

Efficiency in Every Litre: Pricing RO Membrane and Pump Upgrades

A measurement, valuation and contracting framework for desalination retrofits

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Abstract

Background. Reverse-osmosis plants can lose value through membrane fouling, pump wear, control mismatch, energy-recovery underperformance and changes in feedwater or operating duty. Replacement equipment can restore or improve performance, while an equipment purchase alone does not prove an investable saving. Objective. This paper develops a decision framework for valuing membrane, high-pressure pump, motor-drive and energy-recovery upgrades in operating desalination assets. Method. It reviews official materials from the United States Department of Energy, Bureau of Reclamation, IRENA and publicly disclosed operating and supplier information. It then constructs an upgrade system map, a normalised performance benchmark, a hypothetical value bridge, a baseline protocol, a commercial allocation matrix, a risk register and an implementation roadmap. Findings. Financeable savings require a frozen baseline, normalisation for salinity, temperature, recovery and throughput, integrated testing at the delivery boundary, and contracts that allocate fouling, equipment, power-price, outage and interface risks. Membrane replacement can fail when the root cause is untreated fouling. Pump and energy-recovery upgrades create value when measured across the full hydraulic system and maintained across the operating envelope. Implications. Owners should fund diagnosis before procurement, compare retrofit and operating optimisation as one portfolio, value avoided energy and recovered capacity separately, and use post-completion measurement to protect debt and equity returns. All unattributed numerical exhibits are hypothetical decision tools; they are not forecasts, tariffs, valuations, offers or descriptions of a named project.

JEL Classification: G31, G32, L95, Q25, Q40, Q48

Keywords: reverse osmosis, membrane replacement, high-pressure pumps, energy recovery, desalination retrofit, lifecycle cost, performance contract, project finance, water infrastructure, energy efficiency

This paper is an educational and structural analysis prepared for research purposes. It is not investment advice, an offer, or a solicitation. It contains no client information.

1. THE INVESTMENT DECISION

An operating desalination plant can consume more electricity, produce less water or require more cleaning than its original model assumed. The owner then faces a capital decision: repair the existing system, replace membranes, re-rate pumps, add variable-speed drives, upgrade energy recovery, improve pretreatment or combine several measures.

The decision should be expressed as an incremental investment case. The owner needs to know the present condition, the counterfactual without intervention, the expected post-upgrade operating envelope, the outage required, the warranty structure and the cash value of energy, capacity and reliability. Procurement begins after these elements are defined.

2. WHY EQUIPMENT EFFICIENCY IS A SYSTEM QUESTION

Reverse osmosis converts hydraulic pressure into permeate through a membrane. Intake, pretreatment, high-pressure pumps, motors, drives, membranes, pressure vessels, energy-recovery devices, post-treatment and discharge all influence the measured result. An efficient component can perform poorly inside a mismatched system.

The assessment should therefore follow power from the electrical meter to the delivery meter. Pump efficiency, motor efficiency, pressure losses, membrane permeability, recovery, energy transfer, product quality and plant availability interact. The financial model should value net compliant water and net electricity at the agreed boundary.

3. THE EVIDENCE PROBLEM

Historical plant data often reflect changing water demand, feed salinity, temperature, membrane age, cleaning cycles, train availability and operator settings. A before-and-after average can misattribute weather, duty or maintenance effects to the retrofit.

A bankable case needs time-stamped measurements, calibrated instruments and a normalisation protocol. The baseline should identify which variables are observed, which are corrected and which remain commercial risks. The owner should preserve raw data and rejected operating periods so the result can be independently reproduced.

4. REVERSE-OSMOSIS ENERGY USE

The United States Department of Energy explains that RO uses high-energy pumps to pressurise feedwater across a membrane [1]. Its seawater-desalination bandwidth study used a representative state-of-the-art RO desalination-unit intensity of 2.70 kWh per cubic metre under defined salinity, recovery and product-quality assumptions [2].

That value is a reference point rather than a plant guarantee. Total delivered-water energy includes intake, pretreatment, boosting, post-treatment, storage and distribution within the chosen boundary. Salinity, temperature, recovery and pressure losses can move the result materially.

5. UPGRADE POINTS IN THE HYDRAULIC SYSTEM

The system map shows where an upgrade changes pressure, flow or loss. It also identifies the meters needed to verify performance.

Value must be measured across the complete power-to-water boundary

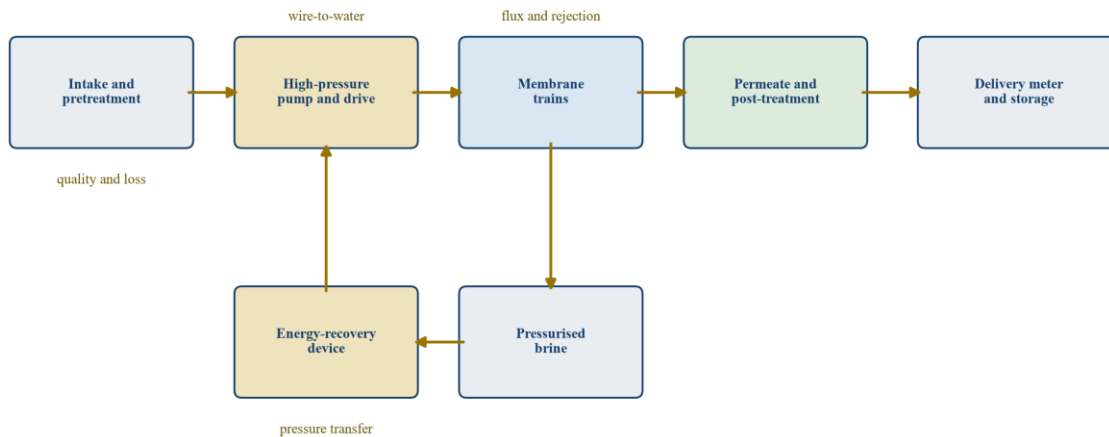


Figure 1. Reverse-osmosis upgrade system and measurement points

Generic architecture; actual trains, instruments and control boundaries depend on plant design.

6. MEMBRANE CONDITION

Membrane performance changes through fouling, scaling, compaction, chemical attack and physical damage. These mechanisms affect flux, salt rejection, pressure and cleaning frequency differently. The diagnostic should distinguish reversible loss from irreversible degradation.

Trend data should be normalised before comparing trains. Differential pressure, permeability, conductivity, recovery and clean-in-place response are more informative together than membrane age alone. Autopsy and laboratory analysis can identify a root cause where operating data remain ambiguous.

7. REPLACEMENT WITHOUT ROOT-CAUSE CORRECTION

A Bureau of Reclamation-sponsored counter-flow RO demonstration reported that one membrane replacement did not restore flux because the new membranes fouled quickly; performance improved after fouling was mitigated and another replacement was installed [3]. The case illustrates the danger of treating a symptom as the asset.

The business case should include pretreatment, chemical regime, hydraulics and cleaning practice. A membrane purchase can destroy value when the operating environment remains unchanged. Root-cause work is part of the retrofit, even when the physical capital sits elsewhere.

8. FOULING AND SCALING

Fouling deposits suspended or biological material on the membrane. Scaling precipitates dissolved minerals. Both can reduce production and increase pressure. The DOE's RO technology material identifies fouling, scaling, degradation and feed pressure as principal performance factors [4].

The owner should quantify source-water events, pretreatment breakthrough, differential pressure and cleaning recovery. The model should convert lost permeability into incremental power, lost output, chemicals, labour, outage and membrane life. A lower-energy membrane can have inferior lifecycle economics if it is less robust under actual feed conditions.

9. PRETREATMENT AS AN UPGRADE ALTERNATIVE

Improved pretreatment can reduce fouling load, extend membrane life and stabilise operation. Options can include media filtration, dissolved-air flotation, ultrafiltration, cartridge improvements, dosing and control changes. Each has energy, chemical, sludge and maintenance implications.

The retrofit screen should compare a membrane-only case with pretreatment-led and combined cases. The best result may use the existing membrane longer. Capital approval should follow the total lifecycle effect rather than the ownership boundary between treatment packages.

10. MEMBRANE SELECTION

Membranes differ in permeability, salt rejection, boron performance, fouling resistance, pressure requirement and chemical tolerance. Selection should use the plant's feedwater and product specification. Catalogue performance is a starting point.

Pilot or train-scale testing should use representative seasonal conditions where feasible. The design should include element arrangement, flux distribution, pressure-vessel loading and compatibility with existing housings. A proprietary element can create supplier concentration and inventory risk that needs commercial treatment.

11. CLEANING ECONOMICS

Cleaning restores part of membrane performance while consuming chemicals, labour, water and outage time. Aggressive cleaning can reduce element life. The optimum interval balances deterioration against cleaning cost and damage.

The Bureau of Reclamation has funded work to model cleaning frequency and scaling economics, reflecting the planning value of these variables [5]. The owner should model condition-based triggers and forecast the consequence of a delayed or ineffective clean.

12. HIGH-PRESSURE PUMPS

High-pressure pumps provide the head required to overcome osmotic pressure and system losses. Their efficiency depends on flow, head, speed, impeller, wear, clearances and operating point. A pump selected for the original duty may operate away from its best-efficiency region after plant modifications.

The assessment should measure electrical input, motor output or efficiency, pump differential head and flow. It should compare observed wire-to-water efficiency with an achievable reference under the same duty. The DOE's pumping resources and tools are designed around this system-level assessment [6][7].

13. MOTOR EFFICIENCY

Motor losses affect every operating hour. Replacement can be justified by efficiency, reliability, power factor, insulation condition or a changed duty. The case should include motor, starter or drive, cooling, harmonics, cabling and installation.

Nameplate efficiency does not prove field performance. Load, voltage balance, rewinding history and drive losses matter. A premium motor can create limited value if the pump remains throttled or hydraulically mismatched.

14. VARIABLE-SPEED DRIVES

A variable-speed drive can match pump output to changing flow or pressure and reduce throttling losses. It also introduces drive losses, harmonics, cooling and control complexity. DOE guidance cautions that drive efficiency varies with speed [7].

The retrofit should model the actual load profile and system curve. Savings at part load may be material, while a plant that operates near constant full load may gain less. Minimum membrane pressure and recovery constraints remain hard limits.

15. PUMP RE-RATING AND HYDRAULICS

Impeller trimming, pump re-rating, parallel staging, pipe modification and valve changes can reduce loss without replacing the whole pump. These measures require a reconciled hydraulic model and field measurements.

The owner should examine suction conditions, cavitation margin, pressure-vessel limits and transient response. A local pressure reduction can shift risk to another train or reduce water quality. The integrated model should preserve compliant production.

16. ENERGY RECOVERY

The brine leaves the membrane array at high pressure. Energy-recovery devices transfer or convert part of that pressure rather than dissipating it. The value depends on transfer efficiency, leakage, mixing, pressure drop, flow balance and availability.

Energy Recovery's 2025 Form 10-K describes pressure exchangers used in seawater RO and reports company performance claims, including high transfer efficiency and reduced main-pump flow [8]. These are supplier disclosures. A project decision requires site-specific guarantees and independent testing.

17. RETROFIT FIT

Adding or replacing an energy-recovery device can require booster pumps, piping, controls, foundations and changes to train hydraulics. Space and outage constraints can dominate equipment cost.

The feasibility study should map tie-ins, pressure ratings, commissioning sequence and fallback operation. A high-efficiency device can underperform when flow is outside its design range. The owner should model the complete operating envelope.

18. BASELINE DEFINITION

The baseline is the expected future performance without the upgrade. It should reflect current degradation, planned maintenance and credible operating changes. Using the original design can overstate savings when the plant could recover performance through ordinary maintenance.

Baseline periods should exclude documented meter failure and abnormal events under a pre-agreed rule. They should retain normal variability. A frozen calculation and data archive protect both owner and supplier from later selection bias.

Table 1. Upgrade baseline and normalisation protocol

Variable	Required evidence	Normalisation treatment	Commercial use
Feed salinity	Calibrated conductivity and laboratory checks	Correct osmotic pressure and expected energy	Separate equipment saving from feed change
Feed temperature	Continuous measurement	Correct membrane permeability	Compare flux across seasons
Product quality	Conductivity and required constituents	Apply compliant-water boundary	Exclude off-specification output
Recovery	Feed, permeate and concentrate flow	Hold or model agreed operating range	Separate water recovery from energy intensity
Throughput	Metered compliant volume	Use specific energy and capacity measures	Value recovered output and energy separately
Train availability	Event and outage log	Apply agreed availability case	Distinguish efficiency from reliability
Membrane condition	Normalised permeability and rejection	Establish degradation curve	Define replacement counterfactual
Power	Revenue-grade electrical meter	Include agreed auxiliary loads	Calculate verified avoided energy

Generic measurement structure; plant-specific engineering determines valid corrections.

19. METERING

Measurement accuracy should be proportionate to the expected saving. Flow, pressure, conductivity, temperature and electrical meters need calibration, time alignment and data-quality rules. Small errors can overwhelm a narrow efficiency improvement.

The protocol should define missing data, drift, aggregation and retention. Independent witness testing can support performance acceptance. Continuous monitoring can establish persistence after completion.

20. NORMALISED SPECIFIC ENERGY

Specific energy is net electricity divided by compliant water produced. The numerator and denominator must share a time interval and boundary. Start-up water, rejected product and recirculation should be treated consistently.

Normalisation should correct variables that neither party controls while preserving risks assigned by contract. Over-correction can turn the test into a model result rather than an operating result. The calculation should be auditable from meter data.

21. CAPACITY RECOVERY

An upgrade can recover lost output, not only reduce energy per cubic metre. The value of recovered capacity depends on offtake, tariff, storage, network need and the cost of alternative water.

The financial model should avoid counting both energy saving and revenue from the same water incorrectly. It should identify the marginal energy, chemicals and maintenance associated with additional output. Capacity has value only when it can be delivered or reduces an existing shortfall obligation.

22. RELIABILITY VALUE

New equipment can reduce forced outages, improve train stability and lower spare-part risk. Reliability value is the probability-weighted cost of avoided events, including replacement water, deductions, labour and damage.

Historical event records should support the estimate. A generic reliability premium is unverified. Warranty and service response can transfer part of the risk, while consequential losses are often capped or excluded.

23. DEGRADATION CURVE

Savings should be assessed over time. Membranes foul, pump clearances change and control performance can drift. The initial test is one point on a lifecycle curve.

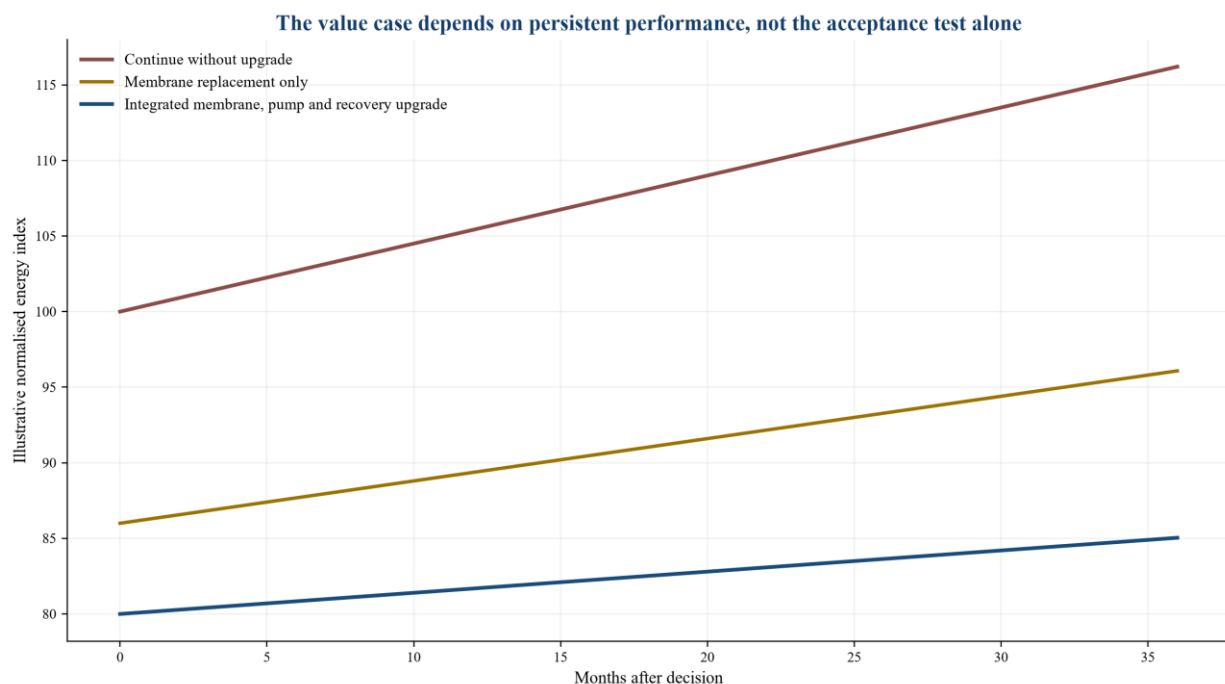


Figure 2. Illustrative normalised performance and upgrade persistence
Hypothetical indices for methodology only; not operating data or an equipment forecast.

24. COUNTERFACTUAL MAINTENANCE

The no-upgrade case still requires maintenance and eventual replacement. Incremental capex should be compared with the timing and cost of those unavoidable actions. Replacing equipment early consumes remaining life.

The model should credit avoided baseline maintenance only once. Deferred spend can have present-value benefit while increasing operating risk. The board should see both cash timing and service consequence.

25. ENERGY-PRICE EXPOSURE

Avoided energy value equals verified kilowatt-hours multiplied by the project's marginal or contracted energy cost. A blended average tariff can be wrong when savings occur in specific hours or affect demand charges.

The model should state escalation, pass-through and hedge treatment. If energy cost is passed to the water offtaker, the project company may receive limited direct benefit unless a sharing mechanism exists. Contract economics determine who owns the saving.

26. CARBON AND RENEWABLE ATTRIBUTES

Lower electricity use can reduce emissions and renewable-generation requirements. The environmental value depends on the marginal power source, applicable accounting method and ownership of attributes.

Carbon value should be separately disclosed and included only where a price, compliance requirement or approved internal policy applies. Avoided emissions alone do not create project cash. They can support green-finance reporting and procurement objectives.

27. CAPITAL COST

Installed cost includes equipment, engineering, owner work, transport, duties, foundations, piping, electrical, controls, spares, commissioning, outage and contingency. A quotation is not an installed budget.

Brownfield uncertainty requires surveys and tie-in planning. The estimate should state maturity and exclusions. Contingency should correspond to unresolved scope and interface risk rather than a generic percentage.

28. OUTAGE COST

Retrofits can reduce production during tie-in and commissioning. Outage cost depends on storage, alternative supply, season, tariff deductions and replacement-water arrangements.

The schedule should seek a low-demand window and coordinate planned maintenance. Parallel installation and bypass can reduce outage at additional cost. The model should compare alternatives on total value.

29. LIFECYCLE COST

Membrane life, pump overhaul, drive replacement, energy-recovery service, chemicals, labour and spares belong in the lifecycle model. A lower initial price can create a higher total cost.

The owner should use a consistent horizon and residual value. Supplier service agreements should be included where required to maintain guarantees. Foreign-currency and obsolescence exposures need sensitivity.

30. HYPOTHETICAL VALUE BRIDGE

The financial case should reconcile the existing asset to the upgraded asset. The exhibit below shows the logic with hypothetical indices.

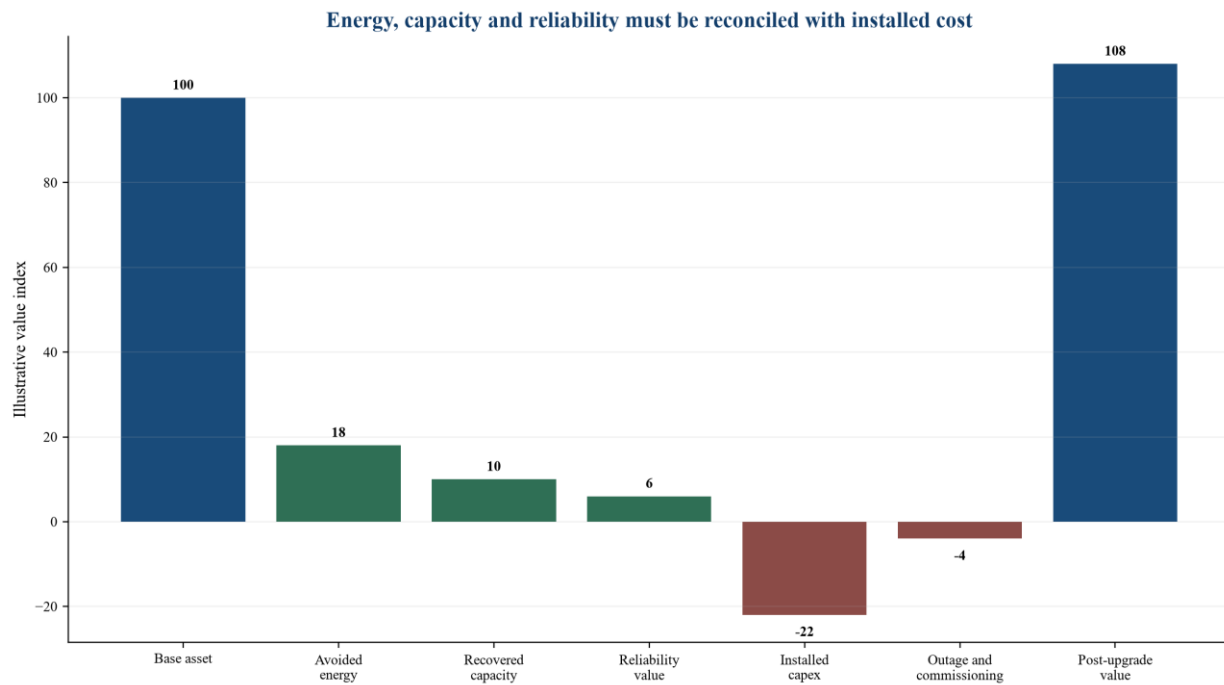


Figure 3. Illustrative value bridge for an integrated RO efficiency upgrade
Hypothetical values; not a project valuation, tariff, forecast or supplier claim.

31. DISCOUNTED CASH FLOW

The upgrade model should use incremental cash flows, taxes, working capital, replacement and residual value. Savings begin after commissioning and decline or persist according to the degradation case.

The discount rate should reflect contract and operating risk. Scenario-weighted cash flows can make technical uncertainty explicit. A single payback period hides performance persistence and terminal assumptions.

32. PAYBACK AND HURDLE RATES

Payback is useful for liquidity and technology-risk screening. It should not replace net present value or service analysis. A short payback based on unnormalised savings can still destroy value.

The board should set approval thresholds by risk, strategic importance and capital availability. Mandatory compliance or water-security work can require a different decision framework from discretionary efficiency capital.

33. DEBT AND COVENANT IMPLICATIONS

An upgrade can improve debt-service coverage by reducing operating cost or increasing availability. It can also require new debt, restricted-payment consent or a reserve draw. Existing finance documents may limit additional capex and security.

Lenders should receive the technical case, contract package, outage plan and downside model. Debt sizing should rely on verified or guaranteed performance, with equity absorbing unproven upside.

34. PERFORMANCE CONTRACT

The supplier or integrator can guarantee energy, output, quality, availability or equipment efficiency. The metric should match the owner's economic case. A component guarantee may not cover system savings.

Acceptance conditions, correction curves, exclusions, liquidated damages and caps require alignment. The owner should retain access to data and test calculations. The supplier needs relief for feedwater and operating conditions outside the agreed envelope.

Table 2. Upgrade commercial structure and value protection

Element	Owner objective	Supplier or contractor obligation	Financeability control
Baseline	Establish credible counterfactual	Accept data and correction method	Frozen protocol and raw-data archive
Completion	Integrate equipment safely and on time	Meet schedule, capacity and quality tests	Security, damages and long-stop date
Efficiency	Deliver persistent energy reduction	Guarantee corrected system performance	Metered boundary and repeat tests
Capacity	Recover compliant output	Meet flow and rejection requirements	Exclude off-specification water
Availability	Preserve service	Support response and spares	Availability test and service-level regime
Degradation	Maintain lifecycle value	Meet persistence or element-life conditions	Warranty, monitoring and retest rights
Interface	Avoid gaps between packages	Coordinate controls, hydraulics and commissioning	Single integration responsibility or interface matrix
Savings ownership	Allocate economic benefit	Provide measurement evidence	Tariff, sharing and pass-through alignment

Generic framework; enforceability and allocation depend on transaction documents and law.

35. EPC OR MULTI-PACKAGE DELIVERY

A single retrofit integrator can wrap membrane, pump, drive, recovery and control performance. The price includes interface risk. Separate packages can preserve specialist competition while leaving integration with the owner.

The procurement strategy should reflect the owner's engineering capability and outage risk. A detailed interface matrix is essential where several suppliers participate. Completion testing must cover the integrated plant.

36. WARRANTY SECURITY

Warranty value depends on the obligor's credit, duration, exclusions and remedy. Parent support, performance security, retention or escrow can strengthen recovery. Warranty caps should reflect the owner's downside.

Long membrane or equipment warranties can require prescribed operation and consumables. The owner should verify that those conditions fit the plant. A warranty that cannot be maintained under normal duty has limited value.

37. MEASUREMENT AND VERIFICATION

Post-completion measurement should repeat the agreed normalisation and include a sufficient operating period. The protocol can draw on investment-grade energy assessment principles reflected in DOE tools such as MEASUR and PSAT [6][7].

Persistence testing after six or twelve months can protect lifecycle value. The contract should state remedy if initial performance passes and later performance falls below the guaranteed curve.

38. DATA GOVERNANCE

Owner, operator, EPC contractor and equipment suppliers may hold different data. The upgrade requires access to historian tags, calibration records, laboratory results, maintenance and control logic.

The contract should establish data rights, cybersecurity, retention and independent access. Supplier algorithms can remain confidential while exposing inputs, outputs and acceptance calculations needed for verification.

39. DIGITAL OPTIMISATION

Controls can optimise pump loading, train sequencing, recovery and cleaning. Their value depends on sensor quality, operating authority and validated constraints. A software recommendation that operators routinely override has limited value.

The owner should pilot control changes, log overrides and protect water-quality limits. Savings from software should be measured separately from hardware where possible. Cybersecurity and fallback modes require testing.

40. PROCUREMENT COMPARISON

Bids should use a common baseline, duty profile, energy price, outage window and lifecycle horizon. Suppliers should disclose exclusions and the source of each claimed saving.

Evaluation should compare installed net present value, guaranteed performance, implementation risk, supplier credit and service capability. A lower equipment price can be inferior when integration and outage sit outside the quote.

41. RISK ALLOCATION

Risk should sit with the party that controls or can price it. Feedwater and demand may remain with the owner or offtaker. Equipment design and workmanship can sit with the supplier. Integration can sit with the EPC contractor or owner according to scope.

Table 3. RO upgrade risk register and decision response

Risk	Evidence required	Commercial response	Investment response
Baseline bias	Raw history and frozen protocol	Independent verification	Reduce recognised savings
Fouling root cause unresolved	Autopsy, feedwater and pretreatment review	Performance condition and pretreatment scope	Defer membrane order
Pump duty mismatch	Field curve and hydraulic model	Wire-to-water guarantee	Re-rate before replacement
Energy recovery underperforms	Flow, pressure and transfer test	Device and system guarantee	Price downside case
Outage exceeds plan	Integrated schedule and contingency	Delay damages and recovery plan	Fund replacement-water exposure
Savings do not persist	Degradation and cleaning model	Retest and warranty remedy	Holdback or staged payment
Power price changes	Tariff and hedge review	Sharing or index mechanism	Separate kWh and price risk
Supplier concentration	Spares, alternatives and credit review	Inventory and support covenant	Reserve and dual-source plan
Existing-finance restriction	Facility and security review	Lender consent	Condition precedent

Generic framework; probability, impact and remedy require plant-specific diligence.

42. PILOT AND TRAIN STRATEGY

A full-plant retrofit may be unnecessary for proof. One train can establish membrane, pump-control and recovery performance while limiting outage and capital. The pilot should represent the intended duty.

Success criteria should include persistence and operating practicality, not only a short acceptance test. The owner should preserve the option to stop, redesign or scale. Common infrastructure may still need early commitment.

43. IMPLEMENTATION SEQUENCE

The sequence begins with data validation and root-cause diagnosis. It then develops the hydraulic model, screens alternatives, pilots material uncertainty, freezes the baseline, procures integrated performance and plans the outage.

Construction, commissioning, acceptance and persistence testing follow. Each gate should have evidence, cost and decision rights. Capital should be released when the preceding gate resolves the uncertainty needed for the next commitment.

44. OPERATIONS READINESS

New equipment changes procedures, spares, controls and training. Operators should participate in design and hazard review. Commissioning should include abnormal operation and fallback modes.

The owner should update preventive maintenance, critical-spares lists, drawings and control narratives before handover. Warranty responsibility should remain clear when the operator intervenes.

45. ENVIRONMENTAL IMPLICATIONS

Energy reduction can lower emissions and renewable-generation needs. Higher recovery can reduce intake per unit of product while concentrating brine. Chemical and cleaning changes can affect discharge.

The environmental assessment should examine net effects across energy, intake, chemicals, waste and brine. A narrow energy metric can hide a worse water or discharge outcome. Permit changes require early review.

46. SUPPLIER DILIGENCE

Supplier assessment should cover technical record, financial strength, manufacturing, quality, warranty history, service footprint, spares and cybersecurity. A specialised component can create long-term dependence.

Public disclosures can inform market context. Energy Recovery's Form 10-K states that lifecycle cost is important in large desalination procurement and describes retrofit exposure as part of its market [8]. Company claims should be verified for the specific site.

47. RED FLAGS

Red flags include savings based on design rather than measured baseline, membrane replacement without fouling diagnosis, pump comparison at different duty, energy-recovery efficiency quoted without system losses, and capacity value without offtake.

Other warnings include outage omitted from capex, supplier-only verification, missing raw data, a guarantee that excludes normal feedwater, and debt service dependent on unguaranteed savings. Each issue needs correction, risk price or a smaller staged investment.

48. INVESTMENT-COMMITTEE SCORECARD

The committee should ask whether the baseline is reproducible, the root cause is established, the option set is complete, the retrofit is integrated, savings are contractually owned, and the downside preserves water service.

Approval conditions can include pilot results, lender consent, independent engineer sign-off, guaranteed installed cost, outage contingency, measurement protocol and supplier security. The decision record should state which value components are guaranteed, expected or excluded.

49. REPORTING AFTER COMPLETION

Monthly reporting should show normalised specific energy, compliant water, recovery, permeability, salt rejection, differential pressure, pump efficiency, energy-transfer performance, availability, cleaning and lifecycle spend.

The finance team should reconcile verified kilowatt-hours, capacity and reliability to cash. Variances should identify operating, price and volume causes. This protects the investment case from narrative drift.

50. PORTFOLIO REPLICATION

A successful retrofit can create a repeatable programme across trains or plants. Replication should use the verified baseline and lessons from the first installation. Feedwater and duty differences still require local adjustment.

Framework procurement can reduce engineering and spare costs. The owner should preserve competition and avoid locking in a design that later data contradict. Each subsequent asset needs its own acceptance evidence.

51. LIMITS OF THE FRAMEWORK

This paper does not price a named upgrade or recommend a supplier, membrane, pump, drive or energy-recovery device. Public materials do not disclose every operating condition, contract or failure. Supplier disclosures are identified as such.

A specific decision requires plant data, calibrated measurements, independent engineering, executed contracts, environmental review and a fully audited financial model. Hypothetical exhibits are methodology only.

52. CONCLUSION

RO efficiency capital should be priced from a normalised power-to-water baseline. Membrane, pump, drive, energy-recovery, pretreatment and control measures should be evaluated as an integrated portfolio. Root-cause diagnosis prevents capital from being spent on a recurring symptom.

The recommended discipline is to measure the complete boundary; freeze the counterfactual; value energy, capacity and reliability separately; include installed cost, outage and lifecycle replacements;

obtain system-level guarantees; test persistence; and reconcile verified performance to cash. This turns an equipment upgrade into an auditable infrastructure investment.

53. BOARD DECISION RECORD

The board paper should state the current condition, root cause, alternative interventions, frozen baseline, expected operating range, installed cost, outage, guarantee, measurement method, scenario returns and service impact. It should disclose which assumptions rely on supplier statements and which have been independently verified.

The approval should define hold points and change control. A materially different feedwater case, scope, tariff or outage should return to the decision authority. This prevents the project from retaining approval after the evidence supporting it has changed.

54. FUTURE OPTIONALITY

An upgrade can create data, control capability and hydraulic headroom that support later renewable integration, capacity expansion or advanced membranes. These options should be described without assigning value until the enabling evidence and rights exist.

The owner can preserve optionality through spare tie-ins, modular controls, data access and equipment envelopes. Optionality should not burden the base case with speculative capital. The first investment should stand on verified water, energy and reliability economics.

55. FUNDING STRUCTURES

The retrofit can be funded from owner equity, existing project reserves, additional senior debt, vendor finance, a green facility or a shared-savings arrangement. The appropriate source depends on asset ownership, covenant capacity, upgrade risk and who receives the saving. Capital with a lower headline rate can be expensive when it captures a large share of upside or restricts operations.

Funding terms should follow the evidence. Proven pump or motor replacements may support conventional debt. A novel membrane or control system may require sponsor capital, staged payment or supplier risk sharing. The model should compare all financing fees, reserves, security, tenor and termination costs with the same upgrade cash flows.

56. SHARED-SAVINGS STRUCTURES

A supplier or energy-service company can fund part of the work and receive a share of verified savings. This aligns payment with outcome and can preserve owner capital. It also makes the baseline, energy price and measurement rules central commercial terms.

The agreement should state minimum service, ownership of equipment, treatment of operating changes, buyout rights and what happens when water output changes. Savings should be calculated from verified kilowatt-hours before applying the agreed price. A shared-savings structure cannot repair a weak baseline; it raises the value of a precise one.

57. OPERATOR INCENTIVES

The operator controls set points, cleaning, maintenance and response to alarms. An upgrade guarantee can fail when incentives reward production without lifecycle efficiency, or efficiency without water availability. The O&M regime should align these objectives.

Performance measures can include normalised energy, compliant volume, availability, membrane condition and planned maintenance. Incentives should use controllable measures and protect public-health limits. The owner should avoid overlapping penalties between the operator and supplier that leave the project unable to recover the same loss from either party.

58. SPARE-PARTS STRATEGY

Retrofits can make existing spares obsolete and introduce new critical components. The installed-cost model should include initial spares, specialist tools, firmware access and training. Lead time matters more than unit price when failure stops a train.

The owner should classify spares by failure probability, consequence and replenishment time. Shared inventory across a plant portfolio can reduce working capital. Supplier-held stock needs enforceable access and transport assumptions. Obsolescence notices and last-time-buy rights protect long-tenor value.

59. FOREIGN EXCHANGE AND IMPORT EXPOSURE

Membranes, pumps, drives and energy-recovery devices may be priced in currencies different from water revenue. The investment case should map purchase, spares, service and future replacement exposure. A one-time construction hedge does not cover a long operating life.

The owner can use tariff indexation, reserves, framework pricing, local service or hedging. Each carries cost and basis risk. Local assembly may reduce logistics and build capability while retaining imported core components. The downside model should use the residual currency exposure after confirmed mitigations.

60. TAX, ACCOUNTING AND CONCESSION TREATMENT

Capital allowance, depreciation, indirect tax and accounting treatment affect owner cash flow. A concession or project agreement may also determine whether the upgrade becomes part of the regulated or handback asset and whether costs are recoverable through tariff.

The board should obtain transaction-specific advice before including these effects. Management estimates should remain separate from engineering savings. Accounting earnings can differ from cash value, especially when existing equipment is retired early or a supplier-financed arrangement contains service and lease elements.

61. CHANGE IN WATER SPECIFICATION OR DUTY

The plant may face tighter product standards, higher salinity, a different recovery target or new dispatch requirements during the upgrade life. The selected equipment should be tested against

credible duty cases. Excess design margin has a cost, while a narrow design can lose value when conditions change.

The investment paper should identify which future cases are contracted, planned or optional. A change clause can allocate the cost of a later specification. The base valuation should include only approved or contractually supported duty, with optional capability shown separately.

62. PORTFOLIO CAPITAL RANKING

Owners with several plants should rank upgrades by verified value per unit of constrained capital. Comparable metrics can include present value, energy saved, compliant capacity recovered, outage exposure and confidence in the baseline. A single league table should retain plant-specific risk rather than reduce every opportunity to simple payback.

The portfolio can combine quick operational measures with larger integrated retrofits. Diversifying implementation teams and outage windows can reduce execution concentration. Capital should move when diagnosis changes the expected return; an early low-cost assessment can be more valuable than reserving funds for a weakly evidenced project.

63. INDEPENDENT ENGINEER ROLE

An independent engineer can review baseline integrity, root cause, design, installed cost, schedule, guarantees and completion tests. The role is particularly valuable when the equipment supplier produced the savings model or the upgrade supports additional debt.

Independence does not remove owner responsibility. The scope should require access to raw data and document material assumptions. Reliance, liability and update obligations should align with the financing decision. The engineer's report should distinguish verified observations, management estimates, supplier claims and unresolved items.

64. COMMISSIONING DISCIPLINE

Commissioning should test individual components, integrated controls, protection systems, water quality, energy performance and fallback operation. The sequence should define temporary operating limits and authority to accept deviations. A short successful run is insufficient when the investment relies on sustained performance.

The completion file should contain calibrated meter records, test calculations, alarms, punch items, as-built documents and operator sign-off. Deferred items need owners and deadlines. Distribution or final supplier payment should follow the agreed evidence rather than mechanical completion alone.

65. DECISION UNDER UNCERTAINTY

Where data remain incomplete, the owner can stage the decision. It can fund additional instrumentation, one membrane train, a pump test or a temporary control trial before committing the full capex. Each stage should resolve a named uncertainty and preserve a stop option.

The value of staging is highest when the next test is inexpensive relative to the possible avoided mistake. The board should compare information value with delay and outage-window cost. A staged programme remains accountable through pre-agreed success, redesign and termination criteria.

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