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Review Paper

Scale-up Strategies for Membrane-Based Desalination Processes: A Review

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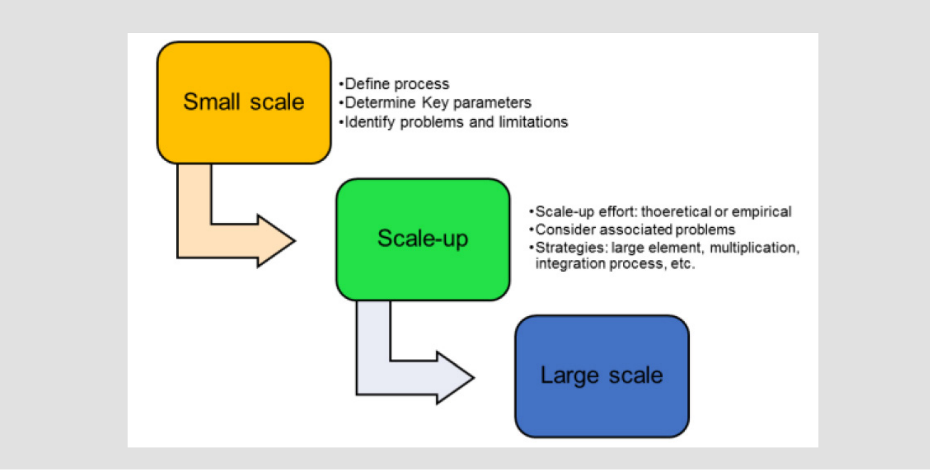
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Effective scale-up is essential to reproduce the success of small scale system• PVP and photocatalysts improved water permeability up to seven folds
- It is desirable to keep operating parameters constant
- Integrated processes give attractive opportunity in pre-treatment up to post-treatment
- Large size membrane element shows potential benefit for large scale installation

ABSTRACT

Membrane-based technologies have increasingly been chosen in desalination processes, which is evidenced by the increase of large-scale plants constructed in recent years. Indeed, several appropriate strategies should be considered to minimize problems faced during the construction, such as membrane system designs, area requirement, energy requirement, operation and maintenance, and environmental impact, which are related to the economic view and process efficiency. Keep the operating parameters constant during the scale-up of the membrane system should also be an important concern to maintain the performance of the membrane system. In this paper, scale-up strategies for the membrane-based desalination process are reviewed, including desalination technology, economic evaluation, industrial challenges, and scale-up effort. In addition, the opportunity of the integrated membrane system is also emphasized.

1. Introduction

The scarcity of fresh water due to the rapid growth of population and industries saline water (brackish and seawater) treatment through the desalination process has received increasing attention in recent years as an alternative solution. More than 17,000 desalination plants have been operated worldwide with an average production rate of 66.5 million m^3/day [1]. There are two categories of desalination technology, namely thermal and membrane-based desalination. Specific energy consumption, water cost, operation and maintenance, and environmental impact are the set of parameters that are used to determine the most desirable processes among distillation technologies [2, 3]. High water quality, simple operation and design, easy scale-up, smaller foot print, lower energy requirement, cost effectiveness, and being environmentally friendly are the prominent advantages that deliver membranes to become the major separation technique

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for the desalination process compared with the conventional technologies. Furthermore, continuous improvement and significant cost reduction lead to membrane-based desalination, particularly reverse osmosis (RO), as the dominant choice in producing fresh water from saline water. It has been reported that almost 60% of global desalination capacity is dominated by RO plants [4]. Typical examples of megaprojects in seawater reverse osmosis (SWRO) plants are the Sorek plant with 624,000 m³/day capacity [5] and Askhelon with 330,000 m^3/day capacity [6] which have been constructed and operated in Israel.

In spite of their advantages, membrane based processes are challenged by some limitations. The major obstruction in membrane-based processes is fouling and scaling phenomena [7, 8]. A comprehensive review of fouling control strategies on membrane-based desalination has been presented in the literature [9–11]. For a larger capacity of the membrane-based desalination plant, space requirement, number of components of membrane elements, pressure vessels, piping and instrumentations being used, and large quantity of waste disposal (brine) are the other challenges. Space requirement and components used in large-scale desalination plants contribute to the increase of investment cost that results in higher overall cost. Meanwhile, brine discharge management becomes a critical concern due to its impact on the environment [12, 13]. Therefore, these aforementioned factors should also be considered during the scale-up steps of the membrane-based desalination process.

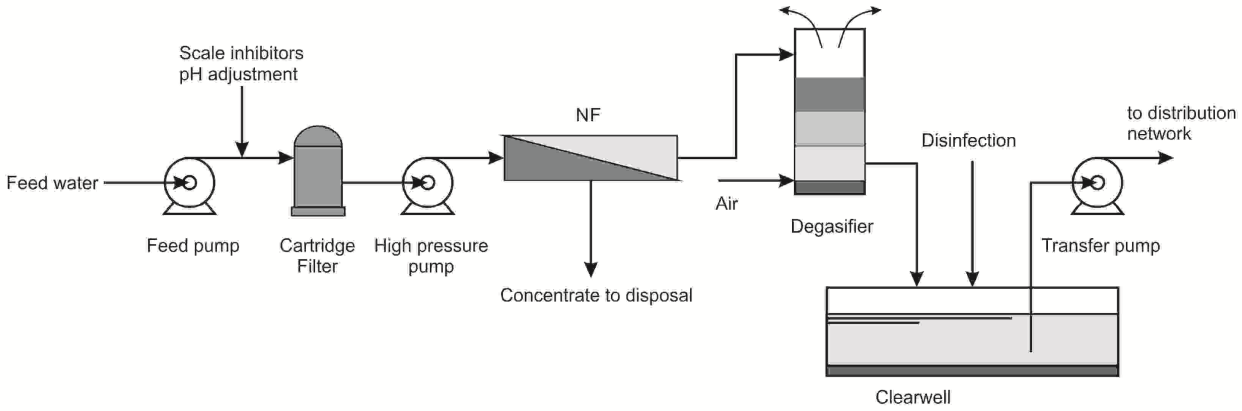


Fig. 1. Schematic flow diagram of NF softening plant. Adapted from [55].

Table 1
Membrane based desalination process.

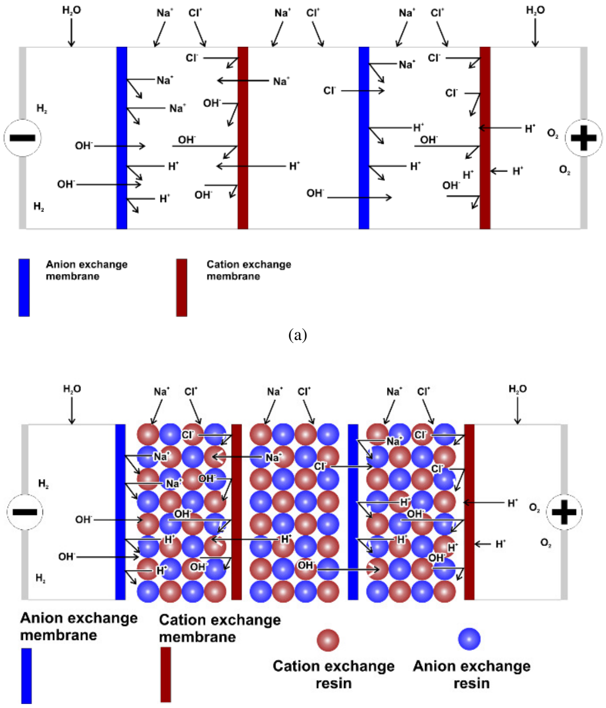
Process	Description	Energy cons. (kWh/m^3)	Sp. water cost ($/$m^3$)
Reverse Osmosis (RO)	Pressure driven Typical feed water: Seawater, brackish water ○ SWRO product: 400-500 ppm TDS [15] ○ BWRO product: 200-500 ppm TDS [15]	○ 2 – 6 [14] ○ SWRO: 4 – 6 [15] ○ BWRO: 1.5 – 2.5 [15]	○ SWRO: 0.45 – 1.72 [15] ○ BWRO: 0.26 – 1.33 [15] ○ 0.53 – 0.83 [16]
Nanofiltration (NF)	Pressure driven Typical feed water: Surface water, brackish water, seawater Removes more than 90 % hardness, 60 % monovalent ions [17]	0.54 (surface water) [18]	0.23 (surface water) [18]
Electrodialysis (ED)	Electrically driven Typical feed water: brackish water Product of brackish water desalination:150-500 ppm TDS [15]	○ 0.4 – 8.7 [14] ○ Concentrating NaCl: 155 kWh/ton NaCl [19]	0.6 – 1.05 [15]
Electrodeionization (EDI)	Electrically driven Typical feed water: RO permeate Product resistivity: 10 – 18 MΩ-cm (ultrapure water)	○ 0.2 – 0.8 [20] ○ 0.69 [21]	0.53 [22]
Membrane Distillation (MD)	Thermally driven Typical feed water: Seawater Product: < 4 µS/cm [25]	1.25 (low grade energy) [23]	0.64 – 1.23 [24]
Membrane Capacitive Deionization (MCDI)	Electrically driven Typical feed water: Brackish water	0.1 – 2.03* [14]	-
Microbial Desalination Cell (MDC)	Electrically driven Typical feed water: Saline water and waste water [26] Removes > 90 % salinity from 30- 35 g/L feed water [26]	-	-

*Data from Capacitive deionization (CDI)
BWRO: Brackish water RO; TDS: Total dissolved solid;

Scale-up is generally performed in several steps, which hold an important role in the success of a commercial scale process. During the steps, investigation of the process performance is focused on achieving optimal operating parameters. Furthermore, factors that affect the overall performance of the process are also considered. In this paper, scale-up strategies in the membrane-based desalination process are reviewed comprehensively. Overview of membrane-based desalination technology, industrial challenges, scale-up effort, and future prospects of the integrated membrane based desalination technology are presented.

2. Overview of desalination

Membrane-based desalination processes that have been fully commercialized since 1987 up to the present time, involve pressure driven membrane, electrically driven membrane and recently, thermally driven membrane processes. The descriptions of these membrane processes are presented in Table 1.



(a)

(b)

Fig. 2. Schematic diagram of (a) ED and (b) EDI.

Those types of membrane processes can be categorized into two groups based on the components that are transported through the membrane, i.e. water or salt. Typically, seawater contains 3.5 g/L of salt components, which means that almost 97% of seawater content is water. Actually, the desalination process seems to be more economical and efficient by permeating salt components through the membrane. However, the enormous quantity of membrane developments, particularly reverse osmosis, is focused on the improvement of membrane hydrophilicity, which offers superior water permeability than other components in seawater. It is considered more efficient and less energy consuming compared with the early RO technology. In this sub-chapter, several membrane-based processes that were recently used in the desalination process are presented. The economics of each membrane process are also evaluated.

2.1. Reverse osmosis (RO)

RO is a pressure driven membrane process where the membrane acts as the selective barrier for a particular component while partially or completely blocking others. Feed solution which contains dissolved solids such as salt is divided into two streams wherein the salt components are rejected into the concentrate stream while the almost pure water is produced in the permeate side. Improvement in RO technology including advances in membrane material, module and process design, pre-treatment, and energy recovery has led to cost reduction which in turn gains interest for its commercial applications [27]. In addition, RO is considered as simple to design and operate compared with other desalination processes [28]. RO is now being used for various applications and becomes a leading technology for brackish and seawater desalination [29–32]. Since the end of the 1970's, energy consumption of SWRO has been reduced significantly due to process improvement [33]. The optimization of RO membrane configuration (single, two-pass or multiple stages) is required in large-scale design, since the specific membrane cost is higher than the specific energy consumption [34]. The two pass of the RO unit are used when the target solute cannot be accomplished in a single pass. However, from an energy consumption point of view, a single pass of RO unit results in a lower specific energy cost than the two-pass process. Up to the present time, there is a continuing investigation on process development of RO technology to achieve a better separation at lower energy demand.

In 1999, approximately 78% of the world's seawater desalination capacity was made up of multistage flash (MSF) plants while RO represented 10% [35]. Nowadays, most desalination plants use membrane-based process, representing 60% of the total number of worldwide plants [4]. A typical example of the largest SWRO desalination plant was commissioned in 2013 in Sorek, Israel, with a production capacity of 624,000 m^3/day potable water as reported by IDE technologies [5]. The system incorporates a 16″ RO element which is arranged vertically and uses 100,000 m^2 land area. The energy consumption is minimized by IDE's Proprietary 3-Center Design (pumping center, membrane center and energy recovery system) and double line intake. This plant is expected to produce water with a maximum energy consumption of 4 kWh/m^3 and contains 0.3 ppm of boron. Every element of the plant was customized to minimize investment costs and environmental impacts. The lower investment costs are achieved by several strategies, such as decreasing the number of pressure vessels, piping headers, control and instrumentation equipment, and reducing its footprint.

2.2. Nanofiltration (NF)

NF is a pressure driven membrane separation process that employs membrane as a selective barrier, which has characteristics between RO and the ultrafiltration (UF) membrane [36]. NF provides higher fluxes than RO and better rejection for small molecules than the UF membrane [37]. NF is able to remove turbidity, microorganisms, hardness, and a fraction of dissolved salts [38]. The membrane used in NF is typically asymmetric with an active top layer [39]. It combines the sieving effect and Donnan's effect for removing uncharged and charged components, respectively [40]. The NF membrane has been widely applied in several areas, such as desalination and concentration [39], separation and purification [41, 42], drinking water [43], and wastewater treatment [44, 45].

Since NF exhibits high rejection for multivalent salts, it is then introduced as pretreatment for SWRO desalination that improves RO flux [46–48]. By integrating NF as SWRO pretreatment in a pilot scale of the desalination plant, a higher recovery ratio of RO could be achieved which is contributed to the reduction of fresh water cost up to 27% [49]. In the other case, the elimination of the scale forming constituent by NF may possibly increase the high top temperature brine (TTB) in the MSF desalination process and prevent the scale formation on desalination equipment, particularly on the heating surface [50]. The scale-up of this NF-SWRO integration plant was constructed at Umm Lujj, Saudi Arabia that increased the SWRO unit water recovery from 26% to 56% [51]. The prospect of the NF membrane as RO pretreatment is discussed further in section 5.

As SWRO pretreatment, NF was found to be successful in removal of turbidity, in the significant removal of hardness and in lowering of the seawater TDS [49] that could improve SWRO performance. In addition, the application of NF can reduce chemical consumption used in conventional pretreatment. However, NF membranes are also prone to fouling that can decrease its performance [52]. Fouling occurrs due to precipitation of inorganic components such as $CaCO_3$ or $CaSO_4$, organic substances, or bacteria [53]. High operating pressure is also the disadvantage of using NF as pretreatment. The high pressure leads to high energy consumption that affects the overall operation cost. Another problem for NF and for pressure-driven membrane filtration in general, is the required further treatment of the concentrate stream [54].

Another typical application of NF is water softening which shows advantages such as lime softening. Bergman [55] compared NF softening and lime softening including the cost of both processes. The typical NF softening plant is illustrated in Figure 1. The results of the study show that operation and maintenance costs of lime softening are lower than NF softening. However, the cost difference is decresed with larger capacity. The advantages of NF softening over lime softening are a superior product quality which have additional removal of color and turbidity, process flexibility, smaller footprint, and no sludge formation.

NF has been applied in desalination of effluent with high concentration of salt [56]. NF was used to treat industrial effluent with a high concentration of salt namely crude iron dextran solution, iminodiacetic acid mother liquor, and raw soy sauce. Results of the study indicate that NF is a viable and promising process for removing monovalent salt from the effluent (e.g. food and chemicals) because NF could effectively reject organic solutes while monovalent inorganic salt passed through easily.

2.3. Electrodialysis (ED)

ED is an electrically driven membrane process that utilizes the ion exchange membrane as the selective separator for ionic substances and electrochemical potential as the driving force [19]. ED has been used for brackish water desalination for over 50 years and the basic process has been significantly modified into several related processes. The ED related processes are conventional ED, electrodeionization, electrometathesis, electrodialysis with bipolar membranes, etc. [57].

ED and related processes are comprised of components including direct current supply, electrode, ion exchange membranes and solvents and electrolytes [58]. An ED module (stack) contains the cation exchange membrane (CM) and anion exchange membrane (AM) which are employed as active separators. Both of the membranes are packed in alternating arrangement between electrodes (anode and cathode) while spacer is inserted in between to form an individual compartment. A stack generally consists of several pairs of diluate and concentrate compartments and a pair of electrode compartments (Figure 2). When an electrolyte solution is transferred through those compartments and an electrical potential is supplied from the electrodes, the cations and anions migrate towards the cathode and anode, respectively. The cations pass through the CM and are excluded by AM. Otherwise, the anions pass through the AM and are excluded by the CM. The ion concentration of solution is depleted in the diluate compartment while it is concentrated in the concentrate compartment.

ED has been considered as a reliable process in water desalination for more than half a century. Moreover, ED exhibits several advantages compared to its competing processes such as RO, distillation and conventional ion exchange [19], that includes:

- Very little pre-treatment is required (compared to RO); membrane fouling and scaling is reduced to minimum due to periodic reverse polarity
- More brine concentration can be achieved (compared to RO); there is no osmotic pressure limitation
- The membrane has long durability
- Lower energy and investment cost (compared to distillation)
- No chemical regeneration is required (compared to conventional ion-exchange).

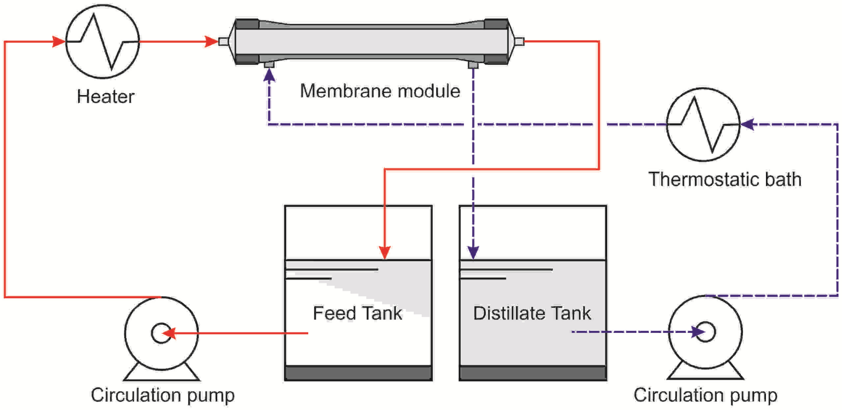


Fig. 3. Schematic diagram of membrane distillation in batch operation. Adapted from [24].

However, ED also has several limitations, which correspond to technical and economic factors. The disadvantages of the ED process are [19]:

- Uncharged species are not eliminated
- Relatively high energy consumption is required when processing solution with high salt concentration
- The investment cost is relatively high for producing diluate with very low concentration
- ED is cost effective for a certain range of feed water salt concentration

2.4. Electrodeionization (EDI)

EDI, a modified ED, has been extensively recognized since the mid-1950s. After the first commercial unit introduction in 1987 [59], EDI has continued to be an attractive deionization process with significant advantages over the conventional ion exchange deionization in the production of ultrapure water from a technological and economical standpoint [20, 60]. The main reason for its commercial success is that EDI eliminates the chemical regeneration process and its associated hazardous chemicals. Therefore, this process is increasingly becoming the dominant choice for producing ultrapure water [61, 62]. EDI is mainly applied for water treatment, but it has also shown potentials to be applied in a number of different applications such as in wastewater treatment, biotechnology and biopharmaceutical, and other potential fields [63-66].

An EDI module (stack) has similar components as those used in ED wherein ion exchange membranes are employed as active separators (Figure 2). In the EDI system, the diluate compartments are filled with electrically active media, such as ion exchange resins. In some cases, the concentrate and electrode compartments can also be filled, depending on the product quality requirement. By employing ion exchange media inside the cells, EDI is expected to be an effective deionization process to treat a solution with higher electrical resistance compared with ED. The ion transfer from the diluting compartment to the membrane surface is almost entirely mediated by the ion exchangers [67].

The EDI performances for ionic separation have been compared with the ED process, e.g. elimination of nitrate [68], water demineralization [69], removal of hardness ions [70], demineralization of brackish water [71], and NaOH recovery [72]. EDI has showed better performances than ED, especially for dilute solution due to higher electrical conductivity provided by ion exchanges filled in the compartments. Recently, the commercial applications of EDI are still focused on high purity water production, since EDI can remove weakly ionized components efficiently through extensive water dissociation.

As mentioned previously, the EDI process has been commercialized in over twenty years and has gained widespread acceptance in the production of ultrapure water. The ultrapure water applications include pharmaceutical manufacturing, steam generation or power plants [61, 73], microelectronics or semiconductor manufacturing [74–76], and academic and clinical laboratories [77]. Several manufacturing industries that use ultrapure water in their process are semiconductor wafer manufacturer, microelectronic device manufacturer, solar panels, or flat-panel displays. The standard design to obtain ultrapure water uses a combination of RO and EDI. With this design, the system can produce water, which has specification concentration near or below detection limits [78].

EDI has many attractive features as summarized in the literature [63]. One of the features is a unique “electro-regeneration” for regenerating the resins. The resins are never fully exhausted; therefore the consumption of a chemical regenerant could be eliminated. It means that the cost for the chemical regeneration process, which is required in a conventional ion-exchange (IX) system including labor and chemical, could be eliminated and replaced by a low cost of electricity. In addition, EDI systems can be operated in a continuous process and able to produce pure water with high resistivity. More than 90% salt rejection could be achieved, which cannot be reached by a conventional ED.

Nevertheless, high investment cost and difficulty in repairing the module due to the complex equipment configuration are the issues that render EDI less popular than the conventional ion exchange in many large scale applications [60, 79]. Scaling is also the problem faced by EDI especially in the concentrate compartment wherein the concentration of bivalent ions such as Mg^{2+} and Ca^{2+} are increased. Those components can be precipitated on the membrane surface due to local pH shift caused by concentration polarization. The resin inside the compartment also has potential problems on increasing pressure drop. The worst condition occurs when the resins are agglomerated in the compartment outlet that provides additional hydraulic resistance. Therefore, many attempts have been conducted to develop EDI stack and configuration for improving module performance and cost [63].

2.5. Membrane distillation (MD)

MD is a thermally driven membrane based separation that utilizes a hydrophobic microfiltration membrane as a selective barrier for separating the vapor phase from feed stream [80]. The hydrophobic nature of the membrane prevents the liquid phase from entering its pores [81]. In addition, vapor pressure difference, which is generated by temperature difference across the membrane, acts as the driving force [80]. The schematic diagram of membrane distillation in batch operation is shown in Figure 3.

The MD process has several potential applications, e.g. production of high-purity water, concentration of ionic, concentration of colloids and other non-volatile aqueous solution, and removal of trace volatile organic compounds [82]. The advantages of MD compared to its competing desalination processes are [83, 84]:

- lower operating temperature
- lower operating pressure than RO
- high solute rejection
- it is not limited by high osmotic pressure
- it can work with high solute concentration
- modular and smaller foot print

Meindersma et al. estimated that the total cost for drinking water with membrane distillation could be less than the RO treatment depending on the source of thermal energy [85]. A pilot scale of the solar driven membrane distillation system has been developed in Aqaba, Jordan, which was designed for a remote area [86]. Chemical pretreatment could be eliminated and will significantly reduce the operational cost of the desalination plant. However, the solar powered membrane distillation technology is still expensive compared to other desalination processes, which is expected to reach $\$18/m^3$ [87].

Despite their advantages, MD technologies have not been commercialized yet in an industrial scale due to several barriers, such as [81]:

- a relatively low permeate flux
- flux declining due to concentration and temperature polarization effects, membrane fouling and total or partial pore wetting
- membrane and module design for MD
- high thermal energy consumption: uncertain energy and economic costs for each MD configuration and application

Therefore, to overcome these challenges, researchers are still proposing any possible efforts to make MD a viable separation process.

2.6. Forward osmosis (FO)

FO is one of the emerging technologies that produces fresh water by utilizing an osmotic pressure difference across the membrane as a driving force [88]. FO has been investigated in a wide range of applications, including saline water desalination, clean energy generation, waste-water treatment, and food processing, which are attributed to a range of benefits [89]. For example, benefiting from the low pressure required to perform FO operation, FO holds the promise of achieving low energy consumption and the operating cost as well [89]. On the other hand, FO also generates clean energy that is induced by the salinity gradient of fresh and saline water (PRO) [89]. Thus, a combination of both functions makes FO a potential technology to face the global water problem and energy crisis. In addition, since FO requires low operating pressure and temperature, FO has potential applications in liquid food and pharmaceutical processing while maintaining the physical properties and quality of products [90, 91]. Nevertheless, the commercialization of the FO membrane has been limited by several challenges, such as severe concentration polarization, low flux membrane, and the availability of appropriate draw solutions (cost effective and non-toxic) [92, 93]. Therefore, there should be further development in membrane materials, draw solutes, and membrane fabrication to bring FO into commercialization. In spite of its limitation, basic research on FO and the development of FO applications are steadily growing [94].

2.7. Membrane capacitive deionization (MCDI)

Capacitive deionization (CDI) is a desalination process that utilizes a capacitive electrode adsorption device and electrical field as a driving force. In CDI, ionic substances are removed when electrolyte solution is transferred through a cell with a couple of electrodes and the electrical field is established [95]. The concept of ion transport in the CDI unit is presented in Figure 4 which is explained in literature [96, 97]. When the electrical field is established, counter ions in the solution migrate toward electrodes and are stored within the electrodes under electrostatic force. On the other hand, when the polarity reversal is applied, the ions are desorbed from the electrodes. The first operation produces desalted water, while the later regenerates each electrode.

However, during the desalting step, ions that have been adsorbed on the electrode are brought back into the solution due to attraction from ions with an opposite charge near the electrode [98]. Therefore, adsorption and desorption occur simultaneously, and thus reduce electrode capacity as well as current efficiency [99, 100]. To overcome the aforesaid problem, CDI is developed by including ion exchange membrane in front of the electrode, which is then called MCDI [101]. The membranes act as barrier that block the co-ions to migrate from the electrode into the solution and are retained in the space between the electrode and the membrane [102]. As a result, salt removal efficiency and current efficiency of MCDI are enhanced compared to CDI [102, 103]. MCDI is energy efficient desalination technology compared to RO and distillation especially for feed water with relatively low salt concentration [95]. Additionally, MCDI is an environmentally friendly process since no contaminants or by products are produced during both the desalination and regeneration process [104].

However, the commercialization of both CDI and MCDI is prohibited by high electrode cost and low salinity limits [14]. Researches in this desalination technology still lack several attempts in different directions, such as development of a comprehensive and robust model, pilot scale demonstration that could provide scalability, cost, salinity limit, and long term operation that could provide information about fouling and scaling in the electrode [14].

Some researchers reported a new concept of MCDI to solve the problem faced by conventional CDI. A new concept of MCDI termed flow-electrode capacitive deionization (FCDI) has been introduced by Jeon et al. [105] and has been tested for seawater desalination. The use of fixed electrodes makes the conventional CDI process inefficient since the effluent stream should be flushed out during the discharging step. Another problem for conventional CDI is the use of a large number of cells for a large capacity unit. In this FCDI concept, the discharging step is not required within the same cell and could be scaled-up by simply increasing the number of flow-electrodes. The study showed that the FCDI cell exhibited excellent removal efficiency (95%). The result also indicated that the FCDI process could effectively overcome the limitations of typical CDI processes.

Lee et al. [106] have proposed a new concept of CDI by combining CDI and the battery system to increase the desalination performance of capacitive techniques termed Hybrid Capacitive Deionization (HCDI). HCDI consists of a sodium manganese oxide ($Na_4Mn_9O_{18}$) electrode, an anion exchange membrane, and a porous carbon electrode. In this process, sodium ions are captured by the chemical reaction in the $Na_4Mn_9O_{18}$ electrode, whereas chloride ions are adsorbed on the surface of the activated carbon electrode during the desalination process. The study showed that HCDI had more than double ion removal soprtion compared to CDI. HCDI exhibited a rapid ion removal rate and excellent stability in an aqueous sodium chloride solution.

2.8. Biomimetic aquaporin membrane

Biomimetic aquaporin membrane is one of emerging desalination processes that exhibits both high water permeability and high solute rejection [107]. Aquaporins are pore-forming proteins and ubiquitous in living cells, which can form the water channel that facilitates water transport and excludes ionic components [107]. For the past several years, a number of studies have been conducted to utilize aquaporins or replicate the protein's functionality in the development of a new biomimetic membrane technology. The complex structure, hydrophobic trans-membrane region, host toxicity, and time consumption are the main obstacle in protein production [107]. These limitations then make most aquaporins only in lab-scale applications [108, 109].

2.9. Microbial desalination Cell (MDC)

MDC is a relatively new method that holds the promise of reduction or elimination of electricity power for the desalination process [26]. MDC is a modified process from the microbial fuel cell (MFC) [110]. Generally, MDC consists of three compartments namely anode, cathode, and center (salt) compartment [111]. Compartments are separated by cation and anion exchange membranes.

In MDC, exoelectrogenic microorganisms generate electrical potential from degradation of organic substances, which are used to drive ions in saline water though the ion exchange membrane [26]. The exoelectrogenic bacteria oxidize substrates in water and release electrons from the anode to cathode [112]. The reactions occur in both anode and cathode chambers, and then create a potential gradient to induce ion migration from the center of the compartment into the anode and cathode compartment. It has been reported that 90% of salt in the solution that contains 30-35 ppm NaCl concentration could be removed by MDC [26]. Furthermore, higher salt rejection, up to 99.99%, could be achieved when it is applied to desalinate brackish water that contains 10 g/L of NaCl (99 %) [113].

As aforementioned, MDC demonstrates its ability to combine energy production, desalination, and waste water treatment in a simultaneous process, which can be applied in wastewater treatment and the desalination field [114]. However, the desalination efficiency of the MDC is limited by fluctuating voltages generated during anode and cathode reactions [115]. Additionally, low solution conductivity at the end of the operation contributes to high cell resistance that prohibits MDC operation [115]. Another challenge in MDC applications for water treatment is biofouling [26]. Therefore, those challenges should be considered in further development of MDC technology to produce a qualified membrane.

2.10. Economic evaluation

The economic evaluation of membrane processes are frequently calculated based on the basic cost of capital investment and operational expenditure. Table 2 shows the summarized evaluation of treatment cost for different membrane based processes that are adapted from several literatures. Total capital cost comprises direct and indirect cost which can be estimated as 1.411 of the total equipment cost [116]. The direct cost covers equipment cost and site development, where 28% of the total direct capital cost is calculated as indirect cost. In evaluating the cost of MD plant, basic equipment cost is calculated based on membrane, pressure vessel, pump and heat exchanger cost. Meanwhile, the operational and maintenance costs include energy, membrane replacement, and chemical consumption. On the other hand, fixed charge is obtained from ammortization rate with a 0.08 ammortization factor [24]. However, it should be noted that the basic cost calculations generally exclude piping and its instrumentation, and other operational costs, such as labor, maintenance, brine disposal, etc. It is shown in Table 2 that the highest desalination cost is required for the MD process, since it requires thermal cost (steam) and investment for the heat exchanger.

Most of the membrane based process costs are mainly dominated by energy and membrane replacement. The energy is dictated by liquid flow transfer and pressure for the pressure driven membrane. Meanwhile, the electrically driven membrane requires charge for ion transportation. Steam is needed by the thermally driven membrane such as the MD process. Membrane cost is essential since the membrane acts as the key separator and contributes to total equipment cost (investment cost). Thus, membrane characteristics play an important role for capital cost reduction. High permeate flux, high selectivity, and long durability are typical characteristics required to reduce membrane cost.

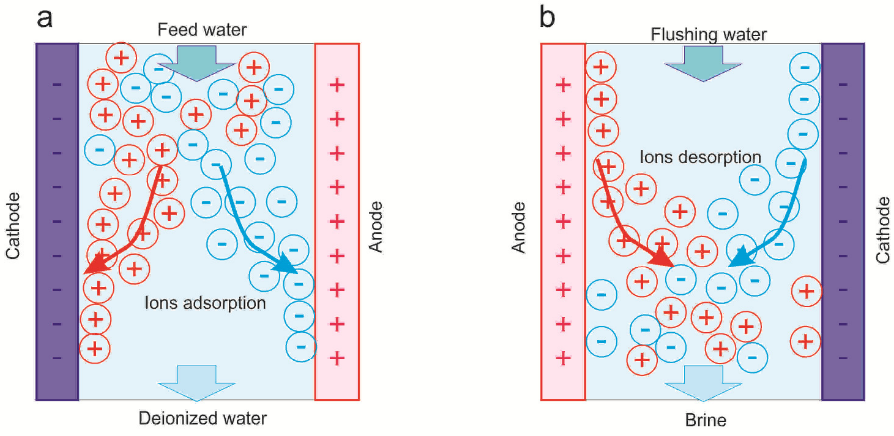


Fig. 4. The schematic concept of CDI: (a) deionization and (b) regeneration process. Adapted from [96].

Table 2
Treatment cost of membrane-based desalination processes.

Cost ($\$/m^3$)	Seawater RO (SWRO)	Brackish water RO (BWRO)	Low-Pressure RO (LPRO)	MD	ED	NF	EDI
Feed water	Seawater	Brackish water[a]	Surface water[d]	Seawater	Brackish water[a]	Surface water[e]	RO-Permeate[f]
Fixed charge	0.311	0.027	0.014	0.229	0.051	0.019	0.133
Energy [b]	0.134	0.024	0.007	0.582[c]	0.028	0.016	0.013
Chemical	0.021	0.022	0.017	0.018	0.013	0.011	0.005
Membrane replacement[g]	0.028	0.024	0.011	0.285	0.067	0.014	0.179
Total water production cost	0.494	0.097	0.050	1.114	0.160	0.060	0.330
Reference	[117]	[118, 119]	[120]	[24]	[118, 121]	[18]	[22]

[a] TDS: 1600 mg/L
[b] Electrical energy 0.03 kWh/m^3
[c] Combination of electrical energy and heat energy
[d] TDS: 500 mg/L
[e] Feed conductivity: 407 µS/cm
[f] Well water: avg 60 µS/cm, RO permeate: 2.5 mg/L
[g] 15% per year (20 years of plant life)

3. Industrial challenges

In spite of the potential advantages of the membrane-based processes, they have some limitations that render the process uneconomic as reported by Michaels (Figure 5) [122]. Most of these limitations are not only contributed by membrane characteristics, but also the hydrodynamics within the membrane module, such as permeation flux [123]. Therefore, numerous attempts have been made to obtain optimized geometry or shear induced accessories in membrane modules [124–126]. A properly designed module will improve the hydrodynamics within the module and enhance the overall system performance [123]. However, module design and fabrication itself also faces industrial challenges, such as compatibility of adhesive, seal, spacer, and feed distributors [127]. Developments in the membrane material and module have been conducted to improve membrane process efficiency, that includes the increase in membrane performances, such as selectivity and flux, membrane durability, chemical resistance, pressure and temperature resistance, high packing density, and lower membrane cost [128]. The development of membrane material will then reduce investment cost related to membrane cost and overcome other limitations.

Among those limitations, fouling is considered as the major obstacle in membrane application, which leads to the rapid flux decline [129]. This type of fouling is summarized in Table 3. Additionally, fouling influences capital investment, which is attributed to the need of additional pretreatment units and energy, material, and chemicals required to overcome the fouling [130]. This fouling phenomenon also contributes to the increase of mass transfer resistance that leads to the increase of trans-membrane pressure to maintain constant flux. Consequently, higher energy is consumed during the desalination process. Moreover, the operational cost is also increased to remove foulants by chemical cleaning.

Due to its major impact on process efficiency and economics, strategies in fouling mitigation have been proposed by many studies according to Sheikholeslami [131]. Those methods can be classified as three categories, namely fouling control, pretreatment technologies, and anti-fouling membranes and modules. In the fouling control strategies, membrane processes could be operated under a particular condition wherein the fouling phenomena remained negligible, such as by operating below critical flux and critical conversion or injecting the antiscalant/antifouling agent. Appropriate pretreatment strategies have a significant effect on reducing fouling in membrane systems. Microfiltration (MF)/UF techniques have been progressively used to reduce fouling of RO membranes instead of conventional pretreatment [131]. The integration of MF/UF as RO pretreatment could significantly reduce the chemical consumption in the pretreatment step. Nevertheless, an optimized design of the membrane module and development of the fouling-resistance membrane also has significant contributions to fouling mitigation as well. Other examples on fouling reduction could also be found in Table 3.

There have been many studies that contribute to the reduction of operating cost for membrane processes especially in energy consumption. For the pressure driven membrane such as RO, the main energy consumption is energy required by the pump to deliver feed water with high-pressure conditions into RO units. Reversible pumps, pelton turbine, turbo exchanger, pressure exchanger, and hydraulic pressure booster are typical energy recovery devices, which have been used to recover energy [128]. By using those devices, dramatic reduction in desalination cost can be achieved. In spite of its success on energy recovery, further development is still investigated to gain more reduction in energy consumption.

Contaminants such as Boron are another challenge for membrane technology in the desalination process to meet the regulation of fresh water quality. Boron is present in seawater at average concentrations of 4.6 ppm [146]. WHO regulated that the maximum concentration of boron in drinking water is 0.5 mg/L [147]. However, Boron rejection over 90% is typically hard to be achieved by the RO membrane [148]. System design is one of the alternative solutions to improve the boron rejection. Typically, the RO membrane system is operated under neutral pH, which is considerably ineffective for removing Boron. For two passes of the RO system, pH of permeate in the first pass could be elevated up to 11 to improve boron rejection [148]. Suitable design of post treatment can also enhance the boron removal by incorporating a conventional ion exchange bed with boron-selective ion exchange resin or ED [149]. Boron-selective resin is able to remove boron from the first pass RO permeate to below 0.1 mg/L [150]. It should be noted that ion exchange requires chemical regeneration when the resins become exhausted. Consequently, it results in another problem that is associated to chemical regeneration. As previously reviewed in section 2, EDI is the deionization process that combines the advantages of conventional ion exchange and ED. Benefiting from the combined process, EDI is able to achieve high removal of ionic components to a relatively low concentration including weakly ionized substances such as boron and silica. It is proven that EDI has a capability to remove boron for more than 99 % as reported in the literature [151]. For example, the study investigated the performance of EDI using feed water with a boron concentration of about 3 mg/L. The results of the study showed that EDI was able to produce diluate water with 25 μg/L (ppb) of boron. Therefore, EDI has the potential to be applied as SWRO post treatment in order to achieve high quality water that meets the requirement of boron maximum level.

Fig. 5. Challenges and limitations in membrane based processes [122].

Nowadays, the way to satisfy the increasing demand of water by increasing desalination plants through scaling-up into larger capacity is challenged by its complexity in the larger system which is associated with the spaced required, number of components (membrane elements, pressure vessels, piping and instrumentations) uses, and the large quantity of waste disposal as brine. In some places, land is very expensive which is considered as the major limitation for obtaining larger capacity due to the investment cost required. To overcome this problem, the manufacturer has investigated the most efficient approach to developing the membrane system that requires a smaller footprint, particularly when the membrane system is constructed at a very large capacity. One of the alternatives is developing a membrane element with larger size, which will be discussed later in the next section. This larger element is expected to reduce the footprint and the number components.

Typically, the desalination process extracts a large volume of water from saline water and discharges concentrated brine back into the environment. The brine concentration is higher than the original feed water (brackish or seawater). Furthermore, for preventing membrane scaling, scale inhibitor or antiscalant is injected prior to RO and remains in the concentrate streams, thus becoming concentrated in the rejected brine. In addition, chemicals used for pretreatment and cleaning are also present. Moreover, pollutant components in the brine can be classified as: corrosion products, antiscaling additives, antifouling additives, halogenated organic compounds (formed by reaction of residual chlorines and bromines with natural organic matters), antifoaming additives, oxygen scavengers, acid, and concentrate [152]. The brine could potentially impact the environment due to its salt concentration and chemical content. The impact involves physicochemical and ecological attributes of receiving the environment wherein the brine is discharged [153]. Brine disposal has the potential to degrade characteristics of receiving water and its severity depends on volume, characteristics, dilution rate prior to disposal, and characteristics of receiving water [152].

Due to the aforementioned problems, many technologies have been investigated to manage brine reject from desalination plants. A comparative study on current and emerging brine management technologies for desalination plants has been reported [154] and the overview of the comparative study will be presented here. According to the final purpose, brine management options are then categorized into four different groups: (1) methods for reducing and eliminating brine disposal, (2) methods for commercial salt recovery, (3) brine adaption for industrial uses, and (4) metal recovery [154]. The comparative study revealed that zero discharge of desalination has very high costs. Meanwhile, the emerging technologies are promising in reducing brine volume although still in a laboratory scale. MD is one of potential alternatives for reducing brine disposal. It requires lower energy than conventional evaporation and could be coupled with solar ponds or residual heat and thus reduces energy consumption. Scaling might be formed on the MD membrane surface due to precipitation of salts that contributes to performance deterioration. However, simply membrane washing using water could be applied to remove salt crystal built on the membrane surface [155]. Technologies, which have been purposed to obtain commercial salts from brine show greater potential than those for reducing waste brine volume. For example, the recovery of gypsum, sodium chloride, magnesium hydroxide, calcium chloride, calcium carbonate, and sodium sulfate could improve cost-effectiveness of the desalination process. However, such an integration process is complex and results in higher cost. In addition to recovering commercial salt, the treatment of brine for industrial usage, such as brine adaption to feed chlor alkali industry, is also a complex process. This option involves appropriate treatment for contaminant removal, and thus needs high capital and operational cost. Metal recovery from brine is another promising issue. However, more research is needed to develop a selective separation process for recovering specific and valuable metals from seawater. Overall, it could be concluded from the comparative studies that technologies for recovering water and reducing brine as performed by the MD process are the most promising process, which exhibited high recovery, a simple process, and lower capital cost.

Another option to solve brine disposal is the application of membrane crystallization (MCr) explained by Drioli et al. [156] as the NF-RO-MCr integration process. MCr is not limited by osmotic pressure and can be therefore operated at high water recovery. The MCr unit further concentrates the brine from NF and RO brine up to salt crystal formation and thus no more brine disposal. The possible results that could be obtained by using MCr are [156]: reduction of brine disposal; improvement of total water recovery; and production of valuable crystalline products. In the so-called integration process that incorporates MCr drives, a new alternative process for achieving zero liquid is discharged. The FO membrane is also considered as a sustainable solution to treat brine disposal from the desalination plant, before it is discharged into the environment [89, 157]. More than 90% of water recovery could be achieved from brine [158]. However, the application of FO for brine treatment is limited by fouling. Regarding this fouling phenomena, Boo et al. [92] have proposed the fouling control strategy in the FO process. They suggested that membrane fouling in the osmotic dilution process can be mitigated by employing relatively simple control strategies that involve hydrodynamic mixing. The high efficiency of hydrodynamic control strategies is attributed to the fact that the osmotic dilution process is a non-pressurized membrane system and, thus, the loose fouling layer near the membrane surface can be readily removed by hydrodynamic shear forces.

4. Scale-up effort

In the RO desalination system, there are parameters that should be considered while designing the process to achieve both optimized performance and be economical, such as membrane configuration. The design consideration of membrane configuration includes array (single or two stage; one or two passes) and number of element per pressure vessel. The contribution of RO unit configuration in overall system performance has been discussed in the literature by Wilf and Bartels [159]. Formerly, SWRO were usually arranged in a two-stage array by using six membrane elements per vessel. The two-stage system is used to obtain high feed and concentrate flow rates for reducing concentration polarization. This lower concentration polarization is then expected to reduce scaling tendency due to lower ion concentration on the membrane surface and lower permeate salinity as well. However, higher feed pressure is needed to provide higher feed flow since pressure drop across the RO train increases. To overcome this problem, the SWRO plant is designed in single stage configuration and the number of elements per vessel is increased (seven to eight elements per vessel). The increasing number of elements per vessel shows advantages in reducing investment cost which was attributed to less vessels required (for the same required membrane area). Meanwhile, the pressure drop of a single stage unit is only about 1 bar compared to 3.4 bars for the two-stage unit, thus reducing power requirement.

SWRO plants are usually designed in one pass, two passes, or even more depending on design parameters such as energy cost, feed water properties, recovery and product quality requirement [146]. More than one pass is required to achieve better product quality (such as for boron removal). Since the product of first pass is used as feed water for the next pass, the system with more than one pass produces water with lower recovery. Furthermore, the system with more than one pass requires higher energy to deliver feed water into the RO units in the next pass with associated to higher pressure drop [146]. Consequently, it increases operational cost. Therefore, design parameters should be optimized.

Table 3
Fouling type and fouling mitigation.

	Description	**Examples**
Fouling type	Particulate	○ Corrosion products, silt and clay ,precipitated crystals, colloidal silica and sulfur, precipitated iron and aluminum compounds from incomplete treatment, high molecular weight organic substances: polysaccharide, peptidoglycans, proteins and humic aggregates
	Organic	○ Refractory natural organic matter derived from drinking water sources, synthetic organic compounds added by consumers and disinfection byproducts (DBPs) generated during disinfection processes of water and wastewater treatment, soluble microbial products formed during the biological treatment processes due to decomposition of organic compounds
	Inorganic	○ Calcium carbonate ($CaCO_3$), barium sulfate ($BaSO_4$), silica (SiO_2), calcium phosphate ($CaSO_4$), coagulant/flocculant residuals may also be present as inorganic foulants.
	Bilogical fouling	○ Algae and microorganisms such as bacteria
Fouling mitigation	Fouling control	• Membrane processes are operated under a particular condition wherein the fouling phenomena remained negligible such as by operating below critical flux or injection of antiscalant/antifouling agent
	Pretreatment technologies	• Appropriate pretreatment strategies such as by applying MF/UF as integrated system (MF/UF/RO)
	Anti-fouling membranes and modules	• Optimized design of membrane module and development of fouling-resistance membrane
	Fouling reduction techniques in porous membrane	▪ Aeration ▪ Intermittent filtration ▪ Backflush ▪ Operating at critical flux ▪ Utilization of moving carrier ▪ Utilization of inclined-plate ▪ Membrane surface modification

References: [129, 131-145]

To bring the process into a commercial scale, the process is usually developed in several steps, namely laboratory scale, sometimes bench scale, pilot scale, and then commercial scale. In a laboratory scale, the process is basically investigated in order to find the important parameter that determines the process and optimization. During bench or pilot scale, the optimized parameters are then ascertained. Meanwhile, in the commercial scale the success of the process is reproduced in a large capacity. Generally, scale-up effort can be classified into two different ways. The first one is theoretical scale-up wherein the scale-up process is conducted through simulation using proven models. Meanwhile, the second one is empirical scale-up where important parameters that are used for scaling-up are obtained during the experimental process in a small-scale plant (laboratory or pilot study). Accordingly, it is desirable to keep operating parameters constant during scale-up for maintaining the performance of the system as operated in a smaller one. Here, both scale-up efforts are overviewed for scaling up the RO system in the desalination process (Section 4.1 to 4.3).

4.1. Theoretical scale-up

Modeling on a full scale RO process can be classified into two main categories [148]: (1) a 'black box' model dealing with average values as inputs and outputs and (2) a more detailed model that addresses the local phenomena through a finite different approach. Since finite difference takes account of the local variations of pressure, flows, and concentrations throughout the system, this approach exhibits more accuracy than the black box model [160]. Several modeling and simulation efforts proposed by researchers are listed in Table 4. The model is now improved by taking into account local phenomena such as fouling, concentration polarization, and boron removal.

For example, Hoek et al. [160] reported a model of full-scale RO that takes account of local pressure, flows, concentrations, and the effect of concentration polarization and fouling. The model is semi-empirical that includes: (i) mass and momentum balance, (2) several fitting parameters, and (3) two empirical correlations. Meanwhile, the input data were collected from an RO pilot system. Results of the study showed that the model was able to reproduce an RO system accurately. Moreover, the model provided information about the dynamics of mass transfer, fouling and scaling in a full scale RO process. However, they also recommended more research for developing comprehensive understanding of the impact of fouling on membrane properties, mass transfer, and system performance.

Recently, Choi and Kim [161] developed a mathematical model that simulates the RO system in a full-scale seawater desalination plant by considering the effect of operating conditions. The effect of recovery ratio, salinity, and temperature were quantitatively analyzed using the model. Additionally, the RO system was optimized in terms of energy requirement and boron removal. The model was then applied to simulate the 2-pass RO system. The model was based on RO membrane transport incorporating concentration polarization and mass balance equation. The model showed efficiency simulation of the RO system. Moreover, performances of RO in wide range operating conditions were analyzed and results concerning economics were also presented. These studies demonstrate the capability of the theoretical approach to scale-up the RO desalination system.

Generally, most membrane manufacturers also develop process modeling packages and share the software free of charge. The examples of the programs are ROSA from DOW, IMS design from hydranautics, CMSPRO from woongjin chemicals, and TorayDS2 from Toray. These programs are useful as they consider feed water fouling and scaling indicators such as ionic components and SDI. These programs are also easily operated and user friendly, thus providing a short cut for engineers to design the system theoretically. Furthermore, some important parameters such as maximum element recovery and minimum concentrate flow are also provided. However, it should be noted that each program is designed for a specific membrane module; therefore they are only suitable for membrane from the manufacturer.

The advantages of the theoretical method are: operating parameters can be estimated during simulation; relatively low cost; and less time needed to obtain optimal conditions. However, since the model is based on a theoretical assumption, it possibly shows different results when applied in actual conditions.

4.2. Empirical scale-up

In the empirical method, the full-scale RO system is designed with the data obtained from the smaller scale, typically from the pilot plant. The major parameter such as flux, recovery ratio, and system array are kept constant and applied for the full-scale system. Through an empirical method, performance of the full-scale system would be close to the smaller system as operated under the same conditions. Fouling and scaling encountered in the process can be observed during such a long-term operation when the pilot scale plant is performed. Thus, foulant and periodic cleaning required can also be determined during this stage. Moreover, optimal operating conditions can be ascertained in the piloting stage. Since the system including its optimal operating condition is proven in the piloting stage, the next step is then increasing the size of the plant. The advantages of the empirical method are: optimal conditions are already proof of actual conditions; problems found during the field test can be solved during operation; the foulant component and periodic cleaning required can be determined. However, the experimental step is relatively high cost since it is time and cost consuming.

Strategies for scale-up of the RO plant into a larger capacity have been discussed by Kim et al. [171] and classified into two different ways. The first way is increasing the size of the single component, which constitutes the system while the second one is increasing the number of the components. The components considered in the scaling-up strategies are RO unit train and pump. Accordingly, they pointed out four different approaches to scale-up RO system, namely; (1) increase the number of RO unit trains and pump units, (2) increase the size of RO unit trains by increasing the number of RO module while using a single pump unit, (3) increase the size of RO unit trains by increasing the size of RO module while using a single pump unit, and (4) Increase the size of pump unit and increase the number of RO unit trains (Figure 6). From a comparative study, they concluded that except for strategy 1, the rest of the strategies are competitive and promising for construction of a large-scale RO plant.

4.3. Large diameter RO element

In some places, land for construction of a new plant is very expensive. Therefore, as the desalination plant becomes larger in capacity, it is then important to minimize the footprint requirement to achieve a lower overall cost. In order to solve this footprint problem for a large capacity of the RO desalination plant, the manufacturer has introduced a larger size of the RO element. The first spiral wound RO module was introduced commercially in 1964 with 4 in. in diameter by 40 in. in length, which is known as the 4040 module [172]. Afterward, a larger diameter element 8 in. in diameter was introduced in 1975 [172] and has become a standard commercial module. With the help of this standard element, the full scale RO plant has gained acceptance as a cost-effective water treatment. However, since the desalination plant has become larger, the use of the 8040 element is no longer efficient. For example, the SWRO plant of 76,000 m^3/day capacity may need more than 4000 modules, 600 RO pressure vessels, and numerous numbers of individual connections and O-ring [173]. It is obvious then that a larger capacity plant requires a larger size of the RO module. The challenge for the manufacturer is to find out the optimum size of the RO module while considering the effective module construction and simplicity in the procedure for loading and unloading the element into pressure vessels. Manufacturers have compared the RO element with different nominal diameter. They can achieve the area ratio of more than 5 by introducing 18 in. in nominal diameter compared to the standard 8″ module [174]. The typical module has been introduced by the Koch Membrane system as the Megamagnum element [173].

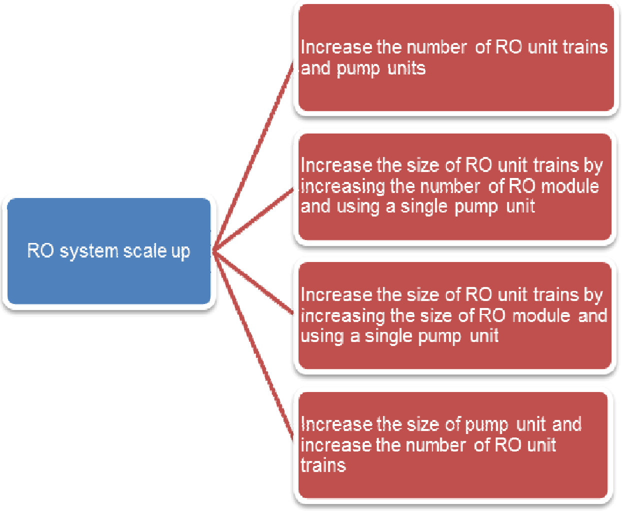


Fig. 6. Scale-up strategies for SWRO system [171].

A study [120] of the larger diameter RO module showed that considerable reduction in total water cost can be acquired for a large scale RO plant in comparison with using the conventional 8040 module (Figure 7). Benefiting from its individual effective area, reduction in the number of piping connections, reduction of footprint required, and ease of operation and maintenance from smaller number of components, the cost savings of RO plant can be achieved. Meanwhile, practical issues which are associated with the larger element have been solved, such as the loading and unloading problem due to element weight and pressure vessel availability [172].

5. Prospect and challenges

5.1. Non-modular UF membrane as prospective pre-treatment

It is well known that the appropriate pretreatment steps determine to a very large extent the success of the membrane based desalination system. The main objective of the pretreatment system is to deliver feed water that meets the requirement for the main process. Furthermore, pretreatment is applied to prevent or mitigate fouling tendency for the RO unit by reducing foulant components. Pretreatment strategies for the SWRO plant have been reviewed elsewhere [175]. Nowadays, MF/UF pretreatment replaces the conventional one as they offer some benefits, those are [176]: lower fouling rate resulting in lower energy consumed; reduced cleaning frequency leading to reduced downtime, reduced chemical consumption, increased membrane life, modular design enabling quick installation, smaller foot-print, and increased membrane durability. Additionally, the UF can remove all suspended particles, some of the dissolved organic compounds, and provide disinfection barrier by excluding viruses [175]. Therefore, UF has gained acceptance as a preferred pretreatment for the RO system.

UF membranes are most commonly available in commercial hollow fiber or the capillary fiber membrane module. Given the demands of reliable long term applications, in addition to chemical and biological resistance, the membrane should also have high mechanical stability. A single fiber breakage, e.g. due to water hammer, will simply cause the whole system to lose disinfection and selectivity – and contaminate all of the product.

Since a single membrane module serves some particular capacity – depending on its type or dimension, a larger capacity can be achieved by multiplying the amount of the modules to work in a paralell configuration. In the topic of modularity, it is about the perspective of “double-edge sword”. Even though it enables easier scale-up and replacement, it is not economically attractive and gives high complexity in the instrumentation and piping system (Figure 8 (a)). Pipe and fitting cost of the modular system increase along with increasing capacity, while it slightly increases in the non modular system (Figure 9).

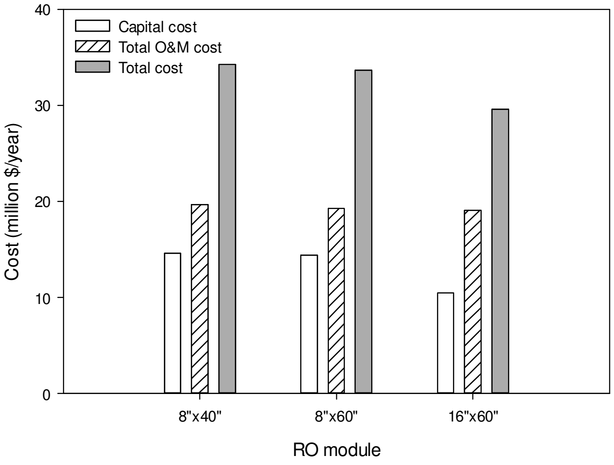


Fig. 7. Cost comparison of 30 m^3/h desalination plant with different module. Data collected from [120].

By increasing the filtration capacity, an additional number of the module is required and followed by increasing complexity and leak potency. According to Figure 9, the number of connection point increases dramatically along with filtration capacity. The number of connection point is also related to connection failure and probability of leaking indirectly. Simplicity in the non-modular piping system allows a single pump application for filtration and backwash [177]. This system uses a reciprocating pump which can be operated back and forth for backwash and filtration (Figure 10). The use of a single pump system will reduce its capital cost and energy cost, respectively.

Beside its superiority over the modular system, the main disadvantage of the non-modular sytem is replacement costs. However, supported by intensive researches in the fabrication of ultra strong fiber, fouling resistance and the advanced potting method, a lifetime of the non-modular system can be prolonged significantly. A non-modular UF membrane is shown in Figure 8 (b).

5.2. Integration of NF membrane as SWRO pre-treatment

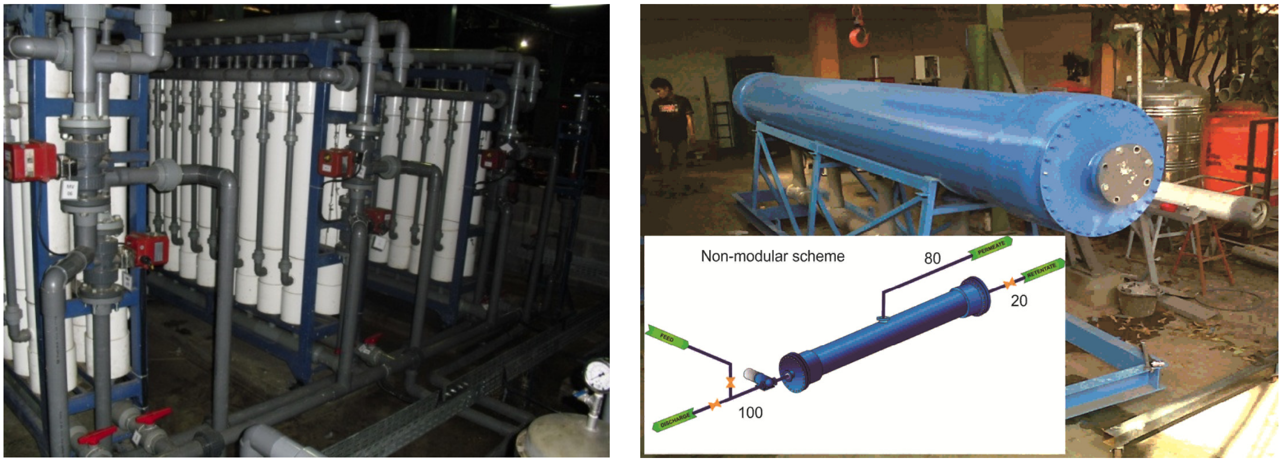
Further improvement in the pretreatment system for the SWRO plant is to incorporate the NF membrane. NF removes turbidity, microorganism, hardness component, and most multivalent ions [178]. Since NF removes a portion of salt concentration, osmotic pressure of the RO feed is reduced and the recovery can be increased. Accordingly, the integration of NF-RO seawater desalination could achieve a better recovery than the SWRO plant based on conventional pretreatment to more than 10% [179, 180]. The NF-SWRO system was demonstrated by Hassan et al. [181]. The result of the study showed that integration of the NF membrane led to significant improvement in the desalination process. For example, recovery is increased and a permeate with high purity is produced from a single stage SWRO (< 200 ppm).

Application of NF as SWRO pretreatment has also been investigated by Llenas et al. [46] by comparing six different NF membranes. These membranes are subjected to remove compounds that are known to form scaling such as $Ca(SO_4)$; $Mg(OH)_2$; $CaCO_3$ etc. from synthetic water. Most of the NF membranes showed superior rejection on calcium sulphate rejection for about 90%. Thus, this result shows the potential of NF membrane as SWRO pretreatment especially for scale prevention. Another promising benefit from integration of NF as pretreatment has been reported by Al-Hajouri et al. [182]. The results of their long-term operation show that NF pretreatment can extend RO membrane life and avoid chemical cleaning of RO.

5.3. EDI as post treatment

The integration process of RO-EDI has become a technology for producing ultrapure water with high quality water, lower cost, and being environmentally friendly [63]. RO delivers high quality water that meets EDI requirements, while EDI provides an excellent polishing step with remarkable silica and boron removal. Typically, in the production of demineralized water from seawater, the main system comprises the SWRO unit, BWRO unit, and mixed bed ion exchange, which act as a polishing unit. EDI is a membrane-based process that combines the advantages of the ED and conventional ion exchange process. Since it does not need any regeneration procedure, this process is far more superior in comparison to the conventional IX process. Thus EDI could be potential to replacing ion exchange as the polishing step for the SWRO plant (Figure 11).

Strong ionized species are more easily transported under the influence of an electric field than weakly ionized species such as boron, silica and dissolved CO_2 that may not be dissociated which exists in a predominantly non-ionized form. The removal of those compounds becomes important in the production of high purity water and every trace constituent present in the feed water must be removed. Therefore, the simulations of the EDI process are presented and focus on silica removal from the BWRO permeate. EDICAD ver. 3.3 (Snowpure.inc) is used to simulate EDI performance for silica removal and Snow Pure Electropure EXL 700 was chosen as the EDI unit and the result is illustrated in Figure 12. It can be seen that all of the variations give satisfactory results with respect to silica removal and producing a high quality product. The lowest silica concentration found in the EDI product was around 64 ppb with feed water silica concentration of around 0.8 ppm. Since silica concentration can be reduced up to 64 ppb, the mixed bed ion exchanger process can completely be replaced by this new installed EDI unit. The primary advantage of the EDI process compared to the mixed bed ion exchanger process is no need of chemical regeneration, which is more economical, safer and environmentally friendly.



(a) (b)

Fig. 8. Large scale system of (a) modular and (b) non-modular UF membranes (UF module: 24", 6.5 m, capacity: 80 m^3/h, 80 % recovery). Courtesy of GDP Filter, Indonesia (gdpfilter.co.id).

Table 4
Model and simulation proposed by researcher for scaling up RO plant.

No.	Author	Description	Ref.
1.	Channabassapa	Mathematical models of transport phenomena across the membrane	[162]
2.	Rao and Sirkar	Approximate design equations for tubular RO processes	[163]
3.	Evangelism	A graphical method for calculation of total membrane length needed for a given recovery ratio	[164]
4.	Voros et al.	An integrated methodology for the design of RO systems used in the production of desalination	[165]
5.	Mandil et al.	Energy recovery of an RO-based desalination process	[166]
6.	Villafafila and Mujtaba	Simulation of tubular RO membrane for desalination and optimisation using a successive quadratic programming (SQP) based method.	[167]
7.	Abbas	Simulation of brackish water desalination using semi-rigorous model	[168]
8.	Hoek et al.	Semi-empirical model of the effects of fouling on the performance of RO system	[160]
9.	Oh et al.	A simple model based on the solution–diffusion theory and multiple fouling mechanisms was developed and used to analyze the performance of RO systems.	[169]
10.	Sassi and Mujtaba	Steady state performance predictions and optimization of the RO process utilizing a set of implicit mathematical equations which are generated by combining solution-diffusion model with film theory	[170]
11.	Park et al.	Mechanistic predictive model that simulates boron removal in full-scale SWRO desalination processes to take into account the effect of membrane fouling	[147]

The remarkable removal of the weakly ionized component such as boron and silica in EDI has been investigated and explained by Wen et al. [151] as follows. Silica and boron removal is associated to water dissociation phenomena occurring in the diluate compartment. Generated OH- ions during water dissociation can ionize both boron and silica. Subsequently, the ionized form of silica and boron can improve removal of both components. The more recent study in the removal of silica and boron from RO permeate using EDI was also reported in the literature [183]. The effects of operating parameters are discussed in their study.

Generally, the commercial EDI stack is specified to treat low conductivity water, i.e. feed conductivity of less than 40 µS/cm. However, recent development of EDI for brackish water treatment (NaCl concentration of 1740 ppm) has been reported [71]. They concluded that EDI is more preferable in the case of treatment of strongly diluted solutions. From a technological point of view, EDI has a more conductive stack than ED. This means for feed water with the same amount of ionic component, EDI requires lower energy than ED. Furthermore, the incorporation of electroactive media inside the EDI cell can enhance ion migration, thus resulting in high quality water with very low concentration of ionic components. These advantages should make EDI as a potential membrane process for brackish water desalination. Thus, it could then give EDI the possibility to replace BWRO in the SWRO desalination plant. Unfortunately, the potential of EDI for producing high water quality from higher feed water conductivity such as brackish water is never discussed. This is possibly due to the dominations of EDI applications in low ionic concentration either in studies or in the commercial field.

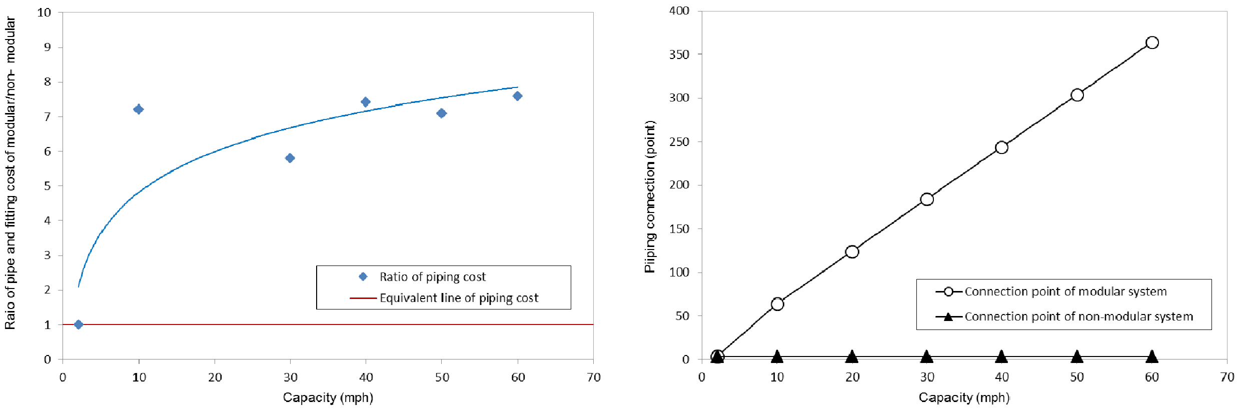
5.4. Energy generation from brine disposal

Another potential of membrane technology application in the future is power generation from salinity gradience between seawater or brine disposal and fresh water by pressure-retarded osmosis (PRO) and reverse electro-dialysis (RED) [184–186]. The osmotic pressure difference induced by two solutions with different salinity is utilized as a driving force. PRO uses a semi-permeable membrane that allows the transport of water from a low-concentration solution (such as river, brackish or treated waste water) into a high-concentration draw solution (sea water) [187]. Energy is generated by a hydroturbine wherein the kinetic energy of the flowing water is converted to electricity. A specific power density in the order of 5 W/m^2 seems possible to be acquired and approximately 40% of the potential energy from the mixing of freshwater with an infinite amount of seawater can be converted to mechanical energy [188]. Norway is a country that has extensively explored the possibility of using PRO for generating energy with its own public company: Statkraft [189, 190].

In the RED membrane process, a number of anion and cation exchange membranes are stacked together in an alternating pattern between an anode and a cathode and allow the selective transport of salt ions [191]. The driving force of such a process is chemical potential owned by solutions. Due to the gradient salinity of two different solutions fed into RED cells, the chemical potential is converted to electrical potential by the transporting ions from high salinity solution into low salinity solution called the concentrate and diluate, respectively. RED has been widely explored in the Netherlands, where several private companies have joined research in the area such as RED Stack and Fujifilm [192, 193]. Moreover, Fujifilm has also applied its ion exchange membrane in a 50 kW RED pilot plant [194]. Feasibility studies have also been conducted to install RED utilizing the mixing process that occurs between San Lorenzo river water and Monterey Beach [195]. However, unsatisfactory results are encountered since only 225 mV and 341 mV can be produced using single and ten cells, respectively. Current developments in the RED process have a strong focus on increasing the power density output and there are five aspects considered as significantly affecting the power density output: membrane potential, ohmic resistance, resistance caused by bulk concentration, boundary layer resistance and power required to drive the pump since it will affect the net energy output [196-198].

Integrated SWRO-PRO and SWRO-RED are promising processes to alleviate water and energy demands, which concern energy production/consumption and water production [193, 199]. It is found from the study that brine from the SWRO unit provides a better high salinity source for energy recovery. Moreover, the discharged brine can be controlled for improving product recovery and minimizing the impact on the environment. In addition, the specific energy consumption of the RO system can be decreased. These integrated processes can be designed as shown in Figures 13 and Figures 14, which have been proposed in the literature [197, 198].

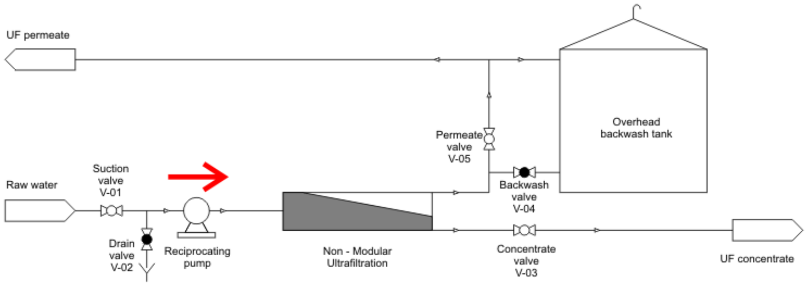
Post et al. [200] compared power density and energy recovery performances of PRO and RED by mixing different types of saline water, i.e. seawater and brine, with river water. They showed that higher potential maximum power density is achieved in RED (2 – 4 W/m^2) than PRO (1.2–1.5 W/m^2), when these membranes are applied in seawater and river water. When applied to brine water, the PRO membrane seems to be more attractive with higher power density and energy recovery.



(a) (b)

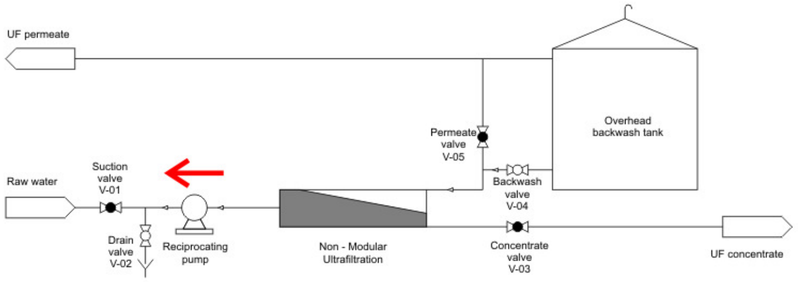
Fig. 9. Pipe and fitting cost (a) and piping connection point (b) of modular and non modular ultrafiltration (calculated by GDP Filter Bandung, Indonesia).

(a) Filtration



Valve Position:
V-01, open
V-02, closed
V-03, adjusted
V-04, closed
V-05, open

(b) Backwash



Valve Position:
V-01, closed
V-02, open
V-03, closed
V-04, open
V-05, closed

Fig. 10. Process flow diagram of single pump system in ultrafiltration process, (a) filtration and (b) backwash. Courtesy of GDP Filter, Indonesia (gdpfilter.co.id).

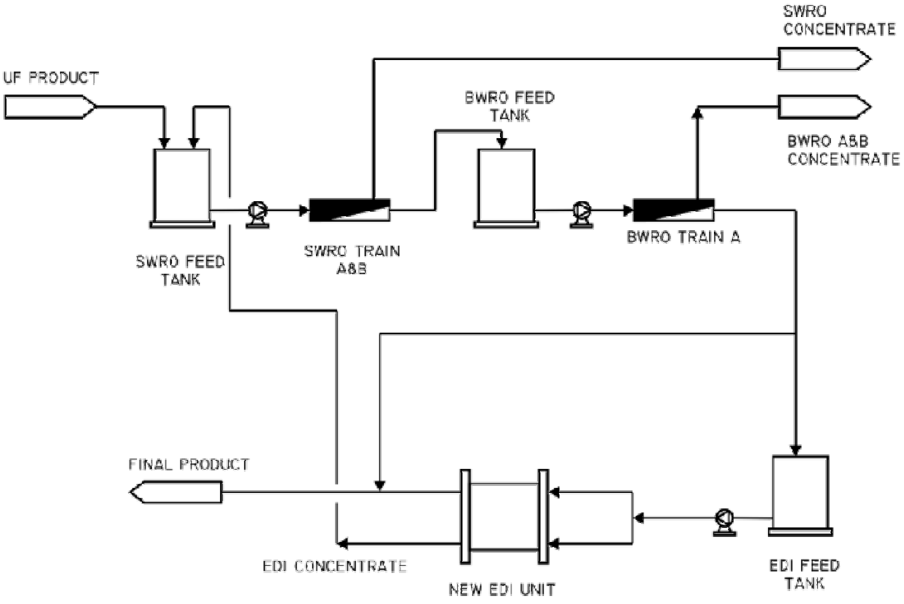


Fig. 11. Schematic flow diagram of system with EDI as the polisher unit.

6. Conclusions

Desalination technologies have become the key solution to overcome the increasing water demand of the population and industrial applications for several decades. Due to its intensive development and attractive features, membrane technology offers new options to achieve energy efficiency and a cost effective desalination process. Improvement in membrane technology including advances in membrane material, module and process design, pre-treatment, and energy saving has led to cost reduction which in turn gains interest to its commercial applications compared to other desalination processes.

Effective scale-up is a critical point of view to reproduce the success of the membrane-based desalination process from a small-scale experience into a larger one. Accordingly, it is desirable to keep operating parameters constant during scale-up for maintaining performance of the system as operated in a small-scale plant. Moreover, problems related to the process should be carefully investigated during lab scale and pilot scale experiments and considered for improvement of the system design. Rapid decline of the permeate flux over time as a result of fouling and scaling is the major obstacle in membrane processes that influences capital investment and operating expenditure. Therefore, strategies in fouling control, antifouling, and the pre-treatment method become critical concerns in scale-up of membrane-based desalination. Other challenges in membrane-based desalination are energy consumption and waste brine management. Typically, energy recovery devices are used to recover energy and lead to significant reduction in desalination costs. Recently, integrated membrane processes give an attractive opportunity in pre-treatment up to post treatment stages to overcome the limit of single units and improve the overall performance. For example, the integration of NF-RO seawater desalination could achieve a better recovery than the SWRO plant with conventional pretreatment. In addition, the EDI membrane could be used as an excellent polishing step of the RO product with remarkable silica and boron removal. Another potential of the integrated-membrane system is power generation from salinity gradient between brine disposal and fresh water by PRO and RED. Integrated SWRO-PRO and SWRO-RED are promising processes to alleviate water and energy demands, which concern energy production/consumption and water production. Nevertheless, problems related to space requirement and complexity of the system due to the number of components should be considered as well. A large size membrane element demonstrates the potential solution to overcome those problems. Typically, a concept of non-modular UF membrane has been introduced.

7. Acknowledgements

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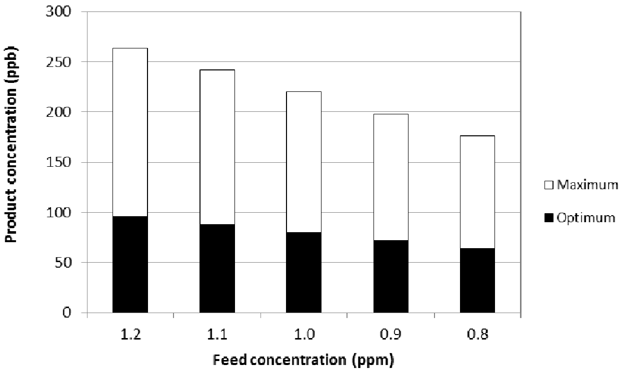

Fig. 12. Profile of silica concentration in EDI product for various silica feed concentration.

8. Abbreviations

AM	Anion-exchange membrane
BWRO	Brackish water reverse osmosis
CDI	Capacitive deoionization
CM	Cation-exchange membrane
ED	Electrodialysis
EDI	Electrodeionization
FO	Forward osmosis
HCDI	Hybrid capacitive deionization
IX	Ion-exchange
LPRO	Low-pressure reverse osmosis
MCDI	Membrane capacitive deionization
MCr	Membrane crystallization
MD	Membrane distillation
MDC	Microbial desalination cell
MF	Microfiltration
MFC	Microbial fuel cell
NF	Nanofiltration
PRO	Pressure retarded osmosis
RED	Reverse electrodialysis
RO	Reverse osmosis
SWRO	Seawater reverse osmosis
TDS	Total dissolved solid
UF	Ultrafiltration
UPW	Ultrapure water

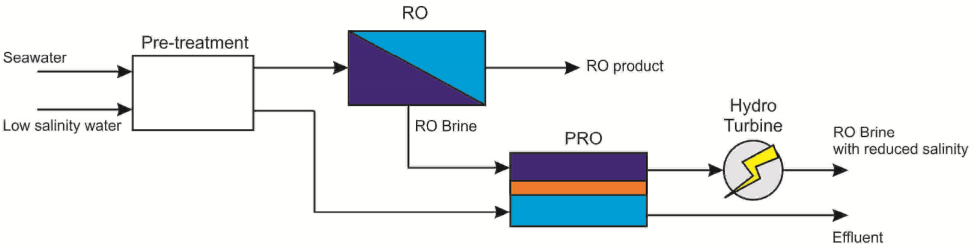

Fig. 13. Schematic diagrams of RO-PRO integrated process. Adapted from [185].

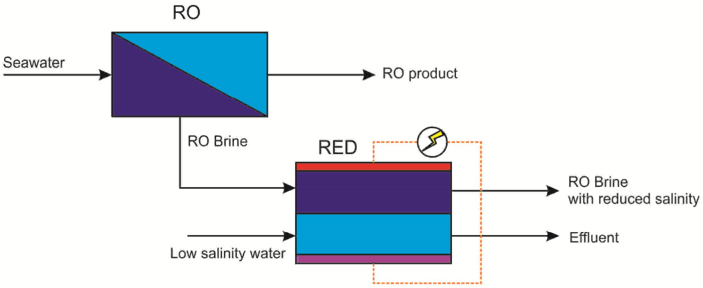

Fig. 14. Schematic diagrams of RO-RED integrated process. Adapted from [186].

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