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Overview of systems engineering approaches for a large-scale seawater desalination plant with a reverse osmosis network

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Abstract

Over 100 papers were reviewed to elucidate factors influencing large-scale seawater desalination plants with reverse osmosis networks (SWRO). This paper consists of subjects such as SWRO systems investigation, system models of pretreatment and RO networks, systems optimization to minimize the total cost of SWRO plant design, and the future direction of SWRO technology. In order to design a large-scale seawater desalination plant, a systematic understanding of SWRO processes should be followed. After investigating all the processes, including site-specific features, seawater intakes, pretreatment systems, RO networks, energy recovery systems, post-treatment systems, brine disposal, and the environmental impact of SWRO desalination, system models are discussed for predicting the performance of each system. Based on the minimal principle of total cost required for a full-scale SWRO plant, optimized results are discussed. Studies needed for developing future SWRO technologies are suggested.

Keywords: Desalination; Reverse osmosis membrane; Seawater; SWRO; Optimization; Systems engineering approach

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1. Introduction

In the 21st century, recognition of a potential water shortage and the unpredictable impact of global warming on overall water scarcity posits that the first and second decades should be referred to as the "water crisis decades" [1]. This shortage can be partially attributed to global population growth, limited natural resources, and increased industrial activities [2]. Consequently, to resolve the water scarcity problem in many regions around the world, seawater is no longer merely a marginal water resource for resource-limited countries. In a recent global industry forecast [1], from as recent as three years ago the global desalination industry can be seen to be rapidly expanding, and this is just the beginning stage of desalination market expansion.

Traditionally, the use of multi-stage flash (MSF), multi-effect distillation (MED), electrodialysis (ED), and reverse osmosis (RO) processes has received significant attention in attempts to improve the reliability and the performance of freshwater production processes. Current research on desalination processes, however, addresses important topics associated with lowering the cost and enabling a more environmentally friendly operation [3]. For this reason, pressure-driven membrane pretreatment processes including microfiltration, ultrafiltration, and nanofiltration; new material development to prevent fouling in reverse osmosis units and corrosion in distillation processes; hybrid (RO+ thermal) seawater desalination processes; and utilization of alternative energy sources including wind, solar, bio, and nuclear energies for desalination processes have been studied.

Overall, consideration of total water production costs, the land scarcity of a nation, and promotion of an environmentally friendly operation suggests that the use of RO processes will be the most economic technology for large-scale seawater desalination processes in the near future [2,4–7].

Fig. 1 illustrates the schematic diagram of a typical seawater reverse osmosis (SWRO) desalination process that includes a seawater intake, pretreatment, a RO system, and post-treatment. As can be seen in the figure, the structure of this paper is designed according to the stream flow direction, starting from the seawater intake and ending at the brine disposal, through a SWRO desalination process. Subjects discussed in this paper are SWRO systems investigation, system models, optimization to minimize the total cost of SWRO plant designs, and the future direction of SWRO technology.

2. Systems investigation

Construction of a large-scale seawater plant with a RO network has the potential to reduce unit product costs, including both capital and operating/maintenance costs. Due to this potential cost reduction, large-scale SWRO plants have become a more attractive process for desalination than others. In fact, ten of the largest SWRO plants [7] are summarized in Table 1. In this systems investigation section, things to be considered for designing and/or simulating the large scale SWRO process are suggested as follows.

2.1. Intake structure and site area

For a large-scale sweater desalination plant, it is quite common that logistics and the cost of delivering pipe segments to the plant site should be considered when locating the intake structure close to the shoreline. Moreover, sub-surface seawater intake at favorable conditions can usually provide much better seawater quality than surface intake; the required depth of the seawater intake structure is typically at least 10–15 m from the mean sea surface level [8]. Thus, for a plant site that excludes an intake structure, a feed water reservoir, pretreatment system, RO system, post-treatment system, and product water storage

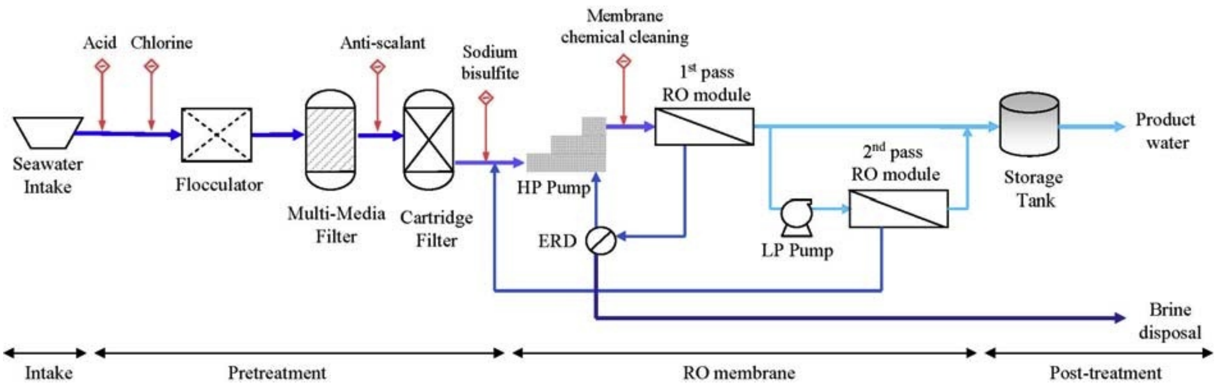

Fig. 1. Schematic diagram of a typical SWRO desalination process.

Table 1
Ten largest SWRO plants in the world (2004)

Country	Location	Capacity (m^3/h)	Year of construction	Membrane manufacturer	Module
United Arab Emirates	Fujairah	7,083	2004	Hydranautics/Nitto	Spiral wound
Saudi Arabia	Median/Yanbu	5,333	1998	Toyobo	Hollow fiber
Spain	Carboneras	5,000	2003	Hydranautics/Nitto	Spiral wound
Trinidad and Tobago	Point Lisas	4,542	2002	Hydranautics/Nitto	Spiral wound
USA	Tampa Bay	3,917	2003	Hydranautics/Nitto	Spiral wound
Saudi Arabia	Al Jubail	3,750	2002	DuPont/Toray	Hollow fiber/ spiral wound
Spain	Cartagena	2,708	2002	Hydranautics/Nitto	Wickel element
Saudi Arabia	Jeddah I	2,367	1989	Toyobo	Hollow fiber
Saudi Arabia	Jeddah II	2,367	1994	Toyobo	Hollow fiber
Spain	Marbella	2,350	1998	DuPont	Hollow fiber

reservoir all have to be considered. Additionally, the site area should include a laboratory, a warehouse for the repairs and general storage, stations for electric transformation, and an administration building. For a RO seawater system, a separate building area is also required for housing intake pump systems including transformer, motor control center, and intake clear well [8].

2.2. Raw seawater conditions

When presented with a new seawater desalination plant project, after on-site drilling and sampling of observation wells is completed, gathering historical information on the composition of raw seawater is required to understand the conditions of the intake-seawater quality. Table 2 describes common compositions of raw seawater at several sites in the Middle East [9–18]. Then, depending on the raw seawater quality at various sites, it is necessary to determine individual guidelines for configuring the pretreatment process, RO system design, membrane selection, and chemical cleaning methods [19].

Table 2
Composition of raw seawater at several sites in the Middle East

	pH	TDS (mg/l)	Temp (℃)	Total alkalinity (mg/l)	Bicarbonate HCO_3^- (mg/l)	Sodium Na^+ (mg/l)	Potassium K^+ (mg/l)	Magnesium Mg^{2+} (mg/l)	Calcium Ca^{2+} (mg/l)	Fluoride F^+ (mg/l)	Chloride Cl^- (mg/l)	Sulphate SO_4^{2-} (mg/l)	Silica SiO_2^- (mg/l)	Barium Ba^{2+} (mg/l)	Phosphate PO_4^{3-} (mg/l)
Kifan site 1 [13]	7.21	11435	28.6	133	133	2462	39	303	693	2.15	4013	3016	2	0.18	<0.05
Kifan site 2 [17]	7.15	10786.6	-	143.3	143.3	3045	55.2	432.4	869.9	1.95	3983.8	3018.9	5.45	<0.05	<0.05
Canary Islands [10]	-	-	-	6600	-	9055.5	251.8	1354.3	205.5	-	21328.5	3300	-	-	-
Crude seawater (Canary Islands) [15]	-	-	-	-	171.9	11810	-	1438.7	448.9	0.5	21317.2	2900	-	-	-
Atlantic Ocean [12]	8	40077	17-20	162		12255	441	1477	464	1.5	22019	3075	1.4	0.4	-
Jeddah, Saudi Arabia (Red sea) [16]	8	41200	32	-	-	-	-	1464	520	-	22000	-	0.4	-	-
Yanbu City [9]	8.1–8.3	41300–46400	25	120–130	-	11700–12500	425–650	1500–1600	490–560	1.5	21600–23500	3000-3200	0.5	-	<0.1
Tajura, Libya [14]	8.3	38000	-	-	163	11600	419	1427	455	-	20987	2915	-	2	-
Bocabarranco[11]	-	38000	-	-	250	11415	450	1520	450	-	20800	3110	5	-	-
Surface seawater (open intake) [18]	8.07	-	19.3	-	161	10945	410	1471	441	1.55	20900	2965	0.2	10	0.02
Well seawater [18]	7.8	-	21.1	-	166	10747	399	1340	438	1.35	20100	2840	1.5	20	0.09
Combined water [18]	7.87-7.92	-	18.6–20.5	-	162	10841	402	1355	441	1.35	20700	2855	0.9	15	0.05

2.3. Pretreatment process

2.3.1. Conventional approach

SWRO design and operation heavily rely on the quality of raw seawater. Therefore, high quality pretreatment processes are a critical issue for improving the performance of SWRO systems [18]. After screening trash from the intake seawater as an initial pretreatment step, coagulation, flocculation, media filtration, and cartridge filter steps are usually included in the pretreatment process to improve the feed water quality for the RO process. Key issues to be considered in the pretreatment step are as follows [8,15,20, 21]:

- Preventing bacterial growth and bio-fouling in the RO membrane.
- Inhibiting scale formation in the RO membrane.
- Regulating the seawater pH to adequate values in the RO membrane.
- Destabilization and agglomeration of colloidal particles and dissolved organics.
- Removal of suspended solids.
- Preventing a sudden appearance of particulate matter in the feed water for the RO membrane.
- Neutralizing the residual active chlorine.

In order to resolve the problems mentioned above, the following approaches are recommended, respectively [8,15,20,21]:

- Sodium hypochlorite (NaOCl), Cl_2, $KMnO_4$, or O_3 can be used to control bio-fouling. H_2SO_4 can be applied to assist the biocide action of NaOCl.
- Sodium hexametafosphate is usually dosed to control scaling. H_2SO_4 can be used to help the action of the scale inhibitors.
- H_2SO_4 can be dosed to regulate the pH for polyamide-type RO membranes.
- Ferric or alum salts are often used to coagulate and flocculate colloidal particles and dissolved organics.
- Anthracite (~1 mm) is often applied during the granular media filtration process to remove suspended solids. The media backwashing process with air is followed by the granular media filtration process to remove captured particles from the filters.
- Cartridge filters are usually tasked with preventing the sudden appearance of particulate matter.
- Sodium metabisulfite ($NaHSO_3$) is primarily used to neutralize the residual active chlorine, especially for a polyamide-type RO membrane.

2.3.2. UF membrane approach

Compared to the ultrafiltration (UF) pretreatment process, there are several major disadvantages of conventional pretreatment processes; significant differences between conventional and UF pretreatments, summarized in Table 3, which affect RO membrane fouling during the RO membrane lifetime [8,9,22–25]. From the table, it can be seen that the UF pretreatment system is more efficient than the conventional one.

2.4. RO membrane process

Cost and performance of RO membrane processes are significantly affected by the following factors [26–38].

2.4.1. Concentration polarization

Concentration polarization effects attributed to solute adsorption and gel layer formation on the membrane surface cause an increase of the osmotic pressure at the membrane and a decrease of the permeate flow flux. It can be described as a combination of two extremes: undisturbed concentration polarization and complete depolarization with a uniform distribution. In other words, gel layers are formed by hydrophobic macromolecules that lead to severe flux decline, and polarization layers are formed by hydrophilic macromolecules causing minimal flux decline.

Table 3
Comparison of conventional and UF membrane pretreatments

	Conventional pretreatment	UF membrane pretreatment
Treated water quality	Unstable and fluctuating water quality depending on raw seawater (Silt Density Index, SDI <4.0)	Stable and constant water quality (SDI <2.0)
Average RO flux	100%	20% higher
RO membrane fouling rate	High fouling potential	Lower fouling potential
RO membrane cleaning frequency	1–2 times per year	4–12 times per year
Typical life time	Filters: 20–30 years, Cartridges: 2–8 weeks	UF/NF membranes: 5–10 years, Cartridges: often not needed
RO membrane replacement rate	100%	33% lower
Capital cost	100%	0–25% higher
Footprint	100%	30–60% smaller
Energy consumption	Lower than UF	Higher than conventional
Chemical dosing rate	High	Lower
Intake line	Long	Shorter
Operation/management costs	High	Lower
Miscellaneous	—	Better boron control

2.4.2. Fouling and scaling

The most important factors affecting the RO membrane process are membrane fouling and/or scaling, resulting in a higher operational cost. Membrane fouling/scaling causes a permeate flux decrease during constant operating conditions. A noticeable permeate flux decline indicates that restoration of original permeability is scarcely possible; inevitably membranes need replacement. Fouling on the membrane surface is mainly caused by natural organic matter (NOM), colloids, and biofilm from bacterial growth (biofouling). Additionally, scaling formed by the precipitation of salts on the membrane surface is often caused by calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$), silica (SiO_2), and iron hydroxide ($Fe(OH)_3$) in the SWRO process. Therefore, a lower consumption rate of treatment chemicals would reduce the scaling and fouling problems due to chemicals. As a result, membrane performance and cost analysis can be projected from the relationship between the foulant/scalant concentrations and fouling/scaling rates.

2.4.3. Chemical cleaning

Use of chemicals is inevitable for cleaning the fouling/scaling from RO membranes. Chemical cleaning methods using alkaline (NaOH), acid (citric acid or H_2PO_4), ethylene diamine tetra-acetate (EDTA), chlorine (Cl_2), and surfactants/detergents have the purpose of removing NOM acids, inorganic scales, scalants (e.g., $CaSO_4$), bio-fouling (biofilm), and colloids, respectively. Here, the type of cleaning agent and its concentration determines the cleaning efficiency. The concentration of the cleaning agent that provides the highest cleaning efficiency is considered the optimum concentration. There are two ways to clean the membrane: cleaning in place (CIP), or cleaning offline. In order to find an optimum membrane CIP cleaning rate, interactions between the foulants/scalants and the membrane and effects between the cleaning procedure and membrane performance should be understood. The optimum cleaning rate (i.e., optimum consumption rate of the cleaning chemicals) enables the final estimation of the RO membrane process operational cost. A preferential cleaning principle for essential foulants was suggested as follows [38]: silica colloids > adsorbed organic compounds > particulate matter (iron and aluminum colloids) > microorganisms > metallic oxides.

2.4.4. Quality and salinity of feed water

In order to increase the permeate recovery rate, RO feed water entering membrane should have a high water quality (i.e., low concentration of particulate matter). The commonly accepted water quality indicators of RO feed water are SDI, turbidity, and suspended solid (SS) concentration; lower values of these indicators and salinity allow for higher permeate recovery rates. As a result, lower specific power consumption can reduce the SWRO plant operational costs.

2.4.5. Feed water temperature

Salt passage is susceptible to variances in the feed water temperature during the RO membrane process. Warm feed water operated at a relatively high temperature (e.g., warm seawater during the summer season or warm feed water reutilized from the cooling systems in heat exchanger) results in an increase of salt passage caused by the thermodynamic increase in the salt osmotic pressure. As a result, an increase of the feed pressure requires greater operational costs to maintain a sufficient driving force for water permeation.

2.4.6. Permeate recovery and salt passage

Membrane properties providing maximum permeate recovery and minimum salt passage rates are the two most important factors in the operation of the RO membrane process. Based on these two factors, membrane designers and manufacturers focus on improving membrane efficiency, as membranes with high permeate recovery and low salt passage properties give rise to preoccupation in the membrane industry market.

2.5. Energy recovery process

In order to reduce the cost of the final product water, it is essential that energy recovery systems that have higher water recovery rates and use less energy with lower installation costs for SWRO systems be utilized [39]. Concentrate water, from the water fed into the RO system with high pressure, has a potential energy that can be transferred from waste pressure to the feed stream flow [40]. Using current technology, this energy recovery system can lower total energy costs by up to 40 % [7]. Typically, there are three types of energy recovery devices in SWRO systems [39,41–43]:

- Energy recovery from brine using a Pelton wheel turbine (PWT): the principle of the PWT energy recovery system is to transfer impinging flow (brine) from one bucket to the next during turbine rotation. Typical PWT efficiencies range from 40 to 60%.
- Energy recovery from brine using a pressure exchanger (PX): PX uses positive displacement to efficiently transfer energy from a high-pressure waste stream containing discharged brine to the incoming process stream. Typical PX efficiency is as high as 95%.
- Energy recovery from brine using a hydraulic turbocharger (HTC): HTC captures the energy of the rejected flow (brine) with a turbine that is directly connected to a pump impeller spinning in the feed stream. Typical HTC efficiency ranges from 50 to 65%.

Among the present generations in the field of pressure transfer, PX has the most elegant design due to its high efficiency and dynamic stability [39], though a competitive energy recovery device in recent SWRO systems is a dual-work exchanger energy recovery (DWEER) device. DWEER technology transfers the hydraulic energy from the brine concentrate to the seawater across a piston where it is used to help power a recirculation pump.

2.6. Post-treatment process

Regarding SWRO desalination, no precise recommendations for permeate quality are currently available [44]. Typical post-treatment in SWRO desalination system involves pH adjustment, minimal remineralization, disinfection, and boron removal; minimally, treatment should meet or exceed the potable water quality standard. Table 4 presents recently proposed general water quality objectives for after post-treatment stabilization, developed by the Marin Municipal Water District SWRO pilot system in the city of Corte Madera in Sonoma County, California [45]. Typical post-treatment to be considered in SWRO systems is summarized as follows [7,44,45]:

- Remineralization and pH adjustment: liming materials followed by carbon dioxide (CO_2) addition are used to remineralize product water before the distribution network; pH is adjusted to a range of 6.8 to 8.1 to meet potable water specifications.
- Disinfection: to kill the bacteria or other organisms in the products by means of UV radiation.
- Treatment of disinfection by-product (DBPs) containing bromide (Br^-) and iodide (I^-).
- Boron removal [46–48]: a boron removal process in post-treatment should be cost effective and reduce the boron concentration to close to zero. In this regard, ion exchange technology using boron selective resins (BSR) is the most appropriate post-treatment to selectively remove boron from permeate water as the high selectivity of BSR is not affected by operating conditions such as temperature, pH, and/or salinity.
- In the view of boron rejection from SWRO membranes, recently developed membranes improved boron rejection efficiency to a range from 92% to 94%. There are several relationships between boron and the surrounding conditions [47,49–51].
- Higher pH condition rejects more boron. At a pH of less than 9.5, approximately 50% of boron is removed, and at pH of 10.5 up to 100% of boron is eliminated.
- Polyamide-type membranes show superior rejection percentages for pH values of less than 9.5.

2.7. Brine disposal and environmental impact

Once SWRO desalination plants and all other required infrastructure is constructed in a coastal area, it is imperative that the high salt concentrations (TDS, ~70,000 mg/L) and other chemicals used in pretreatment and cleaning that could potentially affect the local environment be considered. First of all, the high salt concentration in the brine and several chemical products/ by-products used in the entire SWRO process are inevitably discharged into the sea, and eventually contaminate the marine environment. Second, density differences inhibit a natural mixing and disturb the ecology beneath the sea. Third, when the brine reaches the underlying aquifers from leaks in the pipeline, the presence of chemicals including some heavy metals (iron, copper, zinc, etc.) and cleaning agents may contaminate the groundwater. Last, in a specific case, thermal power generation to produce electricity using oil may indirectly contribute to the process of global warming. Considering the potential magnitude of these destructive impacts on the natural environment, it is crucial that environmentally friendly methods for brine disposal need to be researched. The following are several disposal options recommended elsewhere [7,11,52–54]:

- Deep well injection in non-potable aquifers.
- Utilization of evaporation ponds and zero discharge.
- Link to waste water treatment plants.
- Blending with treated waste water and use same discharged outfall, etc.

Table 4
Proposed general water quality objectives after post-treatment stabilization for the MMWD SWRO pilot system in the city of Corte Madera in Sonoma County, California

Parameter	Units	MMWD treated reservoir			Sonoma County water			SWRO pilot objectives		
		Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
TDS	mg/L	119	136	86	171	186	148	120	180	60
Hardness	mg/L	62	74	52	105	112	96	60	110	60
Alkalinity	mg/L	61	70	49	119	125	110	60	110	50
pH	Units	7.8	7.9	7.8	8.1	8.4	7.8	7.9	8.2	7.8
Color	CU	<3	<3	<3	<3	<3	<3	<3	<3	—
TOC	mg/L	1.6	2.4	1.1	0.9	1.2	0.7	<1	1	—
Sodium	mg/L	16	25	11	20	23	16	30	50	10
Chloride	mg/L	27	37	22	8	10	7	50	70	10
Boron	mg/L	<0.05	<0.05	<0.05	0.28	0.26	0.16	0.3	0.5	—
SAR	—	—	—	—	—	—	—	3	6	—

3. System design models

In a full-scale SWRO desalination process, pretreatment and RO networks can be readily considered for modeling and optimization. Models for UF/MF pretreatment and post-treatment processes can be obtained from the models described here by applying similar mathematical approaches to the desired process. In this section, commonly used models for predicting system characteristics are discussed.

3.1. Pretreatment process models

A typical process in pretreatment is the granular media filter. In granular filtration, particle transport and deposition should be thoroughly understood to predict the transport and fate of colloidal pollutants. Interception, gravitational sedimentation, and Brownian diffusion are the key mechanisms of colloidal particle transport from the pore fluid to the surface of a filter grain [55]. Yao et al. [56] introduced the first filtration model applicable to a water treatment system; however, this model does not include the effect of viscous interaction and/or van der Waals interactions. Thus, in order to obtain an accurate prediction of colloidal filtration, a convective–diffusion equation could be applied by a numerical approach [57].

In practical terms, due to the fact that solving the convective–diffusion equation is not readily available for use, a semi-empirical correlation model for the single-collector contact efficiency in granular filtration developed by Rajagopalan and Tien (R–T) algorithm [58] was proposed. This semi-empirical correlation model was further advanced [55] by considering the influence of viscous interaction and van der Waals interactions, and has recently become more commonly used for predicting the single-collector contact efficiency in granular filtration [59].

3.2. SWRO network model

Although RO technology has significantly advanced in recent years, less consideration has been given to multistage full-scale RO network design [60]. Beginning with the mathematical modeling of transport phenomena across the membrane [61–63], design methods of industrial plants [64,65], and optimization techniques for RO plants [66,67] have been developed using mathematical programming. After El-Halwagi originally presented a structural representation of RO networks (RON) [67], several researchers applied the RON model to optimize RO plants under various conditions [68–71] and retrofitted the model to obtain realistic and economical solutions by optimizing total costs, including both the capital and operational costs [37,72]. Based on the modeling and the optimization of RO membranes including hollow fibers, chronological system engineering efforts for RO membranes are summarized in Table 5.

3.2.1. Model of RO membrane element

A solution/solute diffusion model for predicting membrane performance is one of the most commonly used models in RO system design. The two parameters of water permeability and solute transport (usually denoted as A and B, respectively) are primarily used to modulate the model. These two parameters are usually offered by membrane manufactures; a model with parameters A and B appears elsewhere [73–77]. Then based on the model, the water and the salt fluxes accordingly show the relationships among the feed pressure, permeate pressure, pressure drop in the membrane channel, permeate velocity osmotic pressures at concentrate and permeate, and concentrations of concentrate and permeate.

3.2.2. Model for multi-element module (pressure vessel)

A serial connection of 2–8 RO membrane elements in a pressure vessel can comprise a RO module. The concentrate water rejected by the first membrane element plays a role in the feed water for the second element by the successive order, and so on. For spiral-wound membrane elements, a model of the tubular type membrane element was developed and applied in many industrial fields [69,74,75]. In order to estimate the performance of the membrane elements linked in a series, the performance of a pressure vessel can be simply utilized. When considering the feed spacer distance, the membrane length, the membrane width, and the number of the membrane elements in each RO module (i.e., pressure vessel), the pressure vessel model can determine the optimal numbers and types of membrane elements in a RO module [77].

The total permeate flow rate $Q_{p,n}$ of the nth pressure vessel in a RO unit stage (see Fig. 2), can be calculated from the mass balance equations by combining the total brine flow rate $Q_{b,n}$ and concentration $C_{b,n}$ with the total feed flow rate $Q_{f,n}$ and concentration $C_{f,n}$.

3.2.3. RO network model

Once raw seawater quality and a specific type of membrane module are decided for a SWRO plant design, it is desirable to analyze a cost-effective RON configuration (RO modules, pumps, and energy recovery devices), the operating condition, and the optimal arrangement of the membrane element. To this extent, El-Halwagi [67] and Voros [68,78] presented a structural representation of RON. Fig. 3 shows a simplified RON representation that Lu et al. [76, 77] have recently presented, which applies the stream split ratio, isobaric-mixing constraints, and a PX energy recovery device to the previous RON model.

Pressurization stages N_{ps} and RO stages N_{RO} are the key structures of RON shown in the figure. The number "2" employed in the number of stream junctions (N_{ps}+2) represents the brine and product streams leaving RON. Each stream node inside the pressurization stage represents a stream linked to a high pressure pump, and the pump stream line is connected to a corresponding RO stage. The RO stages are assumed to consist of multiple parallel RO pressure vessels under the same operational conditions. Each stream in the network is supposed to be connected to all the N_{ps}+2 nodes because they are the brine and permeate streams eventually leaving all the RO

Table 5
Chronological systems engineering approaches for RO membranes

Year	Authors (et al.)	Systems engineering approaches for RO membranes
1965	Lonsdale	Homogeneous diffusion model for cellulose acetate membrane [61]
1969	Hatfield	Nonlinear program for maximal flux and optimal arrangement of RO systems in brackish water [91]
1980	Tweddle	Prediction of performance of membrane modules with system analysis [64]
1982	Sirkar	Analytical design to estimate averaged permeate solute concentration in spiral-wound RO module [65]
1984	van Dijk	Optimal design of total unit water cost using raw water TDS, pressure and recovery [66]
1985	Evangelista	Graphical–analytical method to design straight-through and tapered reverse osmosis plants [63]
1992	El-Halwagi	Optimal arrangement, types and sizes of RO units for reverse osmosis networks [67]
1993	Sekino	Analytical model of friction–concentration polarization (FCP) in hollow-fiber RO modules [92]
1996	Malek	Minimal cost analysis per unit membrane area applying large-sized permeates [37]
	Robertson	Dynamic matrix simulations for control of RO desalination pilot plant [93]
	Voros	Mathematical models for performance of various SWRO process units [68]
	Sekino	Analytical model of FCP with Kimura–Sourirajan algorithm applied to hollow-fiber RO modules [94]
1997	Zhu	Optimal design of flexible RON with mixed-integer nonlinear programming (MINLP) [71]
	Voros	Optimal design to minimize total cost of RON plant [78]
1998	van der Meer	Hydraulic model of rejection of mono- and bi-valent ions in spiral-wound RO modules [95]
1999	Al-Bastaki	Mass transport model to predict performance of hollow-fiber RO membranes [74]
	See	RON desalination plant cost analysis with MINLP based on optimal cleaning schedule [72]
2000	Maskan	Optimization of RON operating conditions with a constrained multivariable nonlinear algorithm [69]
	Al-Bastaki	Mathematical analysis of concentration polarization and pressure drop based on flux integration [75]
2001	Wilf	Economic feasibility analysis of SWRO systems based on recovery rate and feed water salinity [96]
2003	Al-Enezi	Design calculations based on feed salinity and temperature in RO desalination process [28]
	Villafafila	Optimization of operating and design parameters using successive quadratic programming (SQP) [82]
	Helal	Optimization of minimum water cost in a hybrid RO/MSF system [97]
2004	Chatterjee	Numerical analysis of hollow-fiber RO module using the three-parameter Spiegler–Kedem (S–K) model [98]
2005	Marcovecchio	Minimization of total cost of hollow-fiber RO seawater desalination using the Kimura–Sourirajan model [81]
	Abbas	Feed-forward neural network model to predict performance of RO experimental set-up [73]
	Vitor Geraldes	Longitudinal variation model for mass/momentum transport in spiral-wound SWRO modules [99]
2006	Senthilmurugan	Mathematical model for separation of two solutes fro aqueous solutions in hollow-fiber modules [100]
	Lu	Optimum design of SWRO system considering membrane cleaning and replacing based on MINLP [76]
2007	Lu	Optimum design of SWRO system under different feed concentrations and product [77]

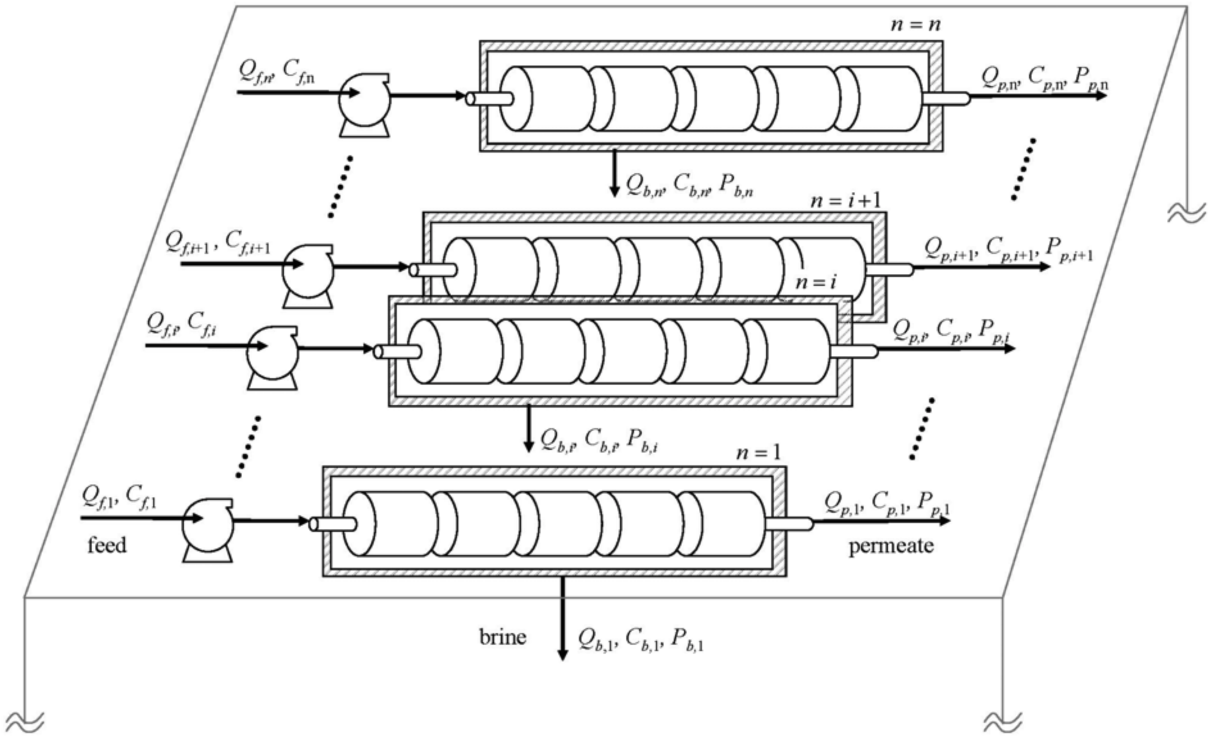

Fig. 2. Schematic diagram of a RO unit train.

stages. The complete mathematical model of RON appears elsewhere [67,68,76–78].

4. System optimization

Once all systems of the SWRO desalination plant are investigated, including the raw seawater quality information, the site condition and area, and the environmental impact, the optimization of the total cost of the SWRO desalination plant needs to be considered. Usually, the total cost is used as an objective function to optimize the design of large-scale seawater desalination plants [77].

4.1. Total cost

The total cost of the plant consists of two terms: capital cost and operation/maintenance cost [37,42]. Capital cost includes all expenditures associated with the implementation for construction (equipment, piping, service utilities, etc.), engineering efforts, and administrative/financing activities. Among them, construction costs are the largest portion of the capital costs, with ranging between 50–85%. Operation and maintenance (O&M) costs consist of plant operation costs (energy, chemicals, replacement of consumables, and labor) and maintenance costs for plant equipment, buildings, and utilities. O&M costs are typically expressed as either all operational expenditures per year (e.g., \$/y) or operational costs for desalinated product water per volume (e.g., \$/m^3).

4.2. Optimization model

Currently, there are several models available for estimating the membrane costs for seawater desalination plants, such as the WTCost© model

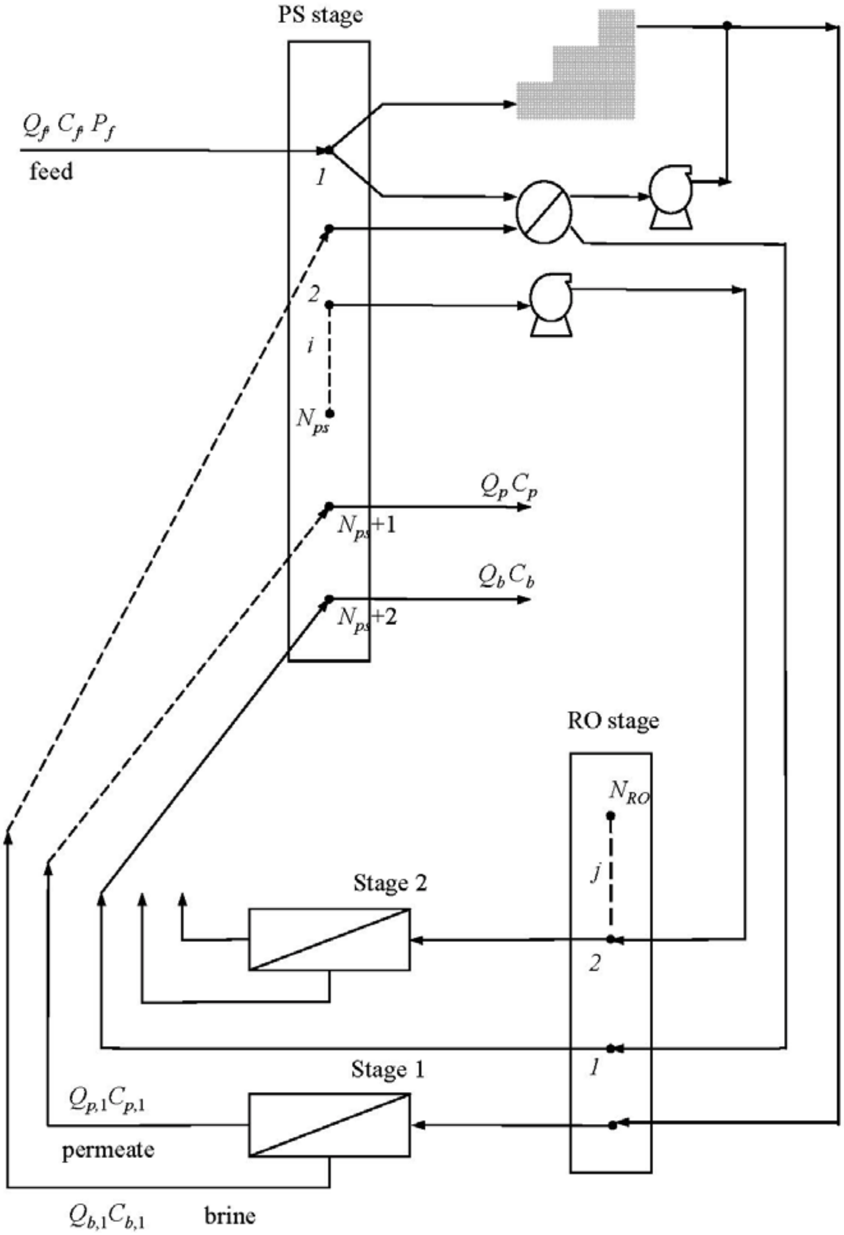

Fig. 3. Structural representation of a RO network.

developed by the US Bureau of Reclamation [79] and the WRA model developed by the Water Reuse Association in the US [80]. These models, however, are not aimed at the optimization of costs but only the estimation of costs of desalination projects. The optimization of a SWRO desalination plant is a minimum principle problem of the total cost. One of the examples for optimizing the total costs commonly used in SWRO [37,71,76,77,81,82], is introduced below.

A mixed-integer nonlinear programming (MINLP) model to minimize the total cost can be formulated as follows [76,77].

$$J = \min_{MINLP} \left[C_T \right] \tag{1}$$

where the objective function (J) is the total annualized cost (C_T).

$$C_T = \left(CC_{in} + CC_{hp} + CC_{px} + CC_{bp} + CC_m \right) 1.411 \times 0.08 + OC_{in} + OC_{hp} + OC_{bp} + OC_m \tag{2}$$

In Eq. (2), CC and OC represent the annualized capital cost and annual operating cost, respectively. In addition, CC_{in}, CC_{hp}, CC_{px}, CC_{bp}, and CC_m indicate the capital cost of the seawater intake pump, the high pressure pump, the pressure exchanger, the booster pump, and membrane purchase, respectively; OC_{in}, OC_{hp}, and OC_{bp} are the energy cost for operating these pumps, and OC_m is the cost of membrane module maintenance. Note that 1.411 is the coefficient that is used to calculate the practice investment and 0.08 is the capital charge rate.

$$CC_{hp} = 52 \left(\Delta P Q_{hp} \right)^{0.96} \tag{3}$$

$$CC_{px} = 3134.7 Q_{px}^{0.58} \tag{4}$$

$$Q_{ps,1} = Q_{hp} + Q_{px} \tag{5}$$

In Eqs. (3)–(5), P, Q_{hp}, and Q_{px} indicate the pressure and flow rates in the high pressure pump and pressure exchanger, respectively; $Q_{ps,1}$ denotes the flow rate of the first pressurization stage (see Fig. 3).

$$C_m = \sum_{j=1}^{N_{\mathrm{RO}}} \sum_{k=1}^{8} Z_{j,k} C_k m_{j,k} n_j + \sum_{j=1}^{N_{\mathrm{RO}}} C_{pv} n_j \tag{6}$$

In Eq. (6), C_m, C_k, and C_{pv} denote the total membrane module cost, the price of the kth membrane element, and the price of the pressure vessel, respectively. Here, the indices j and k represent the jth RO stage out of N_{RO} number of RO stages and the kth membrane type out of a maximum of eight elements. Furthermore, $Z_{j,k}$ is the binary variable, either 0 or 1; $m_{j,k}$ is the number of membrane elements in each pressure vessel; and n_j is the number of pressure vessels employed in the jth RO stage.

(7)

$$\eta_{px} = \frac{\sum (PQ)_{\mathrm{out}}}{\sum (PQ)_{\mathrm{in}}} \times 100 \tag{8}$$

In Eqs. (7) and (8), C_e is the cost of electricity, and f_c is the load factor. Here, η_{hp}, η_{motor}, and η_{px} are the efficiencies of the high pressure pump, the electric motor, and PX, respectively. This MINLP problem can be solved using any commercial solver that can provide the best possible solution.

Possible optimization results of the SWRO desalination process are illustrated in Fig. 4. The conceptual graph can provide insights into the relationships among relevant costs, permeate, and feed concentrations. In the figure, the two regions demarcated by A and B represent the different optimization results in two different RO configurations (e.g., SWRO two-stage serial configuration with intermediate recycle (A) and without intermediate recycle (B)). Fig. 4 indicates that both process parameters and process configurations can affect the optimized costs for SWRO desalination plants.

4.3. Factors influencing total costs

The optimization model described above is one of simplified approaches using reasonable

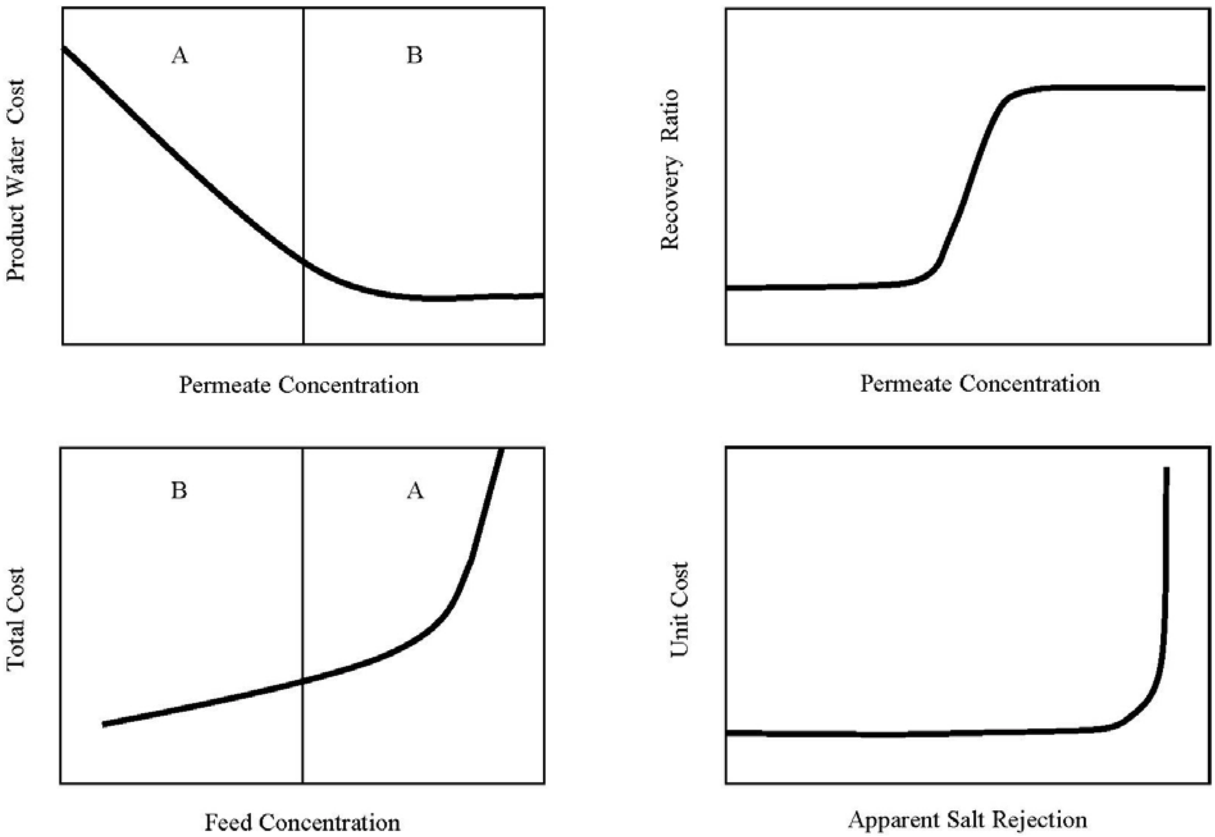

Fig. 4. Conceptual optimization outcomes of relationship among relevant costs, permeate, and feed concentrations. Two regions demarcated by A and B represent the different optimization results in two different RO configurations.

assumptions. When an accurate optimization technique is necessary in the design of a SWRO desalination plant, a systematic approach for the optimization is required. And although all possibilities should be discussed in the optimization of SWRO desalination plant, a reasonable consideration of factors influencing the total costs is essential. Fig. 5 summarizes the factors affecting the total costs, suggesting things to be considered for an accurate cost optimization through an understanding of key factors.

5. Future implications

It is important to continue further development and investment efforts in SWRO desalination programs to resolve water scarcity problems in regions around the world, with the ultimate goal of reducing the cost of final water production [83]. Subsequently, several researches to make the cost of product water cost more economical and enhance process performance are suggested as follows:

5.1. Pretreatment process [83,84]

- In the SWRO desalination process, it is essential to improve methodology for achieving optimal pretreatment. Since extra pretreatments increase O&M costs, a more effective operational design and more sophisticated automation and control will result in lower costs of water production.

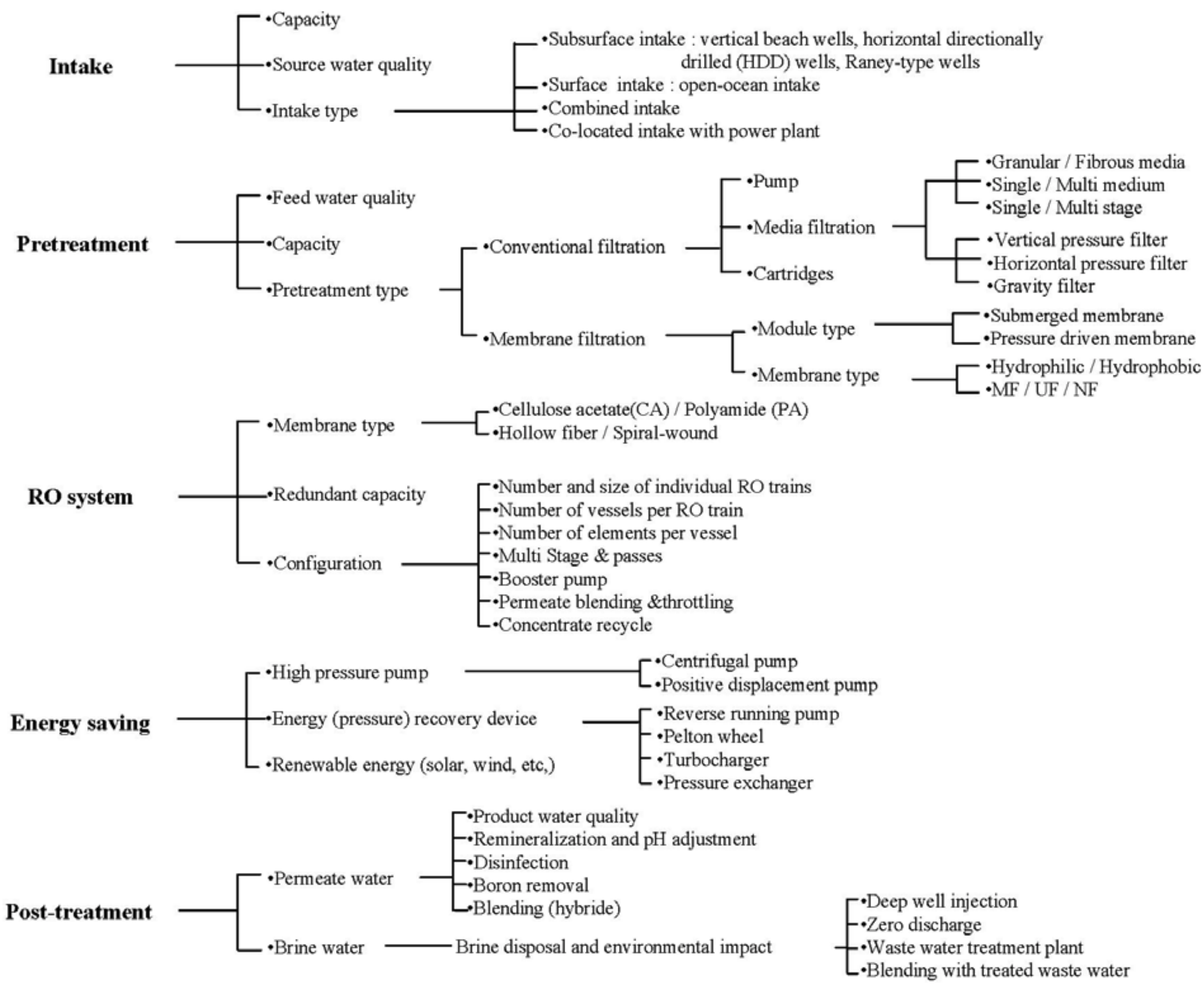

Fig. 5. System factors affecting the total cost in a large-scale SWRO plant.

- Development of an environmentally friendly pretreatment system to control scaling, fouling, and biofouling by reducing the use of chemicals.
- Combination of UF and NF with conventional pretreatment methods.
- Use of natural pretreatments such as beach well intakes.

5.2. RO membrane processes [8,85]

- Better understanding of the mechanism of water transfer and salt rejection in RO membranes at the molecular level will lead to a new era of membrane technologies.
- Increase membrane resistance to oxidizing agents and chlorine.
- Development of large-size membrane elements and membrane compaction techniques.
- Research on the long-term behavior of membranes at elevated temperatures.
- Research on a SWRO/BWRO hybrid system.

5.3. Energy saving processes [83,86–90]

- Renewable energy:

1. Need to continue to invest international efforts toward revolutionary new renewable sources of energy.
2. Co-generation of renewable energy with a present SWRO desalination energy generator should be studied.

- Hybrid systems:
1. Membrane/thermal: (a) increase of up to 49% in RO product water recovery. (b) Flexibility in operation, less specific energy consumption, and low construction cost.
2. NF–RO–MSF–crystallization: (a) Higher water recovery rate (77.2%) and lower water cost (\$0.37/m^3). (b) Reducing scales formed from ions in seawater. (c) High temperature operation. (d) Increase of water productivity.

5.4. Post-treatment processes

- Research on environmental friendly treatment methods (see brine disposal and environmental impact in Systems Investigation section).
- Advanced boron removal technology.

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