce the weaknesses and enhance the advantages of each method.[3] Currently, reverse osmosis is the leading technology for desalination of brackish water and seawater, so hybrid systems generally combine RO with another desalination method since RO is a fully mature, scaled-up desalination technique.

For example, RO water treatment with high salinity and brines generates increases the hydraulic pressure required to overcome the osmotic pressure difference between the feed and permeate, which is why the typical recovery in seawater is 50% and up to 60% for single stage RO, which is a relatively low value compared to thermal technologies. Since membrane distillation has a low sensitivity to salinity, it can be used to increase production of fresh water in hybrid schemes with RO. Nonetheless, the chemical substances used in the pretreatments can have a negative influence by generating scale in the MD membranes, so although hybrid schemes can improve energy efficiency and the overall operational envelope, there can also be negative interactions as well.[3]

Another example of hybridization is a simulation of a FO/RO hybrid system which enabled RO operation below 1 kWh/m^3, reaching a recovery rate of 90% of the feed stream at 0.5g/l feed stream and 80:20 feed stream to draw stream volume ratio. [19]

There are hybrid systems in place today, such as the Ras Al-Khair plant in Saudi Arabia, which is currently one of the largest plants in the world that works with the hybridization of RO and multi-stage flashing (a less efficient thermal desalination method which constitutes 18% of the worlds installed desalination capacity). This plant produces 1,036,000 m^3/day of fresh water: 309,000 m^3/day with RO technology, and 727,000 m^3/day with MSF. The steam collected in the MSF unit can preheat the feed to the RO system, increasing its productivity. Additionally, the costs of cleaning and replacement membranes are reduced. Although this plant does not operate below the “low-energy” classification threshold of 2 kWh/m^3 , it does show that the integration of 2 or more desalination methods in one system can harness energy to be reused, and potentially improve operational performance.[3]

Integration with Renewable Energy

One of the largest trends in the low-energy desalination space is the integration of renewable energy with desalination. Small-scale desalination systems powered by renewable energies have seen a significant boost in recent years. More than 130 desalination plants have been installed in the world using energy sources such as solar, wind, and geothermal. Solar and wind farms are

---

[17] Abed et al., “Batch reverse osmosis desalination modeling under a time-dependent pressure profile" *PubMed Central*. 2021
[18] Warsinger et al., “Energy efficiency of batch and semi-batch (CCRO) reverse osmosis desalination” *Water Research*. 2016
[19] Rodríguez-Roda et al., “Can a forward osmosis-reverse osmosis hybrid system achieve 90 % wastewater recovery and desalination energy below 1 kWh/m3? A design and simulation study” *Desalination*. 2024

currently the most suitable renewable energy sources to incorporate with RO since all three are mature technologies. [3]

However, integration of renewable energy with RO has already been deployed on a large scale. The Al Khafji desalination plant in Saudi Arabia is one of the world's first large-scale, solar-powered desalination plants, which uses reverse osmosis to produce 60,000 m^3 of fresh water per day. Using either flat plate solar collectors, evacuated tub solar collectors, or parabolic trough solar collectors, they can use photovoltaic panels to generate electricity, offsetting some of the energy consumption required for the reverse osmosis process.[20]

Membrane distillation, unlike RO, is a thermal process. MD technology requires low-grade thermal heat and a small amount of pumping electrical energy, which could be entirely supplied by solar thermal collectors and photovoltaic cells, making MD an excellent fit to be fully driven by solar energy, especially in cases of extremely high salinity where traditional RO be much less energy efficient. [21]

---

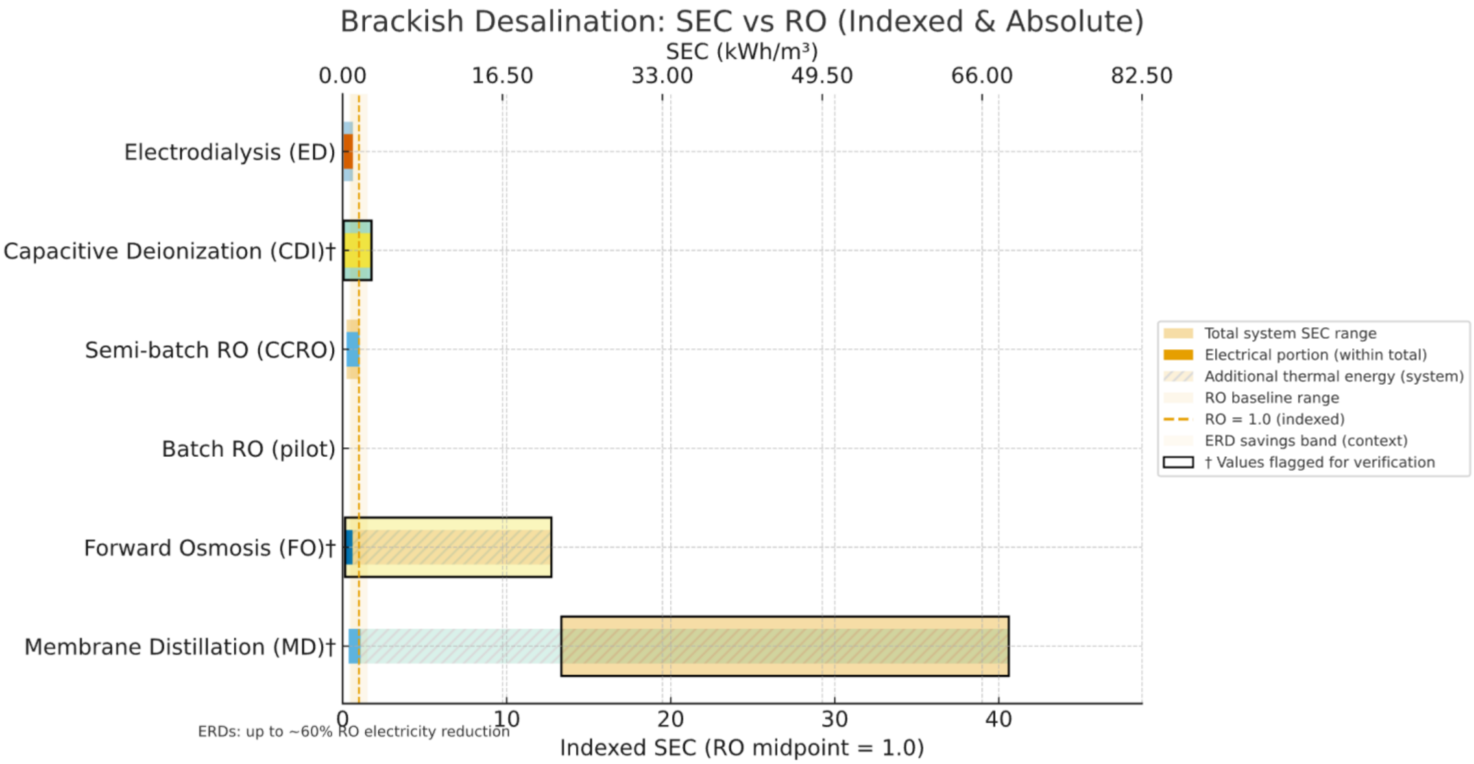
[20] Thrive, 2023. "Simple and effective solar-powered desalination" *thrivabilitymatters.org.* Accessed September 10, 2025. https://thrivabilitymatters.org/simple-and-effective-solar-powered-desalination/

[21] Thermopedia, 2022. "Solar-driven membrane distillation overview" *thermopedia.com.* Accessed September 10, 2025. https://www.thermopedia.com/content/10196

Comparative Benchmarking vs. Reverse Osmosis

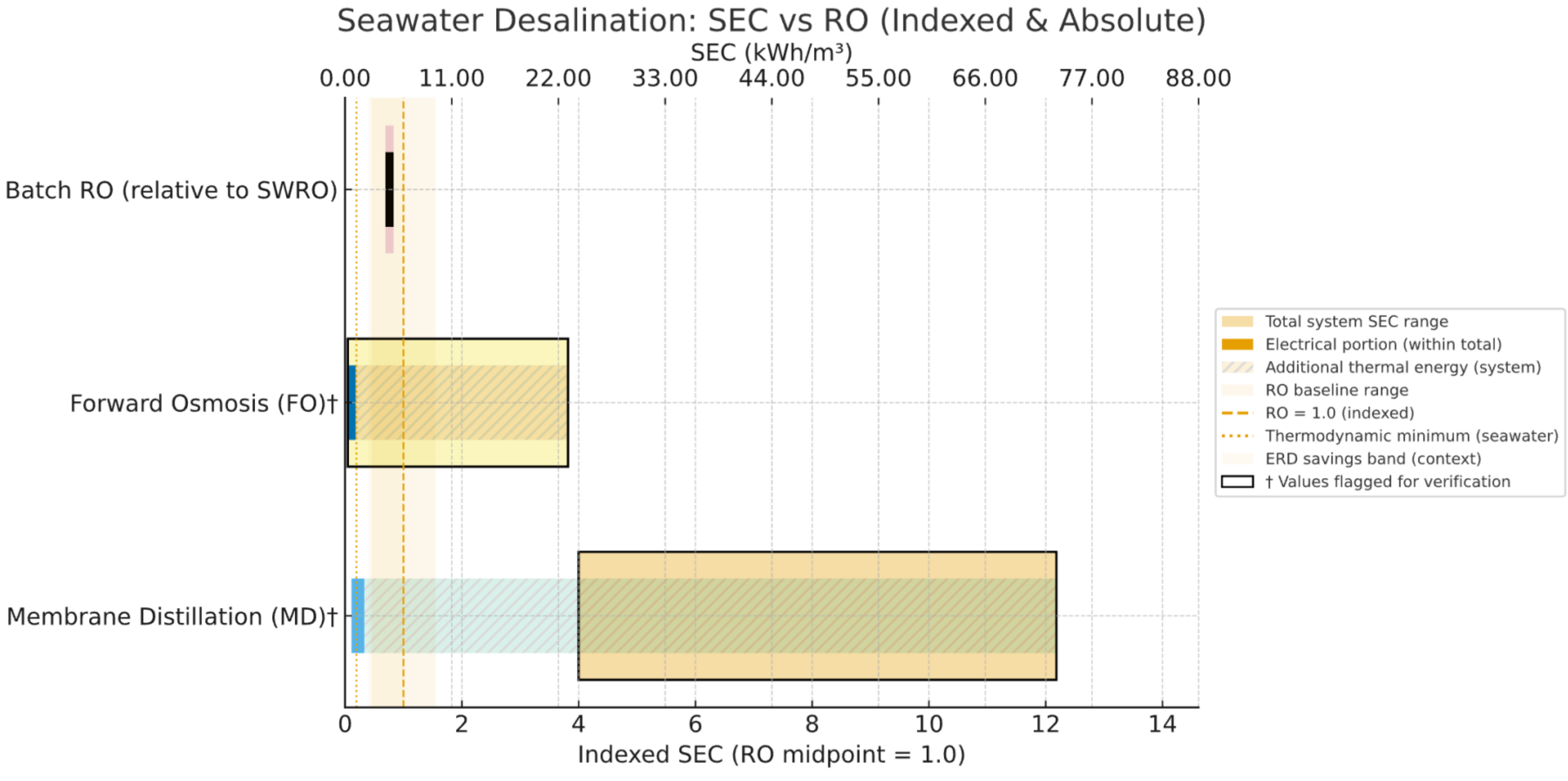
In this section, each approach is compared against SWRO and brackish RO baselines across various parameters. The figures and tables below present measured pilot/demo performance, parameters, and relevant technical specifications. If certain technical parameters were not reported in pilot studies, they were omitted.

Figure 1. Brackish Desalination: SEC vs RO (Indexed & Absolute)



The above figure compares system-level specific energy (SEC) for low-energy desalination approaches against a brackish RO baseline. Bars show the full reported range (electrical plus any required thermal input), with the electrical portion highlighted. Electrodialysis (ED) and semi-batch RO (CCRO) typically operate at or below the RO baseline depending on salinity and removal targets, while capacitive deionization (CDI) spans a broader range that is sensitive to feed conditions (†). Forward osmosis (FO) and membrane distillation (MD) appear electrically light, but system totals increase once thermal energy is included, emphasizing the importance of waste-heat or solar-thermal coupling.

Figure 2. Seawater Desalination: SEC vs RO (Indexed & Absolute)



ERDs: up to ~60% RO electricity reduction

The above figure normalizes alternatives to the seawater RO (SWRO) baseline and overlays the seawater thermodynamic minimum as a dotted reference line. Batch RO configurations can deliver modeled/pilot energy reductions relative to continuous SWRO at comparable conditions. FO and MD again show low electrical demand but higher system SEC once thermal inputs are counted (†), underscoring that integration with low-cost heat sources is decisive. The RO baseline band and index reference show where each option sits relative to the status quo and how much headroom remains versus the physical minimum.

Table 1: Comparative Benchmarking of Quantitative Data Among Low-Energy Desalination Methods

Parameter (x); Approach (y)	Energy Efficiency (kWh/m^3)	Recovery %	Feed Salinity/Feedwater Type	Flux/Productivity
Brackish RO (e.m.)	0.8–2.5 kWh/m^3	60-80%	.5 g/L-30g/L	10-18 Gfd. Can vary[4]
SWRO (e.m.)	2.5–8.5 kWh/m^3	35-50%	>35 g/L	8-12 Gfd. Can vary
Forward Osmosis[22] (p/d)	.151 kWh/m^3	60-92%	Brackish and Seawater	~9–18 LMH
Membrane Distillation (p)	500-1600 kWh/m^3	53-90%	Brackish and Seawater	2-16 LMH
Electrodialysis (p)	0.11-1.04 kWh/m^3 [23]	50%-80%	<10g/L	10-50 LMH
Capacitive Deionization (p)	1.1-2.9 kWh/m^3 [24]	40-67%	2.8 g/L	.82-1.18 m^3/h
Energy Recovery Devices (e.m.)	~60% decrease in energy consumption for RO	N/A	N/A	N/A
Batch RO (p)	3.3 kWh/m^3, which could potentially be reduced to under 1 kWh/m^3 in a full-scale system[25]	82.6%	6.4 g/L	15 LMH
Semi-Batch RO (p)	0.4-1.7 kWh/m^3 [26]	70%-90%	1 g/L – 5g/L	17-44 LMH
Hybridization (p)	Uses 80% of the energy of existing RO process[27]	N/A	Seawater	3.75-8.44 LMH
Renewable Energy (p)	Specific Electrical Energy Consumption: 0.13-0.2 kWh/m^3 [28] Specific Thermal Energy Consumption: 49-810 kWh/m^3	N/A	Study used deionized water, but cited studies show MD configuration can treat up to 350 g/L	Flow rate = 500-1400 L/H

Legend: e.m. = established method; p = pilot ; d = demo

---

[22] Kim et al., "Energy efficient forward osmosis to maximize dewatering rates" *Membranes*. 2025

[23] Walker et al., "Energy Efficiency of Electro-Driven Brackish Water Desalination: Electrodialysis Significantly Outperforms Membrane Capacitive Deionization" *Environmental Science & Technology*, 2020

[24] Jaiti et al., "Comparison of Pilot-Scale Capacitive Deionization (MCDI) and Low-Pressure Reverse Osmosis (LPRO) for PV-Powered Brackish Water Desalination in Morocco for Irrigation of Argan Trees" *PubMed; Membranes*. 2023

[25] Wei et al., "Piloting batch reverse osmosis with a flexible bladder for water recovery from scaling-prone brine" *npj Clean Water*. 2025

[26] Davies, "Direct experimental comparison of batch reverse osmosis (RO) technologies" *Desalination*, 2024

[27] Ali et al., "Pilot-Scale Investigation of Forward/Reverse Osmosis Hybrid System for Seawater Desalination Using Impaired Water from Steel Industry" *International Journal of Chemical Engineering*. 2016

[28] Inkawhich et al., "Temporal Performance Indicators for an Integrated Pilot-scale Membrane Distillation-concentrated Solar Power/photovoltaic System" *SSRN Electronic Journal*. 2023

Table 2: Comparative Benchmarking of Qualitative Data Among Low-Energy Desalination Methods

Parameter (x); Approach (y)	Operational Stability	Fouling Susceptibility	Pretreatment Requirements	General Notes
Brackish RO (e.m.)	Stable, but requires periodic cleaning. [4]	Susceptible due to precipitation of organic salts, accumulation of particulate material, and biofouling	Necessary - Filtration, antiscalant, chlorination[29]	Membrane fouling and durability issues, water recovery reduction with increasing scale
SWRO (e.m.)	Stable, but requires periodic cleaning.	Susceptible due to precipitation of organic salts, accumulation of particulate material, and biofouling	Necessary - Filtration, antiscalant, chlorination	Higher energy requirements, membrane fouling and durability issues; water recovery reduction with increasing scale
Forward Osmosis[22] (p/d)	Stable over extended runs; >90% flux recovery after backwash; productivity only gradually declines with organic-rich feeds	Less than RO, and minimized need for membrane cleaning[30]	Low	Fouling is an issue, but less so compared to RO (easier to clean membrane surface in FO compared to RO). Post treatment energy intensive and necessary
Membrane Distillation (p)	Stable operation with minimal loss in permeate flux for 80+ hours with proper cleaning; cleaning restores >90% flux	Moderate to severe risk if organics or scaling ions present; hydrophobic membranes prone to wetting, scaling, and organic fouling; fouling is reduced by using low-pressure, steady-state operation but increases with contaminated feeds[31]	Little to none	High energy consumption without thermal coupling; low water recovery; low fouling; wide temperature gradient for operation (30-80 degrees C)
Electrodialysis (p)	6+ months of near-continuous autonomous operation in field pilots with PV-powered direct-drive; stable performance	Moderate; scaling increases at high recovery/hardness, organic fouling possible But effectively controlled with standard filtration and operational management, and electrodialysis reversal.[32]	Antiscalants; polarity reversal generally sufficient for mitigating fouling and scaling	High capital costs, can clean membranes using reverse electrodialysis for reduced membrane fouling. Not effecting for high salinity desalination

---

[29] Lenntech, 2025. “Reverse Osmosis Pretreatment” *lenntech.com*. Accessed September 10, 2025. https://www.lenntech.com/ro/ro-pretreatment.htm

[30] Lipnizki et al., “Overcoming the Limitations of Forward Osmosis and Membrane Distillation in Sustainable Hybrid Processes Managing the Water–Energy Nexus” *Membranes*. 2025

[31] Anwar, “Membrane desalination processes for water recovery from pre-treated brewery wastewater: Performance and fouling” *Separation and Purification Technology*. 2020

[32] Winter et al., “Direct-drive photovoltaic electrodialysis via flow-commanded current control” *Nature Water*, 2024

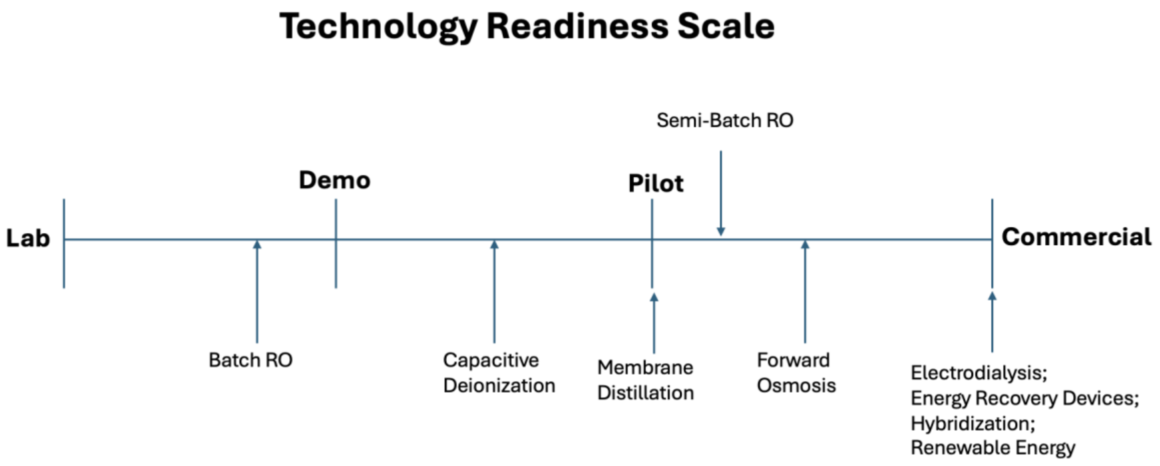
Parameter (x); Approach (y)	Operational Stability	Fouling Susceptibility	Pretreatment Requirements	General Notes
Capacitive Deionization (p)	Stable for 341 days, with greater recovery results and lower energy consumption at low salinities and lower salt removal targets.	Regularly cleaned (2-3 times over 341 days) for fouling mitigation	Cartridge filter for particle filtration	Low energy consumption, cost-effective operation for removing various ions from water. Not effective for high salinity desalination[33] Large-scale commercial CDI systems are not yet widespread due to challenges in electrode durability, operational stability, and scalability.
Energy Recovery Devices (e.m.)	N/A	N/A	N/A	Enables RO plants to be more energy efficient, no adverse impact on operational robustness
Batch RO (p)	1 week of continuous testing comprising 885 batch cycles	Avoids inorganic fouling (scaling) over short term, inconclusive on long term scaling potential.	No mention of pretreatment in this pilot	Less fouling propensity due to better control of the effective driving force. Long-term effects of rapid pressure cycling on critical components may appear
Semi-Batch RO (p)	Potential for scaling long-term	Not mentioned in study	Not mentioned in study	More complex operation and data collection; concerns regarding robustness of system
Hybridization (p)	Tested on continuous operation for 15 hours – water flux in FO process decreased slightly by time due to fouling	Fouling caused by presence of mixture of ions may reduce membrane permeability and affect flux rates over time	Uses nanofiltration as pretreatment or posttreatment to reduce nutrient concentration in the final product water	Can reduce fouling, reduce energy consumption, and increase operational robustness and feedwater envelope depending on hybrid configuration.
Renewable Energy (p)	Operated for 9-months in real world setting.	Not mentioned in study	None in this study because deionized water was used.	Reduces energy consumption using thermal energy, or generated electricity.

---

[33] Akbarzadeh et al, "Capacitive deionisation for water desalination review: experimental and simulation" *Science and Technology of Advanced Materials*. 2025

Technology Readiness Level

In this section, each approach will be assigned a technology readiness level, along with supporting information. The following visual depicts each approach discussed in this Research Brief on the technology readiness scale. Notable benchmarks are lab, demo, pilot, and commercial, where "lab" is the most nascent of technologies, while "commercial" represents the most scaled and mature technologies.



- Forward Osmosis: Pilot/Commercial – plant installed in Zhoushan Islands of China in 2018 with a production of 500 m^3/d. There are still barriers to overcome around the costs of the membranes and use of the extraction solution requiring post-recovery treatments, making profitability economically unfeasible on a large scale.
- Membrane Distillation: Pilot – Membrane distillation has not yet been commercialized for large-scale desalination in spite of its attractive features, especially the possibility of coupling to low-grade sources of energy. Despite its potential as a sustainable desalination technology, MD faces persistent challenges related to membrane durability and operational constraints.[34]
- Electrodialysis: Commercial – Electrodialysis currently accounts for 4% of the global desalination installed capacity.[35] Electrodialysis is only feasible for low salinity desalination, as higher salinities result in high specific energy consumption.
- Capacitive Deionization: Demo/Pilot – While CDI has sparked attention for its potential in low-salinity desalination, electrode durability, operational stability, and scalability remain major challenges.[13]
- Energy Recovery Devices: Commercial – While not an alternate approach to desalination, the implementation of energy recovery devices such as pressure exchangers reduces specific energy consumption of SWRO facilities by up to 60% by harnessing mechanical energy from the pressure

---

[34] Monash et al., "A Comprehensive Review of Advancements in Membrane Distillation for Liquid Separation and Hazardous Contaminants Removal: Innovations in Design, Integration, and Performance" *Environmental Science Water Research & Technology*. 2025

[35] Sistat et al., "Recent advances in capacitive deionization: a comprehensive review on electrode materials" *Journal of environmental chemical engineering*. 2023

gradient required for reverse osmosis operation. [36] Energy recovery devices have been implemented in large-scale plants, such as the Carlsbad Seawater Desalination Plant in Carlsbad, California.[37]

- Batch Reverse Osmosis: Lab/demo - Research is limited, and large-scale use remains under investigation.[17] However, studies and prototyping has occurred within labs, and some of these projects have been funded for future pilot projects.[38]
- Semi-Batch Reverse Osmosis: Pilot/commercial. Also known as Closed Circuit Reverse Osmosis, semi-batch desalination is patented and commercialized by Desalitech Company under the name of Reflex CCRO. [17] However, due to more complex operation and data collection, there are concerns regarding the robustness of the system, including the potential for the rapid pressure change during closed-circuit and purge sequences which can cause membrane integrity problems over long term operation.[39]
- Hybridization: Commercial – Large-scale hybrid desalination plants have existed for years, such as the Ras Al-Khair Power and Desalination plant, which is the world's largest hybrid water desalination plants. It has 17 reverse osmosis units, and 8 multi-stage flashing units. [40]
- Renewable Energy: Commercial – Large-scale desalination plants incorporating renewable energy are currently online, such as the Witsand Water Production Unit, which is the first solar desalination plant in Africa which opened in 2019.[41] Solar and wind farms are viewed as the most suitable renewable energy technologies for integration with RO, because they are all mature technologies.[3]

Stack-Ranking of Approaches

The following section contains a breakdown of scoring for developing a stack-ranking of approaches. The highest score possible is 25, while the lowest score possible is 4. This stack-ranking does not take into account the technological readiness level of each method.

- Energy intensity: 1-10; 10 = most efficient, 1 = least efficient
- Recovery and robustness: 1-5; 5 = very robust operation and high recovery, 1 = operational difficulties and low recovery
- Feedwater envelope breadth and temperature sensitivity: 1-5; 5 = all salinities and wide temperature range, 1 = very limited salinity and temperature range
- Burden due to pretreatment/posttreatment, and brine management: 1-5; 5 = little/no burden, 3 = similar burden to RO, 1 = high burden and constraints

ERD's were excluded from this stack-ranking of approaches since ERD's improve the performance of RO processes by recapturing wasted mechanical energy, and they do not have an impact on recovery %, operational robustness, feedwater envelope breadth, pretreatment burden, temperature sensitivity, or brine-management constraints

---

[36] Energy Recovery, 2025. "Energy Recovery Awarded $31 Million in Desalination Contracts in the Gulf Region" *energyrecovery.com*. Accessed September 10, 2025. https://energyrecovery.com/news/energy-recovery-awarded-31-million-in-desalination-contracts-in-the-gulf-region/#:~:text=Energy%20Recovery's%20PX%20reduces%20energy,for%20more%20than%2030%20years

[37] Carlsbad Desal, 2016. "The Carlsbad desalination project enhancing water reliability for San Diego County" *carlsbaddesal.com*. Accessed September 10, 2025. https://www.carlsbaddesal.com/files/uploads/1/0/0/4/100463770/desalination_process_fact_sheets_012916_webv4.pdf

[38] Purdue University, 2024 "Batch design cuts excess energy consumption in reverse osmosis desalination by 82%" *engineering.purdue.edu*. Accessed September 10, 2025 https://engineering.purdue.edu/ME/News/2024/batch-design-cuts-excess-energy-consumption-in-reverse-osmosis-desalination-by-82#:~:text=From%20this%20evaluation%2C%20Warsinger%20and,excess%20energy%20with%20future%20technologies.

[39] Hwang et al., "Operational optimization of closed-circuit reverse osmosis (CCRO) pilot to recover concentrate at an advanced water purification facility for potable reuse" *Desalination*. 2021

[40] Archirodon, 2025 "Ras Al-Khair Desalination Plant Jubail" *archirodon.net*. Accessed September 10, 2025. https://www.archirodon.net/ras-al-khair-desalination-plant-jubail/

[41] Western Cape Government, 2019 "Official opening of the first solar powered desalination plant in South Africa" *westerncape.gov.za*. Accessed September 10, 2025 https://www.westerncape.gov.za/treasury/article/official-opening-first-solar-powered-desalination-plant-south-africa

Hybrid desalination schemes were excluded from this stack-ranking of approaches, because the desalination methods combined by the hybrid system and how the system itself is built will have varying effects on the recovery %, operational robustness, feedwater envelope breadth, pretreatment burden, temperature sensitivity, or brine-management constraints of the system.

Desalination systems integrated with renewable energy were also excluded from this stack-ranking of approaches since the integration of renewable energy is meant to offset the specific energy consumption of the desalination system. The renewable energy technology itself should not have an impact on the recovery %, operational robustness, feedwater envelope breadth, pretreatment burden, temperature sensitivity, or brine-management constraints of the system.

Table 3: Stack-Ranking of Desalination Approaches

Approach	Energy Intensity (1-10)	Recovery and Robustness (1-5)	Feedwater Envelope Breadth and Temperature Sensitivity (1-5)	Treatment and Brine Management Burden (1-5)	Total Score out of 25
Brackish RO	7	3	3	3	16
SWRO	5	3	3	3	14
FO	6	4	3	1*	14
MD	5*	2	5	5	17
ED	9	4	1	4	18
CDI	9	5	1	4	19
Batch and Semi-Batch RO	8	3	3	3	17

**: Ranking can increase by up to 4 points if renewable energy technologies are integrated to provide energy to necessary thermal processes*

Related Research

Research Papers

Title: A comprehensive review of energy consumption of seawater reverse osmosis desalination plants
Publication Date: August 8, 2019
Author(s): Jungbin Kim, Kiho Park
Institution(s): Korea University
Summary: The paper provides a comprehensive review of energy consumption in seawater reverse osmosis (SWRO) desalination plants. It identifies specific energy consumption (SEC) as the critical cost and sustainability barrier, with modern plants typically operating in the range of 2–4 kWh/m^3. The review highlights the role of energy recovery devices (ERDs), which can cut energy demand by up to half, making them essential to state-of-the-art systems. It also examines contributions from high-pressure pumps, pretreatment, and post-treatment to overall energy use. Despite advances, the study notes that current SWRO still operates above the thermodynamic minimum (~1 kWh/m^3), underscoring efficiency limits. The authors emphasize that further reductions will depend on next-generation membranes, optimized process design, and renewable integration. Ultimately, the review establishes SWRO's current performance benchmarks and the technological gaps that future low-energy desalination approaches must close.

--

Title: Recent desalination technologies by hybridization and integration with reverse osmosis: a review
Publication Date: May 14, 2021
Author(s): Juan Pablo Rodríguez Miranda, Jesús Barrera-Rojas, Felipe Correa-Mahecha, Jhon Jairo Feria-Díaz
Institution(s): District University of Bogotá
Summary: The paper reviews recent advances in desalination technologies that combine reverse osmosis (RO) with thermal processes and renewable energy integration. It highlights hybrid configurations such as MED-RO and MSF-RO that improve energy efficiency, reduce brine discharge, and enhance water quality. The review also covers emerging membrane-based approaches like forward osmosis, membrane distillation, electrodialysis, and capacitive deionization, noting their potential when integrated with RO systems. Renewable energy (solar, wind, geothermal, and ocean energy) is emphasized as key to decarbonizing desalination and lowering costs. Case studies of large-scale hybrid plants in the Middle East and pilot projects globally illustrate both technical gains and challenges in scaling. The authors underline the importance of energy recovery devices, novel membranes, and hybrid operational modes for reducing specific energy consumption. They conclude that hybridization and renewable integration are central pathways for making desalination more sustainable, resilient, and aligned with global climate goals.
--
Title: Forward osmosis membranes: the significant roles of selective layer
Publication Date: September 29, 2022
Author(s): Miao Tian, Tao Ma, Kunli Goh, Zhiqiang Pei, Jeng Yi Chong, Yi-Ning Wang
Institution(s): OriginWater (China), Northwestern Polytechnical University, Nanyang Technological University
Summary: The paper provides a comprehensive review of the role of the selective (active) layer in forward osmosis (FO) membranes. FO is highlighted as a promising low-energy desalination method, particularly suited for treating highly saline or viscous feeds such as industrial effluents and brines. While much of the research in this field has focused on the porous substrate to mitigate internal concentration polarization, the authors stress that the selective layer is equally critical, as it determines solute rejection efficiency and minimizes back-diffusion—both essential for achieving stable performance and high water recovery. The review discusses how substrate properties influence the formation of high-performance polyamide selective layers and examines strategies such as incorporating interlayers and nanomaterials (including carbon nanotubes and metal–organic frameworks) to improve permeability, fouling resistance, and stability. It also highlights the importance of bridging the gap between laboratory-scale advances and practical field deployment, emphasizing that successful large-scale adoption will depend on membranes that balance selectivity, durability, and cost-effectiveness. Overall, the study points to forward osmosis as a promising pathway for reducing desalination energy intensity while addressing key challenges related to membrane design and long-term operation.
--
Title: Forward osmosis membrane fouling and cleaning for wastewater reuse
Publication Date: May 31, 2016
Author(s): Youngbeom Yu, Seockheon Lee, Sung Kyu Maeng
Institution(s): Korea Institute of Science and Technology, Korea Fisheries Resources Agency
Summary: This study evaluates fouling and cleaning behavior of forward osmosis (FO) membranes treating activated sludge effluent. FO showed less severe flux decline compared to reverse osmosis, suggesting greater resilience to fouling under challenging feedwater conditions. Among cleaning strategies tested, osmotic backwashing was most effective at restoring membrane performance, followed by cross-flow adjustment, air scouring, and spacer use. While FO experienced lower overall fouling, biofouling indicators were higher, highlighting the importance of effective cleaning protocols. Spacer addition improved FO performance with high suspended solids, though spacer geometry effects require further study. The work emphasizes that fouling type, cleaning efficiency, and recovery rates are critical for evaluating FO's long-term viability. These insights underline FO's potential advantages in robustness and cleaning flexibility relative to conventional pressure-driven processes.

--

Title: Towards the technological maturity of membrane distillation: the MD module performance curve
Publication Date: March 3, 2023
Author(s): Pablo López-Porfiri, Sebastián Ramos-Paredes, Patricio Núñez & Patricia Gorgojo
Institution(s): Federico Santa María Technical University, University of Manchester
Summary: Membrane distillation (MD) remains a promising desalination technology but lags in real-world deployment due to gaps between academic research and process design. The authors employ coupled mass and heat transfer modeling, simulating MD performance across various membrane geometries, areas, and feed conditions in a direct-contact setup. From these simulations, they derive an MD module performance curve that connects feed inlet parameters (temperature, concentration) to outputs like permeate flow rate, thermal energy use, and outlet temperature. This performance tool offers a framework to predict system-level behavior under diverse operating scenarios. The study emphasizes that bridging the communication gap between membrane developers and process engineers is essential for improving technology transfer. By establishing quantitative design guidelines, the work advances MD toward engineering maturity. Overall, these insights provide a practical roadmap for accelerating MD from lab-scale experimentation to pilot and commercial-scale applications.

--

Title: Desalination by membrane distillation
Publication Date: January 21, 2022
Author(s): Noreddine Ghaffour, Mustakeem Mustakeem, Muhammad Saqib Nawaz, Sofiane Soukane
Institution(s): King Abdullah University of Science and Technology (KAUST)
Summary: This paper reviews membrane distillation (MD) as an emerging thermal-driven desalination process that combines the principles of evaporation with membrane separation. Operating at moderate feed temperatures (50–90 °C), MD achieves very high salt rejection, can handle hypersaline waters, and generally shows lower fouling risk than conventional pressure-driven systems. Four main configurations are discussed: direct contact (DCMD), air gap (AGMD), vacuum (VMD), and sweeping gas (SGMD), each balancing permeate flux, energy efficiency, and operational complexity. Heat and mass transfer mechanisms, along with challenges like temperature polarization and conductive heat loss, are identified as key barriers to efficiency. Membrane properties such as high porosity, hydrophobicity, low thermal conductivity, and optimized pore size are emphasized as critical for performance. Module designs—flat sheet, hollow fiber, and spiral wound—are evaluated for scalability, with spiral-wound systems showing potential for compact and efficient operation. Performance metrics including permeate flux, recovery ratio, gained output ratio, and specific energy consumption are used to benchmark system viability. Recent advances such as hybridization with RO, FO, or MED and localized heating techniques (photothermal or electrothermal) demonstrate pathways to reduce energy intensity and improve robustness. Overall, MD is positioned as a sustainable desalination technology, especially when powered by low-grade solar or waste heat sources.

--

Title: Energy consumption of brackish water desalination: identifying the sweet spots for electrodialysis and reverse osmosis
Publication Date: January 22, 2021
Author(s): Sohum K. Patel, P. Maarten Biesheuvel, Menachem Elimelech
Institution(s): King Abdullah University of Science and Technology (KAUST)

Summary: This study performs a systematic, side-by-side comparison of reverse osmosis (RO) and electrodialysis (ED) for brackish water desalination using rigorous system-scale modeling. Both processes achieve high energy efficiencies (>30%) when assessed over comparable feed salinity, salt removal fraction, recovery rate, and productivity. The analysis reveals that ED is more energy-efficient for treating lower salinities (below ~3 g/L), while RO excels at higher feed salinities (above ~5 g/L) where greater salt removal is required. These findings help pinpoint the operational domains—or "sweet spots"—where each technology performs most efficiently. The study also notes that broader adoption of ED hinges on reducing the cost of ion-exchange membranes to make it economically competitive. Overall, this work provides critical insight into how different desalination technologies align with energy performance targets under varied conditions.

--

Title: Advances and challenges in capacitive deionization: materials, architectures, and selective ion removal
Author(s): Tianting Pang, Frank Marken, Davide Mattia, Junjie Shen, Dengsong Zhang, Ming Xie
Institution(s): Funded by Royal Academy of Engineering
Summary: This study delivers a rigorous, system-level comparison of reverse osmosis (RO) and electrodialysis (ED) across a range of brackish water conditions by modeling specific energy consumption and process efficiency. It finds that ED outperforms RO in energy terms for lower salinity feeds (below ~3 g/L) and modest salt removal, while RO becomes more energy efficient as feed salinity exceeds ~5 g/L and when extensive desalination is required. These insights define the operational domains—or "sweet spots"—where each technology delivers optimal energy performance. The analysis highlights that broader use of ED hinges on reducing ion-exchange membrane costs to enhance economic competitiveness. By mapping energy-intensity trade-offs across varied feed and operational parameters, the paper equips designers with a performance-based guide to selecting appropriate desalination technologies. It ultimately clarifies why RO dominates in global brackish water treatment despite ED's advantages in specific niches, framing energy efficiency as the key differentiator.

--

Title: A comparison of capacitive deionization and membrane capacitive deionization using novel fabricated ion exchange membranes
Author(s): Mahmoud M Elewa, Mervette El Batouti, Nouf F Al-Harby
Institution(s): Arab Academy for Science, Technology, and Maritime Transport, Alexandria University
Summary: This study compares capacitive deionization (CDI) and membrane capacitive deionization (MCDI) using newly fabricated ion-exchange membranes designed for improved selectivity and stability. CDI, which removes ions by electrostatic adsorption onto porous electrodes, is shown to be effective but limited by co-ion expulsion and lower charge efficiency. Incorporating ion-exchange membranes in MCDI significantly enhances salt removal, reduces energy losses, and improves recovery by preventing co-ion leakage. Experimental results demonstrate that MCDI achieves higher ion removal efficiency and lower energy consumption per unit of treated water compared to conventional CDI, especially under higher feed salinities. The novel membranes used in this study exhibit robust mechanical and electrochemical performance, extending operational stability and longevity. Overall, the findings indicate that MCDI, when paired with optimized membranes, represents a more energy-efficient and scalable pathway for desalination and brackish water treatment than CDI.