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SOLAR-POWERED REVERSE OSMOSIS DESALINATION FOR NEOM

Technical Feasibility, Energy Sizing and Economic Assessment

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Abstract : Water scarcity is a pressing challenge in arid regions, and Saudi Arabia is expanding desalination capacity to secure its freshwater supply. This paper assesses the technical feasibility and economic viability of photovoltaic (PV)-powered reverse osmosis (RO) desalination for NEOM, on Saudi Arabia's Red Sea coast. A consistent design case is developed for a 350,000 m3 d−1 plant at 45% recovery and a feed salinity of 41,000 ppm, typical of the Gulf of Aqaba. The feed osmotic pressure is about 3.1 MPa and the flux-based membrane area about 972,000 m2 (26,160 eight-inch elements in 3,740 vessels). At a 65-bar feed pressure, the specific energy consumption is 5.1 kWh m−3 without energy recovery and 2.9 kWh m−3 with energy recovery devices, within the state-ofpractice range. A PV array of about 1.07 km2 (190 MWdc, performance ratio 0.80) and battery storage of about 521 MWh sustain round-the-clock operation. Single-pass permeate of about 250 ppm TDS meets the WHO aesthetic guideline, while a second pass is recommended for boron margin and premium water. Capital cost is estimated at 560–890 million USD and the levelized cost of water at 0.6–1.1 USD m−3 (central value 0.8). PV-RO desalination is technically feasible and competitive for NEOM, with energy recovery and storage identified as the key cost drivers.

***IndexTerms* -** Reverse osmosis; Photovoltaic; Desalination; NEOM; Energy recovery; Levelized cost of water

INTRODUCTION

Freshwater scarcity is among the most pressing challenges of arid and semi-arid regions, where renewable freshwater resources are limited while demand grows rapidly [9]. Seawater desalination has become the main water-supply option for many coastal countries, and reverse osmosis (RO) is today the most widely deployed membrane-based desalination technology because of its lower energy demand relative to thermal processes and its modular character [10, 19]. Nevertheless, RO remains energy-intensive: modern seawater reverse osmosis (SWRO) plants typically consume 2.5–4.0 kWh per cubic metre of permeate when equipped with energy recovery devices (ERDs), and considerably more without them [25, 14, 27]. Renewable-energy-powered desalination has consequently attracted growing attention as a means of decoupling water production from fossil fuels [12, 4, 2]. Saudi Arabia is one of the world's largest producers of desalinated water [13], and its Red Sea coast hosts one of the most saline water bodies on the planet. Open-sea salinities in the Red Sea range from about 36,000 to 41,000 ppm, and the Gulf of Aqaba, on which NEOM is located, is among the most saline basins, with reported values of 40.3–40.8 PSU with little seasonal variation [22, 13]. High feed salinity raises the osmotic pressure that an RO plant must overcome, increasing both capital and energy costs relative to open-ocean seawater [10, 19]. Water management and desalination based on solar energy are explicit priorities of Saudi Arabia's Vision 2030 strategy [24].

At the same time, the Kingdom possesses one of the highest solar resources in the world. The NEOM region receives annual global irradiation of the order of 2,500 kWh m−2 yr−1, with a daily average of about 6.5 kWh m−2, among the highest measured globally [3]. Photovoltaic (PV) systems convert this resource directly into electricity that can drive RO high-pressure pumps. PV-RO configurations have been analysed extensively, from small off-grid units to medium-size plants [21, 7], and recent systematic reviews confirm that solar-powered RO is a mature, rapidly improving option for arid coastal regions [5, 15]. Saudi Vision 2030, which targets 50% renewable electricity by 2030, further positions PV-powered desalination as a strategic national option [24, 8]. The objective of this paper is to evaluate the technical and economic feasibility of a large-scale PV-powered RO desalination plant supplying NEOM using a single, internally consistent design case. The specific objectives are: (i) to close the water mass balance at a realistic recovery ratio and size the RO membrane from the design flux; (ii) to quantify the specific energy consumption (SEC) with and without energy recovery; (iii) to determine the PV array and battery storage required for continuous operation; (iv) to assess permeate quality against the World Health Organization (WHO) guidelines, including boron; and (v) to estimate capital cost and levelized cost of water (LCOW) with sensitivity analysis.

Research Gap

The review of the literature reveals several gaps that motivate the present study. First, most published analyses of PV-RO systems concern small off-grid or medium-size installations, and consistent techno-economic sizing of a large-scale plant under Gulf of Aqaba conditions is scarce [5, 7, 15]. Second, the osmotic-pressure penalty imposed by the high salinity of the northern Red Sea is rarely linked quantitatively to the resulting PV field and storage dimensions [10, 4, 19]. Third, economic assessments frequently report only the capital cost of the desalination unit and omit the storage subsystem, which is a dominant cost driver [9, 8, 17]. Fourth, boron, which governs second-pass needs in SWRO, is rarely integrated into feasibility studies [11]. Finally, brine management, a growing environmental concern for large plants, is seldom incorporated [13].

Research Questions

The present work addresses the following research questions:

- RQ1: What recovery ratio, feed flow and membrane area are required to desalinate Gulf of Aqaba feed water of 41,000 ppm for NEOM?
- RQ2: What is the specific energy consumption of the plant with and without energy recovery devices, and how does it scale the photovoltaic field?
- RQ3: What photovoltaic array area and battery storage capacity are required for continuous, round-the-clock operation?
- RQ4: Does a single-pass RO system meet WHO water-quality guidelines (TDS and boron), or is a second pass required?
- RQ5: What are the capital cost and levelized cost of water of the integrated PV-RO system, and which parameters drive the cost?

RESEARCH METHODOLOGY

Research design. The study adopts a quantitative techno-economic modelling approach. The methodology is a sequential engineering chain: plant capacity → recovery → feed flow → membrane area → pressure → pump power → SEC → PV → battery → CAPEX → LCOW. Each stage is computed with explicit equations and published unit data, so that all reported numbers are internally consistent.

Data sources. Site-specific inputs were taken from published assessments of solar availability in the NEOM region [3] and from oceanographic and desalination data on Red Sea salinity and brine production [22, 13]. Process parameters follow current SWRO practice: recovery 40–50% [19, 25], design flux 12–18 L m^{-2} h^{-1} [19, 14], feed pressure 50–80 bar [25, 14], and membrane salt rejection >99.5% [19]. Economic unit costs are drawn from peer-reviewed reviews [9, 17, 4] and recent life-cycle studies of renewable-powered RO [23].

Modelling approach. The osmotic pressure is computed with the van 't Hoff relation, the membrane area from the design flux, and the SEC from a plant-wide energy balance including ERD recovery [10, 25]. The two-pass configuration follows the multi-pass RO simulation framework [6] and boron behaviour follows [11]. Fouling and scaling behaviour is interpreted in light of membrane autopsy and feedwater-quality guidelines [1, 18].

Validation. The computed SEC is benchmarked against published ranges for SWRO with and without ERDs [25, 14, 27], and the LCOW against recent estimates for renewable-powered RO [23] and conventional SWRO [9, 17]. Sensitivity analyses are performed for irradiation, battery cost, membrane replacement and discount rate.

Limitations. The analysis is steady-state and does not model diurnal transients, membrane ageing or dynamic grid interactions; cost figures are order-of-magnitude estimates for feasibility screening rather than detailed engineering.

MATERIAL AND METHODS

Design basis and water mass balance. The plant is a single-pass SWRO facility with a nominal permeate capacity of 350,000 m^3 d^{-1} (14,583 m^3 h^{-1}). A recovery ratio of 45% is adopted, representative of modern single-stage SWRO (40–50%) [19, 25]. The feed and brine flows follow from the recovery ratio:

giving Q_f = 777,778 m^3 d^{-1} (32,407 m^3 h^{-1}) and Q_b = 427,778 m^3 d^{-1} (17,824 m^3 h^{-1}). A design feed salinity of 41,000 ppm is adopted, consistent with reported Gulf of Aqaba salinities of 40.3– 40.8 PSU and providing a conservative margin for coastal intake [22, 13]. The principal design parameters are summarised in Table 1. Osmotic pressure and concentration polarization. The osmotic pressure of the feed is estimated with the van 't Hoff relation,

$$\pi = i\,C\,R\,T$$

where i is the van 't Hoff factor (≈1.8 for seawater), C the molar concentration (41 g L^{-1} / 58.44 g mol^{-1} ≈702 mol m^{-3}), R the gas constant (8.314 J mol^{-1} K^{-1}) and T the absolute temperature (298 K). This yields π_f ≈3,130 kPa [10, 19]. Along the membrane train the salinity rises to the concentrate value, and the log-mean osmotic pressure is

$$\pi_{avg} = \pi_f\,(1/R)\,\ln[1/(1-R)]$$

$$Q_f = Q_p / R, \quad Q_b = Q_f - Q_p$$

Table 1: Design parameters and computed results of the NEOM PV-RO system (all values from the calculation chain).

Parameter	Value	Unit
Permeate capacity	350,000 (14,583)	$m^3\,d^{-1}$ ($m^3\,h^{-1}$)
Recovery ratio	45	%
Feed flow	777,778 (32,407)	$m^3\,d^{-1}$ ($m^3\,h^{-1}$)
Brine flow	427,778 (17,824)	$m^3\,d^{-1}$ ($m^3\,h^{-1}$)
Feed salinity (design)	41,000	ppm
Osmotic pressure of feed (van 't Hoff)	3,130	kPa
Feed pressure	6,500 (65)	kPa (bar)
Net driving pressure	≈1.7	MPa
Design flux	15	$L\,m^{-2}\,h^{-1}$
Required membrane area	972,000	m^2
Membrane elements (8-inch, 37.2 m^2)	26,160	—
Pressure vessels (7 elements each)	3,740	—
First-pass salt rejection	>99.5	%
Second-pass salt rejection	90 (design)	%
High-pressure pump power (no ERD)	68.8	MW
Total plant power (with ERD)	41.7	MW
SEC (no ERD / with ERD)	5.1 / 2.9	$kWh\,m^{-3}$
Daily energy demand (with ERD)	1,000,560	$kWh\,d^{-1}$
PV module efficiency / performance ratio	18 / 0.80	% / —
Average daily irradiation (NEOM)	6.5	$kWh\,m^{-2}\,d^{-1}$
Required PV array area / DC capacity	1.07 / 190	km^2 / MW_{dc}
Non-sunlight hours / depth of discharge	10 / 0.80	$h\,d^{-1}$ / —
Battery capacity / units (2,500 kWh)	521 / 209	MWh / —

which gives π_{avg} ≈4.16 MPa for R = 0.45. A concentration-polarization factor of β = 1.1 is applied at the membrane surface, giving π_m ≈4.6 MPa [19].

Operating pressure and net driving pressure. The design feed pressure is 6.5 MPa (65 bar), within the typical SWRO range of 50–80 bar for high-salinity seawater [25, 14]. With an element pressure drop of 0.5 MPa, the net driving pressure is

$$NDP = P_f - \Delta P_m/2 - \pi_m \approx 1.7\ \text{MPa}$$

which is adequate for a design flux of 15 $L\,m^{-2}\,h^{-1}$.

Membrane area and system configuration. For a given design flux J, the required membrane area is

$$A_m = Q_p / J = 14{,}583 / 0.015 \approx 972{,}000\ m^2$$

Using standard 8-inch seawater elements with an active area of 37.2 m^2 (400 ft^2), the plant requires about 26,160 elements arranged in approximately 3,740 pressure vessels of seven elements each [19]. Modern high-rejection thin-film composite membranes with nominal NaCl rejection exceeding 99.5% (manufacturer data, e.g., 99.7% for 400-ft^2 seawater elements) are specified [19].

Permeate quality, boron and temperature. For a single pass with 99.5% rejection and feed of 41,000 ppm, the permeate TDS is $C_p = C_f(1-R_s)$ ≈205 ppm (design value 250 ppm), which meets the WHO aesthetic guideline for total dissolved solids (600–1,000 ppm) [26]. Boron is the stricter parameter: boron in Red Sea water is elevated, and single-pass RO rejection of boron at seawater pH is only about 75–85%, so the permeate boron concentration can approach the WHO guideline value of 2.4 $mg\,L^{-1}$ [11]. A second RO pass with a design rejection of 90% reduces both TDS to about 25 ppm and boron well below the guideline, and is therefore recommended for potable margin and premium industrial water [11, 6]. Temperature affects viscosity, permeability and rejection; a design temperature of 25°C is assumed, with the noted trade-off that higher temperatures raise flux but lower boron rejection [19, 10].

Energy balance and specific energy consumption. The plant-wide electrical demand is

$$E_T = E_{hp} + E_{aux} - E_{ERD}$$

where E_{hp} is the high-pressure pumping energy, E_{aux} the intake, pretreatment and post-treatment loads (0.40 $kWh\,m^{-3}$) and E_{ERD} the recovered hydraulic energy. The hydraulic power of the highpressure pump is $W_h = Q_f P_f = 9.00\,m^3\,s^{-1} \times 6.5\,MPa = 58.5$ MW. Without an ERD, the pump electrical demand at 85% combined efficiency is 68.8 MW and the total plant SEC is 5.1 $kWh\,m^{-3}$. With an ERD recovering 96% of the brine hydraulic energy (≈28 MW, about 48% of the pump hydraulic power), the pump demand falls to about 35.9 MW and the total plant SEC to 2.9 $kWh\,m^{-3}$, within the state-of-practice range of 2.5–4.0 $kWh\,m^{-3}$ [25, 14, 27, 20].

PV array sizing. For a daily electrical demand E_d = 1,000,560 kWh and a capacity-factor approach,

$$A_{PV} = E_d / (G\,\eta_{mod}\,PR) = 1{,}000{,}560 / (6.5 \times 0.18 \times 0.80) \approx 1.07\ km^2$$

corresponding to a DC capacity of about 190 MW_{dc} [3]. The performance ratio of 0.80 accounts for soiling, inverter, cabling, temperature and availability losses [2].

Battery storage. For tn = 10 h of non-sunlight operation at 80% depth of discharge,

$$B = E_d\, t_n / (24\, DoD) = (1{,}000{,}560 \times 10) / (24 \times 0.80) \approx 521 \text{ MWh}$$

supplied by about 209 battery modules of 2,500 kWh each [8].

Capital cost. Costs are assembled from published unit costs: the RO plant at 900–1,500 USD per (m3 d−1) of capacity including intake, pretreatment, membranes and ERDs [17, 9]; the PV field at 600–800 USD kW−1 dc ; and lithium-ion storage at 250–400 USD kWh−1 [23, 8]. This yields a capital cost of 560–890 million USD (Table 3).

Levelized cost of water. The LCOW is

$$LCOW = (CRF \times CAPEX + OPEX) / M_{ann}, \quad CRF = d(1 + d)^n / [(1 + d)^n - 1]$$

with discount rate d = 5%, project life n = 25 years, annual production Mann = 127.8 million m3 and an OPEX of 0.35–0.50 USD m−3 covering energy (at a solar LCOE of about 0.045 USD kWh−1), membrane replacement, chemicals and O&M [17, 9, 23]. Sensitivity of the LCOW to discount rate, OPEX, CAPEX, membrane replacement and solar yield is quantified in Fig. 7.

SYSTEM DESIGN

The proposed system couples a utility-scale PV plant with a two-pass SWRO facility through a power management and control unit. Figure 1 shows the schematic, and Table 2 summarises the subsystems.

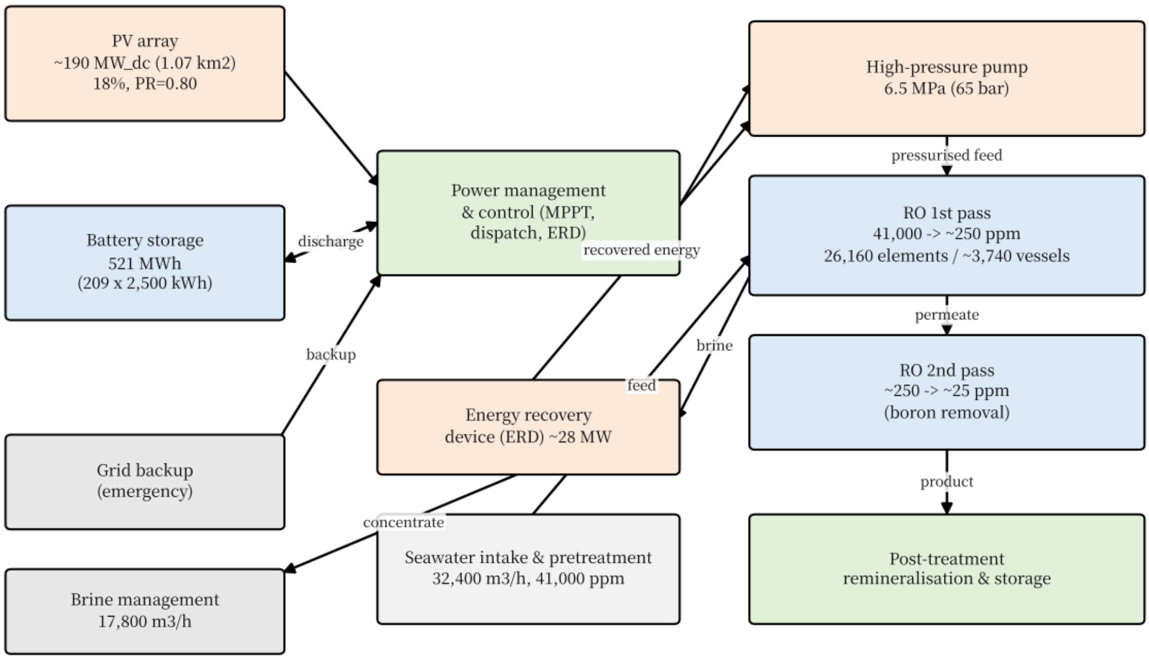

Figure 1: Schematic of the proposed PV-RO system for NEOM: PV array, battery storage, power management, two-pass RO train, ERD and brine management.

Photovoltaic array and inverter. The PV field is sized at about 1.07 km2 (190 MWdc) using modules of 18% efficiency under an average daily irradiation of 6.5 kWh m−2 d−1 and a performance ratio of 0.80 [3, 2]. Bifacial modules with single-axis tracking are recommended to raise the effective yield and reduce the land requirement [2].

RO train and membrane system. The desalination core consists of two RO passes. The first pass operates at 6.5 MPa against the feed osmotic pressure of about 3.1 MPa, with about 26,160 eight-inch elements in 3,740 pressure vessels (7 elements per vessel) organised in multiple trains, delivering a permeate of about 250 ppm [19]. The second pass reduces the first-pass permeate to about 25 ppm and provides boron margin [11, 6]. The high-pressure pump is coupled to an ERD recovering about 48% of the pump hydraulic power [20, 25].

Energy storage and control. A battery bank of 521 MWh (209 modules of 2,500 kWh) is specified at 80% depth of discharge [8]. The power management unit performs maximum-powerpoint tracking, dispatches the battery according to non-sunlight hours, and modulates the ERD to hold the SEC at its minimum [4].

Table 2: Subsystems of the proposed PV-RO system and their design sizing.

Subsystem	Function	Sizing / key parameter
PV array	solar-to-DC conversion	1.07 km^2, 190 MW_{dc}, PR 0.80
Power management	MPPT, dispatch, ERD control	central inverters
High-pressure pump	pressurise feed to 6.5 MPa	58.5 MW hydraulic; 35.9 MW with ERD
RO 1st pass	primary desalination	972,000 m^2, 26,160 elements, 3,740 vessels
RO 2nd pass	polishing / boron removal	250→25 ppm
Energy recovery device	brine energy recovery	≈28 MW recovered (48% of hydraulic)
Battery storage	night-time supply	521 MWh, 80% DoD, 209 units
Post-treatment	remineralisation, disinfection	WHO TDS / boron compliance
Brine management	concentrate handling	17,824 $m^3\,h^{-1}$, dilution, mineral recovery

Results and Discussion

Osmotic pressure and membrane sizing. Figure 2 shows the osmotic pressure of seawater feed versus salinity, with the Red Sea / Gulf of Aqaba band (36,000–41,000 ppm) shaded and the NEOM design point marked. For the 41,000 ppm design feed, πf ≈3,130 kPa; with the log-mean concentration factor of 1.33 and a polarization factor of 1.1, the membrane-surface osmotic pressure is about 4.6 MPa, leaving a net driving pressure of about 1.7 MPa at a 6.5 MPa feed pressure [19, 10]. Feed salinity is one of the dominant site-specific parameters affecting SWRO design on the Red Sea coast, alongside temperature and recovery [10, 25]; the analysis does not claim exclusivity, as rejection, pretreatment, pump efficiency and feed composition are equally important in the overall design.

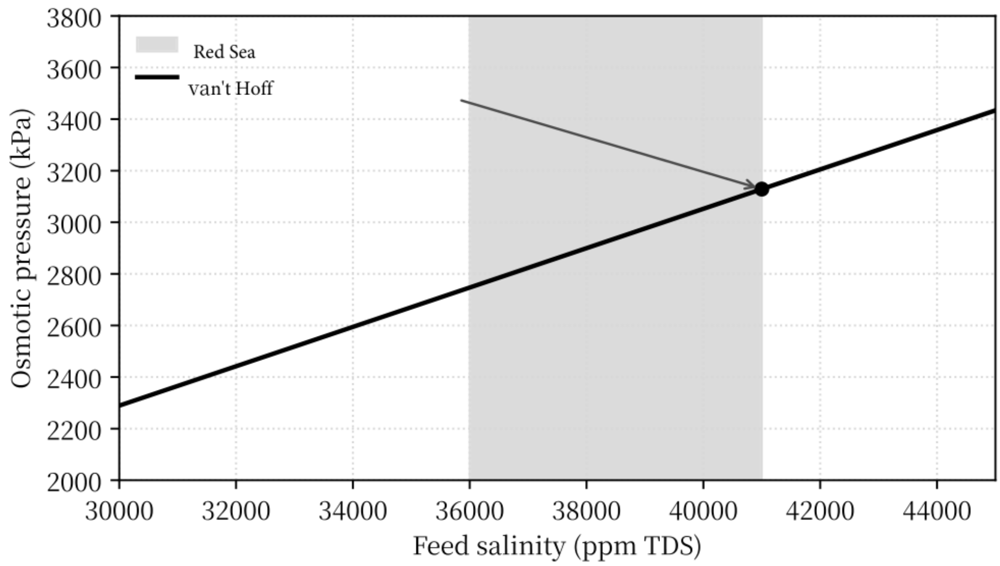

Figure 2: Osmotic pressure of seawater feed versus salinity (van 't Hoff, i = 1.8, T = 298 K). Shaded band: Red Sea - Gulf of Aqaba range; marker: NEOM design point (41,000 ppm, 3,130 kPa).

Water mass balance and recovery. Because the feed flow is fixed by the recovery ratio, the design closes the mass balance: at 45% recovery, 350,000 m3 d−1 of permeate requires 777,778 m3 d−1 of feed and produces 427,778 m3 d−1 of brine. The recovery ratio is the second most important site variable after feed salinity, because it sets the feed flow, the membrane area and the brine volume [19, 25].

Membrane area and system configuration. Figure 3 summarises the salinity reduction across the two-pass configuration. At the 15 L m−2 h−1 design flux the membrane area is about 972,000 m2 (26,160 elements, 3,740 vessels), consistent with the scale of comparable large SWRO plants [19]. The single-pass permeate of about 250 ppm meets the WHO aesthetic TDS guideline of 600–1,000 ppm; the second pass, yielding about 25 ppm, is recommended principally for boron margin and premium industrial water rather than for TDS compliance alone [26, 11].

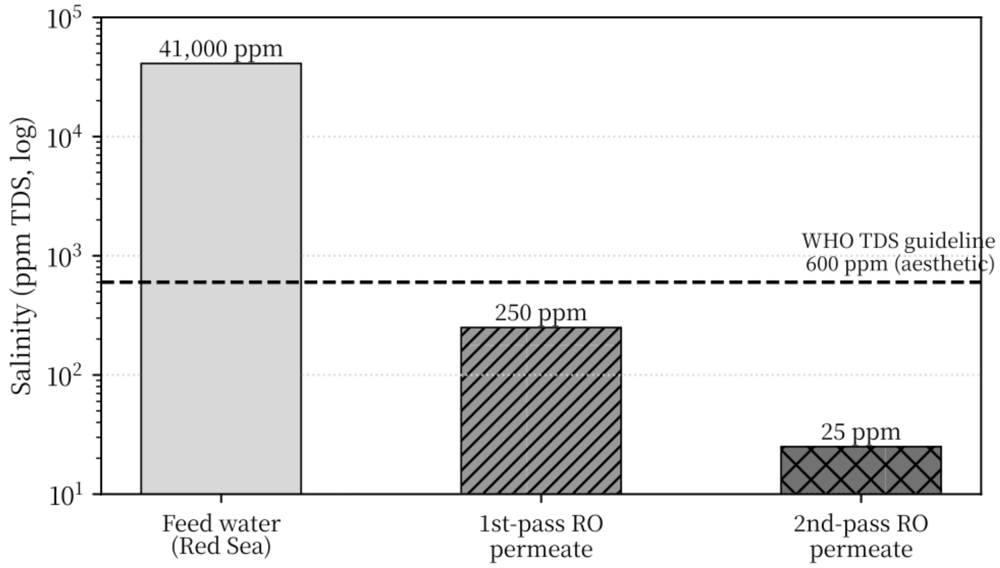

Figure 3: Salinity reduction across the two-pass RO configuration compared with the WHO aesthetic TDS guideline (logarithmic scale).

Boron. Gulf of Aqaba seawater has elevated boron relative to open ocean. At seawater pH, single-pass boron rejection is only 75–85%, so permeate boron may lie close to the WHO guideline of 2.4 mg L−1; the second pass, operating at higher pH or with boron-selective membranes, reduces boron to <0.3 mg L−1 [11]. Boron is therefore the governing water-quality parameter for the second-pass decision.

Energy consumption and energy recovery. Figure 4 compares the SEC of this study with literature benchmarks. Without energy recovery the SEC is 5.1 kWh m−3; with the ERD it falls to 2.9 kWh m−3, within the state-of-practice 2.5–4.0 kWh m−3 range and close to the lowest values reported for full-scale SWRO [25, 14, 27]. The ERD recovers about 28 MW (48% of the highpressure hydraulic power), cutting the pump demand from 68.8 to 35.9 MW. Because the SEC directly scales the PV field and the storage, energy recovery is the most cost-effective single investment in the design [20, 25].

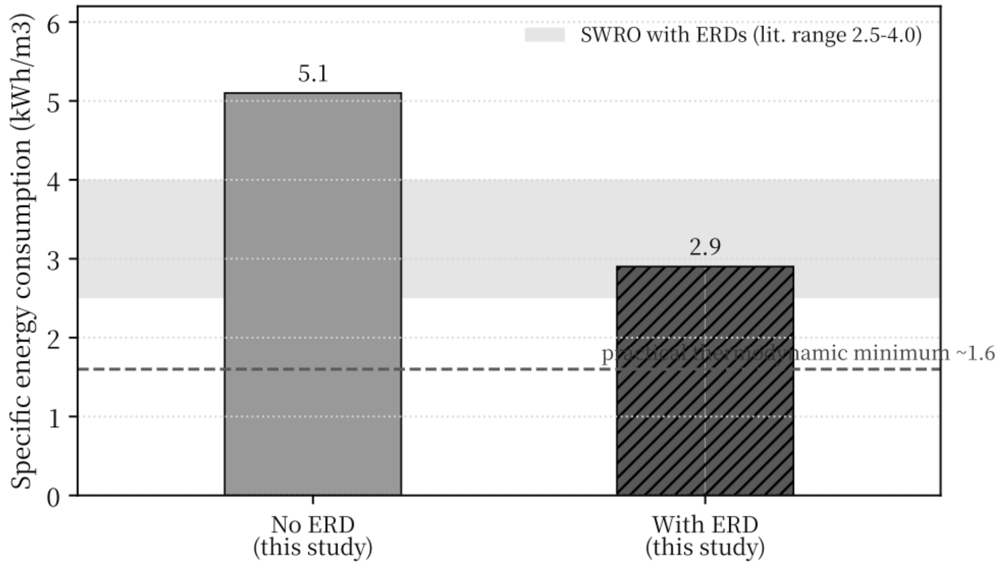

Figure 4: Specific energy consumption: computed with and without ERD, the literature range for SWRO with ERDs (shaded) and the practical thermodynamic minimum.

Photovoltaic array. Figure 5 shows the sensitivity of the required PV area to the daily irradiation. At the NEOM baseline of 6.5 kWh m−2 d−1 and a performance ratio of 0.80, the plant requires about 1.07 km2 (190 MWdc) [3]. The inverse relationship means that improvements in effective irradiation—bifacial modules, single-axis tracking, scheduled cleaning to reduce dust—translate directly into land savings: at 7.5 kWh m−2 d−1 the area falls to about 0.93 km2 [2]. Energy storage. Figure 6 presents the battery capacity versus non-sunlight hours. For 10 h at 80% depth of discharge, the requirement is 521 MWh (209 modules of 2,500 kWh). At lithiumion prices of 250–400 USD kWh−1, storage represents 130–208 million USD, a significant but

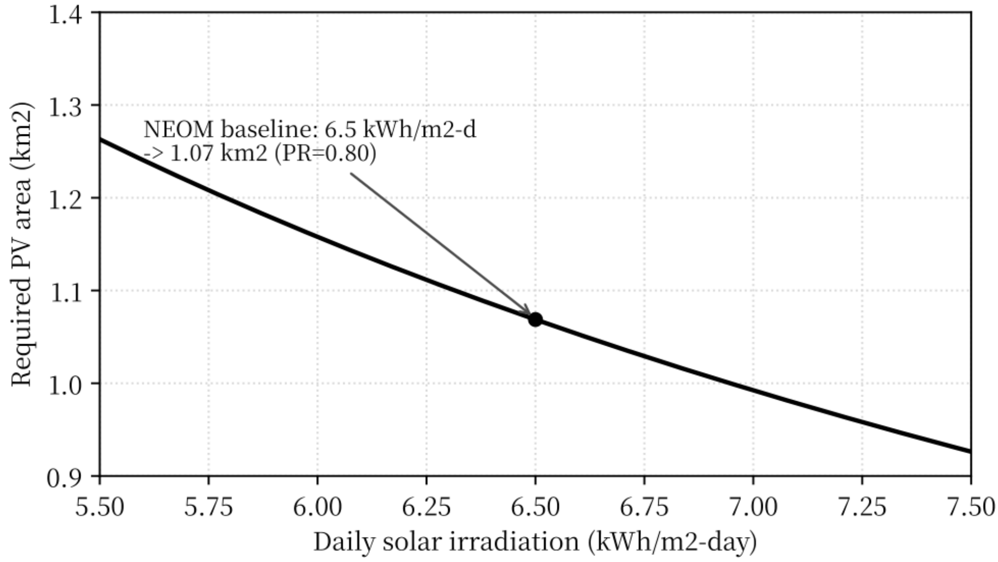

Figure 5: Required PV array area versus daily irradiation (Ed = 1,000,560 kWh d^{-1}, η = 18%, PR = 0.80).

no longer dominant share of the total capital cost [8, 23]. Hybrid long-life flow batteries and demand-side management that reduces effective non-sunlight demand remain attractive options [15].

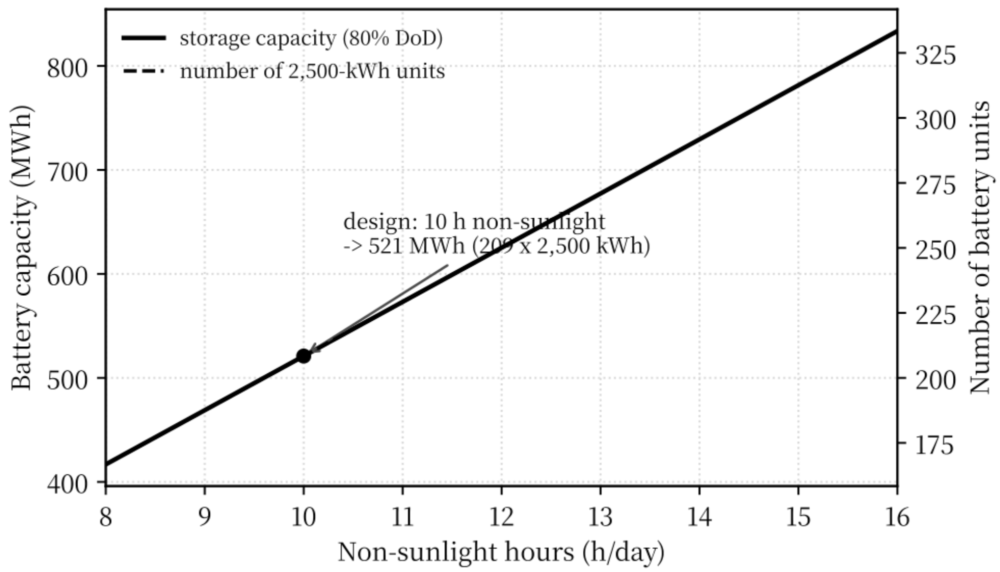

Figure 6: Battery capacity (solid) and number of 2,500-kWh modules (dashed) versus non-sunlight hours at 80% depth of discharge.

Capital cost. Table 3 summarises the capital cost breakdown using plant-capacity-based and capacity-based unit costs. The total is estimated at 560–890 million USD (central value 724 million), of which the RO plant (315–525 million) is the largest component, followed by storage (130–208 million) and the PV field (115–154 million). These figures are consistent with published SWRO capital costs of about 900–1,500 USD per (m3 d−1) [17, 9].

Table 3: Capital cost breakdown of the integrated PV-RO system (low-high estimates, MUSD).

Component	Basis	Low	High
RO plant (350,000 $m^3\,d^{-1}$, 900–1500 USD $(m^3\,d^{-1})^{-1}$)	capacity	315	525
PV field (190 MW_{dc}, 600–800 USD kW_{dc}^{-1})	capacity	115	154
Battery storage (521 MWh, 250–400 USD kWh^{-1})	energy	130	208
Total		561	887

Levelized cost of water and sensitivity. The central LCOW is 0.8 USD m−3, with a range of 0.6–1.1 USD m−3 (discount rate 3–7%, OPEX 0.35–0.50 USD m−3). This is competitive with recent estimates for renewable-powered RO (1.3–1.8 USD m−3) [23] and within range of conventional SWRO (0.4–1.1 USD m−3) [9, 17], reflecting the low solar LCOE and large scale. Figure 7 and Table 4 quantify the sensitivity. The LCOW is most sensitive to OPEX and to the discount rate, followed by CAPEX; membrane replacement and solar yield have smaller effects. Energy recovery remains the highest-leverage technical improvement because it reduces both SEC and OPEX [25, 20].

Brine management and environmental impact. The plant produces 17,824 m3 h−1 of concentrate at about 75,000 ppm, which must be managed to avoid harm to the sensitive coral ecosystems of the Gulf of Aqaba [13, 16]. Dilution through staged discharge, subsurface disposal and mineral recovery are the principal mitigation options [2].

System-level discussion. The three subsystems interact strongly: the SEC determines the PV field, the PV field and the non-sunlight hours determine the storage, and the cost of both

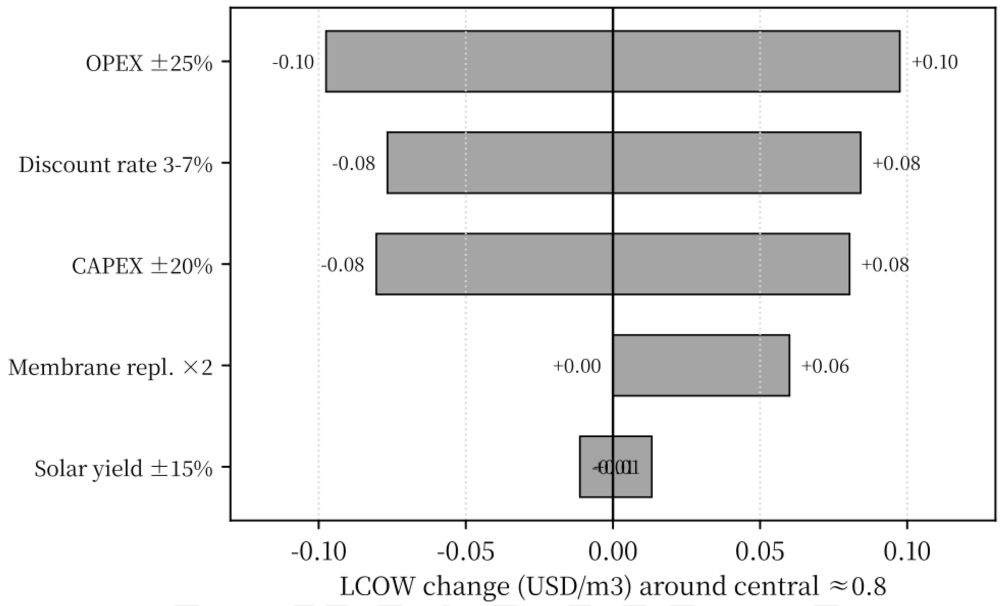

Figure 7: Tornado diagram of LCOW sensitivity to the main economic and technical parameters.

Table 4: LCOW sensitivity: change in USD m^{-3} relative to the central value of 0.8.

Parameter	Low	High
OPEX ±25%	−0.10	+0.10
Discount rate 3–7%	−0.08	+0.08
CAPEX ±20%	−0.08	+0.08
Membrane replacement cost ×2	0	+0.06
Solar yield ±15%	−0.01	+0.01

enters the LCOW. Reducing SEC through ERDs is the highest-leverage improvement, followed by irradiation enhancement and storage-cost reductions [20, 25]. Future work should address artificial-intelligence-based energy optimisation, zero-liquid-discharge brine management, and hybrid PV–wind configurations that shrink the storage requirement [5, 2].

Feasibility Study

Technical feasibility. The technical feasibility rests on four pillars: (i) the solar resource at NEOM is among the highest in the world [3]; (ii) SWRO is a mature technology with a large installed base and continuous efficiency gains [10, 19]; (iii) ERDs reduce the SEC to 2.9 kWh m−3 [25, 14]; and (iv) the two-pass configuration provides TDS and boron compliance [11, 26]. None of the computed components (26,160 elements, 190 MWdc PV, 521 MWh storage) exceeds current commercial capability [8, 5].

Economic feasibility. Table 5 summarises the economic indicators. The CAPEX is 560–890 million USD, the LCOW 0.6–1.1 USD m−3 (central 0.8), and the operating-cost saving relative to fossil-fuelled desalination is 40–60% over 25 years [4, 23].

Table 5: Economic feasibility indicators of the NEOM PV-RO system.

Indicator	Value	Unit
Capital cost (CAPEX)	560–890	MUSD
Annual water production	127.8	$Mm^3\ yr^{-1}$
SEC (with ERD)	2.9	$kWh\ m^{-3}$
LCOW (this study)	0.6–1.1 (central 0.8)	$USD\ m^{-3}$
Conventional SWRO LCOW benchmark	0.4–1.1	$USD\ m^{-3}$
Renewable RO LCOW benchmark	1.3–1.8	$USD\ m^{-3}$
Operating-cost saving vs. fossil (25 yr)	40–60	%

Environmental feasibility. The principal environmental concern is brine discharge into the sensitive Gulf of Aqaba ecosystem [13, 16]; mitigation includes staged dilution, subsurface disposal and mineral recovery [2]. Compared with fossil-fuelled desalination, the PV-powered plant has the potential to reduce operational carbon emissions, supporting Vision 2030's sustainability targets [12, 24].

RISK ASSESSMENT

A structured risk register is presented in Table 6; likelihood and impact are rated low (L), medium (M) or high (H). The two highest-impact risks are membrane fouling and battery degradation. Fouling is mitigated by rigorous pretreatment and monitoring [1, 18], while battery cost is addressed by hybrid storage and demand-side management [8, 15]. The overall risk profile is manageable, and none of the identified risks constitutes a feasibility barrier.

Table 6: Risk register for the NEOM PV-RO desalination system.

Risk	L	I	Mitigation
Membrane fouling and scaling	H	H	Pretreatment, antiscalants, periodic cleaning, autopsy monitoring [1, 18]
PV output variability and cloud cover	M	M	Battery storage, hybrid PV–wind, grid backup [3, 8]
Battery degradation and replacement cost	M	H	Long-life flow batteries, demand-side management, PV oversizing [8, 15]
Brine discharge environmental impact	M	H	Dilution, staged discharge, subsurface disposal, mineral recovery [13, 16]
Dust accumulation on PV modules	H	M	Scheduled cleaning, bifacial modules, tracking [2]
Capital cost overrun and financing	M	H	Phased construction, public–private partnerships, Vision 2030 incentives [9, 17]
Feed salinity fluctuation	L	M	Flexible intake design, permeate blending [13]
Cybersecurity of control system	L	M	Network security protocols, redundant control [2]

CONCLUSIONS

This paper assessed the technical and economic feasibility of photovoltaic-powered reverse osmosis desalination for NEOM using a single consistent design case. The main conclusions are:

- At 45% recovery, a 350,000 m3 d−1 plant requires 777,778 m3 d−1 of feed and produces 427,778 m3 d−1 of brine; the feed flow must not be conflated with the product flow.
- For the 41,000 ppm Gulf of Aqaba feed, the osmotic pressure is about 3.1 MPa and the fluxbased membrane area about 972,000 m2 (26,160 elements, 3,740 vessels) at 15 L m−2 h−1.
- The SEC is 5.1 kWh m−3 without energy recovery and 2.9 kWh m−3 with ERDs; energy recovery cuts the high-pressure pump demand from 68.8 to 35.9 MW.
- A PV array of about 190 MWdc (1.07 km2, PR 0.80) and battery storage of about 521 MWh (209 units) are required for continuous operation.
- Single-pass permeate of about 250 ppm meets the WHO aesthetic TDS guideline; a second pass is recommended for boron margin and premium water.
- The integrated system is estimated to cost 560–890 million USD, with the LCOW at 0.6–1.1 USD m−3 (central 0.8); OPEX and the discount rate are the dominant cost sensitivities.

PV-RO desalination is therefore technically feasible and potentially competitive for NEOM. Compared with fossil-fuelled desalination, it has the potential to reduce operational carbon emissions, although a full life-cycle assessment, including battery manufacturing impacts and brine ecology, remains necessary before claiming environmental superiority. The economics will be determined by energy recovery, storage technology and financing structure, making the project an ideal flagship for Saudi Vision 2030's water–energy strategy [24, 12].

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