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Techno-economic evaluation of different seawater reverse osmosis configurations for efficient boron removal

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ABSTRACT

Seawater reverse osmosis (SWRO) is an efficient process for desalting seawater on large scale. Pre-treatment of the feed seawater and post treatment of product water in addition to the RO module are the key elements of the SWRO economics. Boron concentration level in the feed water can impose extra cost to the desalination process in both RO system and post-treatment to satisfy the regulation for product water. The boron concentration level in the Gulf seawater is extremely high and can reach 9 mg/L in some sites. In this study, three different configurations of RO system to produce water at specific TDS and boron concentration have been proposed and rigorously evaluated for both technical and economic aspects. The proposed configurations include internal stage design (ISD), partial second pass and permeate split. Results showed that different ISD configurations with full flow to the second pass produced the highest quality water (TDS = 7 mg/L and boron = 0.18 mg/L), however, it had insignificant effect on the water production cost. The permeate split configuration resulted in the lowest product cost (8% less than full second pass), while the cost of permeate bypass was 6% less.

Keywords: Boron removal; Seawater reverse osmosis; Economic analysis; Internal staged design; Reverse osmosis system analysis

1. Introduction

While the TDS in seawater has little effect on the thermal desalting processes, it is largely affecting SWRO desalting process. In SWRO, the feed water salinity usually determines the osmotic pressure, and the required high pressure (HP) of the feed pump and thus the energy consumed by the SWRO process. While advanced SWRO membranes can reduce overall salinity in one stage, some ions such as boron usually need more than one stage or special removal treatment to meet the World Health Organization (WHO) guidelines. Recently, WHO increased the boron concentration for drinking water to 2.4 mg/L [1]. Although this new change seems more relaxed for drinking water, the requirement of 0.5 mg/L is still effective for irrigation water since boron demonstrates herbicidal effect on some crops; boron of 1 mg/L concentration is considered toxic to plants [2]. However, many countries have set different limit of boron according to what can be reasonably and economically achieved. The lack of enough data on toxicity of boron on human health also contributes to this limit variations. Examples of boron limits standards (in mg/L) are 0.5 in Oman, 1.0 in the European Union, South Korea, California, Japan and Algeria, 1.4 in New Zealand, 4 in Australia, and 5 in Canada [3].

Concentration of boron in seawater is in the range of 0.5–9.6 mg/L [4,5]. Boron exists in seawater in two forms; boric acid (H_3BO_3) and borate ions $B(OH)_4^-$ (molecular formula $(BO_3)^{3-}$) with their ratio depending on the pH of water [3]. It is known that the SWRO membranes remove charged ions much better than non-ionized salts; hence, borates

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removal is much better than boric acid. Reported boron (boric acid and borate) removal at normal conditions by currently available RO membranes is around 78%–80%, with boric acid rejection in the range of 40%–60% (at pH in the range of 5.5–9.5), and borate ion removal is more than 95% for the same conditions [6,7].

Boric acid (H_3BO_3) behaves as a weak acid in aqueous solution [5,8]. In water, boric acid accepts hydroxide ion from water and releases a proton into solution. The dissociation of boric acid in water can be described as follows:

$$B(OH)_3 + H_2O \Leftrightarrow B(OH)_4^- + H^+ \quad (1)$$

Boric acid dissociation is a function of the pH. When it is above 8.6, the anion $B(OH)_4^-$ is predominant. For pH below 8.6, the uncharged, non-dissociated form of species is predominant [5,8]. One of the main methods for removing boron from seawater is using SWRO desalting system with more than one pass. The pH of the first pass permeate (the second pass feed) can be increased, say to 10 to turn boric acid to borate ions, by adding caustic soda (NaOH) and then use brackish water reverse osmosis (BWRO) membrane elements. Raising the pH from 8 to 10, increases the boron rejection from 55% to more than 90% [9]. Adding NaOH costs about \$0.05/m^3 of feed water [9].

Recently, SWRO membranes of high boron rejection were developed [10] such as

- Toray Industries Inc. (Japan) developed membranes known as TM820A-400 and TM820C of 93% boron rejection, and TM820E-400 of 91% boron rejection.
- DOW Chemical Co. (USA) developed membranes known as SW30XHR-400i of 92.8% boron rejection, SW30HRLE-400 of 91% boron rejection, SW30XLE-400i of 88% boron rejection, and SW30ULE-400i of 87% boron rejection.
- Hydranautics developed membranes known as SWC4+ of 90% boron rejection, SWC4+B of 95% boron rejection, SWC5 of 92% boron rejection, and SWC6 of 91% boron rejection.

Another method is to use selective boron ion exchange resin (BSR) for the first pass permeate and the second pass can be with or without by-pass with double column ion exchange system to ensure a continuous production. It is known that the boron removal by ion exchange is more efficient in diluted water than with seawater. The most widely used BSR for removal of boron from water are boron chelating ion exchange resins [11]. More discussion on boron removal using reverse osmosis can be found in the literature [10,12–14], and on ion exchange BSR removal mechanisms, BSR synthesis, and optimum amounts of used resins (i.e., batch sorption studies) are outlined in the literature [11,13].

Although boron removal using membrane desalination processes received great attention recently, the economic feasibility of most of the proposed systems was not evaluated thoroughly, especially for high boron concentration feeds. The economics of boron removal using RO for seawater of high salinity (45,000 mg/L) similar to one in the Arabian Gulf have never been investigated. In addition, the high boron concentration in the feed water (5.0 mg/L) add another challenge to the process. The techno-economics of SWRO with ISD configuration and permit split systems is a novel part in this work.

This paper investigates the performance and economics (techno-economics) of different RO processes for controlling boron concentration of permeate produced from high-salinity feed water with high boron concentration. Two-pass RO systems are primarily used when high purity permeate is required. Inter-pass pH adjustment with sodium hydroxide is used to enhance rejection of boron and other alkalinity such as silicate.

2. Methodology

One-pass SWRO system cannot produce permeate of the required quality and boron concentration; therefore, only two-pass system will be considered in this work. Three different configurations of two-pass RO process have been studied in this work, namely:

- Two-pass RO-ISD system with full flow to the second pass, and
  - ISD in the first pass only, Fig. 1.
  - ISD in the second pass only, Fig. 2.
  - ISD in both the first and second pass, Fig. 3.
- Two-pass with partial flow to the second pass, Fig. 4.
- Two-pass with permeate split, Fig. 5.

In each of the aforementioned configurations, two cases were considered; one case with the second pass concentrate is recirculated to the first pass feed to lower its TDS, and another case without concentrate recirculation.

ISD system is a common method to optimize element flux through the pressure vessel and to reduce energy consumption in SWRO systems. In ISD, different types of membrane elements are hybridized in the same pressure vessel (PV). Fig. 1 shows six elements PV in the first pass with two configurations; one utilizes two different seawater (SW) membrane elements and the other utilizes three. Fig. 2 illustrates seven elements PV in the second pass with two configurations; one contains two types of brackish water (BW) membrane elements and the other contains three. In the ISD configuration, high salt rejection elements are installed in the lead positions, while high flux elements are positioned at the end to maintain constant flux per element along the PV. The specifications of the selected membrane elements are shown in Table 1.

Fig. 3 shows two-pass RO system with ISD in both passes. The pH of the first pass feed was lowered using H_2SO_4 to reduce the scale formation tendency, while the pH of the permeate of the first pass is increased before feeding to the second pass to improve the boron removal effectiveness of the membranes. Fig. 4 represents the partial flow to the second pass scenario with brine circulation to the first pass feed. Partial second pass reduces both capital and operational cost of the second pass, while the amount of the by-passed permeate is used to control the boron concentration of the final product. Mixing the reject from the second pass with the raw feed water lessens the feed salinity before the first pass and hence further reduces the operating cost.

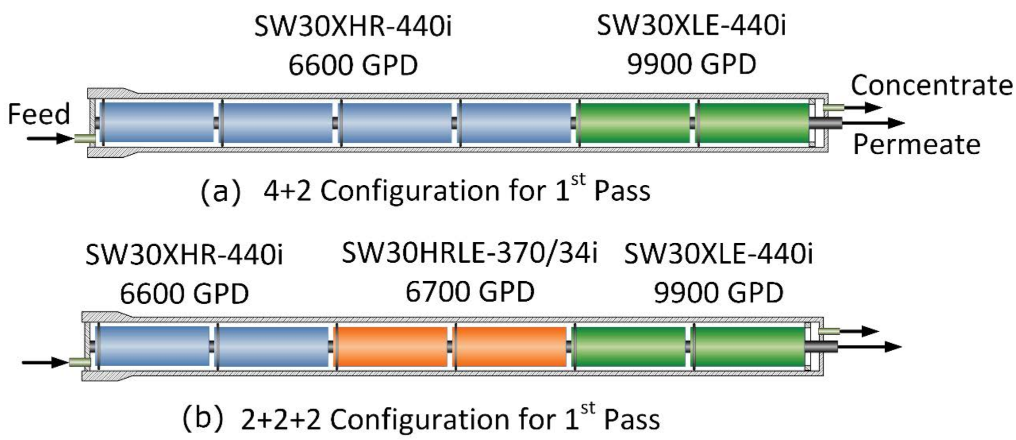

Fig. 1. ISD in the first pass, using two and three types of SW membrane elements in six elements PV, (a) 4 + 2 configuration and (b) 2 + 2 + 2 configuration.

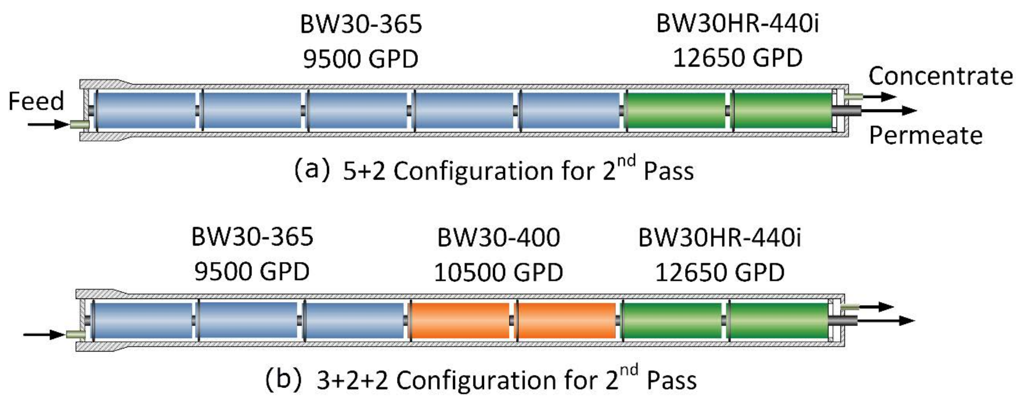

Fig. 2. ISD in the second pass, using two and three types of BW membrane elements in seven elements PV, (a) 5 + 2 configuration and (b) 3 + 2 + 2 configuration.

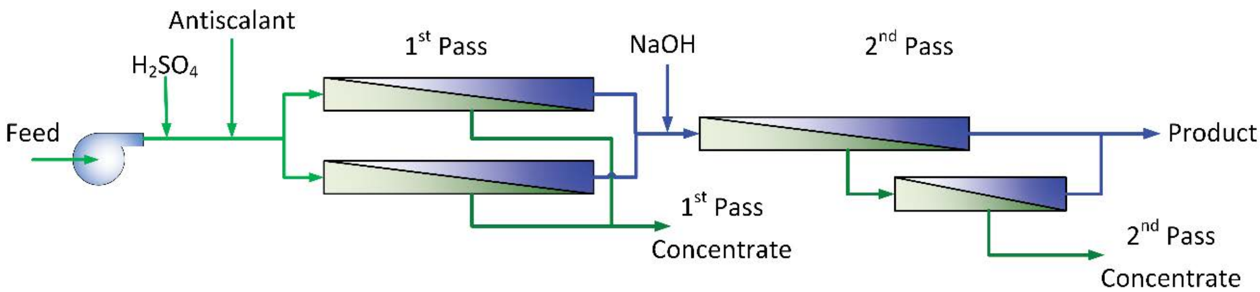

Fig. 3. Two passes system with pH control for the second pass.

Fig. 5 illustrates the permeate split configuration. In this configuration, permeate withdrawn from both ends of the first pass PV. Permeate from the front end (feed side) has higher quality and less boron content. A percentage of this permeate by-passes the second pass and then blended with the final permeate stream. The by-pass percentage is also used to control the quality of the final product. In permeate split SWRO systems, ISD with elements chosen specifically to reduce front permeate TDS and/or control lead element flux were used.

A pilot-scale SWRO desalination plant of 200 m^3/d capacity is simulated and analyzed in this work. The feed water to the plant is supplied from the Arabian Gulf around Kuwait coast. The seawater analysis for the Arabian Gulf around the State of Kuwait is averaged and tabulated from different resource and is shown in Table 2.

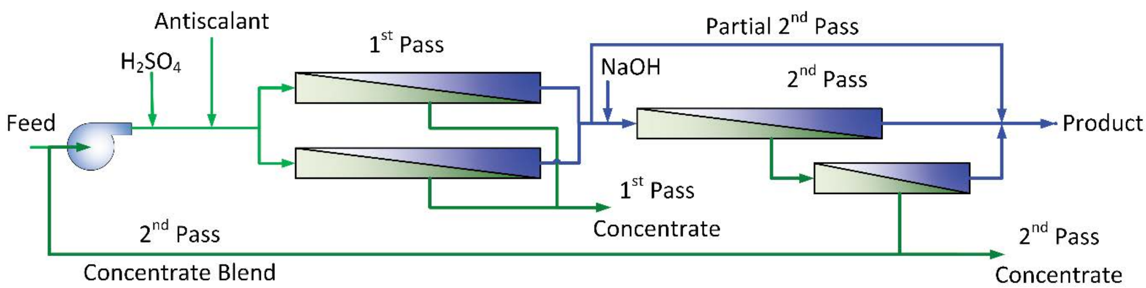

Fig. 4. Partial second pass system and concentrate blending.

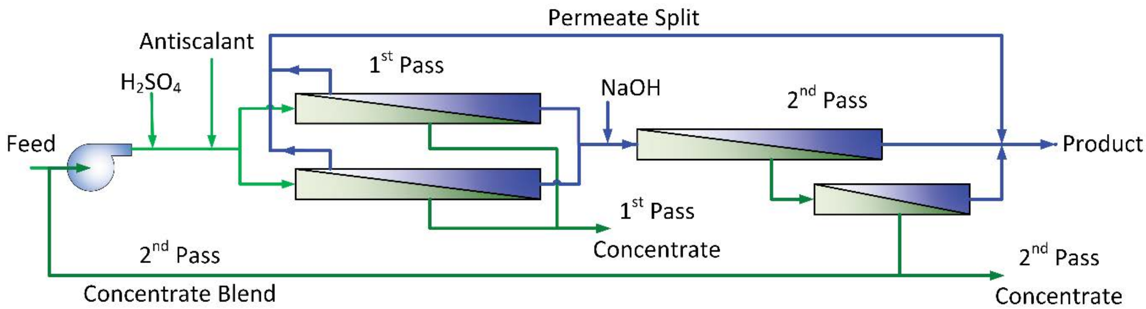

Fig. 5. Two passes system with permeate split and 2nd pass concentrate blending with 1st pass feed.

Table 1
Membrane elements specifications [15]

	Active area		Feed space	Permeate flow		Boron rejection	Salt rejection	Element position	
	ft^2	m^2	Mil	GPD	m^3/d	%	%		
SW30XHR–440i	440	41.0	28	6,600	25.0	93.0	99.82		Front
SW30HRLE–370/34i	370	34.4	34	6,700	25.4	92.0	99.80	Pass1 SW	Mid
SW30XLE–440i	440	41.0	28	9,900	37.4	91.5	99.80		End
BW30–365	365	34.0	34	9,500	36.0	99.5	99.00		Front
BW30–400	400	37.0	28	10,500	40.0	99.5	99.00	Pass2 BW	Mid
BW30HR–440*i*	440	41.0	28	12,650	48.0	99.7	99.40		End

The process design and parameter evaluation were performed using reverse osmosis system analysis (ROSA 9.1) software by DOW [20]. The following considerations were applied on all cases:

- The first pass recovery ratio is adjusted to keep the brine salinity of the first pass in the range (≤65,000 mg/L), while the second pass recovery is adjusted to keep the minimum recommended concentrate flow through the last membrane element and avoid any system design warning.
- The pH of the first pass feed is lowered by adding H_2SO_4 to insure the Stiff & Davis Stability Index (S&DSI) for the concentrate at (–1.0) or less. In addition, anti-scalant is dosed to prevent scale deposition. The pH for the second pass feed (permeate of the first pass) is adjusted at 10 by adding NaOH to increase boron removal efficiency of the membrane element.
- TDS of the final product is set to be less than 200 mg/L, and boron concentration less than 1.0 mg/L. For full second pass configuration, the product TDS and boron concentration are exceptionally low because of the full flow through the second pass. In permeate split and partial second pass configurations; the percentage of by-pass is used to adjust and control the product TDS and boron concentration.

3. Process economics

The cost of producing 200 m^3/d of permeate has been estimated. The product cost was divided into capital expenditure (CAPEX) and operating expenses (OPEX). CAPEX included the RO system, pretreatment system, site preparation, engineering, indirect and contingency costs. The OPEX consists mainly of the energy, chemicals, additives, membrane replacement, labor and maintenance costs. However, it was not possible to obtain a general formula to estimate the cost of all necessary components, since the actual cost depends on different influential factors such as location, time, quality of equipment, labor and services availability.

Table 2
Feed seawater analysis [16–19]

Parameter			Units
Ammonia	NH_3	0.526	mg/L
Potassium	K^+	491.69	mg/L
Sodium	Na^+	14,738.59	mg/L
Magnesium	Mg^{2+}	1,665.03	mg/L
Calcium	Ca^{2+}	556.47	mg/L
Strontium	Sr^{2+}	7.67	mg/L
Barium	Ba^{2+}	0.142	mg/L
Carbonate	CO_3^{2-}	17.800	mg/L
Bicarbonate	HCO_3^-	143.60	mg/L
Nitrate	NO_3^-	0.80	mg/L
Chloride	Cl^-	26,057.00	mg/L
Fluoride	F^-	2.93	mg/L
Sulfate	SO_4^{2-}	3,674.41	mg/L
Silica	SiO_2	1.59	mg/L
Boron	B	5.01	mg/L
Aluminum	Al^{3+}	0.256	mg/L
Total iron	Fe	0.021	mg/L
Carbon dioxide	CO_2	10.80	mg/L
Total alkalinity	Alk	163.50	mg/L as $CaCO_3$
Total suspended solids	TSS	6.03	mg/L
Turbidity	–	3.05	NTU
pH	–	8.32	–
Total dissolved solids	TDS	46,313.00	mg/L

Normally, the cost estimates are often based on numerous assumptions that can be varied from reference to reference. The purpose of the cost analysis in this work is to compare the main costs components of the proposed process configurations using the same assumptions under similar operating conditions.

Table 3 summarizes CAPEX categories included in this study. The cost of other equipments is listed in Table 3, which includes pumps, valves, control systems, etc., is considered equal to the cost of the RO equipment. The assumed equipment prices are shown in Table 4, while the assumed operation and maintenance prices are shown in Table 5. For comparative purposes, it was assumed that site and construction costs were $1,500,000 for a single-pass system, $1,600,000 for partial double-pass system and $1,700,000 for double-pass system with concentrate recirculation as proposed in the study by Kim et al. [21].

The following illustrates the details of the economic model used in this study:

RO equipment cost for the first pass

$$\begin{aligned} &\text{1st Pass SWRO} \\ \text{PV Cost} &= \text{PV Price} \times \text{No of PV} \\ \text{Elem. Cost}_{\text{SWRO}} &= \text{Elem. Price} \times \text{No of Elem.} \\ \text{Train Cost} &= \text{Train Price} \times \text{No of PV} \\ \text{SWRO Cost} &= \text{PV Cost} + \text{Elem. Cost}_{\text{SWRO}} + \text{Train Cost} \end{aligned} \tag{2}$$

RO equipment cost for the second pass

$$\begin{aligned} &\text{2nd Pass BWRO} \\ \text{PV Cost} &= \text{PV Price} \times \text{No of PV} \\ \text{Elem. Cost}_{\text{BWRO}} &= \text{Elem. Price} \times \text{No of Elem.} \\ \text{Train Cost} &= \text{Train Price} \times \text{No of PV} \\ \text{BWRO Cost} &= \text{PV Cost} + \text{Elem. Cost}_{\text{BWRO}} + \text{Train Cost} \end{aligned} \tag{3}$$

Table 3
CAPEX items [21]

RO equipment	Pressure vessel, membrane elements, trains
Other equipment	Pumps, controls, cleaning system, piping, permeate post-treatment equipment
Pretreatment equipment	Chemical dosing system, filtration system
Site and construction	Raw water intake, feed storage tanks, site preparation, buildings and construction
Engineering	Construction supervision, process and system design
Other indirect	Financing, interest during construction

Table 4
Equipment cost assumptions

Equipment price			Remarks
SWRO pressure vessel	2,500	$	Cost of each SWRO PV
SWRO membrane element	600	$	Cost of each SWRO element
SWRO trains	4,500	$	Cost of train frame and header connections per PV
BWRO pressure vessel	1,750	$	Cost of each BWRO PV
BWRO membrane element	600	$	Cost of each BWRO element
BWRO trains	3,000	$	Cost of train frame and header connections per PV
Pretreatment equipment	55	$	Cost of pretreatment equipment per m^3/d of feed

Table 5
Operation cost assumptions

Operation price	
Chemicals (pretreatment), \$/m³ of feed	0.02
Chemicals (pH adj. NaOH), \$/ton NaOH	465
Chemicals (pH adj. H_2SO_4), \$/ton H_2SO_4	282
Electricity, \$/kWh	0.06
Membrane replacement/year	15%
Maintenance of equipment cost	3%
Labor of the total O&M cost	25%
Interest rate/year	7%
Project life time, year	25
Loading factor/year	90%

Total RO equipment cost

$$\text{RO Equipment Cost} = \text{SWRO Cost} + \text{BWRO Cost} \tag{4}$$

Pretreatment equipment cost includes intake systems and pre-filters

$$\begin{pmatrix}\text{Pretreatment}\\ \text{Equipment Cost}\end{pmatrix} = \begin{pmatrix}\text{Pretreatment System}\\ \text{Cost per m}^3\text{ of Feed}\end{pmatrix} \times \begin{pmatrix}\text{Feed Flow Rate}\\ \text{m}^3\text{/day}\end{pmatrix} \tag{5}$$

Other equipment cost includes pumps, valves and control systems

$$\text{Other Equipment Cost} = 100\% \times \text{RO Equipment Cost} \tag{6}$$

Total equipment cost

$$\begin{pmatrix}\text{Equip.}\\ \text{Cost}\end{pmatrix} = \begin{pmatrix}\text{RO Equip.}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Pre. Equip.}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Other Equip.}\\ \text{Cost}\end{pmatrix} \tag{7}$$

Site and construction cost includes the buildings and foundations for the equipment

$$\text{Site \& Construction Cost} = \text{Const. Price} \times \text{Plant Capacity} \tag{8}$$

Sum of equipment and construction cost

$$\begin{pmatrix}\text{Equip. \& Const.}\\ \text{“E\&C Cost”}\end{pmatrix} = \begin{pmatrix}\text{Equip.}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Site \& Const.}\\ \text{Cost}\end{pmatrix} \tag{9}$$

Engineering cost includes system design and project management

$$\text{Engineering Cost} = 20\% \times \text{E\&C Cost} \tag{10}$$

Indirect cost includes financing and interest during construction

$$\text{Indirect Cost} = 50\% \times \text{E\&C Cost} \tag{11}$$

Contingency cost

$$\text{Contingency Cost} = 10\% \times \text{E\&C Cost} \tag{12}$$

Total cost of equipment, construction, indirect and contingency

$$\text{Total Cost} = \begin{pmatrix}\text{E\&C}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Engineering}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Indirect}\\ \text{Cost}\end{pmatrix} + \begin{pmatrix}\text{Contingency}\\ \text{Cost}\end{pmatrix} \rightarrow (\$) \tag{13}$$

Cost of capital factor (CRF)

$$\text{Capital Recovery Factor} = \frac{i(1+i)^n}{(1+i)^n - 1} = \text{CRF} \tag{14}$$

Annual capital cost (ACC)

$$\text{ACC} = \text{Total Cost} \times \text{CRF} \rightarrow (\$/\text{year}) \tag{15}$$

Capital expenses as \$ per cubic meter of product water

$$\text{CAPEX} = \frac{\text{ACC (\$/year)}}{365 \times \text{Plant Capacity (m}^3\text{/day)} \times \text{Loading Factor}} \rightarrow (\$/\text{m}^3) \tag{16}$$

Operating cost items

- Electric power consumption for the first pass

  1st Pass Pumping Power

$$\text{Elec. Power}_{1P} = \frac{\dot{m}_{\text{feed}} \times P_{\text{feed}}}{\eta_{\text{pump}} \times \eta_{\text{motor}}} \tag{17}$$

- Electric power consumption for the second pass

  2nd Pass Pumping Power

$$\text{Elec. Power}_{2P} = \frac{\dot{m}_{\text{feed2P}} \times P_{\text{feed2P}}}{\eta_{\text{pump}} \times \eta_{\text{motor}}} \tag{18}$$

- Electric power consumption in pretreatment

$$\text{Elec. Power}_{\text{pre}} = 1\% \times \text{Elec. Power}_{\text{net}} \tag{19}$$

Mechanical power recovered from the concentrate stream using energy recovery turbine

$$\text{Recovered Power} = \dot{m}_{\text{concen}} \times P_{\text{concen}} \times \eta_{\text{ERT}} \tag{20}$$

Net electric power consumption in the system

$$\begin{pmatrix}\text{Elec.}\\ \text{Power}_{\text{net}}\end{pmatrix} = \begin{pmatrix}\text{Elec.}\\ \text{Power}_{1P}\end{pmatrix} + \begin{pmatrix}\text{Elec.}\\ \text{Power}_{2P}\end{pmatrix} + \begin{pmatrix}\text{Elec.}\\ \text{Power}_{\text{pre}}\end{pmatrix} - \begin{pmatrix}\text{Recovered}\\ \text{Power}\end{pmatrix} \tag{21}$$

Specific electric power consumption, power consumption per cubic meter of the product

$$\text{Spec. Power} = \frac{\text{Elec. Power}_{\text{net}}}{\text{Plant Capacity} \times 24} \rightarrow \left(\text{kWh/m}^3\right) \tag{22}$$

Cost of electric power consumption as \$/m^3

$$\text{Cost of Power} = \text{Spec. Power} \times \text{Elec. Tariff} = C_1 \tag{23}$$

Cost of chemicals used for the pretreatments as \$/m^3

$$\text{Cost of Chem}_{\text{pre}} = \frac{\text{Chem}_{\text{pre}} \times \dot{m}_{\text{feed}} \times 24}{\text{Plant Capacity}} = C_2 \tag{24}$$

Cost of chemicals used for the first pass for pH adjustment as \$/m^3

$$\text{Cost of Chem}_{1P} = \frac{\text{Chem}_{1P} \times \text{Dose}_{\text{Acid}} \times \dot{m}_{\text{feed}} \times 24}{\text{Plant Capacity}} = C_3 \tag{25}$$

Cost of chemicals used for the second pass for pH adjustment as \$/m^3

$$\text{Cost of Chem}_{2P} = \frac{\text{Chem}_{1P} \times \text{Dose}_{\text{Base}} \times \dot{m}_{\text{feed}} \times 24}{\text{Plant Capacity}} = C_4 \tag{26}$$

Cost of membrane replacement, 15% of the membrane will be replaced yearly, \$/m^3

$$\text{Mem. Replace} = \frac{15\% \times \left(\text{Elem. Cost}_{\text{SWRO}} + \text{Elem. Cost}_{\text{BWRO}}\right)}{365 \times \text{Plant Capacity} \times \text{Loading Factor}} = C_5 \tag{27}$$

Cost of maintenance, 3% of the equipment cost, \$/m^3

$$\text{Maintenance} = \frac{3\% \times \text{Equip. Cost}}{365 \times \text{Plant Capacity}} = C_6 \tag{28}$$

Labor cost, 25% of the operating cost, \$/m^3

$$\text{Labor} = 25\% \times \left(C_1 + C_2 + C_3 + C_4 + C_5 + C_6\right) = C_7 \tag{29}$$

Total operating and maintenance expenses (OPEX), \$/m^3

$$\text{OPEX} = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 \tag{30}$$

Total cost of water per cubic meter of permeate, \$/m^3

$$\text{Total Cost} = \text{CAPEX} + \text{OPEX} \tag{31}$$

4. Results and discussion

4.1. Technical evaluation

Due to high concentration of boron in feed seawater, two-pass SWRO system is utilized in this investigation. In two-pass system, the pH of the first pass is lowered below 7.5 by adding H_2SO_4 to the feed. In addition, antiscalant is added to control the scale formation of the brine side at the rear elements. The pH of the second pass feed is increased by using NaOH to enhance boron removal ability of the membrane. The effect of increasing the pH on final permeate TDS and boron concentration is shown in Fig. 6.

As shown in Fig. 6, increasing the pH of the second pass improves boron rejection of the system and reduces permeate TDS until the pH reaches 10. Beyond pH = 10, boron rejection improvement is still evident but the permeate TDS drastically increases. At pH = 12, the TDS is 70 mg/L and boron is higher than the value at pH = 11. This behavior can be attributed to the relationship between the pH of feed water and the NaOH dosage required. The effect of the anticipated feed pH on the required NaOH dose amount and resultant Na ions concentration in the adjusted feed to the second pass is shown in Fig. 7. Up to pH = 10, there is no noticeable change in Na concentration in adjusted feed, and hence permeate TDS does not increase in Fig. 6. Beyond pH = 11, the NaOH dose causes a significant rise in Na ions concentration in feed water, and hence total TDS of permeate increases. For this reason, pH = 10 for the second pass was used in the rest of the simulation below.

The effect of different ISD configurations of a two-pass system has also been investigated in this work. ISD for the

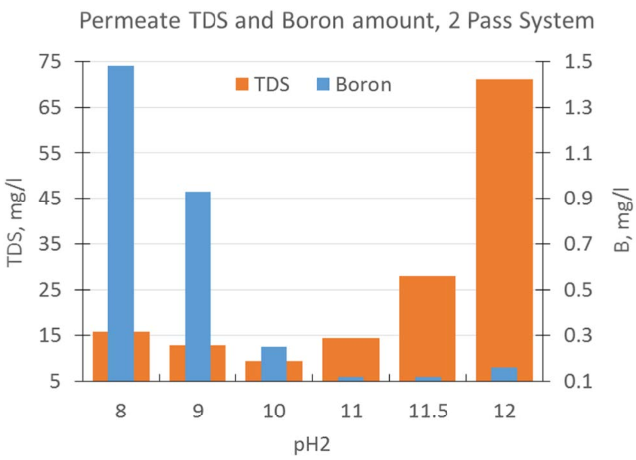

Fig. 6. Effect of the pH of the second pass on permeate TDS and boron contents.

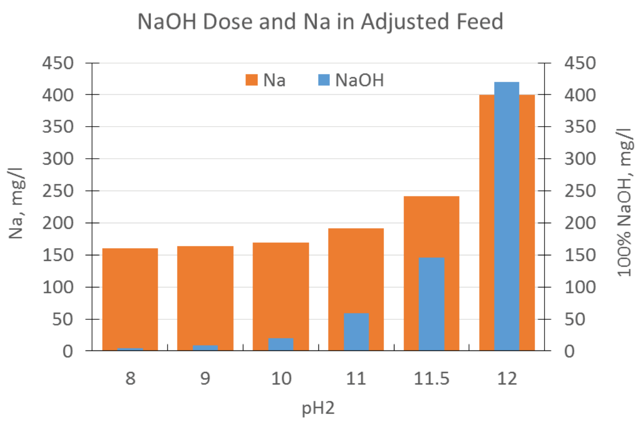

Fig. 7. NaOH dose and amount of Na in the adjusted feed.

first pass only, ISD for the second pass only, and ISD for both. Boron concentration and TDS of the final permeate when using ISD in the first pass only are shown in Fig. 8. ISD is used in the first pass only with two and three different elements that are shown in Table 1. The Case number in Fig. 8a represents the element's configuration. For instance, "Case 1 + 5" means the first element is SW30XHR-440i while the rest (five elements) are SW30XLE-440i. "Case 1 + 2 + 3" in Fig. 8b means that, first element is of type SW30XHR-440i, two elements (second and third elements) are of type SW30HRLE-370/34i and last three elements of type SW30XLE-440i. Using more membrane elements of the high salt rejection type improves the permeate quality in terms of low TDS and boron concentration, while using ISD with three elements showed small change on the TDS and boron concentration of the final permeate. It is worth to mention that the TDS and boron levels are extremely low because the entire permeate from the first pass flows through the second pass.

Fig. 9 shows TDS and boron concentration for ISD used in the second pass only. Fig. 9a shows ISD using two different elements in the PV, while Fig. 9b represents three different element types in the PV. It is clear that using more elements of the type BW30HR–440i improves the boron rejection, as shown in Case 7 + 1 in Fig. 9a. The reason is that type of membrane has high permeate flux as well as high salt and boron rejection as illustrated in Table 1. The lowest TDS was achieved using ISD with two element types rather than three. Detailed discussion on the effect of the ISD on permeate quality and energy consumption can be found in Kim and Hong [22].

The partial-second-pass system has been investigated in this study with two different configurations. First, partial second pass by blending part of the first pass permeate with the final product. Second, partial second pass by using permeate split configuration. Each case is investigated with and without second pass brine recirculation to the first pass feed.

Fig. 10 shows permeate TDS and boron concentration for different partial second pass configurations. Full second pass shows extremely low TDS and boron with and without brine recirculation, while the permeate split configuration is the second in both TDS and boron, and the highest concentration occurs in the case of partial second pass configuration. The reason behind that is the quality of the blended permeate. In the case of permeate split, the quality of the blended permeate is much higher than the partial second pass case. It is worth noting that with brine recirculation, the

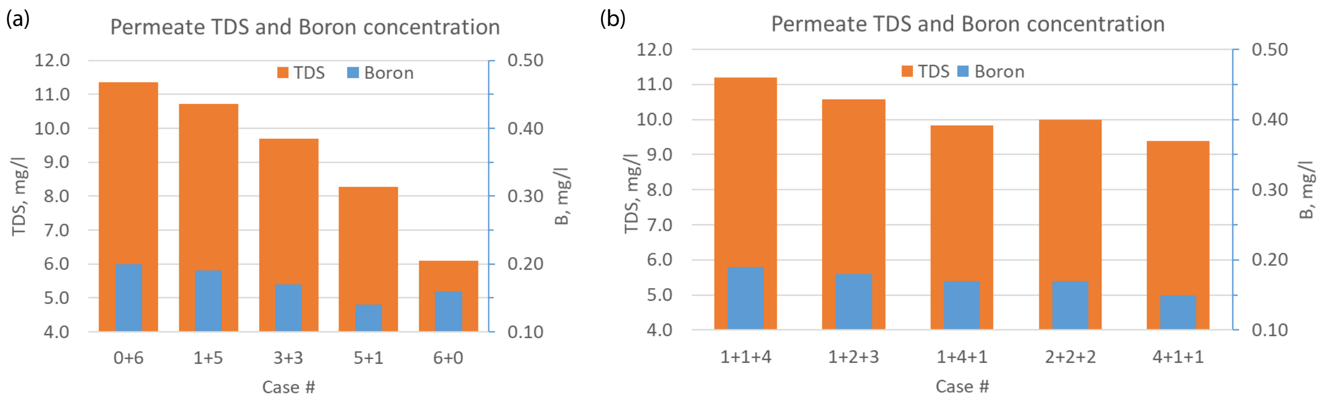

Fig. 8. TDS and boron concentration for ISD in the first pass only. (a) ISD with two types of membrane elements and (b) ISD using three types of membrane elements.

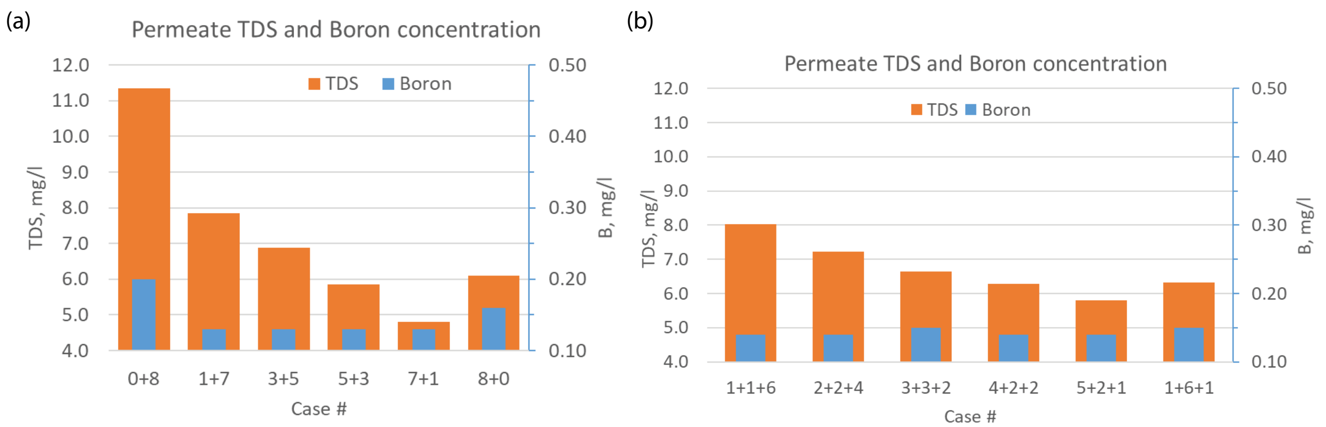

Fig. 9. TDS and boron concentration for ISD in the second pass only. (a) ISD with two types of membrane elements and (b) ISD using three types of membrane elements.

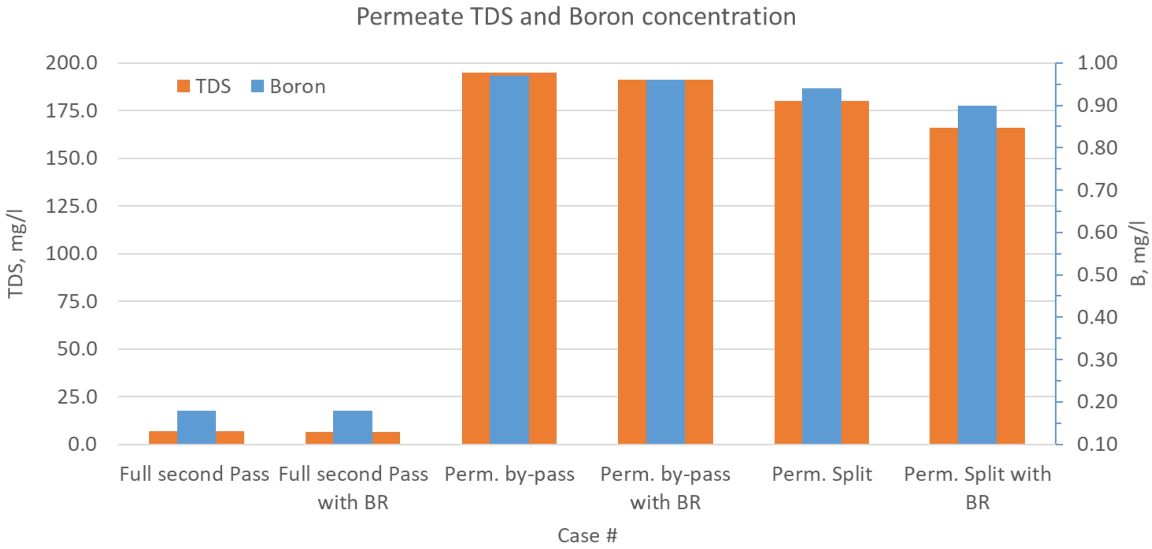

Fig. 10. Different partial second pass configurations.

salinity of the feed water after blending with the circulating brine from the second pass is lower than the feed seawater, and for this reason, the recovery ratio of the first pass is increased and that will be shown through the economic analysis of these cases. A novel permeate split configuration for single-pass SWRO is presented in the study by Kim and Hong [23].

4.2. Economic model results

The proposed SWRO system configurations have been evaluated economically for comparison. Sample results of the proposed economic model are shown in Tables 6 and 7. The distribution of cost by category is shown in Figs. 11 and 12.

The total capital cost is 55% while the operating and maintenance cost is 45% of the total product cost. The equipment cost represents around 30% of the total CAPEX, while the indirect, engineering and construction cost is 70% of the CAPEX.

Electric energy consumption is the main OPEX item with more than 30% of the operating and maintenance cost of the SWRO system.

The CAPEX, OPEX and total production cost for different ISD configurations are shown in Figs. 13 and 14. The effect of ISD on water production cost is insignificant compared with its effect on TDS and boron concentration. The two-element ISD showed noticeable impact on production cost compared with the three-element ISD.

Water production cost of different partial second-pass-flow configurations are shown in Fig. 15. Brine circulation has positive effect on the production cost, where water production cost reduced about 6% on average when brine recirculation is implemented in the process. The reason is due to the TDS dilution caused by mixing the brine of the second pass at lower concentration compared with feed seawater with the main feed. The permeate split SWRO process resulted in the lowest production cost among all proposed processes and showed good results for TDS and boron concentration. The reasons behind this cost variations are interdependent. For example, in full flow through the second pass, both CAPEX and OPEX of the second pass are high due to the bigger flow rate, and hence more membrane elements, energy and chemicals are to be used. For partial second pass configurations, the permeate flow to the second pass is substantially reduced due to the bypass. For permeate split configuration, the cost was lower than the permeate by-pass due to the high quality of the product water extracted from the lead membrane elements compared with the ordinary permeate from first stage. As mentioned

Table 6
CAPEX breakdown for ISD in the first pass

CAPEX estimation		
PV cost, $	7,500	
Mem. elem. cost, $	10,800	SWRO
Train cost, $	13,500	
SWRO system cost, $	31,800	
PV cost, $	1,750	
Mem. elem. cost, $	4,800	BWRO
Train cost, $	3,000	
BWRO system cost, $	9,550	
Pretreatment equipment cost, $	51,371	
RO equipment cost, $	41,350	
Other equipment cost, $	41,350	
Site and construction cost, $	200,000	
Sub total, $	334,071	
Engineering cost, $	66,814.22	
Indirect cost, $	167,035.6	
Contingency cost, $	33,407.11	
Total cost, $	601,327.98	
Capital cost factor	0.0858	
Capital cost, $	0.7854	$/m^3

Table 7
OPEX breakdown for ISD in the first pass

OPEX estimation	
Pumping energy (1st pass), kW	26.596
Recovered energy (1st pass), kW	38.543
Pumping energy (2nd pass), kW	2.331
Total electric energy consumption, kW	29.217
Specific energy (two passes), kW-h/m^3	3.471
Pretreatment and aux. energy (1%), kW-h/m^3	0.289
Specific energy consumption, kW-h/m^3	3.506
Power cost, \$/m^3	0.2104
Chem. (pre) cost, \$/m^3	0.0934
Chem. (pH1 adj) cost, \$/m^3	0.0826
Chem. (pH2 adj) cost, \$/m^3	0.0298
Mem. replacement, \$/m^3	0.0356
Maintenance cost, \$/m^3	0.0551
Labor cost, \$/m^3	0.1267
O&M cost, \$/m^3	0.6336

earlier, the controlling factor for the second pass recovery is boron concentration of the final permeate. Blending high quality permeate (from lead elements) allows for increasing the recovery ratio of the second pass while final permeate still within the concentration limits. Increasing the recovery ratio of the second pass increases the overall recovery ratio of the SWRO system and hence reduces the product cost as shown in Fig. 15.

5. Conclusions

Boron removal from seawater using reverse osmosis system is proposed and evaluated technically and economically. Three SWRO systems configurations are investigated: (a) full second pass, (b) partial second pass and (c) permeate split. Brine recirculation has been implemented and tested against the cases without recirculation in each of these three configurations. In addition, the effect of ISD has been investigated. Results showed that ISD configurations with full flow to the second pass produce the highest quality for the final permeate (TDS = 7 mg/L and B = 0.18 mg/L).

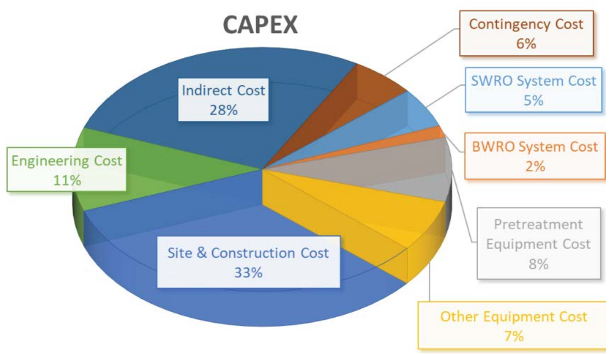

Fig. 11. CAPEX breakdown for ISD in the first pass.

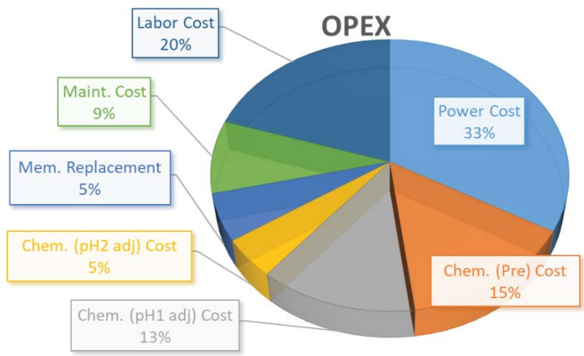

Fig. 12. OPEX breakdown for ISD in the first pass.

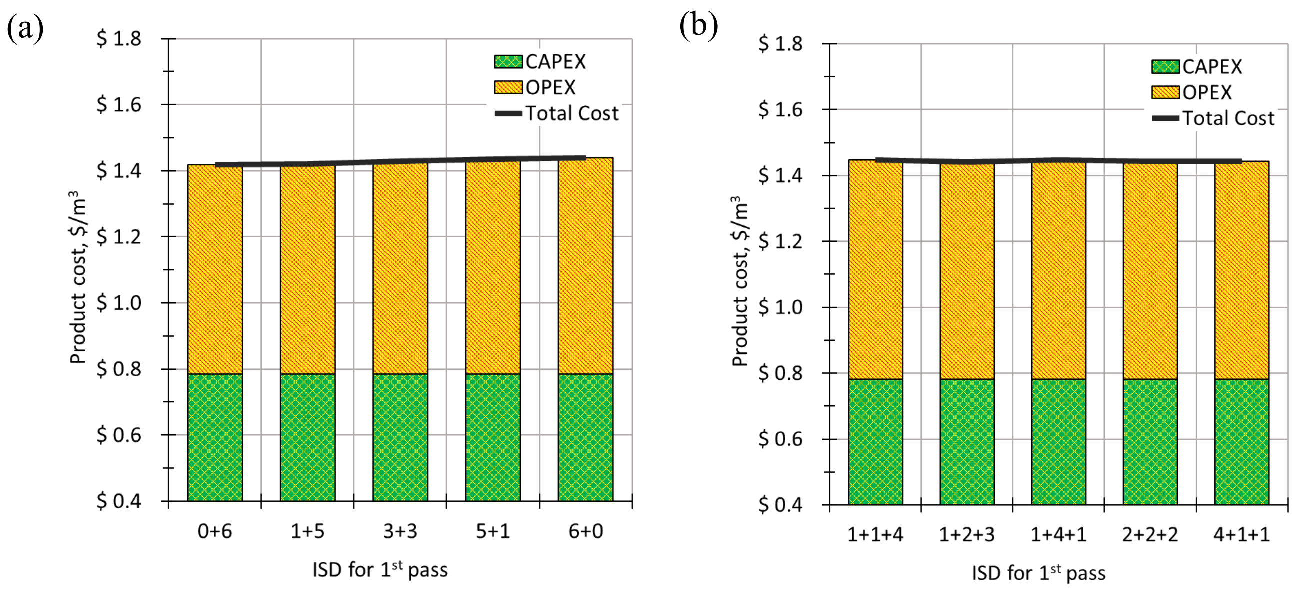

Fig. 13. CAPEX, OPEX and total product cost for ISD in the first pass using (a) two different membrane elements and (b) three different membrane elements.

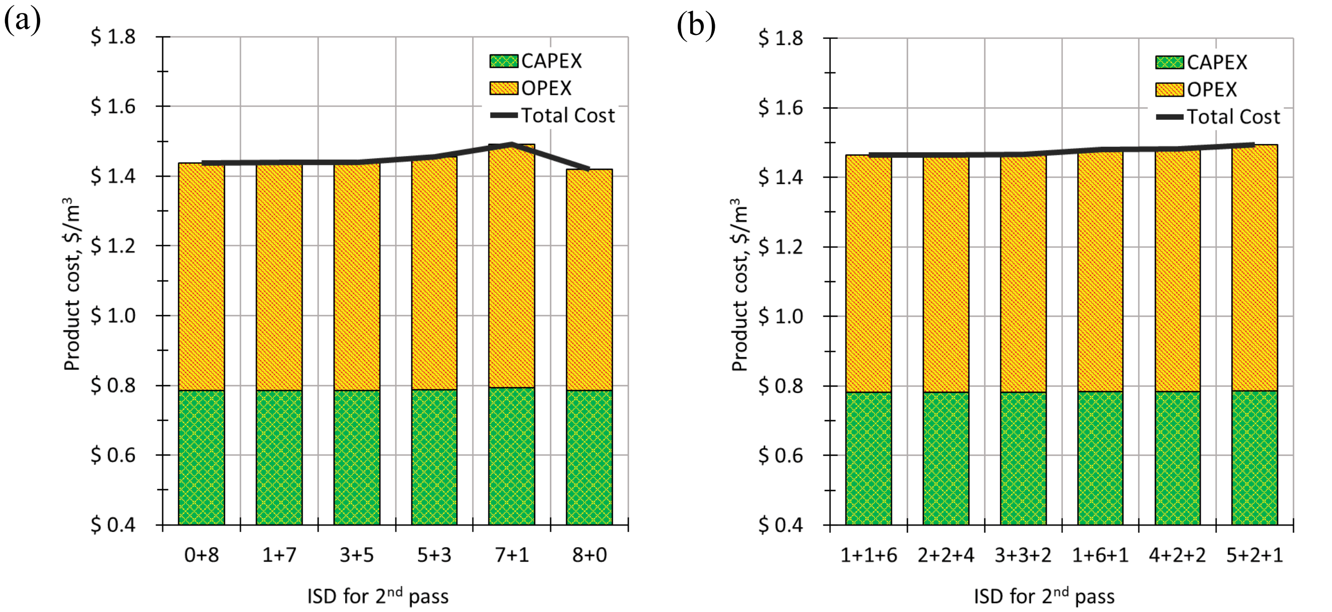

Fig. 14. CAPEX, OPEX and total product cost for ISD in the second pass using (a) two different membrane elements and (b) three different membrane elements.

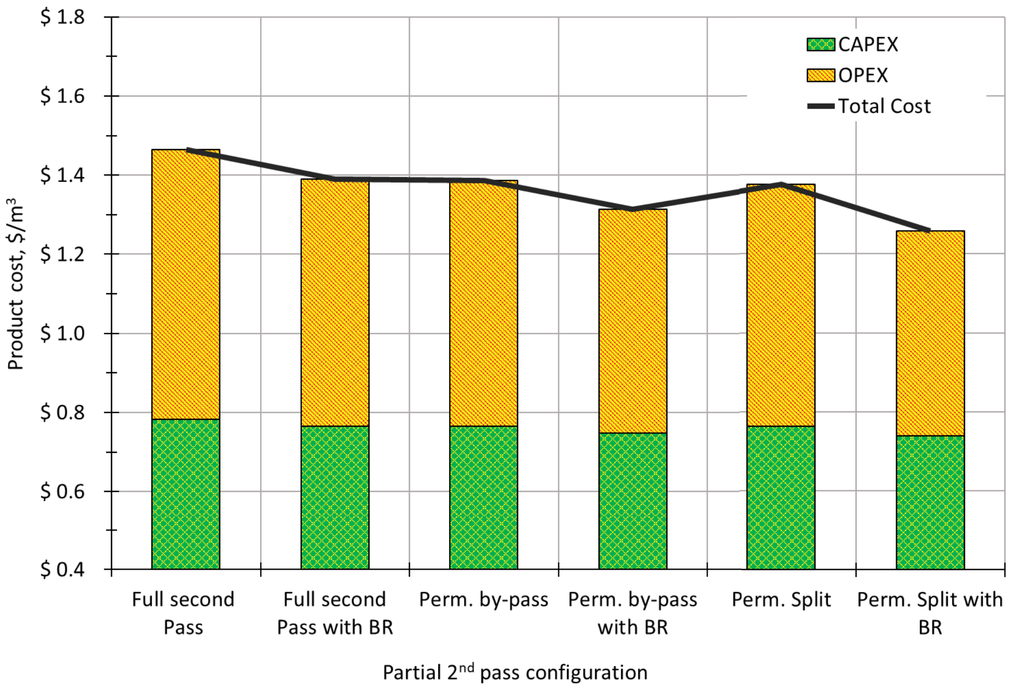

Fig. 15. CAPEX, OPEX and total product cost for different partial-second-pass configurations.

ISD, however, has minimal effect on the water production cost. The permeate split configuration resulted in the lowest product cost (8% less than full second pass) with product water of TDS = 173 mg/L and B = 0.92 mg/L. The product cost of permeate by-pass was 6% less than the base configuration of full flow through the second pass with product water quality of TDS = 193 mg/L and B = 0.97 mg/L.

Symbols

ACC — Annual capital cost
BWRO — Brackish water reverse osmosis
CRF — Cost of capital factor
ERT — Energy recovery turbine
GPD — Gallon per day
i — Interest rate, %

ISD — Internal stage design
$\dot{m}_{feed}$ — Feed flow rate, m^3/d
n — Project life time, year
P_{feed} — Feed pressure, bar
PV — Pressure vessel
SWRO — Seawater reverse osmosis
TDS — Total dissolved solids
η_{motor} — Pump motor efficiency
η_{pump} — Pump efficiency

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