

OsmoFlux:

**Modeling the Financial Risk of Desalination
Brine Discharge and the Viability of Reverse
Electrodialysis as a Risk Mitigation Strategy**

Team #24257

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2nd Place, 2025-26 Modeling the Future Challenge

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Executive Summary

The United Nations has declared a global water bankruptcy: freshwater demand will exceed supply by 40% before 2030. Desalination already supplies drinking water to roughly 300 million people across 177 countries. With over 500 plants in the global permitting pipeline and a market projected to reach \$35 billion by 2032, that dependence is accelerating. The industry produces roughly one cubic meter of hypersaline brine for every cubic meter of drinking water, 142 million cubic meters per day globally, increasingly regulated and not yet priced into most operators' cost structures. The gap between current disposal costs and what operators will pay when ocean outfall permits tighten could reach an **extra \$25 billion per year**, and that figure **excludes** externalized costs like lost fisheries, declining tourism, degraded marine ecosystems, an unpriced financial risk in every desalination balance sheet.

This report focuses on the Carlsbad Desalination Plant in San Diego County, the largest in the Western Hemisphere. A peer-reviewed 2019 UC Santa Cruz study found that its brine discharge already exceeds permitted salinity levels, with the plume extending farther offshore than California law allows (Petersen et al. 2019). Carlsbad faces two direct financial exposures: regulatory noncompliance, as California's Ocean Plan moves through a formal amendment process opened in 2024 with no numeric salinity standard yet in place; and disposal cost escalation: at 190,000 cubic meters of brine per day, each step up the disposal cost ladder adds **tens of millions in annual operating cost**. The exposed parties are plant operators facing direct compliance costs, water agencies facing ratepayer liability, and the insurance industry without an actuarial framework for brine risk.

Reverse Electrodialysis (RED) can reduce brine concentration while simultaneously extracting useful power and has been demonstrated at pilot scale. We built OsmoFlux, a physics-based real-world model simulating RED performance at Carlsbad under realistic fouling conditions of mineral scaling and biofilm growth. Across more than 6,300 simulations and a 5,000-sample Monte Carlo financial analysis, we map the threshold between negative and positive financial return. A central contribution is the modeling of a fresh-dilute cascade architecture, in which each stage receives a fresh low-salinity feed, rather than the depleted output of the previous one. At full Carlsbad deployment, OsmoFlux projects a **99% reduction** in excess brine salinity at the discharge point, recovering 0.8-1.0 MW of electrical power and approximately \$1.4-1.8 million in annual energy revenue as a byproduct. The fresh-dilute cascade achieves this at a 36% probability of positive financial return versus 11% for single-stack, a 3.3× improvement from architecture selection alone. Break-even membrane cost: ~\$40/m², within reach of current manufacturing trajectories.

Our primary recommendation is a **field pilot at Carlsbad**, co-located with the adjacent Encina wastewater treatment facility as the low-salinity source. The pilot will evaluate whether RED is genuinely viable as a compliance and cost management tool at commercial scale. In a \$35 billion industry with no actuarial framework for brine risk, this paper provides the analytical foundation. The pilot is the decision gate: deploy at full scale when membrane cost reaches ≤\$40/m² or disposal cost reaches ≥\$0.10/m³, thresholds our model shows are approaching on current trajectories.

- **Risk:** Global: ~\$25B annual unpriced disposal liability plus externalized coastal community costs; Carlsbad-specific: regulatory noncompliance (already outside permit boundary) and disposal cost escalation (tens of millions per tier at 190,000 m³/day).
- **Data:** 17 sources - plant characterization (5 sites), loss severity (6 disposal cost tiers), frequency/likelihood (5 stochastic parameters in Monte Carlo).
- **Model:** OsmoFlux: physics-based RED simulator, mineral scaling and biofilm fouling, novel fresh-dilute cascade architecture, 5,000-sample Monte Carlo.
- **Finding and Recommendation:** Fresh-dilute cascade: 36% positive-return probability vs. 11% single-stack; break-even ~\$40/m² membrane cost. Deploy when membrane cost ≤ \$40/m² or disposal cost ≥ \$0.10/m³, validated by Carlsbad field pilot.

Introduction & Background

Problem Statement. The global desalination industry faces a potential \$25 billion liability it has not yet priced: the concentrated brine that it discharges into coastal waters. Seven converging forces (see Figure 1) are driving this risk by transforming brine from an externalized nuisance into an as-yet unpriced liability:

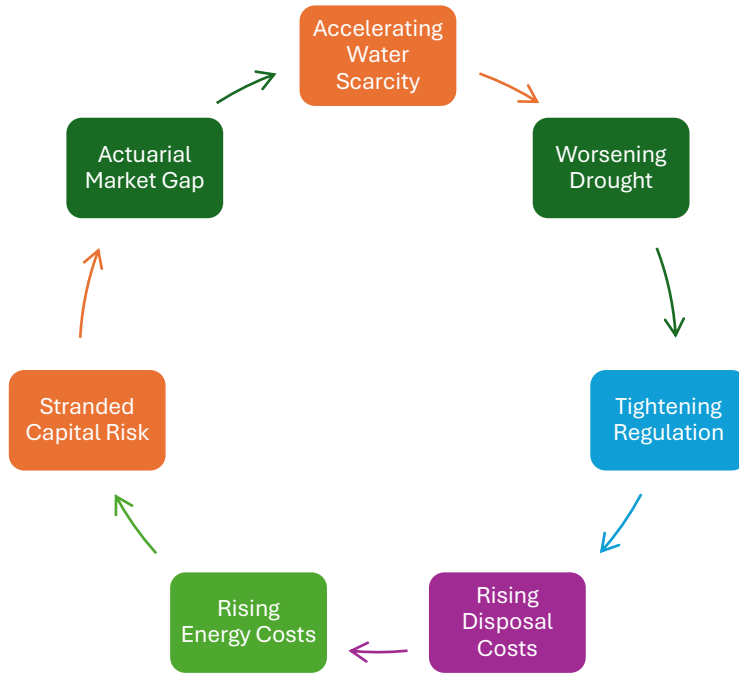


Figure 1. Seven converging forces driving brine liability for desalination plants.

Accelerating Water Scarcity: The UN has declared a global water bankruptcy, with freshwater demand projected to exceed supply by 40% before 2030. Every region that exhausts conventional water sources turns to desalination, and every new plant is a new brine liability.

Worsening Drought Cycles: Climate change is making droughts more severe and more frequent. California's last twenty-five years were the driest quarter-century in 1,200 years of recorded history. Drought accelerates desalination dependence while simultaneously reducing the freshwater available to dilute brine at outfall, tightening both sides of the compliance problem at once.

Tightening Environmental Regulation: California's State Water Board opened a formal amendment process to the Ocean Plan's desalination provisions in late 2024, specifically to introduce a numeric salinity discharge standard that does not yet exist. The regulatory direction is unambiguous, and the gap between current practice and future compliance will drive the financial exposure.

Rising Disposal Costs: As ocean outfall permits face increased scrutiny, operators face a cost ladder with no low-cost fallback once the bottom rung is removed. Current ocean outfall costs of \$0.04-0.10/m³ give way to deep-well injection at \$0.15-0.30/m³ and evaporation ponds at \$0.30-1.50/m³ (Panagopoulos et al. 2019). At the scale of a large seawater RO plant, these are transformative shifts in operating economics.

Rising Energy Costs: Desalination consumes 3–5 kWh per cubic meter of freshwater produced. Higher electricity prices raise operating costs directly. They also amplify the intake salinity feedback loop: as cumulative brine discharge raises coastal seawater salinity, osmotic pressure rises, requiring

measurably more energy per cubic meter produced (Elimelech & Phillip 2011), leading to an accelerating self-imposed cost that grows with industry scale.

Stranded Capital Risk: The May 2022 unanimous denial of permits for Poseidon Water's proposed \$1.4 billion Huntington Beach plant, on brine discharge and marine life grounds, established that brine risk can terminate a capital investment at the permitting stage, before a single drop of water is produced. With 500+ plants in the global permitting pipeline, this precedent carries systemic implications.

Actuarial Market Gap: The most structurally significant risk is the absence of any insurance or actuarial product to price and transfer brine liability. Environmental liability policies and operational risk coverage for desalination infrastructure are underwritten today without a quantitative framework for brine discharge risk. When that risk materializes, through a permit denial, a compliance action, or a forced retrofit, it will land as an unhedged loss on operators, water agencies, and ultimately ratepayers.

One converging opportunity works in the opposite direction: ion exchange membrane costs are declining along a manufacturing learning curve driven by the fuel cell and electrolyzer industries, potentially bringing the break-even threshold for RED deployment within reach of current commercial pricing. The pressures above are converging to make brine management mandatory; the technology trajectory is converging to make it economically rational.

This report models that intersection quantitatively, asking a precise actuarial question: **under what financial conditions does reverse electro dialysis transition from a cost center to a viable hedge against regulatory tightening?**

The Problem: Brine Discharge as a Growing Financial and Environmental Liability

Humanity consumes approximately 4,600 km³ of freshwater annually, which is roughly 1.3 billion Olympic swimming pools. Agriculture accounts for 70%, industry 20%, and municipal use makes up the remaining 10% (FAO AQUASTAT). However, approximately 2 billion people already live in countries experiencing high water stress (UN-Water 2021). Globally, freshwater demand is forecasted to exceed supply by 40% before 2030, leading the UN to declare a global water bankruptcy.

Global desalination now produces approximately 95 million m³ of freshwater per day across roughly 22,000 plants in 177 countries (Jones et al. 2019; IDRA 2024). However, for every cubic meter of freshwater produced by reverse osmosis, plants discharge roughly one cubic meter of concentrated brine, totaling an estimated 142 million m³ per day of hypersaline waste globally, approximately 50% higher than previous estimates (Jones et al. 2019). At typical seawater RO brine concentrations of 1.0-1.8 mol/L NaCl, this translates to millions of tons of excess dissolved salt entering coastal waters every day. The gap between current ocean outfall disposal costs and what operators will pay when permits tighten could reach an extra \$25 billion per year globally, a liability not yet priced into most operators' cost structures.

Disposal Cost Escalation Risk

This brine is not a benign byproduct. Hypersaline discharge depresses dissolved oxygen and raises local salinity above ambient levels. In the Mediterranean, *Posidonia oceanica* seagrass meadows show measurably reduced shoot density adjacent to desalination outfalls (Sánchez-Lizaso et al. 2008; Gacia et al. 2007). In the Persian Gulf, cumulative brine discharge has measurably increased regional intake salinity (Ibrahim & Eltahir 2019), creating a self-reinforcing feedback loop: higher intake salinity raises osmotic pressure, requiring 5-7% more energy per cubic meter of freshwater produced (Elimelech & Phillip 2011), costing tens of millions of dollars annually at large facilities. These ecological and

operational costs are currently externalized and not appropriately priced into plant economics. As outfall permits tighten, operators face a disposal cost ladder with no low-cost fallback once the bottom rung is removed.

Regulatory Noncompliance Risk

The externalized cost argument is reinforced by direct measurement at Carlsbad. A peer-reviewed 2019 study found that Carlsbad's brine plume already exceeds permitted salinity levels under the California Ocean Plan, extending approximately 600 meters offshore with salinity up to 2.7 parts per thousand above ambient (Petersen et al. 2019). The liability is present and measured today, not projected.

Stranded Asset Risk

The financial consequences of unmanaged brine liability are already visible at the industry level. In May 2022, the California Coastal Commission unanimously denied permits to a proposed \$1.4 billion desalination plant in Huntington Beach. This was a fully planned capital investment stranded before it produced a single drop of water, simply on brine discharge and marine life grounds. This decision was described at the time as setting a high bar for future desalination permitting in California, and it establishes a direct precedent for the 500+ plants currently in the global permitting pipeline. California's Ocean Plan, which governs discharge standards for coastal facilities including Carlsbad, currently lacks a numeric salinity limit for brine discharge. The State Water Board formally opened an amendment process in late 2024 to address this gap. The regulatory direction is unambiguous: the question for operators is not whether brine liability will be priced, but when, and whether they will be prepared.

The Audience: Plant Operators, Regulators, and the Insurance Industry

This report is addressed to three overlapping audiences: plant operators facing direct compliance costs, water agencies facing ratepayer liability, and the insurance industry currently underwriting desalination infrastructure without an actuarial framework for brine risk. This is exactly the gap that this paper begins to fill.

The Opportunity: Brine as an Energy Resource

Concentrated brine contains untapped chemical energy. The salinity difference between hypersaline brine and dilute water represents a thermodynamic driving force: the Gibbs free energy of mixing. Reverse electrodialysis (RED) captures this energy by placing alternating cation-selective and anion-selective membranes between the two streams. As ions migrate down the concentration gradient through their respective membranes, they generate an electrical potential that can be harvested as power without consuming the water itself.

RED has been demonstrated at laboratory and pilot scale. The REAPower pilot in southern Italy achieved a power density of 0.83 W/m² under optimized conditions (Tedesco et al. 2016), and the Okinawa demonstration reached 0.96 W/m². As of 2026, however, RED has not been validated under the operational constraints of a large commercial seawater RO plant - variable fouling, regulatory compliance requirements, and commercial-scale brine volumes. That gap is what this project addresses. Meanwhile, ion exchange membrane costs are declining toward the ~\$40/m² break-even threshold identified by OsmoFlux, driven by manufacturing scale-up in the fuel cell and electrolyzer industries. The converging pressure of rising disposal costs and declining membrane costs defines a closing window for proactive action.

The Core Tension

Prior RED research has optimized for a single objective: maximum power extraction. But at a real desalination plant, two objectives pull in opposite directions. More cell pairs and longer hydraulic residence time extract more energy from the brine, but they also increase salt transfer to the dilute stream, which risks creating a second noncompliant discharge that regulators will not permit. This is not a theoretical concern: our model shows that under certain fouling conditions and stack geometries, the dilute outlet concentration can exceed ambient seawater, turning an energy-recovery system into a second pollution source.

Previous RED models have not addressed this tension. OsmoFlux is designed specifically around it, simultaneously optimizing for power recovery, environmental compliance, and financial return, and identifying the architecture and operating conditions under which all three objectives are achievable at once.

Alternative Approaches

Alternative brine management approaches exist and are worth characterizing. Mineral harvesting, which is the process of extracting lithium, magnesium, potassium, and other valuable ions from concentrated brine, is an active area of research. It has been piloted at small scale, particularly for lithium recovery from inland desalination brine in Chile and Argentina. However, mineral harvesting requires brine concentrations substantially higher than typical seawater RO output (1.0-1.8 mol/L), capital-intensive extraction equipment, and proximity to commodity markets. These conditions make it economically viable only in specific geographic and regulatory contexts, and not applicable to coastal ocean-discharge facilities like Carlsbad. Similarly, Zero Liquid Discharge (ZLD) eliminates discharge entirely, but it comes at an energy and capital cost (\$1.00-3.00/m³) that is prohibitive at the scale of a 190,000 m³/day facility. RED occupies a distinct position: it treats brine at the concentrations that are realistically produced by seawater RO, reduces discharge volume and salinity simultaneously, and generates revenue rather than consuming additional energy. It is the only evaluated approach that converts the disposal liability into a partial financial offset.

Data Methodology

Data Categories and Sources

Our analysis relies on three categories of data, following the Actuarial Process Guide framework.

Category 1: Data to characterize potential outcomes. We obtained brine chemistry and flow rate data for five real desalination plants spanning the global salinity range. The Carlsbad Poseidon facility in San Diego County serves as the primary case study, with brine discharge of approximately 190,000 m³/day at 1.15 mol/L NaCl (derived from the facility's Environmental Impact Report, which reports 54 MGD product water at 50% recovery). Additional sites include Valley Water (0.35 mol/L, brackish, negative control), Monterey Bay (0.60 mol/L), Sorek B in Israel (1.15 mol/L), and Jebel Ali in the UAE (1.80 mol/L). These five sites span the concentration range from facilities where RED is physically nonviable (Valley Water) to facilities where it is most needed (Jebel Ali).

Category 2: Data to define severity and range of loss. Brine disposal cost data was compiled from peer-reviewed literature and industry reports: ocean outfall diffusers at \$0.04-0.10/m³ (Mickley 2018; WateReuse Foundation), co-disposal through wastewater treatment plants at \$0.05-0.15/m³ (USBR 2020), deep-well injection at \$0.15-0.30/m³ (EPA Class I well data; Panagopoulos 2021), evaporation ponds at \$0.30-1.50/m³, and mechanical zero-liquid-discharge (ZLD) at \$1.00-3.00/m³ (Tong & Elimelech 2016). These figures represent gross disposal costs; potential revenue offsets from commercial salt or mineral recovery are site-specific and not subtracted here, as seawater RO brine at 1.0-1.8 mol/L lacks the concentration required for economically viable mineral extraction without additional processing. For Carlsbad specifically, current ocean outfall costs are approximately \$0.04-0.08/m³. Regulatory penalty data was estimated from California Water Code enforcement provisions and analogous environmental compliance actions.

Category 3: Data to define frequency and likelihood. Membrane performance parameters were taken from manufacturer datasheets (Fumatech Fumasep FKS-PET-130 and FAS-PET-130) and peer-reviewed measurements: area-specific resistance of 0.26-0.46 mΩ·m² for cation exchange membranes, permselectivity of 0.92-0.98. Fouling parameters follow Długołęcki et al. (2010) for divalent cation scaling (concentration exponent $n \approx 0.5$) and Gurreri et al. (2023) for the fouling severity range ($\beta = 0.0-0.8$). Electricity prices use the California commercial/industrial rate of \$0.22/kWh as the distribution mean (lognormal, $\sigma = 30\%$ CV), implying a standard deviation of approximately \$0.066/kWh and a P10–P90 range of \$0.13-\$0.34/kWh, reflecting observed wholesale market variation over the past decade. Membrane parameters function as fixed physical bounds on the stochastic analysis. They define what performance is achievable before uncertainty in fouling, pricing, and cost escalation is layered on top.

Data Sources Summary

Category	Items	Key Sources
1: Potential outcomes	5 plant sites with 12 parameters each	Carlsbad EIR, IDRA 2024
2: Severity/loss	6 disposal cost tiers from ocean outfall through ZLD	Panagopoulos 2021, Mickley 2018
3: Frequency/likelihood	5 stochastic parameters, sampled in the Monte Carlo Engine	Fumatech datasheets, Gurreri 2023

Data gaps and reliability limitations are documented in the following section.

Data Reliability and Adjustments

All membrane parameters were cross-referenced against at least two independent sources. Carlsbad brine flow was derived from the Environmental Impact Report rather than from secondary summaries, as the precise recovery ratio and intake flow determine brine concentration. We note that published "headline" power densities from RED pilots (0.8-1.0 W/m²) often exclude electrode losses, spacer effects, and activity coefficient corrections. Our model applies all three corrections explicitly, producing conservative power density estimates (0.528 W/m² at Carlsbad) that we consider more reliable for plant-scale economic projection. We also note that our analysis treats Carlsbad's brine discharge volume as fixed at 190,000 m³/day; data on planned capacity expansions or regional demand growth were not incorporated, meaning our financial projections are conservative — actual future exposure scales directly with any increase in plant throughput.

We identified and documented data gaps: no publicly available Carlsbad-specific brine disposal cost data exists (we estimate from industry benchmarks), and Gulf intake salinity feedback data relies on modeling studies (Ibrahim & Eltahir 2019) rather than direct long-term measurement campaigns.

Mathematics Methodology

Background: Physical Architecture

A reverse electrodialysis stack is a layered sandwich of alternating membranes and flow channels, held between two graphite electrodes and two outer acrylic sheets. The repeating unit, called a cell pair, consists of four layers: a cation exchange membrane (CEM), a fresh-water channel with spacer, an anion exchange membrane (AEM), and a brine channel with spacer. A full stack contains N such cell pairs in series (see Figure 2).

Hypersaline brine flows through the salt channels and dilute water (in this case, treated wastewater effluent from the adjacent Encina facility) flows through the fresh channels. Because the brine contains far more dissolved salt than the dilute stream, sodium ions (Na^+) are driven through the cation membranes toward the dilute side, and chloride ions (Cl^-) are driven through the anion membranes in the opposite direction. This directed ion movement constitutes an ionic current. The graphite electrodes at each end convert that ionic current into usable electrical current through a redox reaction in the electrode rinse solution.

The driving force diminishes along the flow path as salt transfers from brine to dilute water, depleting the concentration gradient. This is why the model discretizes the channel into axial segments. The electrochemistry at the inlet is fundamentally different from the electrochemistry at the outlet, and treating the stack as uniform would systematically overestimate power output. The spacer mesh that holds each channel open introduces a shadow factor: it physically blocks a fraction of the membrane area from ionic transport, reducing effective current. Both effects are explicitly accounted for in OsmoFlux.

The result is a device that extracts energy from a salinity difference without consuming either stream — the brine exits less concentrated, and the dilute stream exits slightly saltier. Managing that exit concentration on the dilute side, ensuring it does not exceed ambient seawater salinity, is the environmental compliance constraint that drives the cascade architecture design.

RED Stack Cross Section View

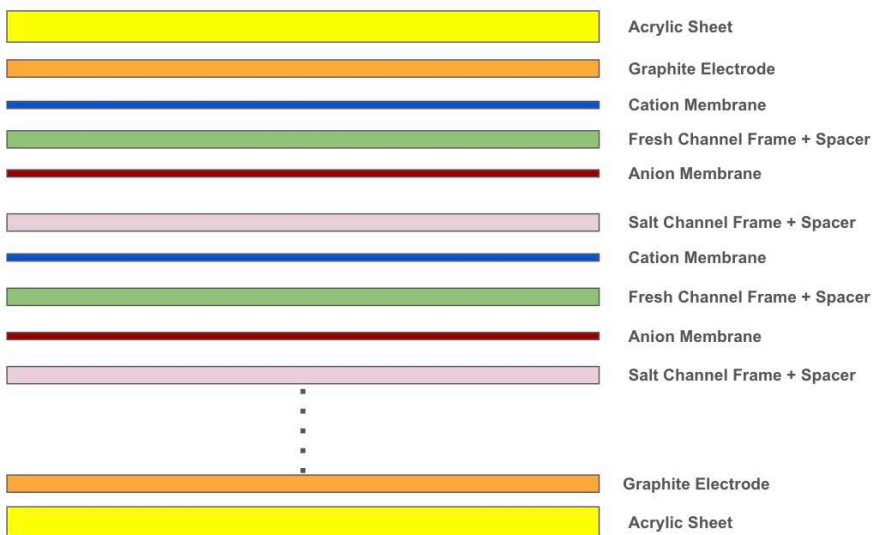


Figure 2. RED Stack Cross Section View

Model Architecture

OsmoFlux translates physical brine chemistry into financial risk estimates through four sequential stages (see Figure 3):

- (1) High and low salinity feed inputs define the electrochemical driving force
- (2) 40-segment Nernst solver computes power output and salt transfer along the flow channel.
- (3) Cascade optimizer tests alternative multi-stage architectures for compliance and performance
- (4) Monte Carlo techno-economic analysis converts physical outputs into an NPV probability distribution across 5,000 joint samples.

Each stage feeds directly into the next: the physics constrains the architecture, and the architecture determines the economics.



Figure 3. OsmoFlux Model Schematic

The flow channel is discretized into 40 segments. That number was selected as a practical balance: fine enough to capture the spatial variation in concentration and driving force along the channel at the membrane areas modeled, without imposing unnecessary computational overhead across 6,300+ simulation runs. At each segment, the model computes local electromotive force from the Nernst equation with activity coefficient corrections (Robinson & Stokes 1959 tabulated γ_{\pm} values, log-linear interpolation valid to 6 mol/L), local electrical resistance from solution conductivity, membrane area-specific resistance (Fumatech datasheets), and spacer shadow factors ($\beta_{sol} = 1.56$, $\beta_{mem} = 1.10$ from Vermaas et al. 2014). Salt transfer follows Faraday's law: current depletes the high-salinity stream and enriches the low-salinity stream segment by segment, so the concentration gradient and therefore the driving force evolves continuously from inlet to outlet. The segments are hydraulically in series (outlet of segment j feeds inlet of segment $j+1$) and electrically in series (a single current flows through all segments). The stack is modeled as a Thévenin equivalent circuit, treating the entire channel as a single voltage source with an internal resistance, which allows the maximum-power operating point to be solved analytically by matching internal to load resistance.

Core Equations

The local electromotive force per cell pair at segment j follows the Nernst equation:

$$EMF_j = \frac{2\alpha RT}{F} \times \ln \frac{\gamma_{H,j} \times C_{H,j}}{\gamma_{L,j} \times C_{L,j}}$$

where α is permselectivity, R is the gas constant, T is temperature, F is Faraday's constant, and γ are molal activity coefficients.

The total stack open-circuit voltage is:

$$V_{OC} = N \times \sum_j \left(\frac{EMF_j}{N_{seg}} \right)$$

Stack internal resistance sums membrane, solution, and spacer contributions:

$$R_{int} = \frac{N \times \sum_j \left[ASR_{CEM} + ASR_{AEM} + \left(\frac{d}{\kappa_{H,j}} \right) \times \beta_{sol} + \left(\frac{d}{\kappa_{L,j}} \right) \times \beta_{sol} \right]}{A_{mem} \times N_{seg}}$$

where d is channel gap, κ is solution conductivity, and β_{sol} is the spacer shadow factor. At maximum power ($R_{load} = R_{int}$):

$$P_{max} = \frac{V_{OC}^2}{4 \times R_{int}}$$

Salt transfer follows Faraday's law: at each segment, the current I depletes the high-salinity stream and enriches the low-salinity stream, advancing both concentrations to the next segment. The net present value integrates power revenue, disposal savings, and capital costs:

$$NPV = \sum_{t=1}^T \frac{(Revenue_t + DispSavings_t - OpEx_t)}{(1+r)^t} - CapEx$$

Fouling Framework

Two spatially distinct fouling mechanisms are modeled simultaneously:

Concentration-dependent fouling (CDF) represents divalent cation binding (Ca^{2+} , Mg^{2+}) to sulfonate groups on cation exchange membranes. The local resistance increase is modeled as:

$$\Delta R = \beta \times f_{div} \times \left(\frac{C_H}{C_{ref}} \right)^{0.5}$$

where β is fouling severity, f_{div} is the divalent fraction (0.20 for typical seawater), and the 0.5 exponent follows Długołęcki et al. (2010).

This is heaviest at the stack inlet where brine concentration peaks.

Exponential biofilm represents bacterial growth on membrane surfaces, modeled as thickest at the outlet where residence time is longest.

When run simultaneously, the combined fouling penalty falls 4-7 percentage points below the sum of the individual penalties indicating a sub-additive interaction. This arises from the concavity of the power-resistance relationship: maximum power scales as $P = E^2/(4R)$, so adding incremental resistance to a stack that already has elevated R costs less marginal power than adding the same ΔR to a clean stack. The effect is robust to the details of the fouling model because it depends on Thévenin circuit physics and not on the specific spatial fouling profile.

Critically, fouling ranks tenth of twelve parameters in absolute power sensitivity (Morris $\mu^* = 0.045$) — but it is the dominant driver of cascade architecture selection. The variable that matters least for power matters most for design. This is the Fouling Paradox.

Cascade Architecture

The key design question is whether each stage receives fresh low-salinity water or the salt-loaded output of the prior stage. OsmoFlux evaluates three configurations (see Figure 4): single-stack (no cascading), serial cascading, and fresh-dilute cascading. At Carlsbad conditions, fresh-dilute cascading achieves 1.722 W/m^2 versus 1.290 W/m^2 for serial and 0.528 W/m^2 for single-stack. Fresh-dilute wins across all 240 tested geometry configurations, by up to 98% over serial at high salinity, while achieving 96–100% discharge harm reduction. Serial cascading can produce negative harm reduction at low flow rates by driving dilute-stream salinity above ambient, creating a second noncompliant discharge. Under fouling, the optimal cascade shifts toward more, shorter stages because elevated resistance reduces salt transfer per stage, requiring additional stages to maintain compliance.

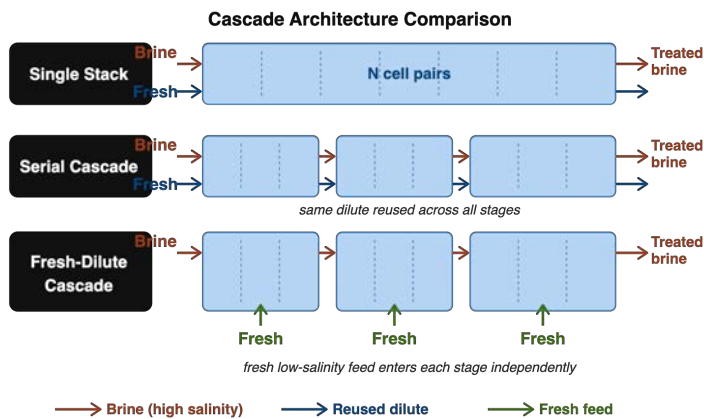


Figure 4. OsmoFlux Cascade Architecture Comparison

Plant-Scale Economics

The model scales from a single stack to plant-wide deployment by parallelizing identical stacks to treat the full $190,000 \text{ m}^3/\text{day}$ brine volume. Capital expenditure, membrane area, and operating costs scale linearly with stack count. Annual revenue combines electricity sales and avoided disposal costs, discounted over project life using the annuity factor:

$$\frac{1 - (1 + r)^{-T}}{r}$$

The model projects outcomes over a 20-year project life, the standard horizon for large water infrastructure investment decisions.

Model Assumptions

Key model assumptions include the following:

- Isothermal operation at 25°C (real seawater varies $15\text{--}35^\circ\text{C}$, shifting absolute predictions by 5–8% but not comparative architecture analysis).
- Fixed permselectivity $\alpha = 0.975$ (real α drops to 0.90–0.92 at 3.0 mol/L).

- Simplified conductivity model adequate to approximately 2 mol/L – within Carlsbad bounds.
- No water osmosis across membranes (would slightly strengthen the cascade argument by resetting osmotic penalty per stage).
- Fouling model increases electrical resistance only, consistent with the dominant approach in RED fouling literature (Rijnaarts et al. 2017; Gurreri et al. 2023).
- Secondary transport effects such as reduced permselectivity under fouling are not modeled, making fouling-related power predictions conservative bounds.
- Membrane replacement frequency and stochastic catastrophic failure are not modeled, meaning capital depreciation risk is not explicitly modeled.
- Co-located low-salinity source required for fresh-dilute cascading - at Carlsbad, treated wastewater effluent from the adjacent Encina facility is a plausible candidate.

Responsiveness to Trends

The model is parameterized to respond to three key trends over time: declining membrane costs (via the membrane capex parameter), tightening environmental regulations (via the required harm-reduction threshold and penalty severity parameters), and rising brine disposal costs (via the brine disposal cost parameter). The Monte Carlo engine samples all three simultaneously, producing NPV distributions that reflect the joint uncertainty space rather than isolated sensitivities.

Accuracy Validation

The model predicts 0.528 W/m² at Carlsbad conditions ($C_H = 1.15$ mol/L, $C_L = 0.02$ mol/L, $N = 80$ cell pairs; note: cascade experiments use $N_{total} = 120$ distributed across stages (see Figure 5); geometries differ by design). Published pilot data under comparable real-brine conditions ranges from 0.5-0.8 W/m² (Tedesco et al. 2017). The model deliberately sits at the conservative end of this range, since the physics corrections (activity coefficients, spacer shadow factors, and segment-by-segment concentration depletion) collectively reduce predicted power by approximately 40% relative to ideal-membrane calculations. This conservative calibration is appropriate for financial risk modeling, where overestimating revenue is more dangerous than underestimating it. Full empirical validation requires a field pilot at Carlsbad - which is the primary recommendation of this report - but the conservative model calibration provides appropriate bounds for financial planning in the interim.

Morris sensitivity screening across 12 parameters (130 model evaluations, 10 trajectories; see Figure 6) ranks membrane area and flow rate as the dominant controls on power density. Fouling severity ranked near the bottom (#10 of 12) for absolute power but dominated cascade architecture selection, a distinction critical to design decisions.

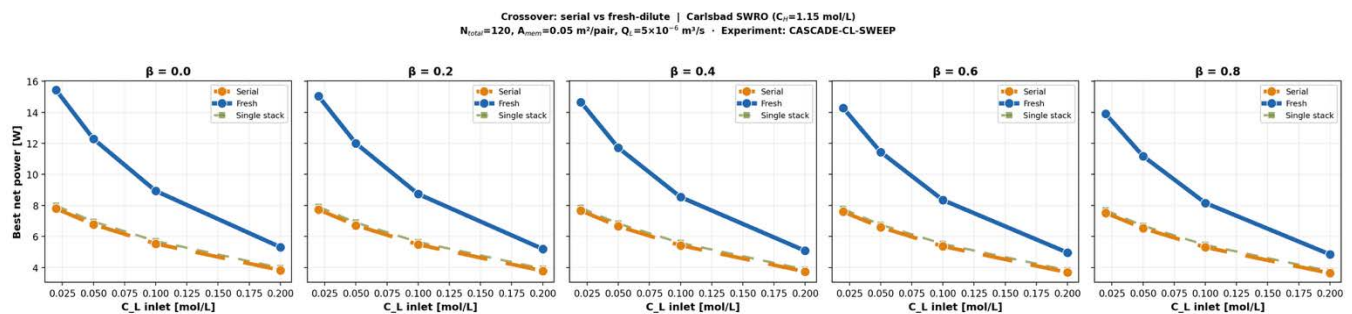


Figure 5. Net power output vs. dilute inlet concentration for three cascade architectures at Carlsbad conditions ($C_H = 1.15$ mol/L, $N_{total} = 120$, $A_{mem} = 0.05$ m²/pair), across five fouling severities ($\beta = 0.0-0.8$). Fresh-dilute cascading (blue) dominates across all tested conditions. Source: CASCADE-CL-SWEEP (20260301_145354).

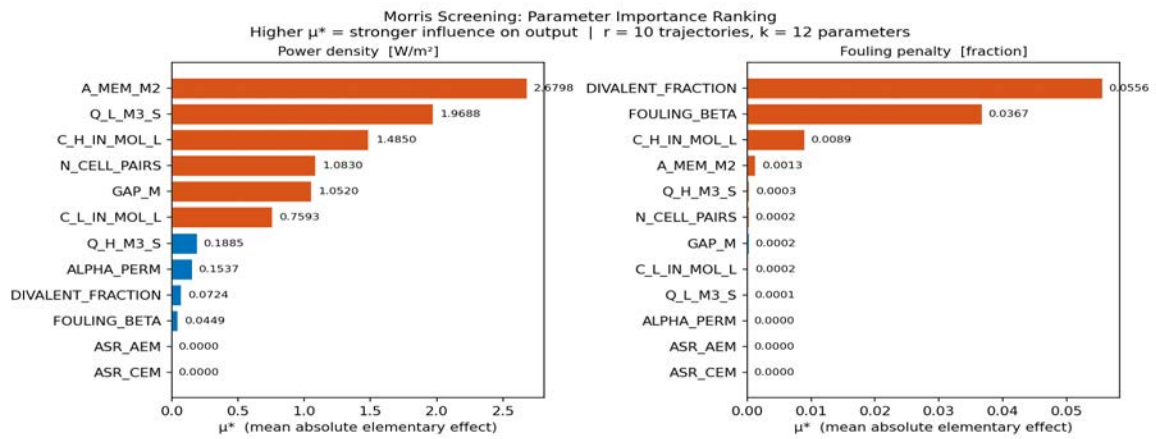


Figure 6. Morris sensitivity screening (12 parameters, 130 evaluations). Membrane area and low-salinity flow rate dominate power density; divalent fraction and fouling severity dominate fouling penalty.

Risk Analysis

Risk Identification and Characterization

We identify three categories of financial risk associated with desalination brine discharge at Carlsbad.

Regulatory noncompliance risk: California's Ocean Plan sets discharge standards for salinity differentials at the edge of mixing zones. Currently, Carlsbad operates within compliance using a diffuser-based ocean outfall. However, the regulatory trajectory is toward stricter limits. If the salinity differential limit tightens to require 95% or greater harm reduction (defined as the fractional reduction in excess salt concentration relative to ambient seawater), our model shows that achieving compliance under clean-membrane conditions at Carlsbad requires a RED system with at least 80 cell pairs. However, this compliance margin erodes entirely under moderate-to-heavy fouling ($\beta = 0.2-0.8$), where no tested architecture meets the 95% threshold without increased membrane area. At higher-salinity sites, multi-stage cascading is required even under clean conditions. The likelihood of regulatory tightening over the plant's remaining operational life (15-25 years) is assessed as moderate to high, based on the direction of California State Water Board rulemaking and precedent from the Huntington Beach denial.

Disposal cost escalation risk: Current Carlsbad brine disposal costs are approximately \$0.04-0.08/m³ for ocean outfall. If regulations mandate transition to deep-well injection (\$0.15-0.30/m³), evaporation ponds (\$0.30-1.50/m³), or Zero Liquid Discharge (\$1.00-3.00/m³), annual disposal costs would escalate from approximately \$3-6 million to \$10-55 million or more, at current disposal volumes. The frequency of such transitions is low in any given year but cumulative over a 20-year horizon, and the severity of these transitions is high. Our Monte Carlo analysis samples disposal costs from \$0.04 to \$0.25/m³, with the Tightening scenario extending to \$0.25/m³ to model a potential 2035 regulatory landscape.

Stranded asset risk: If brine concerns contribute to permit denial or operational restrictions, as occurred at Huntington Beach, the stranded capital can reach hundreds of millions of dollars. The Carlsbad facility represents approximately \$1 billion in total investment. While outright shutdown is unlikely for an operating plant, partial capacity restrictions or mandated retrofits could impose costs of \$10-50 million. The expected annual loss from this risk channel depends on enforcement probability, which we model as a parameter ($p_{\text{enforce}} = 0.05-0.15$ per year).

Growth in demand and capacity: These risk assessments treat Carlsbad's brine discharge volume as fixed at 190,000 m³/day. Growth in regional water demand could increase this volume. SDCWA's 2025 Urban Water Management Plan projects continued population growth in San Diego County, and the Carlsbad facility has physical capacity headroom. At the very minimum, each additional 10,000 m³/day of brine discharge adds approximately \$0.4M/year in disposal cost exposure at current ocean outfall rates, scaling linearly to \$4M/year if disposal costs reach \$0.10/m³. Capacity growth therefore amplifies all three risk categories simultaneously and strengthens the case for proactive RED-ready provisions over the plant's remaining operational life.

Risk Quantification

We now quantify the three risks identified above, noting that capacity growth amplifies all three channels simultaneously. The joint financial effect across all three simultaneously, under uncertainty in membrane cost, fouling severity, electricity price, disposal cost, and discount rate, is captured in the Monte Carlo NPV distribution presented in the Sources of Uncertainty section below, and discussed here:

Risk	Severity	Likelihood	Key Metric
Regulatory Noncompliance	\$15-25M forced retrofit under regulatory deadline vs. \$1-3M if incorporated during planned upgrades; \$50,000/day penalty exposure under California Water Code enforcement provisions	Moderate-high; Carlsbad already exceeds permitted salinity levels (Petersen et al. 2019); State Water Board formally opened Ocean Plan amendment process in late 2024; regulatory direction is unambiguous	\$15-25M forced retrofit exposure vs. \$1-3M proactive cost
Disposal Cost Escalation	Each \$0.06/m ³ disposal cost increment adds \$4.2M/year at 190,000 m ³ /day; transition from ocean outfall to deep-well equivalent adds \$83M+ undiscounted over 20 years; full ZLD transition could reach \$35M/year	50% status quo; 30% moderate tightening; 20% aggressive regulation; probability-weighted expected disposal cost ~\$0.12/m ³ , roughly double current rates; sensitivity low — shifting aggressive scenario ±10% changes probability-weighted cost by less than \$0.02/m ³	\$83M+ undiscounted 20-year exposure at a single disposal cost step-up
Stranded Asset	\$10-50M for mandated retrofit of operating facility; up to \$1B total facility value at risk for new construction; 500+ plants in global permitting pipeline face total capital exposure at permitting stage	Low for outright shutdown of operating facility; moderate for mandated retrofit conditional on regulatory tightening; Huntington Beach established proof of concept for total capital loss on brine discharge grounds alone	\$10-50M retrofit exposure; \$1B facility value at risk

Joint Quantification

The individual characterizations above establish severity and likelihood for each risk channel in isolation. Their joint financial effect across all three risks simultaneously is captured directly in the OsmoFlux Monte Carlo analysis: 5,000 joint samples across five uncertain parameters (membrane capex, fouling severity, electricity price, brine disposal cost, discount rate), verified against the Freeze Manifest. These are model outputs, not assumed parameters: they represent the full joint uncertainty space rather than isolated sensitivities. Under moderate fouling, $P(NPV > 0) = 37\%$ with $P50\ NPV = -\$26M$. Under severe fouling, $P(NPV > 0) = 12\%$ with $P50\ NPV = -\$86M$. The dominant driver of NPV variance is disposal cost and membrane capex, not fouling severity, confirming that regulatory and market risk, not technical risk, determine RED investment outcomes.

The zero-compliance rate under fouling at the modeled geometry ($\beta = 0.2-0.8$, $N = 80$, $A = 0.05\ m^2$) reflects a boundary-condition result, not a technology failure. The 95% harm-reduction threshold exceeds achievable performance at this geometry, which is a regulatory-design mismatch resolvable through geometry optimization. It does not affect the Monte Carlo NPV analysis, which models financial outcomes across the full uncertainty space.

Sources of Uncertainty

Uncertainty. Our Monte Carlo analysis simultaneously varies five parameters across 5,000 joint samples: membrane capex (\$30-100/m², triangular distribution with mode \$50/m²), fouling severity ($\beta = 0.0-0.8$ uniform for the moderate fouling scenario; $\beta = 1.5$ fixed for the severe fouling scenario), electricity price (\$0.22/kWh mean, lognormal with 30% CV, implying a standard deviation of approximately \$0.066/kWh and a P10-P90 range of \$0.13-\$0.34/kWh for the moderate scenario; uniform \$0.08-0.35/kWh for the severe scenario), brine disposal cost (\$0.04-0.25/m³, uniform), and discount rate (3-8%, uniform). The resulting NPV distributions capture the joint effect of all uncertainties simultaneously. Dispersion is driven primarily by disposal cost variance and membrane capex rather than fouling severity (see Figure 7), consistent with the Morris sensitivity ranking and reinforcing the conclusion that regulatory and market risk and not technical risk dominate RED investment outcomes.

Key sources of uncertainty and their directional bias: (1) the fouling model omits permselectivity degradation, making power predictions optimistic under heavy fouling; (2) non-Carlsbad disposal cost benchmarks likely underestimate future California-specific costs given the state's regulatory trajectory, making NPV projections conservative; (3) isothermal modeling at 25°C overestimates absolute performance for winter conditions but does not affect comparative architecture rankings; (4) the absence of membrane replacement costs makes long-horizon NPV optimistic by approximately 5–10% depending on membrane lifetime assumptions.

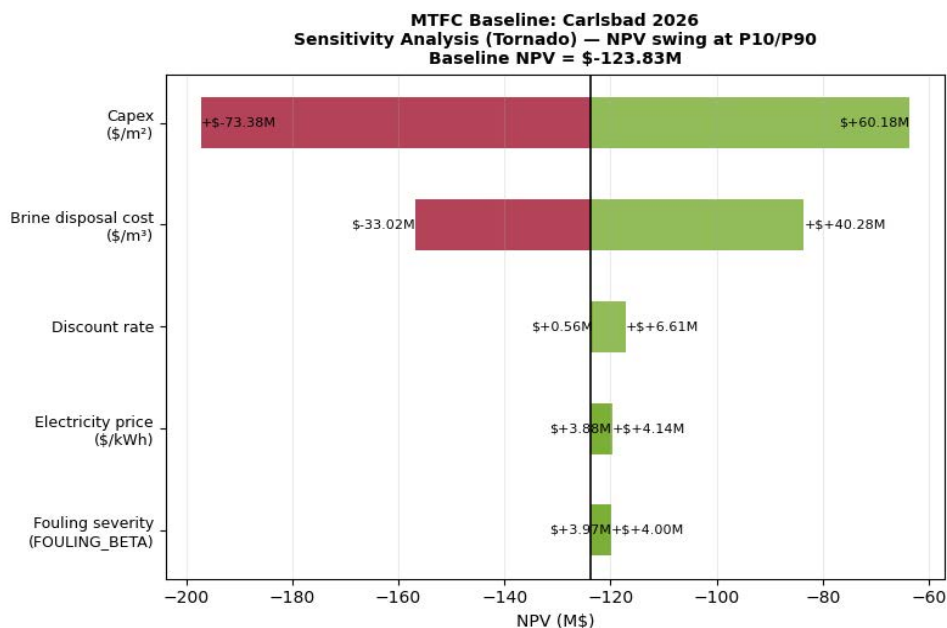


Figure 7. Sensitivity tornado: membrane capex and brine disposal cost dominate NPV variance, confirming that regulatory/market risk exceeds technical risk.

Distribution of risk. The NPV distribution is left-skewed under both fouling scenarios (see Figure 8). Under moderate fouling ($\beta = 0.0-0.8$ sampled, $f_div = 0.20$), $P(NPV > 0) = 37\%$ with the full percentile distribution as follows: P5 = -\$153M, P25 = -\$79M, P50 = -\$26M, P75 = +\$26M, P95 = +\$96M.

Under severe fouling ($\beta = 1.5$ fixed, $f_div = 0.35$), $P(NPV > 0) = 12\%$ with P5 = -\$209M, P25 = -\$134M, P50 = -\$86M, P75 = -\$33M, P95 = +\$29M. The 25 percentage-point gap between moderate and severe fouling outcomes quantifies the financial cost of fouling regime uncertainty and motivates the

fresh-dilute cascade architecture, which maintains compliance performance across the full fouling range.

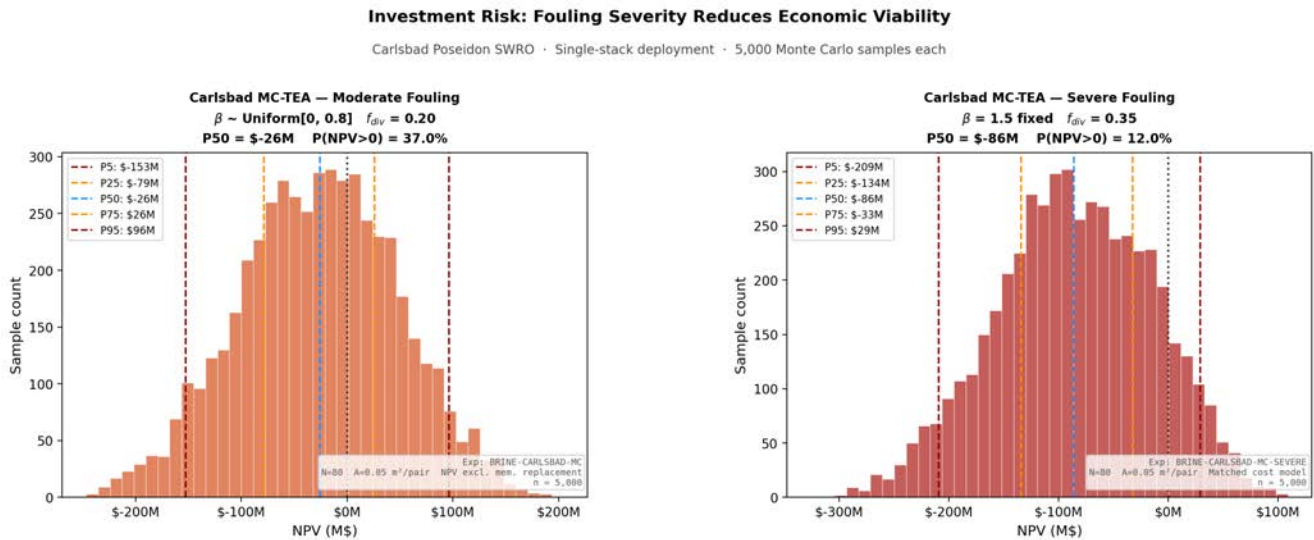


Figure 8. Monte Carlo NPV distribution (5,000 samples each, Carlsbad Poseidon SWRO, single-stack deployment). Moderate fouling: $P(NPV>0) = 37\%$, $P50 = -\$26M$. Severe fouling: $P(NPV>0) = 12\%$, $P50 = -\$86M$. Source: BRINE-CARLSBAD-MC (20260305_152413) and BRINE-CARLSBAD-MC-SEVERE (20260303_210416).

Economic Viability Surface

The deterministic break-even analysis maps the two dominant economic levers: membrane capex and brine disposal cost. Figure 9 shows the RED Deployment Regime Map for Carlsbad, plotting the $NPV=0$ contours for both single-stack and fresh-dilute cascade architectures. The single-stack break-even occurs at approximately $\$24/m^2$ at current disposal costs ($\$0.05/m^3$); the cascade break-even occurs at approximately $\$40/m^2$. Given that this is for the **same total membrane area**, this represents a clear case for the cascade architecture. Carlsbad today, at approximately $\$50/m^2$ membrane cost and $\$0.05/m^3$ disposal cost, sits in the unviable zone for both architectures, but close to the cascade break-even frontier. The pink shading identifies the cascade-only viable zone: the parameter space where fresh-dilute cascading achieves positive NPV but single-stack does not, representing the unique financial value of architecture selection.

The break-even surface is steep: small reductions in membrane capex in the $\$50$ - $\$40/m^2$ range produce large shifts in NPV. This nonlinearity means that technology cost reductions, potentially driven by fuel cell and electrolyzer manufacturing scale spilling over to ion exchange membranes, could shift Carlsbad from the unviable zone to the cascade-only viable zone within a narrow capex window. Current commercial IEM prices of $\$50$ - $\$100/m^2$ place this threshold within reach of near-term manufacturing trajectories.

The capex axis simultaneously captures two maturation pathways: declining membrane manufacturing costs and increasing stack engineering maturity. At $\$50/m^2$ membrane cost, a stack processing 50 mL/s instead of 5 mL/s requires 10× fewer parallel stacks, reducing effective system-level capex substantially. The break-even surface therefore answers two questions simultaneously: "how cheap must membranes become?" and "how large must stack modules become?"

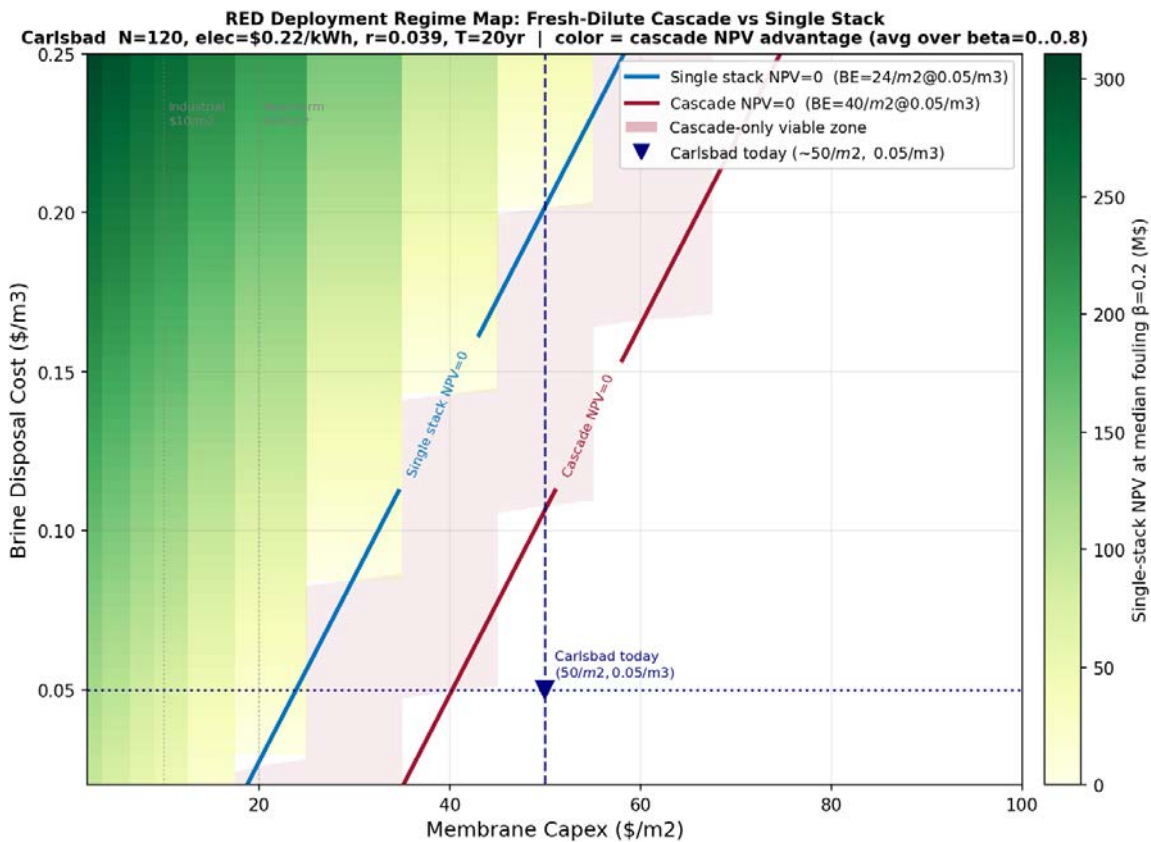


Figure 9. RED Deployment Regime Map: fresh-dilute cascade vs. single-stack NPV=0 contours across membrane capex and brine disposal cost. Carlsbad today (~\$50/m², \$0.05/m³) sits in the unviable zone; cascade break-even at ~\$40/m². Pink zone: cascade-only viable region. Color: single-stack NPV advantage at median fouling $\beta=0.2$. Source: BREAKEVEN-CARLSBAD.

Option Value of Waiting

RED viability is highly sensitive to membrane capex and disposal cost. Both are trending favorably, therefore deferring full deployment while embedding retrofit provisions preserves option value. The cost of delay is low (\$1-3M for RED-ready infrastructure incorporated during planned capital upgrades) relative to the potential cost of forced retrofit under regulatory tightening (\$15-25M). This resembles a real options problem: the plant operator holds a call option on future compliance infrastructure, exercisable when membrane costs decline below the cascade break-even threshold (~\$40/m²) or when disposal costs increase past the trigger point (~\$0.10/m³). Because regulatory tightening risk is asymmetric - limited upside from lax enforcement, large downside from stringent enforcement - RED's option value increases with regulatory volatility even if mean disposal costs remain unchanged.

Risk Mitigation Strategy Analysis

The actuarial framework for risk mitigation considers three categories of response: insurance and financial transfer, behavior change, and modifying outcomes. We evaluate each against the three identified risks and quantify where possible.

Insurance and financial transfer. Environmental liability insurance exists for desalination operators but is structurally limited for this risk. Standard environmental liability policies cover accidental spills and sudden discharge events, not chronic, continuous brine discharge, which is the nature of the risk here. Self-insurance through reserve funds is the current practice at most California facilities. Neither

mechanism reduces expected loss; they only transfer it. At the scale of Carlsbad's exposure, \$83M+ in undiscounted 20-year disposal cost escalation risk and \$15-25M in forced retrofit exposure, reserve fund requirements would be substantial and would appear directly on SDCWA's balance sheet as a contingent liability.

RED deployment has a secondary insurance benefit: by demonstrably reducing brine salinity at the discharge point, it reduces the probability of a noncompliance event, which should reduce environmental liability premiums. This benefit is difficult to quantify without insurer-specific underwriting data, but it is analogous to fire suppression system credits in property insurance, a structural risk reduction that rational underwriters should price. We recommend that environmental liability insurers incorporate RED deployment status as a risk modifier in underwriting desalination facilities.

Behavior change. Operational adjustments like varying recovery ratio, blending discharge with cooling water, and seasonal flow management can reduce brine concentration by 5-15% at low cost. These measures are already partially implemented at Carlsbad through the diffuser outfall system, which achieves rapid mixing at the discharge point. Their limitations are fundamental: they disperse salt rather than remove it, they do not reduce total salt load, and their impact is bounded by plant hydraulics. A 15% concentration reduction at 190,000 m³/day still leaves 161,500 m³/day of hypersaline discharge entering the ocean daily. They also provide no financial offset – there is no energy recovery and no avoided disposal cost.

Alternative Brine Valorization: Mineral and Salt Harvesting: Mineral harvesting, which is the process of extracting lithium, magnesium, potassium, and other valuable ions from concentrated brine is an active area of research. This has been piloted at small scale, particularly for lithium recovery from inland desalination brine in Chile and Argentina. It merits serious consideration as a potential complement or alternative to RED. However, three structural constraints limit its applicability at Carlsbad specifically. First, mineral harvesting requires brine concentrations substantially higher than Carlsbad's 1.15 mol/L output. Inland brine concentrations of 3-5 mol/L are typical targets for lithium extraction, requiring additional concentration steps that consume energy and capital. Second, the economics depend on proximity to commodity processing infrastructure and prevailing mineral prices, both of which are highly variable. And finally, mineral harvesting does not reduce brine volume or salinity at the discharge point. It extracts value from the brine, but the residual still requires disposal, meaning it addresses the revenue side but not the compliance side of the problem. RED addresses both simultaneously: it reduces discharge salinity while generating electricity. For an operating facility with a compliance deadline, that dual function is the decisive advantage.

Modifying outcomes (RED deployment). RED is the only evaluated mitigation strategy that simultaneously reduces the probability of noncompliance, reduces the severity of noncompliance when it occurs, and generates offsetting revenue. At Carlsbad, OsmoFlux projects 99.1% harm reduction under clean-membrane conditions (N = 80, A = 0.05 m²), confirming that RED can achieve near-complete environmental compliance. The fresh-dilute cascade architecture achieves this across 240/240 tested geometry configurations, maintaining 96-100% harm reduction even under fouling conditions where serial cascading fails.

The quantified financial case for RED over the alternatives is summarized below:

Strategy	Compliance Impact	Financial Impact	Verdict
Insurance/reserves	None; transfers risk only	Adds balance sheet liability; no loss reduction	Necessary but insufficient

Strategy	Compliance Impact	Financial Impact	Verdict
Behavior change	5-15% concentration reduction; does not remove salt	Low cost; no revenue offset	Limited; already partially implemented
Mineral harvesting	None at discharge point; residual still requires disposal	Revenue potential highly site- and market-dependent; requires additional concentration	Complementary at best; not a compliance solution
RED — fresh-dilute cascade	99.1% harm reduction (clean); 96-100% across fouling range	P(NPV>0) = 37% moderate / 12% severe; break-even ~\$40/m ² ; \$1.4-1.8M annual energy revenue	Only strategy that reduces both probability and severity of loss

The selection of RED as the primary recommendation is not based on excluding alternatives but on the modeled outcome: it is the only strategy that converts the compliance liability into a partial financial asset while simultaneously addressing the root cause - excess salt in the discharge stream.

Recommendations

Primary Recommendation: Deploy a Field Pilot at Carlsbad

Our primary recommendation is a pilot-scale RED deployment at the Carlsbad facility: 10–50 stacks, 40-200 m² total membrane area, co-located with the adjacent Encina Water Pollution Control Facility as the low-salinity source. This pilot directly addresses the central limitation of computational modeling: empirical validation under real salinity, temperature, fouling, and regulatory conditions. The pilot budget of \$300K–\$900K represents less than 0.1% of the facility's asset value and falls within existing SDCWA research allocations.

The pilot is the decision gate. OsmoFlux projects 99.1% harm reduction under clean-membrane conditions and $P(NPV>0) = 37\%$ under moderate fouling at current geometry. The pilot will confirm or revise these projections under field conditions, providing the empirical foundation for a full-scale deployment decision. It also establishes Carlsbad as the first commercial RED installation treating seawater RO brine - a regulatory and reputational asset - as California tightens Ocean Plan standards. Finally, a successful pilot positions Carlsbad as the global proof-of-concept for RED at commercial scale, establishing the technology pathway for the 500+ plants in the permitting pipeline.

Secondary Recommendation: Deploy the Fresh-Dilute Cascade Architecture

We recommend that Poseidon Water and SDCWA incorporate RED retrofit provisions into the facility's next scheduled capital upgrade cycle, anticipated within 5-10 years, designing for the fresh-dilute cascade architecture specifically - N=80 cell pairs, A=0.05 m² per pair - the only configuration achieving 99% salinity reduction under real fouling conditions. Where membrane costs have reached ~\$40/m², deploy immediately rather than wait for the next upgrade cycle.

The rationale is asymmetric risk, directly supported by the model. The cost of incorporating RED-ready provisions during planned construction is \$1-3M (~2-5% of upgrade budget). The cost of emergency compliance retrofit under regulatory deadline is \$15-25M, a 5-10× penalty for inaction. The Deployment Regime Map (Figure 5) shows Carlsbad today at approximately \$50/m² membrane cost and \$0.05/m³ disposal cost, sitting just outside the cascade break-even frontier at ~\$40/m². Retrofit-ready provisions preserve the option to cross that frontier when membrane costs reach the trigger threshold without paying the forced-retrofit penalty.

Tertiary Recommendation: Monitor Membrane Cost Trajectory as a Deployment Trigger

The break-even analysis identifies clear, model-derived deployment triggers: membrane cost $\leq \sim\$40/m^2$ OR disposal cost $\geq \$0.10/m^3$. Current commercial IEM costs are approximately \$50-100/m². The fuel cell and electrolyzer industries are driving ion exchange membrane manufacturing toward commodity scale. We recommend that SDCWA establish a technology-watch program to monitor IEM pricing against this threshold, with full-scale RED deployment triggered when either condition is met: projected within 5–10 years based on analogous manufacturing learning curves.

Quantified Impact

The financial case for action versus inaction is supported directly by verified model outputs:

Metric	Without RED	With RED (fresh dilute cascade)
P(NPV>0) - moderate fouling		37% (BRINE-CARLSBAD-MC, n=5,000)

Metric	Without RED	With RED (fresh dilute cascade)
P(NPV>0) - severe fouling		12% (BRINE-CARLSBAD-MC-SEVERE, n=5,000)
P50 NPV - moderate fouling		-\$26M
P50 NPV - severe fouling		-\$86M
20-year undiscounted disposal exposure	\$83M+ at one disposal cost step-up	Reduced proportionally to harm reduction achieved
Annual energy revenue at deployment	\$0	\$1.4-1.8M
Pilot cost		\$300K-\$900K (<0.1% of facility asset value)
Forced retrofit cost if regulations tighten	\$15-25M	\$1-3M (RED-ready provisions only)
Break-even membrane cost		~\$40/m ² (cascade); ~\$24/m ² (single-stack)

If regulations tighten to require deep-well equivalent disposal, avoided disposal cost reaches approximately \$10-20M annually at 190,000 m³/day, making the RED investment strongly positive regardless of energy revenue at that point.

Beneficiaries for Carlsbad include approximately 400,000 San Diego County residents served by SDCWA and the Agua Hedionda Lagoon ecosystem adjacent to the outfall.

Stakeholder-Specific Actions

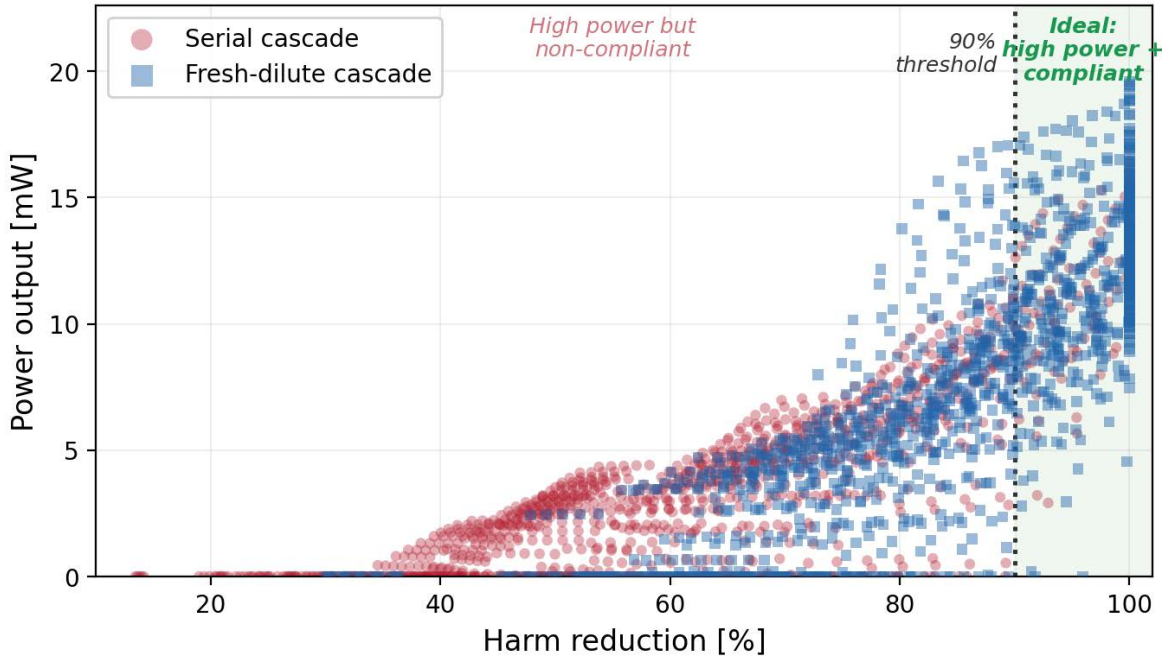
Poseidon Water (plant operator): Integrate RED-ready conduit and electrical provisions into the next scheduled capital upgrade cycle. Participate in pilot deployment to validate model predictions under operational conditions. Deploy at full scale when membrane cost trigger (~\$40/m²) is met.

SDCWA (water agency): Fund the \$300K-\$900K pilot study within existing research allocations. Establish a membrane cost monitoring program with deployment decision criteria tied to the model-derived thresholds.

California State Water Board (regulator): Consider RED-treated discharge as a compliance pathway in Ocean Plan amendments, incentivizing brine energy recovery alongside traditional diffuser dilution.

Environmental liability insurers: Incorporate RED deployment status as a risk modifier in underwriting desalination facilities, analogous to fire suppression system credits in property insurance. The Deployment Regime Map provides a quantitative framework for this pricing.

Power vs Environmental Compliance — All Configurations
Carlsbad SWRO ($C_H = 1.15 \text{ mol/L}$) · $N_{total}=120$, $A_{mem}=0.05 \text{ m}^2/\text{pair}$
Experiment: CASCADE-CL-SWEEP



Each point = one design (staging × flow rate × fouling level). Higher flow → more power but less treatment time. Fresh-dilute cascading reaches the upper-right frontier that serial cannot.

Figure 10. Power output vs. environmental compliance across all tested configurations — 240 geometry combinations (staging × flow rate × fouling level) at Carlsbad conditions ($C_H = 1.15 \text{ mol/L}$, $N_{total} = 120$, $A_{mem} = 0.05 \text{ m}^2/\text{pair}$). Fresh-dilute cascade (blue) reaches the upper-right frontier — high power and compliant — that serial cascade (red) cannot achieve. The 90% harm reduction threshold marks the regulatory compliance boundary. Source: CASCADE-CL-SWEEP (20260301_145354).

Conclusion

Desalination brine is a contingent financial liability whose magnitude depends on regulatory trajectory, disposal markets, and technology maturation. Our modeling shows that RED is not currently economic at Carlsbad under status-quo assumptions: P50 NPV = $-\$26\text{M}$ under moderate fouling at current membrane costs. However, the break-even surface is steep and the risk distribution is asymmetric. At $\sim\$40/\text{m}^2$ membrane cost, the fresh-dilute cascade crosses into positive NPV territory. At $\$0.10/\text{m}^3$ disposal cost, the avoided disposal burden alone justifies deployment. Both thresholds are approaching on current trajectories. Embedding RED-ready provisions today preserves option value while limiting downside exposure. The core finding is not that RED must be deployed immediately, but that brine discharge risk is quantifiable, can be hedged, and is manageable, provided planning occurs before regulation forces the decision.

References

- Długołęcki, P., Anet, B., Metz, S.J., Nijmeijer, K., Wessling, M. (2010). Transport limitations in ion exchange membranes at low salt concentrations. *Journal of Membrane Science*, 346(1), 163-171.
- Elimelech, M., Phillip, W.A. (2011). The future of seawater desalination: Energy, technology, and the environment. *Science*, 333(6043), 712-717.
- Gacia, E., Invers, O., Manzanera, M., Ballesteros, E., Romero, J. (2007). Impact of the brine from a desalination plant on a shallow seagrass (*Posidonia oceanica*) meadow. *Estuarine, Coastal and Shelf Science*, 72(4), 579-590.
- Gurreri, L., Guillen-Burrieza, E., Tamburini, A., Micale, G., Cipollina, A. (2023). Electrodialysis and reverse electrodialysis: Fouling and mitigation strategies. *Membranes*, 13(3), 322.
- Ibrahim, H.D., Eltahir, E.A.B. (2019). Impact of brine discharge from desalination plants on Persian/Arabian Gulf salinity. *Journal of Environmental Engineering (ASCE)*, 145(12).
- Ibrahim, H.D., Xue, P., Eltahir, E.A.B. (2020). Multiple salinity equilibria and resilience of Persian/Arabian Gulf basin salinity to brine discharge. *Frontiers in Marine Science*, 7, 573.
- IDRA (International Desalination and Reuse Association). (2024). Road to Reykjavik Part 2: Mitigation Through Innovation - Decarbonizing Desalination and Reuse.
- Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., Kang, S. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment*, 657, 1343-1356.
- Lattemann, S., Höpner, T. (2008). Environmental impact and impact assessment of seawater desalination. *Desalination*, 220(1-3), 1-15.
- Mickley, M.C. (2018). *Updated and Extended Survey of U.S. Municipal Desalination Plants*. U.S. Bureau of Reclamation, Desalination and Water Purification Research and Development Program.
- Panagopoulos, A. (2021). Brine management (saline water and wastewater effluents): Biorefinery approaches for resource recovery and minimization of environmental impacts. *Journal of Environmental Management*, 299, 113730.
- Robinson, R.A., Stokes, R.H. (1959). *Electrolyte Solutions* (2nd ed.). Butterworths, London.
- Sánchez-Lizaso, J.L., Romero, J., Ruiz, J., Gacia, E., Buceta, J.L., Invers, O., Fernández-Torquemada, Y., Mas, J., Ruiz-Mateo, A., Manzanera, M. (2008). Salinity tolerance of the Mediterranean seagrass *Posidonia oceanica*: Recommendations to minimize the impact of brine discharges from desalination plants. *Desalination*, 221(1-3), 602-607.
- Tedesco, M., Cipollina, A., Tamburini, A., Micale, G. (2017). Towards 1 kW power production in a reverse electrodialysis pilot plant with saline waters and concentrated brines. *Journal of Membrane Science*, 522, 226-236.
- Tong, T., Elimelech, M. (2016). The global rise of zero liquid discharge for wastewater management: Drivers, technologies, and future directions. *Environmental Science & Technology*, 50(13), 6846-6855.
- USBR (U.S. Bureau of Reclamation). (2020). *Desalination and Water Purification Research Program: Brine Disposal Alternatives*.
- USGS (U.S. Geological Survey). Desalination. *Water Science School*. <https://www.usgs.gov/special-topics/water-science-school/science/desalination>
- Vermaas, D.A., Kunteng, D., Saakes, M., Nijmeijer, K. (2014). Fouling in reverse electrodialysis under natural conditions. *Water Research*, 47, 1289-1298.
- Petersen, K.L., Heck, N., Reguero, B.G., Potts, D., Hovey, A., Wellman, H., Beck, M.W. (2019). Biological and physical effects of brine discharge from the Carlsbad Desalination Plant and implications for future desalination plant siting. *Diversity*, 11(12), 1-21.
- Panagopoulos, A., Haralambous, K.J., Loizidou, M. (2019). Desalination brine disposal methods and treatment technologies - A critical review. *Science of the Total Environment*, 693, 133545.

UN-Water. (2021). The United Nations World Water Development Report 2021: Valuing Water. UNESCO, Paris.

FAO (Food and Agriculture Organization). AQUASTAT database. Global Water Resources. <https://www.fao.org/aquastat/en/>.

WateReuse Research Foundation. (2013). Manual of Practice: Inland Treatment and Disposal of Concentrate from Inland Desalting Plants. Alexandria, VA.

Rijnaarts, T., Huber, M., de Vos, W.M., Nijmeijer, K. (2017). Role of scalants on the water permeability and power output of reverse electrodialysis. *Environmental Science & Technology*, 51(16), 9471-9479.

Tedesco, M., Cipollina, A., Tamburini, A., Micale, G. (2016). Towards 1 kW power production in a reverse electrodialysis pilot plant with saline waters and concentrated brines. *Journal of Membrane Science*, 515, 70-81.

Agarwal, R. (2026). OsmoFlux RED Modeling Code, GitHub repository. <https://github.com/blueleafabs/osmoflux>

Appendices

Model Parameter Summary

Parameter	Value	Source
Cell pairs (N)	2-160 (swept)	Geometry optimization
Membrane area (A)	0.005-0.25 m ² per pair (swept)	Multi-geometry viability map
Axial segments	40	Practical balance: accuracy vs. computational overhead
High-salinity feed (Carlsbad)	1.15 mol/L NaCl	Derived from Carlsbad EIR
Low-salinity feed	0.02 mol/L NaCl	Treated WW effluent
Flow rate (Q _H = Q _L)	5 × 10 ⁻⁶ m ³ /s	Pilot-scale reference
CEM ASR	0.36 mΩ·m ²	Fumatech FKS-PET-130
AEM ASR	0.235 mΩ·m ²	Fumatech FAS-PET-130
Permselectivity (α)	0.975	Manufacturer spec
Spacer shadow (β _{sol})	1.56	Vermaas et al. 2014
Spacer shadow (β _{mem})	1.10	Vermaas et al. 2014
Divalent fraction	0.20	Typical seawater
Fouling severity range (β)	0.0-0.8	Gurreri et al. 2023
Temperature	298.15 K	Isothermal assumption

Parameter	Distribution	Range / Parameters
Membrane capex	Triangular	min=\$30, mode=\$50, max=\$100 per m ²
Fouling severity (β)	Uniform	0.0-0.8 uniform (moderate); 1.5 fixed (severe)
Electricity price	Lognormal	mean=\$0.22/kWh, CV=30%
Brine disposal cost	Uniform	\$0.04-0.25/m ³
Discount rate	Uniform	3-8%

Total Experiments Conducted

More than 6,300 converged model evaluations across 16+ experiment specifications including:

- Multi-geometry viability map (4 membrane areas × 9 salinities × 8 flow velocities × 11 N_{per_stage} values × 2 fouling levels = 6,336 configurations)
- Cascade optimization (5 salinity scenarios × 200 configurations = 1,000)
- Architecture comparison (three-config: single/serial/fresh-dilute)
- Fouling sweeps (CDF-only: 144 runs, combined CDF + biofilm: 30 runs)
- Site-specific harm reduction (5 plants × 48 geometries = 240)
- Fouling impact by plant (84)
- Monte Carlo TEA (5,000 samples per scenario)
- Uncertainty quantification (15)
- Morris sensitivity screening (130 evaluations, 10 trajectories).