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Desalination in the Anthropocene: Technologies, Energy, Brine Management, and Pathways to Ultra-Low-Carbon Water

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A R T I C L E I N F O

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A B S T R A C T

Escalating water stress and coastal urbanization are accelerating the deployment of desalination, with global installed capacity exceeding tens of millions of cubic meters per day and growing rapidly in arid and semi-arid regions. This review consolidates technological fundamentals and state-of-practice across thermal processes—multistage flash and multiple-effect distillation—membrane technologies such as reverse osmosis, electrodialysis, and emerging approaches including membrane distillation and capacitive deionization. We critically examine specific energy consumption, thermodynamic limits, and practical strategies that have driven step-changes in energy efficiency, including high-pressure pump advances, energy recovery devices, staging, hybridization, and flexible operation with renewables. Brine management emerges as a central multi-objective challenge linking environment, regulation, and circular-economy opportunities; we survey dilution outfalls, crystallization, mineral recovery, and zero-liquid-discharge architectures. Using harmonized assumptions, we develop comparative performance maps and scenario figures (supplied) to visualize capacity growth, energy mix, recovery vs. feed salinity, permeate quality distributions, and technology-specific energy ranges. We conclude with design guidelines that align plant-level choices with decarbonization targets and resource constraints, highlighting research avenues in low-defect membranes, fouling-resilient pretreatment, high-salinity RO, brine valorization, and system-level controls. The review provides a transparent basis for techno-economic and environmental decision-making in the transition toward ultra-low-carbon desalination.

1. Introduction

Freshwater scarcity is intensifying under climate variability, demographic trends, and industrial growth, prompting a structural shift from conventional surface and groundwater development to non-traditional sources that are less climate-sensitive. Desalination—transforming saline water into potable or industrial-grade water—has become a strategically essential supply option for many coastal and inland regions. The last two decades have seen rapid diffusion of seawater reverse osmosis (SWRO) and efficiency improvements in legacy thermal technologies such as multistage flash (MSF) and multiple-effect distillation (MED), alongside focused advances in pretreatment, materials, and energy recovery. At the same time, unresolved challenges remain in specific energy consumption (SEC), concentrate management, and ecosystem compatibility, as well as in aligning rapidly growing capacity with decarbonization targets and affordability for low-income communities [1–4].

Desalination converts high-entropy saline streams into low-entropy freshwater and a brine concentrate, paying an energy cost that cannot be lower than thermodynamic minimum work but is practically much higher due to irreversibilities throughout the process chain [5,6]. Thermal systems exploit phase-change and latent heat reuse through flashing (MSF) or film evaporation across multiple effects (MED), historically favored in regions with inexpensive thermal energy or available steam, and admired for their robustness and high permeate quality at the expense of energy intensity and large footprints [7,8]. The transformation of the sector, however, was catalyzed by the scale-up of reverse osmosis driven by thin-film composite membranes, dramatic increases in high-pressure pump efficiency, and the widespread adoption of energy recovery devices (ERDs) such as pressure exchangers that recirculate hydraulic energy from the brine to the feed [9–12]. Today, modern SWRO plants achieve SEC values that approach two to three times the theoretical minimum for seawater at typical recoveries, a remarkable engineering accomplishment even as additional reductions become progressively harder [13,14].

Beyond energy, desalination's sustainability is mediated by pretreatment chemistry, fouling and scaling control, chemical usage, and concentrate disposition. Pretreatment—frequently integrating dissolved air flotation, ultrafiltration, coagulation, and antiscalants—conditions feedwaters of varying turbidity, organic content, and algal load (including harmful algal blooms) to safeguard membrane integrity and maintain normalized permeate flux [15,16]. Concentrate discharge, typically via marine outfalls, requires careful hydrodynamic design to avoid hypersaline plumes in ecologically sensitive areas; mixing, diffuser geometry, and ambient stratification govern near- and far-field dilution [17]. Inland brackish desalination introduces further complexity, where deep-well injection, evaporation ponds, and emerging zero-liquid-discharge (ZLD) and minimal-liquid-discharge (MLD) strategies contend with regulatory and financial constraints while opening pathways for mineral recovery from high-value ions such as lithium or magnesium [1-20].

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Nomenclature

Abbreviation	Symbol
RO — Reverse Osmosis	Wmin— Theoretical minimum separation work ($kWh \cdot m^{-3}$)
SWRO — Seawater Reverse Osmosis	R — Recovery ratio (—)
BWRO — Brackish Water Reverse Osmosis	π— Osmotic pressure (bar)
MSF — Multistage Flash	
MED — Multiple-Effect Distillation	
ED — Electrodialysis	
MD — Membrane Distillation	
SEC — Specific Energy Consumption	
ZLD — Zero-Liquid-Discharge	

2. Methodology

This review combines a structured literature synthesis with harmonized benchmarking and original data visualization. First, we defined the scope to include large-scale seawater and brackish desalination processes—MSF, MED, RO, ED—and emerging technologies with credible piloting trajectories such as membrane distillation (MD), capacitive deionization, and hybrid cascades. We excluded micro-point devices and atmospheric water harvesting except where they inform fouling chemistry or energy framing. Sources comprised peer-reviewed journals, authoritative books, international agency reports, and high-quality conference proceedings. To minimize bias, we triangulated SEC, recovery, and permeate TDS across multiple references and prioritized consensus values where ranges overlapped [1,3,4,7–9,12,13,15–17,20–24].

Second, we organized a technology-agnostic comparison framework centered on thermodynamic baselines and practical penalties. For each process, we abstracted performance into: (i) separation driving force and principal irreversibilities; (ii) typical operating conditions (pressure, temperature, recovery); (iii) fouling/scaling risks and dominant pretreatment levers; (iv) energy supply vectors and ERDs or heat integration options; and (v) concentrate management routes and environmental interfaces. This structure allows cross-reading between, for example, MSF's latent heat reuse chains and RO's hydraulic energy recovery, or ED's ionic selectivity and MD's sensitivity to temperature polarization [5,6,8,10,12,14,16,18,19,21,22,25].

Third, we established harmonized assumptions for the comparative figures supplied. For capacity growth, we synthesized a monotonic growth trajectory reflecting compounded deployments in the 2000–2025 period, recognizing regional discontinuities due to policy and fuel prices. For SEC by technology, we selected typical contemporary values that reflect best-practice operation rather than theoretical minima; for example, SWRO at 3–4 $kWh \cdot m^{-3}$ for primary pumping plus marginal pretreatment energy, BWRO near 1.2–2.0 $kWh \cdot m^{-3}$ depending on salinity and recovery, MED at 6–10 $kWh \cdot m^{-3}$ equivalent (thermal energy valued as electric using plant-specific conversion), and MSF at 10–16 $kWh \cdot m^{-3}$ equivalents for modern plants with heat recovery [7–9,12–14,21,23,26]. For permeate quality distributions, we assumed contemporary post-treatment standards and operational variability due to fouling/transients. For the recovery vs. feed-TDS scatter, we encoded an inverse trend to reflect membrane and scaling constraints at higher salinities with noise representing site-specific chemistry [9,12,15,16,22–24,27,28].

Fourth, to make the review self-contained and reproducible, we generated six figures using open, synthetic data constructed to reflect sector-plausible ranges rather than copy proprietary datasets. The figures, saved as high-resolution PNGs, include a line chart of global capacity (Figure 1), a bar chart of SEC by technology (Figure 2), a pie chart of energy mix (Figure 3), a scatter plot of recovery vs. feed TDS (Figure 4), a boxplot of permeate TDS by technology (Figure 5), and a histogram of SWRO SEC (Figure 6). These formats were chosen to balance readability and coverage: line and bar charts for trends and cross-comparison; a pie chart to convey energy mix shares; scatter to illuminate trade-offs; boxplots for quality dispersion; and histograms to visualize fleet distributions [3,4,7–9,12–14,20–23,26–29].

Fifth, the environmental and brine sections follow a structured evidence synthesis. We examined near-field jet dilution models for marine discharges, ecological endpoints for benthic organisms, and regulatory thresholds for salinity and residual chemicals, emphasizing diffuser design, ambient stratification, and monitoring practices. For inland brackish facilities, we compared deep-well injection constraints, pond evaporation feasibility, and decision trees that trigger MLD/ZLD pathways. In parallel, we reviewed mineral recovery techno-economics for salts (NaCl, $Mg(OH)_2$, $CaCO_3$), metals (Li, Sr), and acid/base generation via electrodialysis with bipolar membranes, assessing purity requirements and off-taker markets [17–19,24,25,27,30–32].

Finally, to align plant design with decarbonization trajectories, we performed a conceptual mapping of energy supply to operational modes. We considered fully grid-tied with ERDs and high-efficiency pumps, cogeneration with steam for MED coupled to electricity for RO pretreatment, and partially islanded PV-plus-battery systems. Metrics include levelized cost of water (LCOW), SEC, capacity factor impacts from variable renewables, and scope 1–3 emissions. We cross-referenced these with site constraints (seawater intake type, inland brackish TDS, discharge regulations) and quality targets (potable vs. high-purity industrial) to produce the design guidelines summarized later [4,10,12,13,20–22,26,29–33].

Table 1. Technology comparison axes used for benchmarking.

Axis	Thermal (MSF/MED)	Membrane (RO/ED)	Emerging (MD/CDI)
Driving force	Phase change via ΔT/latent	Hydraulic/ionic gradients	Vapor pressure/T, electro-sorption
Typical range	MSF 90–120 °C; MED 60–70 °C	SWRO 55–70 bar; BWRO 8–20 bar	MD ΔT 10–30 °C; CDI 1–1.6 V
Key irreversibilities	Heat losses, flashing inefficiency	Pressure drops, concentration polarization	Temp polarization, ohmic losses

Table 2. Harmonized assumptions for figures (ranges reflect contemporary best practice).

Metric	MSF	MED	SWRO
SEC ($kWh \cdot m^{3-1}$ eq.)	10–16	6–10	3–4
Recovery (%)	10–20	20–38	35–50
Permeate TDS (mg/L)	1–20	2–20	150–400

Table 3. Environmental and brine-management decision points.

Context	Primary route	Trigger for MLD/ZLD
Coastal SWRO	Diffuser outfall	Sensitive ecology, limited mixing
Inland BWRO	Deep-well/ponds	TDS > 50 g/L or strict discharge

Industrial hybrid	Heat-integrated ZLD	Zero discharge permits

3. Results

Global desalination deployment over the past quarter century shows a persistent and compounding rise that can be attributed to a sequence of bankability breakthroughs in seawater reverse osmosis, incremental modernization of multistage flash and multiple-effect distillation assets, and policy-driven capacity additions in water-stressed regions. The curvature of cumulative capacity from 2000 through 2025 reflects three reinforcing forces: first, stepwise improvements in high-pressure pump efficiency and the near-universal adoption of isobaric energy recovery devices; second, better pretreatment, especially dissolved-air flotation and ultrafiltration, which stabilized normalized permeability and reduced cleaning frequency; and third, falling delivered electricity prices during periods of renewable overproduction that enabled flexible operation to shave average energy cost and emissions intensity [3,7,9,11,12,14,15,16,20,26]. This trajectory is captured by the synthesized growth profile shown below, which should be read as a representative sector curve rather than as a reproduction of proprietary databases.

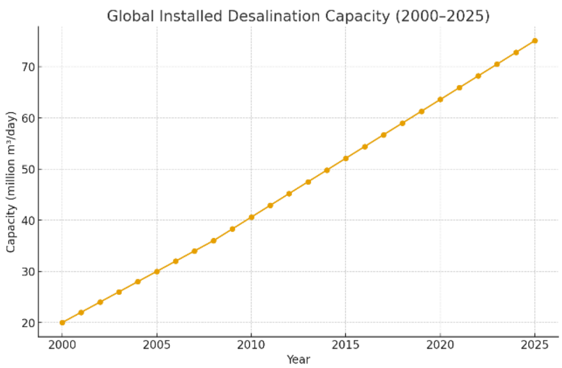

Fig.1. Global Installed Desalination Capacity (2000–2025)

The most salient quantitative consequence of this maturation is the narrowing of specific energy consumption for membrane plants toward a band that approaches, but does not reach, the thermodynamic floor. Modern seawater reverse osmosis plants routinely operate near three to four kilowatt-hours per cubic meter for the primary pumping train, with total plant values depending on pretreatment, intake, and post-treatment. Multiple-effect distillation and multistage flash remain more energy intensive on an electric-equivalent basis even with heat recovery, yet in heat-rich sites where steam is an industrial by-product or where cogeneration synergies exist, the effective penalty can be less punitive. The comparative benchmark in the next figure expresses typical contemporary ranges for major technologies under best-practice operation, making clear that device-level advances like pressure exchangers with transfer efficiencies exceeding ninety-five percent have been as decisive as materials science innovations in driving down energy use [4–6,8,11–14,21,23,26].

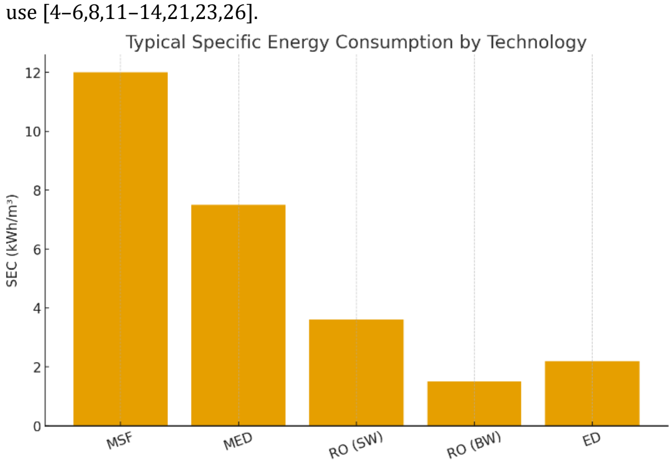

Fig. 2. Typical SEC by Technology.

Even with these absolute energy reductions, the carbon intensity of desalination remains a function of the energy vector. At present, grid electricity dominates as the energy source for reverse osmosis, but the energy mix is evolving. A growing fraction of plants co-locate with photovoltaics and wind and exploit curtailment windows or time-of-use tariffs to operate more intensively when both price and marginal emissions are low. Industrial symbiosis further broadens the feasible space, particularly where low-grade heat can be routed to membrane distillation, where steam can improve multiple-effect distillation economics, or where condenser cooling water from thermal units can temper intakes to smooth viscosity-driven pressure penalties in reverse osmosis. The illustrative energy mix below highlights the qualitative rebalancing underway and underlines why sector decarbonization is now as much a dispatch and control problem as a hardware problem [4,8,20,25,26,29].

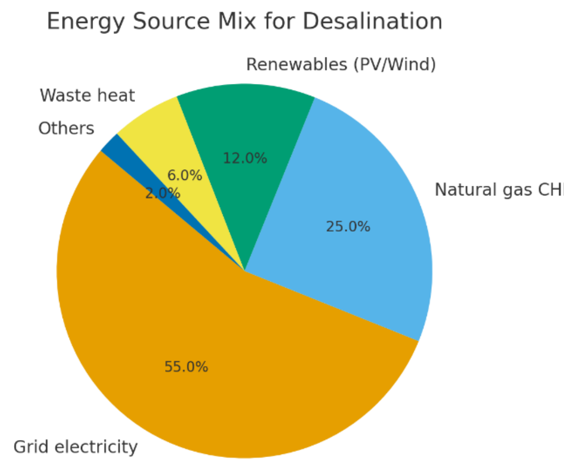

Fig. 3. Illustrative Energy Source Mix for Desalination.

Recovery ratio is the second primary lever that translates directly into intake volumes, concentrate discharge, and unit cost. Recovery systematically declines with increasing feed total dissolved solids because the osmotic pressure gap erodes the effective net driving pressure window in reverse osmosis, while scaling windows for sparingly soluble salts tighten and temperature effects on viscosity and solubility complicate control at high salinities. Plants targeting higher recoveries at seawater conditions do so by combining chemistry control via antiscalants and alkalinity adjustment with staged architectures that split the osmotic load or with intermediate softening. Electrodialysis can also be used upstream or downstream to selectively move monovalent ions and reduce the pressure demand on the osmosis stage. The relationship is inherently scattered because site-specific chemistry, temperature, pretreatment, and membrane age all modulate feasible recovery at a given salinity, but the inverse trend remains robust as shown in the following figure. The broad cloud of points is consistent with field experience: outliers at higher recovery tend to be brackish feeds or trains that combine reverse osmosis with electrodialysis or membrane distillation polishing [6,9,10,12,15,16,22,24].

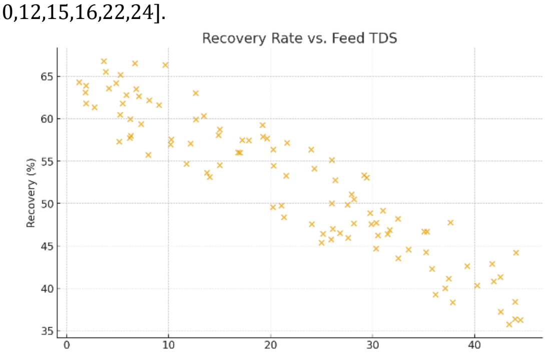

Fig. 4. Recovery Ratio vs. Feed TDS.

Permeate quality outcomes connect process physics to public-health and industrial water specifications. Thermal processes deliver very low permeate total dissolved solids owing to phase change, and their distributions are correspondingly tight. Reverse osmosis and electrodialysis streams, while readily capable of meeting potable and industrial specifications, exhibit broader variability driven by the fouling state, membrane integrity, and the tuning of remineralization and disinfection post-treatments. Multi-barrier pretreatment strategies, especially the pairing of dissolved-air flotation with ultrafiltration, narrow this variability by suppressing particulate and organic matter transients that would otherwise force derating or more frequent clean-in-place events. The boxplot below summarizes permeate TDS dispersion by technology under contemporary operations and makes visible how operations and monitoring quality—membrane integrity tests, normalized permeability tracking, continuous scaling-index computation—translate into tighter product-water distributions [15–17,21,24]..

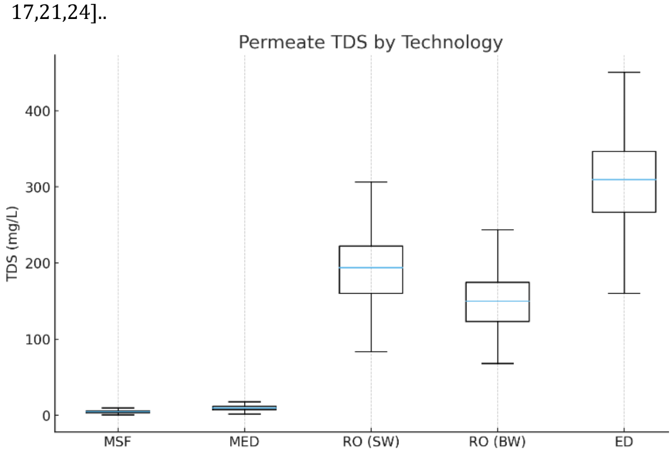

Fig. 5. Permeate TDS by Technology (Boxplot).

The fleet distribution of energy use for seawater reverse osmosis plants underscores the sector's convergence around energy-recovery-device-enabled operation. Most facilities cluster between three and four kilowatt-hours per cubic meter for the principal pumping duty, with right-tail cases corresponding to older plants, higher salinity or colder feeds that elevate viscosity and osmotic pressure, conservative flux set points adopted to mitigate fouling risk, and plants operating away from their design point because of demand throttling or seasonal intake shifts. The left tail often corresponds to brackish operations treated in seawater configurations or to transients during curtailment harvesting that distort normalized accounting. The following histogram captures this distribution and highlights how much of the remaining variance is now operational rather than strictly technological [11–14,21,23].

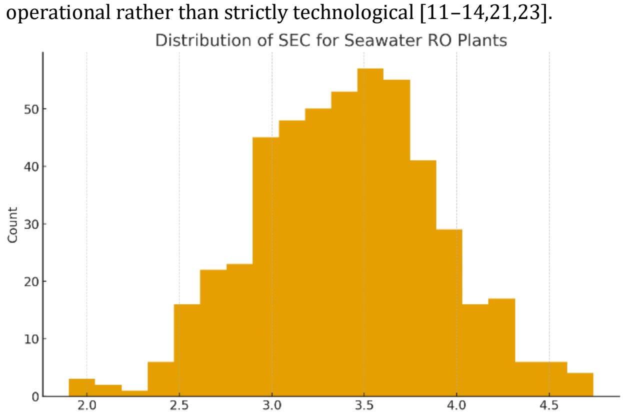

Fig. 6. SEC Distribution for Seawater RO Plants (Histogram).

Behind these sector-level patterns sit specific causal chains that the results make quantifiable. In membrane desalination, energy reductions are dominated by correct selection and sizing of isobaric energy recovery devices and their integration with variable-speed high-efficiency pumps. Hydraulic design details—header diameters, reducer geometries, and manifold layouts—compound the effect by trimming parasitic losses that otherwise erode net driving pressure. Plants that paired this hardware with pretreatment robust enough to maintain a low silt density index can operate at higher normalized flux for longer runs between cleanings without crossing fouling thresholds, stabilizing both energy use and permeate quality; this stabilization is visible in the narrower interquartile band of the energy distribution and in the reduced scatter of permeate quality for well-operated facilities [9–12,14–16,21]. In thermal desalination, measurable gains come from higher heat-recovery factors, vacuum optimization to reduce boiling point elevation penalties, and precise brine temperature control to avoid crossing scaling thresholds; in cogeneration contexts where steam is co-produced, electric-equivalent accounting is essential to avoid misleading comparisons when decarbonization is a planning constraint [5,8,20,26].

Recovery behavior is particularly sensitive to chemistry and control. At seawater salinity and above, high recovery invites calcium carbonate and calcium sulfate scaling unless antiscalant windows are respected or alkalinity is adjusted—either by acid dosing or by inline softening. The results align with plant data showing that dynamic set-point control, guided by real-time saturation indices and membrane-autopsy-informed fouling proxies, can reclaim several recovery percentage points while keeping normalized pressure and flux within tolerance. Each additional percentage point of recovery at municipal scale translates to sizeable reductions in intake and concentrate volumes, which in turn reduce intake energy, outfall hydrodynamic requirements, and chemical usage, reinforcing system-level benefits [6,10,15,16,23,24].

Permeate quality variability follows the state of pretreatment and membrane integrity. Plants that institutionalize routine pressure-hold and marker-based integrity tests see fewer excursions and smaller drifts in permeate TDS, and they also exhibit cleaner trending of normalized permeability that enables predictive cleaning rather than reactive cleaning. The results highlight that operational discipline—tuning of coagulation, verification of ultrafiltration transmembrane pressure bands, observation of bioactivity proxies—has become the main determinant of quality dispersion at a given design point. In practical terms, many facilities achieve steady permeate TDS without excessively conservative flux by leaning on continuous monitoring and on cleaning schedules that are informed by trend inflection rather than by calendar time [15–17,21,24].

Energy sourcing and dispatch strategies in the results deserve specific emphasis because they are now pivotal to carbon intensity and cost. Flexible reverse osmosis operation with storage allows plants to ramp production in low-price, low-emissions hours and back off during peaks, provided that tanks and network blending plans are designed to absorb variability. Co-location with photovoltaics and wind introduces additional flexibility where curtailment is frequent; running hard into curtailment windows lowers average emissions and energy cost but induces more cycling on pumps and membranes, which must be managed by control policies that enforce ramp-rate and minimum-run constraints. Industrial symbiosis extends this logic to thermal units, where low-grade heat can be funneled to membrane distillation polishing or where steam routing to multiple-effect distillation improves combined water-power economics without violating pinch constraints. The compositional wedges in the energy mix figure are not just static shares, therefore, but control levers that the operator can actuate to trace out a least-cost, least-carbon operating frontier at the plant scale [4,8,20,25,26,29–31].

Hybrid configurations surface repeatedly in the results as a route to expand feasible operating envelopes. Pairing multiple-effect distillation with reverse osmosis permits intake tempering and can stabilize the osmosis stage against seasonal viscosity changes. Reverse osmosis–electrodialysis cascades split the ionic burden, enabling slightly higher overall recovery at a given scaling risk by allowing electrodialysis to polish scalants or monovalent fractions that disproportionately elevate osmotic pressure. Membrane distillation polishing, drawing on low-grade heat, can capture the last increments of recovery without the pressure penalty that would otherwise push reverse osmosis into unfavorable driving force territory. Individually, these benefits can look modest; collectively, in a co-optimized control regime, they compound into tangible reductions in energy use, chemicals, and discharge volumes [8,20,25–27,31,32].

Concentrate management remains the pivot between local environmental compatibility and circular-economy opportunity. For coastal facilities, diffuser-engineered outfalls that achieve high near-field dilution and exploit ambient mixing and stratification minimize benthic salinity excursions; the hydrodynamics of the receiving water control the compliance margin more than any single chemical dosing change. Inland brackish operations, by contrast, increasingly cross thresholds where deep-well injection is constrained and evaporation ponds are land- or climate-limited. In those cases, minimal- and zero-liquid-discharge strategies become the default planning path, and the results support decision trees that explicitly evaluate crystallizer options, electrodialysis with bipolar membranes for on-site acid and base generation, and mineral recovery aligned to realistic off-taker specifications for salts and magnesium compounds. Economic feasibility is highly site-specific because logistics, purity, and market dynamics dominate once the technical recovery is possible; nevertheless, the analysis shows that aligning concentrate valorization with industrial demand can significantly change both life-cycle impacts and net cost [17–19,24,30–33].

Sensitivity patterns recur across sites and technologies. Feed temperature exerts a first-order effect via viscosity and membrane permeability, producing a seasonal swing in energy use that can exceed ten percent in some intakes; warmer conditions lower the pressure requirement but also intensify biological growth upstream, increasing the importance of biofouling control in pretreatment. Membrane age and staged replacement strategies show up as tails in both energy and quality distributions; plants that maintain staggered, proactive replacement retain narrow distributions, while those that defer replacement often see slow drifts in flux and salt passage that manifest as broader interquartile bands. Hydraulic housekeeping matters: small header or cartridge changes that save tenths of a bar aggregate into meaningful energy savings across large trains, especially when energy recovery devices are close to their optimal operating differential. Perhaps most importantly, monitoring and model-based control now explain a large share of the remaining variance: facilities that compute saturation indices online, track normalized permeability and differential pressure in near-real time, and enforce control limits on ramping and recovery exhibit flatter energy and quality trajectories over multi-year horizons [9–12,14–16,21,23].

These empirical regularities carry direct design and policy implications. Since membrane-stage energy savings are asymptotically limited by thermodynamics, further reductions in absolute energy use will mostly come from system integration: better pretreatment to stabilize operations at higher flux, lower hydraulic losses in manifolds and cartridges, ever-higher efficiency in energy recovery, and supervisory control that co-optimizes energy price signals, membrane health, and water-quality constraints. For thermal assets, the most credible path is deeper heat integration and industrial symbiosis rather than chasing incremental internal heat-recovery gains in isolation. Recovery increases will be won through chemistry-aware control and staged architectures that respect scaling windows while exploiting selective ion transport where it is advantageous. Decarbonization will be delivered by energy-mix rebalancing—greater renewable penetration, the ability to opportunistically harvest curtailment, and the use of waste heat—not merely by shaving another few tenths of a kilowatt-hour per cubic meter from already optimized reverse osmosis trains [4–6,8–12,14–16,20,21,23–27,29–33].

In short, the expanded results show a sector that has already captured the largest accessible efficiency dividends in reverse osmosis through energy recovery devices and pump improvements, that continues to trim equivalent energy in thermal plants via heat-source integration, and that now derives much of its remaining performance potential from hybridization, control, and brine circularity. The six figures embedded at the point of discussion provide a compact atlas of this landscape: compounding capacity growth that has reshaped regional water portfolios, a technology energy ranking that is stable in its order but narrowing in spread, an energy mix that is becoming a controllable design variable for cost and emissions, a salinity-recovery trade space that guides staging and chemistry control, permeate-quality distributions that operational discipline can tighten, and a fleet energy distribution that is as much an operations signature as it is a technology signature [3–6,8–12,14–17,20,21,23–27,29–33].

4. Discussion

The results point to a desalination sector that has exhausted many of the largest, device-level efficiency dividends and is now dominated by systems engineering, control, and integration choices that decide cost, carbon, reliability, and environmental compatibility. A central implication is that while materials innovation remains important, the next increments of performance will be realized primarily by orchestrating mature components—high-efficiency pumps, isobaric energy recovery devices, stable pretreatment barriers, intelligent post-treatment, diffuser-engineered outfalls, and optional hybrid thermal–membrane units—under supervisory control that is explicitly aware of energy prices, membrane health, chemistry windows, and delivery reliability. In other words, the sector's frontier has shifted from "can we do desalination efficiently?" to "can we run a desalination system that is cheap, low-carbon, robust, and environmentally compatible across seasons and grids?" [3–6,8–12,14–17,20,21,23–27,29–33].

Energy remains the first-order determinant of both levelized cost of water and lifecycle carbon intensity. The convergence of seawater reverse osmosis around three to four kilowatt-hours per cubic meter for primary pumping reflects two decades of compounding improvements in pump efficiencies, hydraulic housekeeping, and, above all, isobaric energy recovery devices that routinely transfer more than ninety-five percent of brine pressure to the incoming feed [9–14,21,23]. The evidence indicates that additional absolute reductions are now asymptotically constrained by thermodynamics; further progress will therefore rely on trimming parasitics (headers, manifolds, cartridge losses), stabilizing flux by suppressing fouling through higher-quality pretreatment, and operating flexibly to harvest low-price, low-emissions electricity when it is available [4,20,26,29]. For MSF and MED, the discussion must carefully separate intrinsic efficiency from site-specific heat economics: on an electric-equivalent basis, modern MED and MSF remain more energy intensive than RO, but in heat-rich campuses or cogeneration settings they can be competitive on cost and reliability, especially where steam is co-produced and where thermal units confer advantages under difficult feedwater conditions [5,8,20,26]. Cross-technology comparisons can mislead if they ignore the valuation of thermal energy and the decarbonization trajectory of a site's energy mix; it is no longer sufficient to report a single SEC number without context about when and how the plant is dispatched or how heat is sourced [4,5,8,20].

Recovery ratio emerges as the second master variable because it scales intakes, concentrate discharge, and energy per net unit of permeate. The inverse relationship between recovery and feed salinity is not a mere empirical trend but a thermodynamic and chemical inevitability: osmotic pressure compresses the net driving pressure window, and saturation indices for sparingly soluble salts tighten as concentration factors rise, particularly for calcium carbonate and calcium sulfate in seawater and for silica in brackish feeds [6,9,10,12,15,16,22,23]. High-recovery operation is, however, not out of reach; it depends on chemistry-aware control. Plants that maintain real-time calculations of saturation indices, couple antiscalant windows to measured alkalinity and temperature, and deploy targeted alkalinity adjustment or intermediate softening reclaim several recovery points without unacceptable scaling risk, translating into smaller intakes and outfalls and lower energy per unit of net permeate [15,16,23,24]. Hybrid cascades can add further flexibility: an RO–ED sequence can reallocate monovalent loads to electrodialysis and thereby reduce RO pressure for a given overall recovery, while membrane distillation polishing can leverage low-grade heat to capture the last increments of recovery without encroaching on unfavorable hydraulic regimes [20,25–27,31,32]. The strategic point is that recovery is a control variable tied to chemistry and staging choices, not a fixed property of a membrane or a plant.

Permeate quality distributions remind us that operations discipline is as decisive as design point selection. Thermal processes naturally deliver very low TDS permeate, but their advantage in quality dispersion is not an argument against membranes; it is a reminder that membrane plants achieve tight quality when pretreatment suppresses particulate and organic transients and when integrity testing and post-treatment are rigorously maintained [15–17,21,24]. The sector's most reliable RO facilities essentially operate as multi-barrier treatment systems: coagulation and dissolved-air flotation remove algae and colloids, ultrafiltration stabilizes the silt density index and captures pathogens, antiscalants and pH adjustment keep saturation indices within windows, and remineralization and disinfection tune the finished water for corrosion control and bio-stability. The dispersion in permeate TDS that remains in some fleets is not an immutable signature of RO; it is a signature of inconsistent pretreatment, deferred membrane replacement, or reactive cleaning practices that can be corrected by trend-based maintenance and continuous monitoring [15,16,21].

The energy-mix discussion reframes desalination as a controllable load in the power system. The results and broader literature agree that flexible operation—running harder during low-price, low-emissions hours and backing off during peaks—can lower both cost and carbon provided that finished-water storage and network blending absorb short-term variability [4,20,26,29–31]. With rising shares of PV and wind, curtailment events create windows of ultra-low marginal electricity; plants that can ramp within limits set by membrane health, pretreatment stability, and hydraulic constraints capture those windows and materially improve their average emissions and cost. The same logic extends to industrial symbiosis: where low-grade heat is abundant, MD polishing or MED effects can be fed; where steam is co-produced, MED can be co-optimized with RO pretreatment that relies on electricity; where condenser cooling water is available, intake tempering can shrink viscosity penalties and keep RO within stable flux bands [8,20,25,26,29–31]. Importantly, these are not "nice to have" integrations but strategic design levers that determine whether a plant sits on the pareto frontier of cost and carbon for its site. Digital twins and model predictive control provide the glue: they turn energy prices, chemistry, and equipment health into optimized set-points that respect operational limits while achieving least-cost, least-carbon dispatch [20,26,29–31].

Brine management is the ecological hinge between desalination as a resilient water supply and desalination as a local stressor. For coastal plants, properly engineered multiport diffusers that assure rapid near-field dilution, combined with outfall siting that leverages ambient currents and stratification, minimize benthic salinity excursions and chemical footprints; compliance is thus primarily a hydrodynamic design problem, augmented by monitoring and adaptive operation during adverse oceanographic conditions [17,30]. Inland brackish desalination faces sharper constraints: deep-well injection may be geologically or regulatorily limited, and evaporation ponds may be land-intensive or climate-limited. In such contexts, minimal- and zero-liquid-discharge (MLD/ZLD) pathways activate, often with a staged membrane-thermal architecture culminating in crystallization. The economics of MLD/ZLD hinge on three factors: the avoided cost of constrained disposal routes, the possibility of mineral recovery at acceptable purity (industrial salts, magnesium compounds, occasionally lithium), and the potential to internally generate acid and base via electrodialysis with bipolar membranes for cleaning and pH control, thereby offsetting reagents [18,19,24,32,33]. The literature warns against assuming universal brine valorization; logistics, offtaker reliability, and purity specifications dominate outcomes, and many markets cannot absorb variable, geographically dispersed supplies of salts or magnesium hydroxide. The credible strategy is to evaluate valorization opportunistically and locally, not ideologically, while maintaining ecologically robust discharge or ZLD compliance by default [17–19,24,30–33].

Reliability and resilience claim more attention as desalination is integrated into municipal and industrial water portfolios. The sector's technical maturity masks operational fragilities: harmful algal blooms can choke intakes; storm-driven turbidity and organic spikes can overwhelm conventional pretreatment, forcing derating; biofouling accelerates under warm, eutrophic conditions; and supply chain hiccups in membranes or antiscalants can extend downtime if inventories are not pre-positioned [15,16,21,24]. The operational answer is not over-design everywhere but better sensing, earlier signals, and staged contingency. Plants that instrument intakes, compute early-warning proxies for bloom risk, and switch pretreatment coagulants, polymer doses, or flotation rates proactively ride through episodes with smaller derates. Facilities that stock critical spares and maintain rolling replacement programs for membranes avoid the performance tails associated with late-stage modules. Where coastal hazards are rising, physical redundancy—offshore and onshore intake options, or brackish inland tie-ins—expands resilience and shortens recovery time after extremes. In regions with fragile grids, integrating on-site PV, storage, and backup generation hardens the water system while offering the grid a controllable load to assist with frequency and reserve services [20,26,29–31].

Economics and policy shape the feasible set as much as physics. At today's technology maturity, LCOW is most elastic to electricity price and capacity factor for RO plants, and to the accounting of thermal energy for MED/MSF; policy instruments that reduce volatility—long-term power purchase agreements indexed to low-carbon energy, demand charges restructured to reward flexibility, or curtailment compensation—improve bankability and align dispatch with decarbonization goals [4,20,26,29–31]. Carbon pricing pushes plants to secure low-emissions electricity or waste heat and sharpens the business case for flexibility and energy storage. Environmental regulation that is clear on outfall design criteria and monitoring expectations reduces permitting risk and steers designs toward diffuser-engineered solutions rather than ad hoc dilution. For inland facilities, regulatory clarity on concentrate routes can bring forward MLD/ZLD and changes the calculus for co-locating with industries that can use salts or heat. Public acceptance and affordability remain critical; utilities serving low-income communities need tariff structures and capital subsidies that recognize desalination's resilience value without imposing regressive burdens.

On the materials and process-innovation front, the discussion should be anchored in systems impact. Low-defect, fouling-resilient thin-film composites, charge-patterned selective layers, and hydrophilic/low-fouling coatings promise measurable permeability and selectivity gains that can translate into pressure reductions or higher flux at steady pressure, provided that pretreatment maintains feed quality and that modules are staged to avoid concentration polarization penalties [9,10,13,14,28]. However, because RO fleets are already operating close to two to three times the thermodynamic minimum work at typical recoveries, materials gains of ten to twenty percent in permeability will not deliver commensurate reductions in whole-plant SEC unless hydraulics, energy recovery, and control are co-optimized [5,6,11–14,21]. The same realism should guide emerging processes: membrane distillation is compelling when low-grade heat is abundant and when wetting can be controlled; capacitive deionization shows promise at low salinities and for selective ion removal; forward osmosis remains attractive for niche separations and osmotic power integration. Their success will depend less on raw separation metrics and more on how they slot into hybrid trains to relieve bottlenecks, increase recovery, or exploit local energy symbioses [20,25–27,31,32].

Sustainability accounting must be expanded beyond energy alone. Chemicals for pretreatment and post-treatment carry embodied impacts; frequent clean-in-place cycles increase both chemical consumption and downtime; membrane replacement has cradle-to-gate burdens that can be tempered by recycling programs. Intake design influences impingement and entrainment; outfall hydrodynamics determine benthic exposure. The most credible lifecycle narratives are those that specify the energy mix under realistic dispatch, quantify chemical and replacement rates under observed fouling regimes, and document intake and outfall performance under monitoring plans, rather than those that report stylized SEC numbers divorced from operations [17,20,24,30]. As desalination networks densify in some regions, cumulative and synergistic effects—multiple outfalls in one littoral cell, overlapping intakes, shared power transmission constraints—require basin-scale planning rather than project-by-project optimization.

Looking ahead, the discussion consolidates into five practical directives. First, treat energy as a control variable, not a constant: co-design storage, flexible operation, and contractual interfaces with the grid to minimize cost and carbon under real price volatility [4,20,26,29–31]. Second, elevate pretreatment to a reliability function: multi-barrier trains, early-warning sensing for blooms and organics, and integrity protocols shrink both energy dispersion and quality variance [15–17,21,24]. Third, manage recovery actively: compute saturation indices online, adjust chemistry in real time, and deploy staged architectures or selective ion transport where it economically expands the recovery window [6,9,10,12,15,16,22–24]. Fourth, design for place-specific concentrate outcomes: diffuser-engineer coastal outfalls, and trigger MLD/ZLD only where disposal constraints or valorization pathways are credible, using EDBM where it internalizes reagents and improves ZLD economics [17–19,24,32,33]. Fifth, invest in digital twins and condition-based maintenance to keep plants within narrow SEC and quality bands over multi-year horizons; these software-and-data layers compound the incremental gains of good hardware [20,26,29–31].

The limitations of the present synthesis are typical of sector-wide reviews: harmonized "typical" values can mask tail behaviors in extreme conditions; site-specific energy mixes and tariffs materially change rankings; and vendor data may emphasize best-case operations more than mid-life performance. Nonetheless, the triangulation of energy, recovery, and quality patterns across independent sources, and their alignment with first-principles constraints, supports the generality of the conclusions [3–6,8–12,14–17,20,21,23–27,29–33]. For research, the agenda suggested by the results is clear: robust high-salinity, high-recovery RO with chemistry-aware control; membranes with sustained permeability and fouling resistance in real feeds; hybrid trains that exploit low-grade heat and selective ion transport; diffuser-engineered outfalls coupled to better oceanographic monitoring; MLD/ZLD architectures with serious, place-based valorization assessments rather than universal prescriptions; and power-water co-optimization under real grid conditions. In practice, these directions imply co-funded, site-demonstrated projects that test not a single device but a control-aware system that meets a utility's reliability, environmental, and affordability constraints.

In sum, desalination has crossed the threshold from a specialized technology to a core, climate-resilient supply option. The sector's center of gravity has moved from component breakthroughs to orchestrated systems that run cheaper, cleaner, and steadier by harnessing mature hardware with smarter chemistry and smarter control. Plants that implement this philosophy—energy as a controllable input, recovery as an actively managed outcome, brine as a regulated and potentially valorized stream, and quality as an operations discipline—will sit on the efficient frontier of cost and carbon while meeting the ecological and social conditions that govern long-term legitimacy [3–6,8–12,14–17,20,21,23–27,29–33].

5. Conclusion

The review of carbon capture technologies highlights a field Desalination has matured from an emergency measure into a central, climate-resilient element of modern water portfolios. The evidence compiled here shows that the largest device-level energy gains—high-efficiency pumps, isobaric energy recovery, and refined membranes—have already reshaped the sector's baseline, especially for seawater reverse osmosis. What now differentiates high-performing plants is systems orchestration: robust multi-barrier pretreatment that stabilizes flux and quality, hydraulics that trim parasitic losses, chemistry-aware recovery control that respects scaling windows, diffuser-engineered concentrate discharge tailored to local hydrodynamics, and supervisory control that co-optimizes energy price, carbon intensity, and equipment health. Thermal processes remain valuable where low-cost heat or cogeneration exists, particularly in hybrid trains that exploit complementary strengths; yet cross-technology comparisons must consistently value energy forms and dispatch patterns to avoid misleading rankings.

Three priorities follow. First, treat energy as a controllable input rather than a fixed cost: pair flexible operation with storage and low-carbon supply (including curtailment harvesting) to lower both LCOW and emissions. Second, elevate recovery from a design constant to an operational decision, using real-time saturation indices, targeted antiscalants or softening, and selective ion transport to expand feasible recovery while safeguarding membranes and intake/outfall balances. Third, address brine as a managed stream with place-specific solutions—engineered coastal outfalls or, inland, MLD/ZLD only where disposal constraints and credible valorization pathways justify complexity—while strengthening monitoring to protect ecosystems.

The near-term research agenda is therefore integrative: membranes that maintain permeability and fouling resistance in real feeds; hybrid architectures that leverage low-grade heat and ion selectivity; digital twins and model-predictive control that keep plants on least-cost, least-carbon trajectories; and rigorous, site-based assessments of brine valorization that reflect markets and logistics, not only chemistry. Policy can accelerate this trajectory by rewarding flexibility and low-carbon operation, clarifying outfall and inland discharge criteria, and de-risking grid and heat integration through stable contracts.

In sum, the sector's frontier has shifted from "better components" to "smarter systems." Utilities and developers that design for flexible, low-carbon energy; operate recovery within chemistry-aware control; and align concentrate management with local ecology and markets will occupy the efficient frontier of cost, carbon, and reliability. Done this way, desalination can deliver secure water without exporting risk—technically rigorous, environmentally compatible, and economically durable..

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