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A Techno-Economic Study of Reverse Osmosis Desalination for Extreme Salinity Under Seasonal Temperature Variations: A Red Sea Water Case Study

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Abstract

Producing both potable water and high-pure Boiler Feed Water (BFW) from the Red Sea Water, an environment characterized by extreme salinity (often 40,000–42,000+ ppm) at temperatures up to 35 °C presents severe thermodynamic and economic challenges. This study conducts a comprehensive techno-economic optimization of single and two-pass Reverse Osmosis (RO) systems tailored for both potable water and high-pressure industrial boiler feedwater, respectively, utilizing localized Egyptian economic parameters, including an industrial electricity tariff of $0.033/kWh. Through IMSDesign simulations across a 15–35 °C thermal gradient, the performance of five commercial membranes was systematically evaluated for a 100 m³/h capacity plant. The primary pass assessment revealed that the standard low-differential membranes (SWC4-LD) are optimal for single-pass potable water production (achieving a Total Water Cost of $0.680/m³), while the SWC5-LD provides the most strategic energetic baseline for a two-pass boiler feedwater (BFW) system. For the secondary polishing pass, uniform membrane configurations forced a strict trade-off between specific energy consumption (SEC) and permeate quality. Consequently, a novel hybrid architecture deploying high-rejection CPA6-MAX elements in stage 1 and ultra-low pressure ESPA2-LD elements in stage 2 was introduced. This hybridization successfully achieved natural inter-stage flux balancing. The finalized deterministic cost model confirmed that the integrated SWC5-LD primary pass coupled with the hybrid secondary pass represents the ultimate techno-economic optimum. This configuration delivered highly secure BFW quality (5.49 ppm TDS) with a minimized SEC of 3.53 kWh/m³, achieving the lowest Total Water Cost of $0.961/m³ for the integrated plant.

Keywords: Desalination, Reverse osmosis, Red Sea Water, Techno-economic analysis, IMSDesign software, Seasonal temperature variations, Multi-Stage/Hybrid configurations, Boiler feedwater

Introduction

Freshwater scarcity has emerged as a paramount global crisis, particularly in arid and semi-arid zones. Despite water covering the majority of the Earth's surface, accessible freshwater constitutes less than 1% of this total, necessitating urgent alternative solutions[1]**.** Egypt exemplifies this critical situation; the nation relies on the Nile River for 97% of its renewable water resources, making it highly vulnerable to upstream hydrological changes and climate variability. Currently, the annual water share currently stands at 560 m^3 significantly below the water poverty threshold. Driven by rapid population growth, this share is projected to plummet below the absolute scarcity limit of 500 m^3 by 2030[2]**.**

Among the various commercial desalination technologies available, Reverse Osmosis (RO) has emerged as the globally dominant process, accounting for over 68% of the installed capacity worldwide and representing the primary technological choice for Egypt's newly established mega-plants [3]. To sustain this technological trajectory, the Egyptian government is currently executing an ambitious master plan to expand the nation's cumulative desalination capacity, targeted to reach approximately 6.4 million m^3/day by 2050 Consequently, seawater desalination is no longer viewed merely as an alternative operational option, but rather as an imperative strategic measure to safeguard and sustain long-term urban and industrial development, particularly along the extensive coastlines of the Red Sea and the Mediterranean [3].

Historically, the early commercialization of Seawater Reverse Osmosis (SWRO) in the 1960s and 1970s faced a significant economic barrier; excessive energy consumption. Early asymmetric cellulose acetate membranes required operating pressures up to 105 bars, resulting in a specific energy consumption (SEC) exceeding 10 kWh/m^3[4]. The subsequent development of thin-film composite (TFC) polyamide membranes in the late 1970s and 1980s significantly reduced the hydraulic resistance, lowering the required pressures and pushing the SEC down to approximately 6.6 kWh/m[6,7]. However, the true breakthrough in the economic

viability of SWRO was driven by the integration and continuous evolution of Energy Recovery Devices (ERDs) [7].

In feed seawater via a positive displacement mechanism, achieving remarkable efficiencies exceeding 95%. This technological evolution has drastically minimized the SEC of modern SWRO plants to approximately 2.5–3.5 kWh/m³, making RO highly competitive against conventional thermal desalination processes[10,11].

Despite its widespread adoption and economic feasibility, deploying Seawater Reverse Osmosis (SWRO) in the Red Sea region introduces unique thermodynamic and operational challenges. The Red Sea is classified among the most extreme marine environments globally, characterized by exceptionally high salinity levels often averaging 44,000 mg/L, its salinity is higher than standard ocean water (35,000 ppm), and natural osmotic pressure is significantly elevated; this requires high-pressure pumps to overcome the osmotic barrier. Pumping these high salinities typically requires between 3.5 to 5.5 kWh/m³ of water produced, depending on the plant's configuration and the efficiency of its pumps in addition to severe seasonal thermal fluctuations where surface water temperatures can peak at 35 °C[10,11,12]. These aggressive boundary conditions profoundly impact membrane performance; while elevated feed temperatures favorably reduce water viscosity and the hydraulic pressure required by high-pressure pumps, they simultaneously increase the kinetic energy of dissolved ions. This thermodynamic shift significantly accelerates salt passage through the polymeric membrane matrix, severely compromising the permeate quality and threatening compliance with stringent industrial and potable water standard [11].

High-pressure boilers in power plants require high pure makeup water with near-zero salinity to prevent severe system degradation. According to standard specifications, the feedwater must maintain an electrical conductivity of 0.1 S/cm, with sodium, chloride, and sulfate concentrations strictly limited to a range of 2 to 5 parts per billion (ppb). Furthermore, silica and total organic carbon (TOC) must not exceed 10 ppb and 100 ppb, respectively[13]. These strict limits are crucial because highly volatile silica can vaporize and precipitate on low-pressure turbine blades, causing mechanical damage. Simultaneously, organic impurities decompose under high temperatures into carbon dioxide (CO2) and organic acids, leading to severe equipment corrosion[13]. To

reliably achieve these stringent purity standards while optimizing energy consumption, the implementation of advanced multi-stage or two-pass reverse osmosis (RO) systems is essential[8].

Extensive research has been conducted to optimize the (SEC) and operational costs of (SWRO) systems. Pan et al. presented a critical review on the technical-economic assessment of RO, emphasizing the interconnectivity between water recovery, energy-water efficiency, and the fundamental trade-off between kinetics and energetics[4]. Similarly, Zouhri et al. conducted a comprehensive techno-economic study utilizing response surface methodology to evaluate the performance of different RO membranes, demonstrating that optimizing the transmembrane pressure and conversion rate is critical for minimizing the specific energy consumed per cubic meter[14]. Furthermore, Karagiannis and Soldatos assessed the global desalination cost literature, confirming that membrane replacement and energy consumption remain the primary drivers of the total water cost[15].

To achieve stringent water quality targets such as those required for high-pressure boiler feedwater while maintaining economic viability, recent literature has shifted towards hybrid and multi-stage RO configurations. Harby et al. provided a comprehensive review of reverse osmosis hybridization with various desalination techniques, concluding that hybrid RO systems are superior to standalone RO in enhancing water recovery, reducing specific energy consumption, and mitigating the environmental impacts of concentrated brine [16].

In a foundational optimization study, Kim et al. developed mathematical models for the structural representation of multi-stage RO networks, proving that a systematic engineering approach can successfully minimize the total capital and operational costs of complex RO plants. Operating such optimized desalination configurations in aggressive environments like the Red Sea, however, requires specific design considerations[8]. Elsaie et al. comprehensively reviewed water desalination technologies in Egypt, noting that while RO is the predominant choice along the Red Sea coast, the region's hypersaline conditions pose significant operational challenges. These aggressive boundary conditions necessitate robust techno-economic evaluations and tailored membrane configurations, such as hybrid multi-pass systems, to overcome the severe osmotic pressure penalties and prevent rapid flux decline[17].

A critical review of the existing literature reveals a notable research gap concerning the techno-economic optimization of SWRO systems operating under these extreme, localized conditions. While the evolution of membranes and ERDs is well-documented, many predictive models focus exclusively on standard seawater conditions (~35,000 mg/L) to achieve municipal drinking water limits[14]. There is a pronounced scarcity of research systematically evaluating the operational trade-offs between energetic efficiency (using modern ERDs) and permeate quality when utilizing different commercial membrane architectures such as standard low-differential versus high-surface-area modules under the severe thermal stress of the Red Sea. Furthermore, current literature lacks comprehensive methodologies detailing the sequential upgrading of these single-pass SWRO configurations to produce ultrapure water (UPW) suitable for high-pressure industrial boiler feedwater, an application that strictly demands near-zero conductivity and minimal silica content[13].

To address this gap, the present study formulates a rigorous predictive and techno-economic evaluation of a medium-scale RO plant situated on the Egyptian Red Sea coast. Utilizing advanced simulation modeling across a seasonal temperature gradient (15 °C to 35 °C), this research investigates the performance of multiple commercial membrane configurations coupled with isobaric ERDs. The primary objective is to identify the optimal design array that minimizes the Total Water Cost (TWC) by incorporating localized economic parameters specifically the Egyptian industrial electricity tariffs while ensuring robust, continuous compliance with both drinking water guidelines and the stringent purity requisites of boiler feedwater.

Methodology:

Pretreatment is a critical step in ensuring successful RO desalination by reducing membrane fouling and scaling. In this study, all cases were simulated using feedwater pretreated with a multi-media filter (MMF) and a cartridge filter (CF) which made reduction to suspended solid around 50%. The feedwater conditions applied in this study were based on a real seawater sample collected from the intake point of a refinery facility located on the Red Sea coast in Egypt. This sample represents the actual raw water quality encountered in industry, as presented in Table 1, which was maintained consistently across all simulated cases to ensure the validity and comparability of the performance evaluation. Also, the framework of the present study is addressed in Table 2.

Table 1: Pre-treated seawater feed analysis.

Parameter	Unit	Pre-treated seawater feed
pH	-----	7.3-8.5
Conductivity,	µS/cm	56000-66000
Chlorides,	ppm	20700-24400
Sulphate,	ppm	6000-7000
Silt density index (SDI)	------	<5
Total hardness	as $CaCO_3$	7000-7500
Calcium, hardness	as $CaCO_3$	65-75
TSS	ppm	5
TDS	ppm	34000-40000
Total Alkalinity	ppm	100-220
Free chloride	ppm	Nil-0.3
Calcium	ppm	24-30
Mg	ppm	1600-1850
Total silica	ppm	Nil-0.40
Total iron	ppm	Nil-0.07

Table 2: Summary of methodology adopted in the present study

Objective	Method / Analysis	Basis / Input Data	Main Output
Evaluate thermal stress on single-pass SWRO elements	Parametric simulation across a seasonal temperature gradient (15 °C to 35 °C with 5 °C increments) via Hydranautics IMSDesign.	Pre-treated Red Sea water sample (TDS ~44,000 mg/L), fixed plant capacity of 100 m^3/h, and 45% recovery rate.	Temperature-dependent hydraulic profiles: Feed Pressure (bar), Specific Energy Consumption - SEC (kWh/m^3), and Permeate TDS (mg/L).
Select the optimal baseline membrane for potable water	Comparative technical assessment of five commercial elements (SWC4-LD, SWC4-MAX, SWC5-LD, SWC5-MAX, SWC6-MAX).	Detailed membrane specifications (Active area, feed spacer geometry, and test flux) operate under localized Red Sea limits.	Identification of the thermodynamic limits of ultra-permeable modules and the validation of robust high-rejection elements.
Upgrade the system for industrial Boiler Feed Water (BFW)	Dual-pass system modeling by adding a secondary Brackish Water RO (BWRO) stage to process primary permeate.	Target final product quality of 90 m^3/h capacity, demanding near-zero conductivity and ultra-low silica.	Establish a stable primary energetic baseline using the SWC5 family to shift the purification burden to Pass 2.

Resolve the energy-quality trade-off in the secondary pass	Simulation and structural analysis of uniform arrays versus a customized "Membrane Hybridization" strategy.	Uniform ESPA2-LD array, uniform CPA6-MAX array, and a Hybrid configuration (CPA6-MAX in Stage 1 / ESPA2-LD in Stage 2).	Quantification of hydraulic bottlenecks; validation of natural inter-stage flux balancing without auxiliary booster pumps.
Determine the ultimate localized economic plant configuration	Deterministic financial calculation incorporating annualized capital and operational costs (Equations 7 to 10).	Localized industrial electricity tariff ($0.033/kWh), fixed CAPEX base ($3.6M), 4% maintenance rate, and bulk membrane commercial prices.	Detailed component breakdown of the Total Water Cost - TWC ($/m³), identifying the absolute minimum economic design array.

Model Verification

To verify the reliability of the IMSDesign simulation model, a benchmarking test was conducted by reproducing the results of a published study by Robles-Lizárraga et al.[18]. The reference study utilized a single-pass configuration with SWC6-MAX membranes to treat seawater (33,979 ppm TDS), reporting a Specific Energy Consumption (SEC) of 1.91 kWh/m³ and a permeate TDS of 380 ppm.

By applying identical input parameters and calibrating the high-pressure pump efficiency to 78% to reflect the reference study's conservative operational baseline our simulation yielded an exact SEC match of 1.91 kWh/m³ and a permeate TDS of 355 ppm. This discrepancy in permeate quality is marginal (<7%) and acceptable for simulation purposes. This close agreement confirms the accuracy of the software configuration and validates the modeling approach employed for the Red Sea scenarios in this study.

1. Plant Capacity and single -Pass System Design

Based on the chemical characterization of the feed water, the fundamental design parameters for the seawater reverse osmosis (SWRO) plant were established to meet the operational demands of a medium-scale facility. The permeate production capacity was fixed at 100 m^3/h across all simulated scenarios, representing a typical scale that reflects the operational dynamics of industrial desalination plants. To ensure performance stability and mitigate the operational risks under the aggressive boundary conditions of the Red Sea, the system recovery rate

was conservatively fixed at 45% This design threshold is strictly governed by the thermodynamic and hydraulic limits of high-salinity desalination [19]. Given the elevated feed TDS (~44,000 mg/L), operating beyond a 45% recovery would exponentially increase the brine concentration towards the trailing elements of the pressure vessel, resulting in an excessive osmotic pressure penalty[9]. Consequently, this would demand hydraulic feed pressures that challenge the maximum mechanical operating limit of standard commercial vessels and elements (82.7 bar or 1200 psig) [20].

Furthermore, maintaining a 45% recovery rate serves as a critical preventive measure against severe concentration polarization and minimizes the localized saturation index of divalent scaling ions such as Calcium, Magnesium, and Sulfates thereby protecting the thin-film composite polyamide layer from irreversible chemical scaling and rapid flux decline [4,21].

The engineering configuration of the system was standardized to a single-pass design as schematically illustrated in Figure 1, comprising pressure vessels loaded with 6 membrane elements each (6 elements/vessel). This unified structural framework ensures a fair and accurate comparative analysis of the thermodynamic performance across the different membrane models.

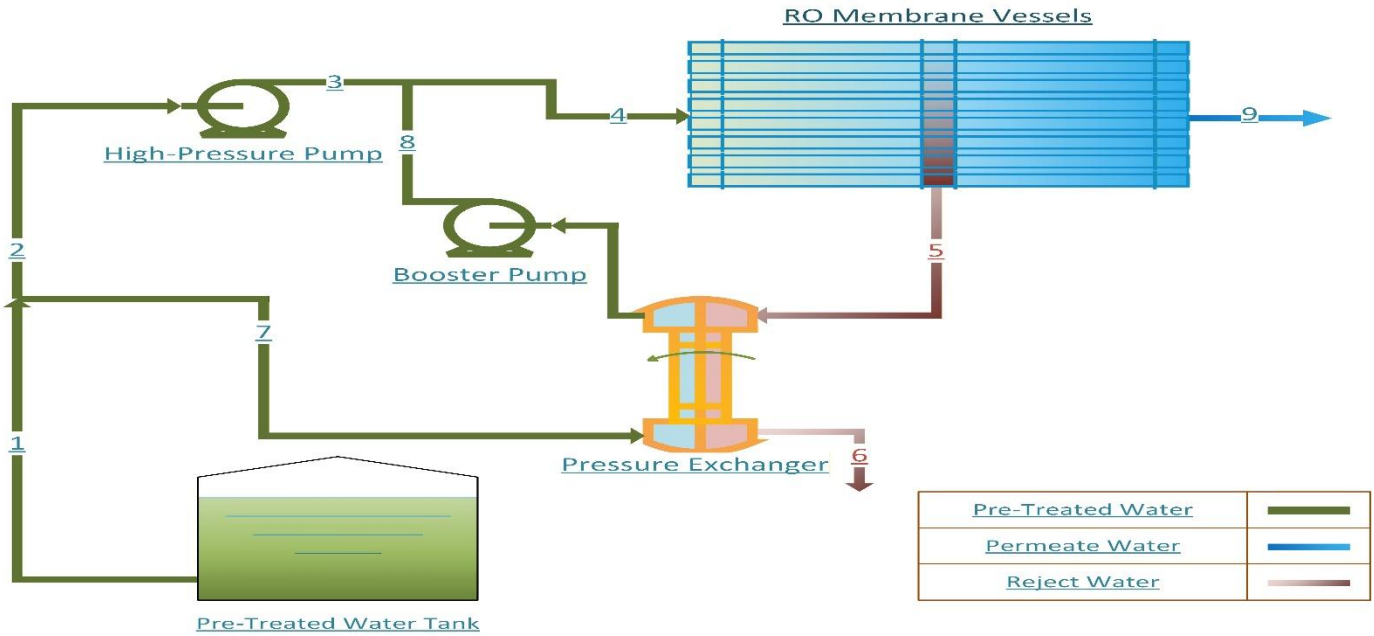


Figure 1: Schematic flow diagram of the simulated single-pass seawater reverse osmosis (SWRO) system, including the high-pressure pump (HPP) and energy recovery device (ERD).

1.1.Simulation Setup and Membrane Selection

To conduct technical analysis and parametric evaluation with high engineering precision, the advanced simulation software IMSDesign, developed by Nitto Hydranautics, was utilized. This software serves as an industry-standard tool for modeling RO membrane performance, accurately predicting specific energy consumption (SEC) and salt passage under varying operational conditions.

The methodological focus was directed toward evaluating the Seawater Composite (SWC) membrane family, with a particular emphasis on investigating the impact of the active surface area and feed spacer design on the overall plant economics. Accordingly, five distinct membrane models were selected, encompassing both the standard Low-Differential (LD) configurations and the Maximum Active Area (MAX) variants. The comprehensive technical parameters for these selected membranes are summarized in Table 3.

1. **SWC4-LD:** Represents the conventional option featuring ultra-high salt rejection capabilities.
2. **SWC5-LD:** Represents a balanced option that optimally combines high water permeability with excellent salt rejection.
3. **SWC4-MAX:** Offers a larger active surface area (440 ft^2) while maintaining superior rejection characteristics inherent to the SWC4 family.
4. **SWC5-MAX:** The maximum surface area variant of the SWC5 series, designed to maximize productivity and substantially reduce energy consumption.
5. **SWC6-MAX:** Engineered specifically as an ultra-high permeability membrane designed for operation at exceptionally low feeding pressures.

Table 3: Comprehensive technical specifications and operational limits of the selected Hydranautics SWRO membranes

Membrane Model	Active Area (ft^2)	Feed Spacer (mil)	Nominal Salt Rejection (%)	Nominal Permeate Flow (m^3/d)	Standard Test Flux ($m^3/m^2/d$)	Max. Operating Pressure (bar)	Max. Element ΔP (bar)	Max. Temp. (°C)
SWC4-LD	400	34	99.80	24.6	0.66	82.7	1.0	45
SWC5-LD	400	34	99.80	34.1	0.92	82.7	1.0	45
SWC4-MAX	440	28	99.80	27.3	0.67	82.7	1.0	45

SWC5-MAX	440	28	99.80	37.5	0.92	82.7	1.0	45
SWC6-MAX	440	28	99.80	50.0	1.22	82.7	1.0	45

1.2. Parametric Evaluation and Temperature Effect

To comprehensively assess the thermodynamic behavior and operational flexibility of the selected SWC membranes, a systematic parametric evaluation was executed using the IMSDesign simulator. The core of this evaluation involved simulating the plant's performance across a temperature spectrum representative of the severe seasonal variations typical of the Red Sea region.

The feed water temperature was systematically varied from 15 °C to 35 °C at 5 °C increments (i.e., 15, 20, 25, 30, and 35 °C). During these sequential iterations, the primary structural and hydraulic design parameters specifically the permeate capacity (100 m^3/h) and the system recovery rate (45%) were held strictly constant. This controlled approach was critical to isolate the thermal effects on the membrane's physical properties without introducing compounding variables.

For each temperature setpoint and membrane configuration, three primary Key Performance Indicators (KPIs) were meticulously monitored and recorded:

1. Feed Pressure (bar): To evaluate the hydraulic energy required to overcome the osmotic pressure and maintain the target permeate flux.
2. Specific Energy Consumption - SEC (kWh/m^3): To quantify the direct impact of temperature fluctuations on the operational energy footprint.
3. Permeate Quality (ppm TDS): To assess the integrity of salt rejection capabilities under varying thermal stresses.

This parametric methodology enables a definitive quantification of the inherent operational trade-offs in SWRO systems: as feed temperature increases, water viscosity decreases yielding lower feed pressures and improved energy efficiency (lower SEC). Conversely, the increased kinetic energy at higher temperatures enhances salt diffusion through the polymeric matrix, thereby potentially compromising the permeate water quality.

2. Second Pass Design and Hybrid Configuration for Boiler Feed Water

The selection of the SWC5 membrane family for the first pass was driven by a strategic "fit-for-purpose" engineering approach. While previous simulations indicated that these highly permeable membranes experienced permeate quality deterioration under high Red Sea thermal stresses making them marginal for direct drinking water production, they consistently achieved the lowest Specific Energy Consumption (SEC). Because producing high-pressure Boiler Feed Water (BFW) inherently dictates the necessity of a second polishing pass to remove silica and trace ions (regardless of the first-pass permeate quality), the optimal strategy is to leverage the SWC5 family to minimize the massive hydraulic energy penalty of the first pass, effectively shifting the final purification burden to the second pass.

To upgrade this first-pass permeate to meet the stringent specifications for industrial BFW, a second-pass Brackish Water Reverse Osmosis (BWRO) system was designed and simulated. The integrated architecture of the proposed desalination plant, including the pre-treatment stages, the primary SWRO pass with energy recovery, and the specialized two-stage second pass, is schematically illustrated in Figure 2.

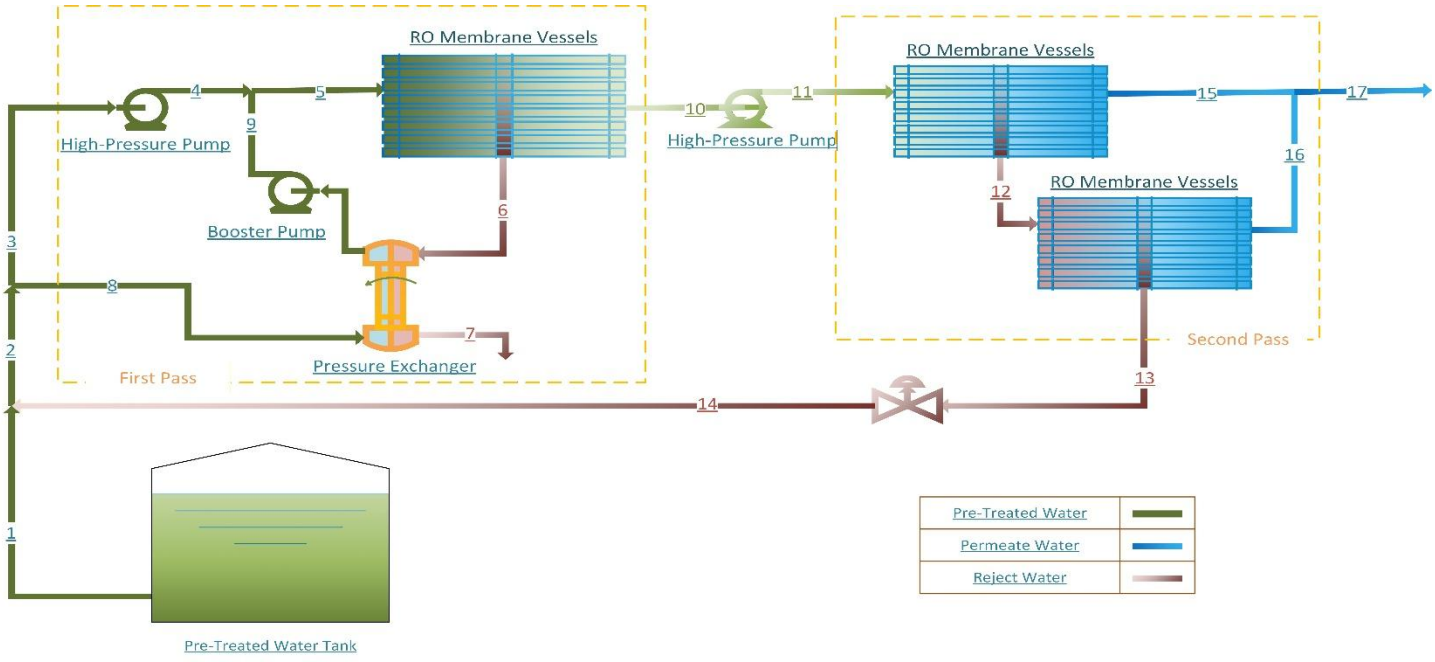


Figure 2: Schematic flow diagram of the integrated two-pass reverse osmosis (RO) system, designed for boiler feed water production, featuring high-pressure energy recovery, and a dual-stage second-pass configuration.

2.1. Membrane Selection

Membrane selection for the second pass strategically bracketed the technological spectrum of commercial BWRO elements to evaluate the trade-off between quality and energy. The evaluated membranes included the **CPA6-MAX** (Composite Polyamide), representing the industry standard for maximum salt and silica rejection, and the **ESPA2-LD** (Energy Saving Polyamide), representing ultra-low-pressure operation and maximum energy efficiency. The comprehensive technical specifications for these selected BWRO membranes are summarized in Table 4. There are three scenarios as follows:

1. Maximum Energy Efficiency Scenario: Utilizing ESPA2-LD elements uniformly across both stages to evaluate the absolute minimum operational expenditure (OPEX).

2. Maximum Quality Scenario: Utilizing CPA6-MAX elements in both stages to secure unparalleled UPW quality regardless of the hydraulic energy penalty.

3. Hybrid Configuration: Implementing a "membrane hybridization" strategy by assigning CPA6-MAX to the first stage (to secure primary silica rejection) and ESPA2-LD to the second stage.

This strategic deployment leverages the high permeability of the ESPA membrane to naturally compensate for the hydraulic pressure drop and increased salinity in the second stage, achieving flux balancing without the necessity of an auxiliary inter-stage booster pump.

Table 4: Technical specifications and operational limits of the selected Hydranautics BWRO membranes for the second pass.

Membrane Model	Active Area (ft^2)	Feed Spacer (mil)	Nominal Salt Rejection (%)	Nominal Permeate Flow (m^3/d)	Max. Operating Pressure (bar)	Max. Temp. (°C)
CPA6-MAX	440	28	99.76	45.4	41.4	45
ESPA2-LD	400	34	99.60	37.9	41.4	45

3. Economic Evaluation

To accurately assess the economic viability of the proposed reverse osmosis (RO) configurations for Red Sea water desalination, a comprehensive techno-economic evaluation was conducted. The total water cost (TWC) per cubic meter was calculated by quantifying both the capital expenditures (CAPEX) and the operational and maintenance expenditures (OPEX) using real market data and recent literature[9].

The specific investment cost (CAPEX) for the RO plant was estimated based on historical data for seawater desalination plants located in the Red Sea region. According to recent global reports, the average capital cost for such facilities is approximately $1.5 million per million liters per day (MLD), which translates to $36,000 per m^3/h of installed capacity[22]. The economic life of the plant was assumed to be 25 years with an annual interest rate of 5%, representing standard financial assumptions for large-scale desalination projects in the Middle East [3]. A plant availability factor of 90% was utilized to account for routine maintenance and cleaning downtime [3].

For the OPEX estimation, the primary variables included energy consumption, membrane replacement, maintenance, and chemical additives. Energy cost is recognized as the most influential factor in seawater RO economics[23]. While early regional assessments suggested an average tariff of $0.07/kWh [14]. this study adopted a highly localized and current industrial electricity tariff of $0.033/kWh, strictly based on the latest official rates provided by the Egyptian Electric Utility and Consumer Protection Regulatory Agency (Egypt ERA)[24]. Maintenance costs were fixed at 2% of the total CAPEX, while chemical costs for anti-scalants and cleaning-in-place (CIP) procedures were estimated at an average of $0.03/$m^3$[3].

A critical aspect of this evaluation involved differentiating membrane replacement costs based on the specific module types evaluated in the study. The lifespan of the polymeric SWRO membranes was conservatively set to 5 years[3, 6, 14]. To reflect current market dynamics, the unit price for the standard low-differential membrane (SWC4-LD) was set to $650, whereas the high-surface-area variant (SWC4 MAX) was priced at $731[25].

By integrating these realistic economic parameters into the simulation environment, the model provides a highly reliable comparative analysis of the specific energy consumption (SEC) versus the total water production cost for both standard and high-productivity membrane configurations. To accurately estimate the capital expenditure (CAPEX) for the integrated two-pass RO system, the unit replacement costs for the selected membrane modules were obtained from certified commercial distributors. Based on bulk commercial pricing, the unit costs for the primary-pass seawater elements were fixed at $525 for the standard SWC5-LD and $575 for the high-productivity SWC5 MAX. For the secondary brackish water pass, the unit cost of the high-rejection CPA6 MAX membrane was fixed at $500, whereas the ultra-low energy ESPA2-LD membrane was priced at $460 [20].

3.1. **Mathematical Formulation of the Economic Model for the single-Pass System**

To validate the software outputs and provide a transparent, deterministic economic evaluation, the manual calculation of the unit water cost was conducted using established mathematical models in desalination literature. The total unit cost of the produced water (C_w), expressed in $/m³, is defined as the sum of the annualized capital cost C capital, the annual energy cost(C_{energy}), and the annual operation and maintenance costs ($C_{O\&M}$), divided by the total annual volume of water production (Vw) This relationship is governed by the following equation[21] :

$$C_w = \frac{C_{capital} + C_{energy} + C_{O\&M}}{V_w} \qquad \text{Eq (1)}$$

a. Annual Water Production (V_w): The total annual volume of product water is calculated by multiplying the hourly permeate flow (Qp) by the operating hours per year, factoring in the plant availability factor (fa) to account for routine maintenance and cleaning downtimes [2]:

$$V_w = Q_p \times 24 \times 365 \times f_a \qquad \text{Eq (2)}$$

b. Amortized Capital Cost ($C_{capital}$): To convert the total fixed capital expenditure (CAPEX) into an annual cost, the Capital Recovery Factor (CRF) was applied [21]. The CRF is a function of the annual interest rate (i) and the expected economic lifespan of the plant in years (n):

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \text{Eq (3)}$$

$$C_{capital} = CAPEX \times CRF \quad \text{Eq (4)}$$

c. Annual Energy Cost (C_{energy}): Energy cost represents the most significant variable parameter among the different membrane configurations. It is calculated by multiplying the Specific Energy Consumption (SEC) derived from the simulation by the total annual water volume and the local electricity tariff (E_R) [4].

$$C_{energy} = SEC \times V_w \times E_R \quad \text{Eq (5)}$$

d. Operation and Maintenance Costs ($C_{O\&M}$): The $C_{O\&M}$ encompasses the costs of membrane replacement, chemicals, and general maintenance. The annual membrane replacement cost (C_{mem}) specifically varies depending on the membrane model (e.g., LD vs. MAX) and is determined by the total number of elements (Ne), the unit price of the membrane (Pe), and the guaranteed membrane lifespan (tm)[8].

$$C_{mem} = \frac{N_e \times P_e}{t_m} \quad \text{Eq (6)}$$

3.2. Economic Model Formulation for Second Pass in the Two-Pass System

To evaluate the economic viability of upgrading the single-pass configuration to a two-pass system for boiler feedwater production, the economic model was expanded to assess both passes as an integrated unit. This approach prevents the double-counting of shared capital expenditures (such as intake and pretreatment facilities) and accurately reflects the interdependent thermodynamics of the dual-pass array[13]. The comprehensive economic assessment was conducted based on the following modified parameters:

a. Annual Water Production (V_w)

In a dual-pass system, the final annual product volume is strictly based on the permeate flow exiting the second pass ($Q_{p,\,pass2}$), as the first-pass permeate is utilized as feed for the second pass, and the second-pass concentrate is typically recirculated.

$$V_w = Q_{p,pass2} \times 24 \times 365 \times f_a \quad \text{Eq (7)}$$

b. **Amortized Capital Cost ($C_{capital}$):**

The Total Capital Expenditure ($CAPEX_{total}$) was modified to incorporate the incremental construction

and equipment costs of the second pass. Upgrading to a full two-pass RO system typically increases the base CAPEX by a ratio ranging from 1.27 to 1.38[26]. The amortized annual capital cost is then calculated using the Capital Recovery Factor (CRF)[21]:

$$CAPEX_total = CAPEX_pass1 + CAPEX_pass2$$

$$C_{capital} = CAPEX_{total} \times CRF \quad \text{Eq (8)}$$

c. Annual Energy Cost (C_{energy})

The energy cost calculation utilized the Total Specific Energy Consumption (SEC_{total}) derived from the simulation. This value aggregates the energy demands of the primary high-pressure pump, the secondary inter-pass booster pump, and the isobaric Energy Recovery Device (ERD)[8].

$$C_{energy} = SEC_{total} \times V_w \times E_R \quad \text{Eq (9)}$$

d. Operation and Maintenance Costs ($C_{O\&M}$)

To accommodate the Hybrid Membrane Design implemented in the second pass alongside the primary SWC elements, the annual membrane replacement cost (C_{mem}) equation was expanded into a summation function. This modification accurately accounts for the varying unit prices (P) and quantities (N) of the distinct membrane models (e.g., SWC, CPA, and ESPA) utilized across the entire integrated system over their guaranteed lifespan (t_m)[8,22].

$$C_{mem} = \left((N_{SWC} \times P_{SWC}) + (N_{CPA} \times P_{CPA}) + (N_{ESPA} \times P_{ESPA})\right)/t_m \quad \text{Eq (10)}$$

Results and discussion

1. Comparative Performance Analysis of Individual Membrane Models for a Single-Pass Potable Water Production System

This section presents a detailed evaluation of the thermodynamic and hydraulic responses of the five selected membrane models under varying feed water temperatures (15 °C to 35 °C). The analysis focuses on three primary key performance indicators: feed pressure, specific energy consumption (SEC), and permeate water quality (TDS).

1.1. SWC4-LD: The Standard Baseline Configuration

The SWC4-LD membrane serves as the baseline for this study, representing the conventional high-rejection standard. As demonstrated in Table 5, this configuration exhibited the highest energy demand while maintaining superior salt rejection. As the temperature increased from 15 °C to 35 °C, the required feed pressure decreased by approximately 7 bar, translating to a nearly 10% reduction in SEC (from 3.14 to 2.83 kWh/m³). Concurrently, the permeate TDS increased from 222.8 to 484.3 mg/L. Notably, even under severe thermal stress at 35 °C, the SWC4-LD successfully maintained the permeate quality strictly below the 500 mg/L threshold, ensuring continuous compliance with potable water standards.

Table 5: Effect of feed water temperature on the performance of SWC4-LD membrane

Feed Water Temperature (°C)	Feed Pressure (bar)	Specific Energy Consumption (kWh/m³)	Permeate TDS (mg/L)
15	71.9	3.14	222.8
20	68.7	3.00	273.1
25	67.0	2.92	323.3
30	65.8	2.87	396.9
35	64.9	2.83	484.3

1.2. SWC4-MAX: Surface Area Optimization

The transition to the SWC4-MAX model highlights the hydraulic advantages of maximizing the active surface area (440 \ ft^2). As shown in Table 6, distributing the required volumetric flux over a larger active area consistently reduced the localized transmembrane pressure. This structural optimization resulted in a feed pressure reduction of approximately 2 bar across all temperature setpoints compared to the LD counterpart. Consequently, the SWC4-MAX provides a measurable improvement in energy efficiency without significantly compromising the robust salt rejection characteristics inherent to the SWC4 family.

Table 6: Effect of feed water temperature on the performance of SWC4-MAX

Feed Water Temperature (°C)	Feed Pressure (bar)	Specific Energy Consumption (kWh/m³)	Permeate TDS (mg/L)
15	69.5	3.04	249.1
20	66.8	2.93	305.6

25	65.4	2.87	362.0
30	64.4	2.82	444.7
35	63.8	2.80	542.9

1.3. SWC5-LD: Enhanced Permeability Dynamics

The SWC5-LD membrane introduces a shift toward high-permeability operations. Table 7 indicates a substantial drop in energy requirements, with the SEC falling to 2.66 kWh/m³ at elevated temperatures. However, this energy conservation inherently induces a quality trade-off; the permeate TDS reached 626.5 mg/L at 35 °C. This behavior underscores the physical principle that enhanced water permeability in the polyamide layer is fundamentally coupled with an increased salt diffusion coefficient, particularly under elevated thermal kinetics.

Table 7: Effect of feed water temperature on the performance of SWC5-LD membrane

Feed Water Temperature (°C)	Feed Pressure (bar)	Specific Energy Consumption (kWh/m³)	Permeate TDS (mg/L)
15	63.1	2.76	285.7
20	61.6	2.69	351.5
25	62.1	2.71	459.1
30	60.8	2.66	512.6
35	60.8	2.66	626.5

1.4. SWC5-MAX: The Optimal Techno-Economic Compromise

The SWC5-MAX configuration emerges as the optimal balanced candidate within this comparative framework. By coupling high-permeability chemistry with a maximized surface area, this model achieved excellent energy metrics, stabilizing at an SEC of 2.64–2.65 kWh/m³ at temperatures above 25 °C Table 8. While the permeate TDS peaked at 700.0 mg/L at 35 °C marginally exceeding strict potable limits it remains well within acceptable for high-purity industrial requirements such as boiler feed water production, the SWC5-MAX serves as a highly strategic first-pass option. The substantial energy conserved during this primary desalination stage can effectively offset the additional power required to operate a second-pass RO system, thereby achieving the ultra-pure water quality mandated for high-pressure boilers while maintaining a highly favorable overall techno-economic profile.

Table 8: Effect of feed water temperature on the performance of SWC5-MAX membrane

Feed Water Temperature (°C)	Feed Pressure (bar)	Specific Energy Consumption (kWh/m³)	Permeate TDS (mg/L)
15	61.8	2.71	318.2
20	60.7	2.66	391.9
25	60.3	2.65	464.6
30	60.2	2.64	571.8
35	60.4	2.65	700.0

1.5. SWC6-MAX: Ultra-High Permeability and Associated Quality Risks

Table 9 delineates the performance of the SWC6-MAX, an ultra-high permeability membrane that dictates the absolute minimum energy footprint in this study. The feed pressure plummeted below 60 bar across all conditions, yielding an exceptional SEC of 2.57 kWh/m³. However, this extreme energy efficiency is accompanied by severe quality deterioration. At 35 °C, the permeated TDS surged to 1059.7 mg/L, critically breaching all standard thresholds for drinking water.

Table 9: Effect of feed water temperature on the performance of SWC6-MAX

Feed Water Temperature (°C)	Feed Pressure (bar)	Specific Energy Consumption (kWh/m³)	Permeate TDS (mg/L)
15	59.2	2.60	495.9
20	58.5	2.57	621.5
25	58.4	2.57	776.8
30	58.5	2.57	908.3
35	58.9	2.59	1059.7

While previous literature, such as the Puerto Peñasco desalination study, identified the SWC6-MAX membrane as the optimal choice for minimizing energy and production costs, our results reveal severe performance limitations for this model. This discrepancy arises from fundamentally different operating conditions. Unlike the referenced study, our simulation evaluates Red Sea water, which features extremely high initial salinity. When this high salinity is combined with thermal stress (up to 35 °C), the SWC6-MAX completely lost its salt rejection capacity, failing to meet the required water quality standards. Consequently, this proves that selecting the "optimal" membrane is not a universal rule. Instead, it is a highly site-specific engineering decision

strictly dictated by local operating parameters, primarily feed water chemistry and temperature variations**.**

The thermodynamic trade-offs of the evaluated membranes are visually synthesized as follows: Figure 3 illustrates the effect of feed water temperature on Specific Energy Consumption (SEC), while standard low-permeability membranes (e.g., SWC4-LD) exhibit a continuous decrease in energy demand, ultra-permeable models (e.g., SWC6-MAX) quickly reach a plateau, this flattened curve indicates a rigid energy profile that becomes unresponsive to further reductions in water viscosity.

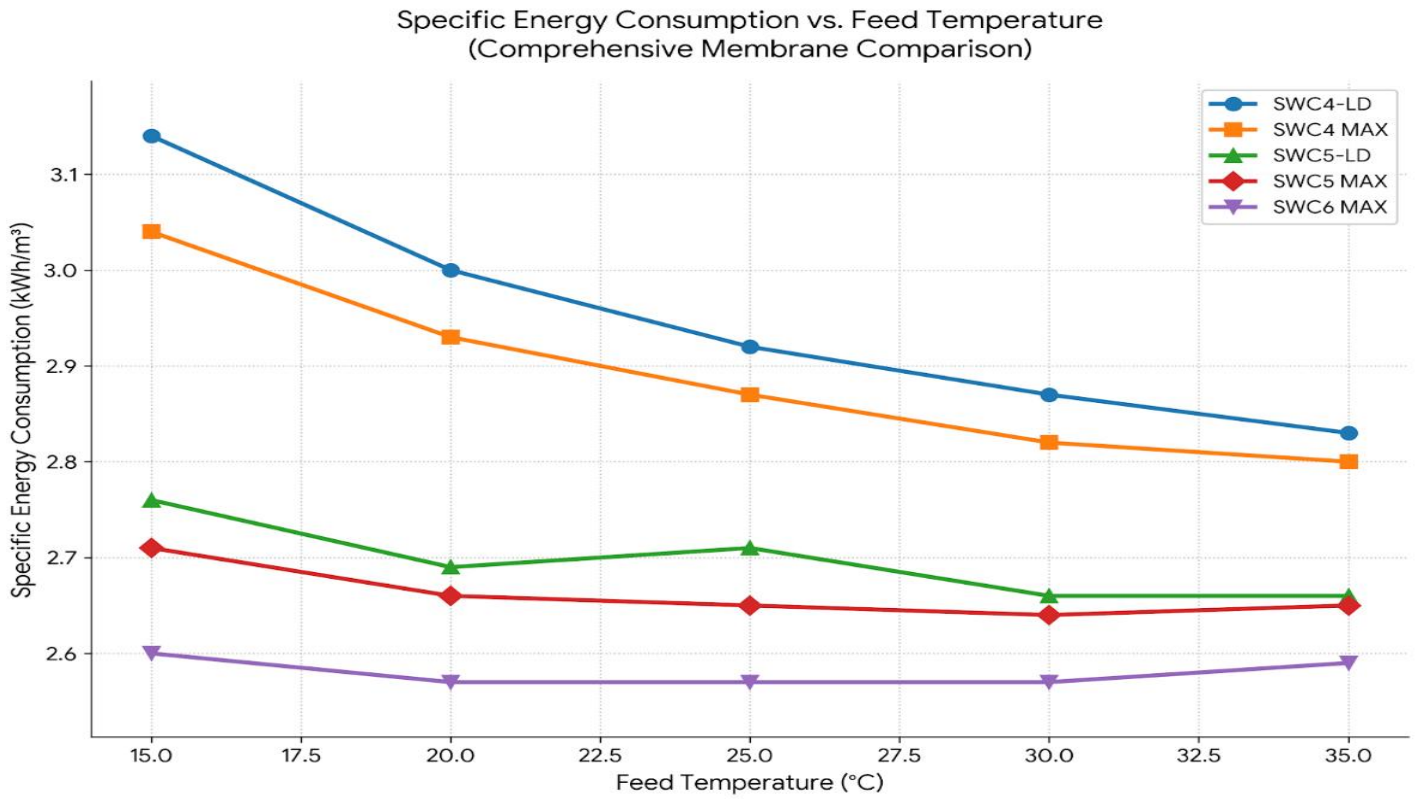


Figure 3: Effect of feed water temperature variations on the Specific Energy Consumption (SEC) across different SWC reverse osmosis membrane models.

Conversely, Figure 4 demonstrates a universal and steep exponential surge in permeate TDS across all membranes under thermal stress. Analyzed concurrently, these figures expose a critical asymmetric trade-off: the marginal energy savings achieved at elevated temperatures are disproportionately outweighed by the severe and exponential degradation in salt rejection capabilities.

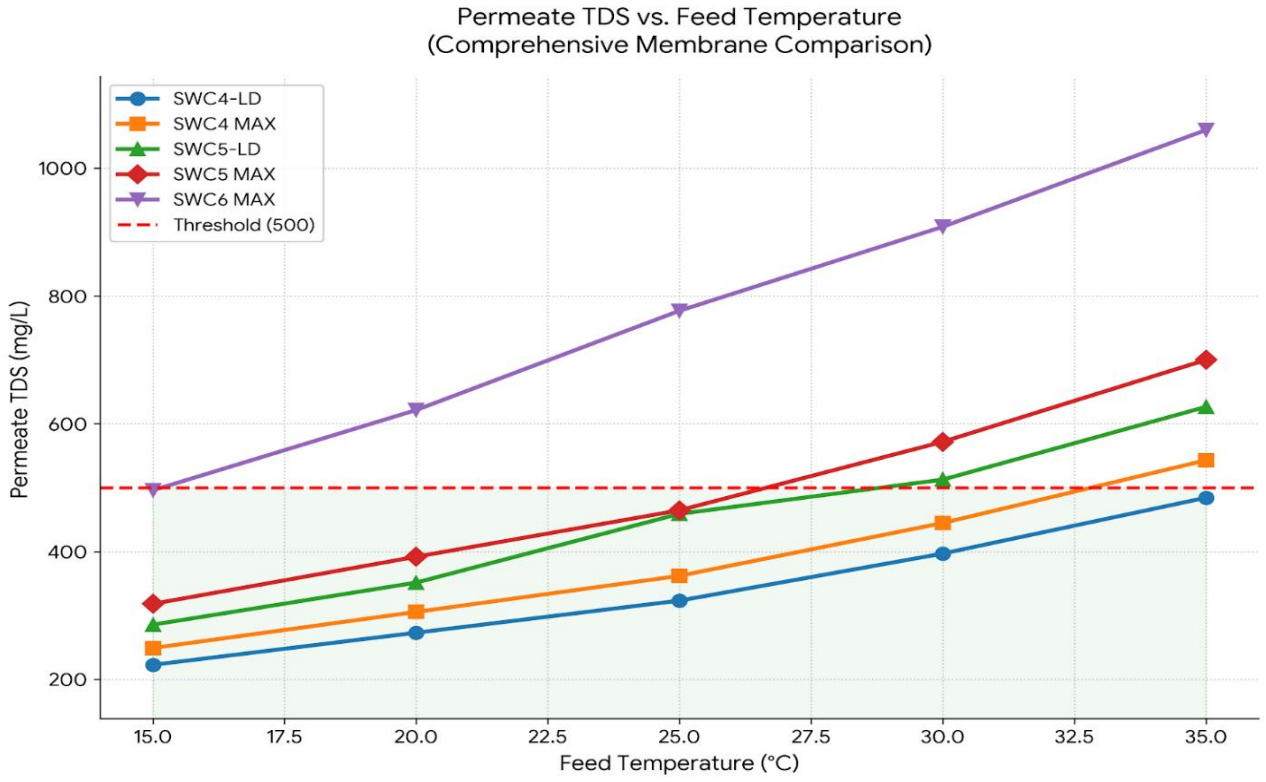


Figure 4: Effect of feed water temperature variations on the permeate Total Dissolved Solids (TDS) across different SWC membrane models.

1.6.Techno-Economic Assessment for Single-Pass Potable Water Production System

The application of the deterministic mathematical model established in Section 3.1 yields a highly profound and counter-intuitive techno-economic finding. By integrating the physical simulation outputs (Specific Energy Consumption) with the localized Egyptian economic parameters specifically the low electricity tariff (0.033$/kWh) and the distinct membrane unit prices the exact Total Water Cost in USD ($/m³) was calculated for the two potable-compliant models using Eq (1).

To compute these values, the fixed components of the economic equations were first resolved. As dictated by Eq (2), for a plant capacity (Qp) of 100 m^3/h operating at a 90% availability factor (fa = 0.9), the total annual water production (Vw) equates to 788,400 m^3\year. The total CAPEX was calculated at $3,600,000. Applying Eq (3) for a plant economic life (n) of 25 years and an annual interest rate (i) of 5%, the Capital Recovery Factor (CRF) is determined to be 0.07095. Subsequently, utilizing Eq (4), this translates to a specific

amortized capital cost of 0.324$/m³.

Applying the remaining fixed O&M parameters as structured in Eq (6) namely, maintenance at 4% of CAPEX, chemicals at $0.04/m³, and a 5-year membrane lifespan isolates the annual energy cost (C_{energy}). Calculated via Eq (5), the energy cost serves as the primary variable component, directly governed by the local electricity tariff of 0.033$/kWh. A comprehensive breakdown of these fixed techno-economic parameters used as the baseline for the cost evaluation is summarized in Table 10.

Table 10: Summary of the fixed techno-economic parameters applied in the mathematical cost model

Parameter Description	Symbol / Equation Reference	Value	Unit
Hourly Permeate Flow	Q p	100	m^3/h
Plant Availability Factor	fa	0.90	-
Total Annual Water Production	Vw (Eq. 2)	788,400	m^3/year
Total Capital Expenditure	CAPEX	3,600,000	USD ($)
Plant Economic Life	n	25	Years
Annual Interest Rate	i	5.0	%
Capital Recovery Factor	CRF (Eq 3)	0.07095	-
Specific Amortized Capital Cost	$C_{capital}$/Vw (Eq. 4)	0.324	$/m^3$
Maintenance Cost	$C_{O\&M}$ component	4.0	% of CAPEX
Chemicals Cost (Antiscalant & CIP)	$C_{O\&M}$ component	0.04	$/m^3$
Membrane Economic Lifespan	t_m	5	Years
Industrial Electricity Tariff	ER (Eq. 5)	0.033	$/kWh

The calculated unit water costs across the thermal gradient are comprehensively detailed in Table 11. These final values were derived by integrating the fixed parameters with the temperature-dependent variable SEC Eq (5), alongside the specific membrane replacement costs defined in Eq (6). Specifically, the distinct unit prices of $650 for the SWC4-LD and $731 for the SWC4-MAX were directly incorporated into the $C_{O\&M}$ component to calculate the annualized membrane depreciation over their guaranteed 5-year lifespan.

Table 11: Deterministic Total Water Cost ($/m³) calculation for SWC4-LD and SWC4-MAX utilizing localized economic parameters

Feed Water Temperature (°C)	SWC4-LD SEC (kWh/m³)	SWC4-LD Total Cost ($/m³)	SWC4-MAX SEC (kWh/m³)	SWC4-MAX Total Cost ($/m³)
15	3.14	0.690	3.04	0.692
20	3.00	0.686	2.93	0.688

25	2.92	0.683	2.87	0.686
30	2.87	0.681	2.82	0.685
35	2.83	0.680	2.80	0.684

The mathematical cost model Table 10 reveals a critical design paradox specific to the Egyptian industrial context. Thermodynamically, the high-surface-area SWC4-MAX membrane exhibits superior energy efficiency. Economically, however, the standard SWC4-LD membrane proves more viable, achieving a lower minimum production cost of \$0.680/m³ at 35 °C, compared to \$0.684/m³ for the SWC4-MAX.

This divergence stems directly from the localized, low industrial electricity tariff (\$0.033/kWh). The financial value of the mechanical energy conserved by the SWC4-MAX is too marginal to offset its higher capital and annualized replacement costs (\$731 per element versus \$650 for the LD). Consequently, in regions with low energy costs, membrane depreciation dominates OPEX, making standard configurations more cost-effective than their high-permeability counterparts.

To validate the deterministic model, the calculated unit costs (\$0.680–\$0.690/m³) were benchmarked against global SWRO economic literature. The simulated results fall precisely within the standard industry range of \$0.50 to \$1.20/m³ [16], confirming the reliability of the IMSDesign simulation and the commercial viability of the proposed plant design.

2. Simulation Results of the Two-Pass Boiler Feedwater (BFW) production System

The simulation phase evaluated the two-pass Reverse Osmosis system utilizing two different primary membranes for the first pass: the high-area SWC5-MAX and the standard low-differential SWC5-LD. For each primary case, three distinct scenarios were simulated for the second pass (Max Energy Efficiency, Max Quality, and Hybrid Design) to identify the local optimum.

Crucially, the Total Water Cost (TWC) presented in this evaluation was not solely extracted from the simulation software; rather, it was comprehensively calculated utilizing the integrated techno-economic mathematical model (Eq 7 to 10-Modified) established in the methodology section. This ensures a highly accurate reflection of the hybrid membrane replacement costs and the cumulative system energy demands.

2.1. Two-Pass System Configuration Using SWC5-MAX in the First Pass

As shown in Table 12 Selection of the Optimal Scenario Utilizing identical membranes across both stages created a strict polarization. While the ESPA2-LD scenario minimized the SEC, it yielded a significantly higher Permeate TDS (9.29 ppm), putting a heavy purification burden on downstream polishing units (e.g., Mixed Bed). Conversely, the CPA6-MAX scenario guaranteed Ultra-Pure Water (4.65 ppm) but imposed a severe hydraulic penalty. The Hybrid Design (CPA6-MAX / ESPA2-LD) is selected as the optimum for Case A. It successfully maintained an excellent BFW quality (5.68 ppm) while naturally balancing the permeate flux, reducing the SEC to 3.58 kWh/m³.

Table 12: Quality performance of Pass 2 scenarios (Base Pass 1: SWC5-MAX)

Scenario	Membrane Configuration (Stage 1 / Stage 2)	Pass 2 Feed Pressure (bar)	Permeate TDS (ppm)	Total SEC (kWh/m³)
1. Max Energy Efficiency	ESPA2-LD / ESPA2-LD	10.1	9.29	3.31
2. Max Quality	CPA6-MAX / CPA6-MAX	18.4	4.65	3.70
3. Hybrid Design	CPA6-MAX / ESPA2-LD	15.9	5.68	3.58

2.2. Two-Pass System Configuration Using SWC5-LD in the First Pass

As shown in Table 13 Selection of the Optimal Consistent with the previous case, the single-membrane configurations failed to achieve a techno-economic balance. The Hybrid Design once again proved its superiority. By strategically deploying the ESPA2-LD in the second stage, the required feed pressure dropped to 14.4 bar, lowering the total system SEC to 3.53 kWh/m³, all while achieving an outstanding Permeate TDS of 5.49 ppm (a 30% quality improvement over the ESPA design). Thus, the Hybrid Design is the undisputed optimum**.**

Table 13: Quality performance of Pass 2 scenarios (Base Pass 1: SWC5-LD)

Scenario	Membrane Configuration (Stage 1 / Stage 2)	Pass 2 Feed Pressure (bar)	Permeate TDS (ppm)	Total SEC (kWh/m³)
1. Max Energy Efficiency	ESPA2-LD / ESPA2-LD	10.0	7.93	3.33
2. Max Quality	CPA6-MAX / CPA6-MAX	17.1	4.34	3.66
3. Hybrid Design	CPA6-MAX / ESPA2-LD	14.4	5.49	3.53

2.3. Economic Evaluation of the Integrated Two-Pass Boiler Feedwater (BFW) production System

To ensure a transparent and reproducible economic evaluation of the integrated two-pass RO system, all fixed input parameters and commercial reference values utilized in the mathematical model were consolidated. The baseline capital expenditure (CAPEX) for the primary pass was adopted from standard regional cost estimations, while the incremental construction cost required for the secondary pass was incorporated using a recognized CAPEX multiplier. Furthermore, operational variables including maintenance rates, chemical consumption, and the localized industrial electricity tariff `were strictly aligned with recent literature specific to the Egyptian context. Table 14 summarizes the complete set of techno-economic parameters and module replacement costs applied in calculating the TWC**.**

Table 14: Summary of the fixed techno-economic parameters and commercial reference values applied in the integrated two-pass model**.**

Parameter Description	Symbol	Value	Unit
Final Permeate Flow (Pass 2)	Qp	90	m^3/h
Plant Availability Factor	fa	0.90	-
Total Annual Water Production	Vw	709,560	m^3/year
Base CAPEX (Pass 1)	$CAPEX_{base}$	3,600,000	USD
Two-Pass CAPEX Multiplier	M_{pass2}	1.33	Ratio $CAPEX_{base}$
Total Capital Expenditure	$CAPEX_{total}$	4,788,000	USD
Plant Economic Life	n	25	Years
Annual Interest Rate	i	5.0	%
Capital Recovery Factor	CRF	0.07095	-

Specific Amortized Capital Cost	C capital/V	0.478	m^3
Maintenance Cost Rate	$C_{O\&M}$ component	4.0	%of Total CAPEX
Chemicals Cost	$C_{O\&M}$ component	0.04	m^3/$
Membrane Economic Lifespan	t_m	5	Years
Industrial Electricity Tariff	ER	0.033	kWh/$
SWC5-MAX Commercial Unit Price	SWC5 -MAX	731	$/element
SWC5-LD Commercial Unit Price	PSWC5 -LD	650	$/element
CPA6-MAX Commercial Unit Price	CPA6 - MAX	700	$/element
ESPA2-LD Commercial Unit Price	ESPA2-LD	550	$/element

To transparently determine the ultimate economic viability of the two optimized hybrid configurations, (TWC) was calculated component by component using the mathematical model established in Section 3.2.

The fixed costs (Capital, Maintenance, and Chemicals) remain constant across both scenarios as they share the same base infrastructure. The differentiating factors are the Annual Energy Cost (C_{energy}) and the Membrane Replacement Cost (C_{mem}). The dynamic operational costs (Energy and Membranes) along with the final computed TWC are detailed in Table 15.

Table 15: Detailed breakdown of the (TWC) for the optimized hybrid configurations.

Cost Component (USD/m³)	**Equation Reference**	**SWC5-MAX + Hybrid Pass 2**	**SWC5-LD + Hybrid Pass 2**
Capital Cost ($C_{capital}$)	Eq. 8	0.478	0.478
Maintenance Cost	4% of CAPEX	0.270	0.270
Chemicals Cost	Fixed	0.040	0.040
Energy Cost (Cenergy)	Eq. 9	0.118 *(SEC = 3.58)*	0.116 *(SEC = 3.53)*
Membrane Replacement (C mem)	Eq. 10	0.063	0.057
Total Water Cost (TWC)	$\sum$	0.969 $/m³	0.961 $/m³

The rigorous mathematical calculation definitively confirms the superiority of (SWC5-LD + Hybrid Pass 2) configuration. Although both hybrid configurations successfully provided ultra-pure Boiler Feed Water (TDS < 6 ppm), Case B achieved a lower Total Water Cost of 0.961 $/m³ compared to 0.969 $/m³ for (SWC5-MAX + Hybrid Pass 2) configuration.

This economic advantage is driven by two synergistic factors:

1. **Lower CAPEX/Replacement:** The SWC5-LD membranes possess a more cost-effective commercial unit price ($650 vs $731), which significantly reduced the annualized membrane replacement burden.
2. **Superior OPEX:** The lower feed pressure requirement generated by the LD baseline reduced the specific energy consumption to 3.53 kWh/m³, yielding direct savings in the continuous electrical tariff.

Therefore, the integrated system utilizing SWC5-LD (Pass 1) and a hybridized CPA6-MAX / ESPA2-LD (Pass 2) is officially established as the most robust, energy-efficient, and economically viable desalination architecture for industrial high-pressure boiler feedwater in the Red Sea region.

Conclusions

This research paper presents a comprehensive techno-economic evaluation addressing the engineering challenges of producing both potable water and high-pure Boiler Feed Water (BFW) from the Red Sea Water, an environment characterized by extreme salinity and severe thermal fluctuations. Through advanced simulation and economic modeling of single and Two-Pass Reverse Osmosis (RO) systems, the following main conclusions can be drawn:

- **Thermal Sensitivity and Potable Water Compliance:**

The parametric evaluation across a 15–35 °C thermal gradient demonstrated a critical trade-off between energy conservation and salt rejection. While elevated temperatures lower water viscosity and reduce energy demand, they exponentially accelerate salt diffusion. Ultra-high permeability membranes (e.g., SWC6-MAX) achieved the lowest specific energy but critically failed to meet WHO drinking water standards at 35 °C due to excessive salt passage. Conversely, standard low-differential membranes (SWC4-LD) exhibited robust thermal resilience, securing continuous potable water compliance (TDS < 500 ppm) and achieving the lowest production cost of $0.680/m³ in a single-pass array.

- **The Strategic Baseline for (BFW):**

Although standard membranes are economically ideal for potable water, producing high-pressure BFW requires a different architectural strategy. Shifting to high-permeability, low-differential membranes (SWC5-

LD) in the primary pass minimizes the massive hydraulic burden of treating Red Sea water. This strategic selection conserves sufficient energy to operate the necessary secondary polishing pass without inflating the overall operational expenditures.

- **Limitations of Uniform Systems and the Efficacy of Hybridization:**

The secondary pass analysis revealed that relying on a single membrane type imposes a strict limitation. Utilizing exclusively ultra-low-pressure membranes conserves energy but jeopardizes boiler integrity due to elevated salt passage. Conversely, relying solely on high-rejection membranes creates hydraulic bottlenecks, unjustifiably escalating feed pressures. In contrast, the "Membrane Hybridization" strategy proved its absolute superiority. By integrating CPA6-MAX elements in the first stage to secure silica and salt rejection, alongside ESPA2-LD elements in the second stage, the system achieved natural "Flux Balancing" without the necessity for inter-stage booster pumps.

- **Optimal Configuration and Economic Viability:**

Based on the comprehensive evaluation, the integrated system comprising the SWC5-LD for the primary pass coupled with a hybridized CPA/ESPA secondary pass constitutes the ultimate techno-economic optimum for industrial applications. This engineered architecture successfully achieved stringent water quality compliance for boilers (TDS = 5.49 ppm) while minimizing the Total Specific Energy Consumption (SEC) to 3.53 kWh/m³. Applying the localized industrial cost model, this integrated system realized the lowest Total Water Cost (TWC) of 0.961 $/m³.

In conclusion, this research provides an applied model and a sustainable engineering solution for industrial facilities to manage severe thermal variations, enhance the efficiency of desalination plants, protect high-pressure thermal equipment, and reduce long-term operational expenditures in harsh marine environments.

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Authors' contributions

Islam M. Ismail: Process simulation, Data analysis, Visualization, Writing (original draft & editing). Dr. Walaa Osman: Supervision, Methodology, Validation, Writing (review & editing). Dr. Eman Abdelwahab: Supervision, Conceptualization, Validation, Writing (review & editing).

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Data availability

The data supporting the findings of this study are clearly stated in the study and are available from the corresponding author upon reasonable request. However, certain facility-specific datasets were provided under confidentiality restrictions and are not publicly available. Access to such data may be considered only through the data owner's formal request process and prior written authorization.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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