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Optimization of two-stage seawater reverse osmosis membrane processes with practical design aspects for improving energy efficiency

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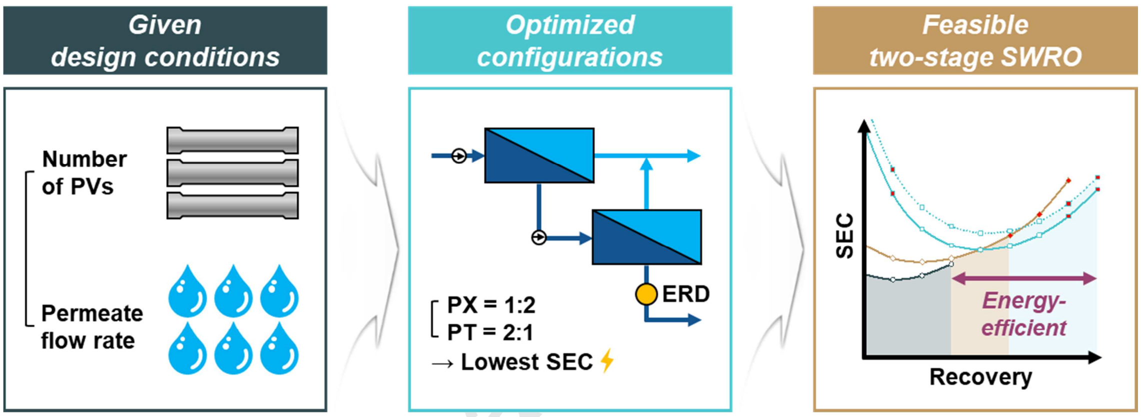
Highlights

- Two-stage SWRO is fundamentally analyzed and optimized for seawater desalination.
- SEC of two-stage SWRO is higher than that of single-stage in typical recovery.
- Water quality of single- and two-stage SWRO is similar at the same average flux.
- Optimal ratios of permeate flow rate and number of PVs vary depending on ERD types.
- Two-stage SWRO is more energy-efficient at a high recovery rate (e.g., 50–70%).

Graphical Abstract



Abstract

While single-stage is the general configuration for seawater reverse osmosis (SWRO), the two-stage design can increase the overall recovery of an SWRO system. Due to its high-recovery operation, the specific energy consumption (SEC) of two-stage SWRO is higher than that of single-stage. Thus, the two-stage configuration has not been extensively applied in the current desalination market. In contrast, recent studies have reported that the two-stage design can lower the SEC of SWRO compared to that of single-stage. However, the analyses were biased towards SEC, and the practical design aspects (e.g., permeate quality, water flux, and design ratios) were not systemically considered. Thus, this study examines the applicability of a two-stage SWRO system with a capacity of 100,000 m^3/d that employs 1200 pressure vessels (PVs). Two-stage SWRO actually consumed a greater amount of energy than that of single-stage for typical SWRO recovery with the same number of PVs. In contrast, single- and two-stage SWRO produced permeate similar in quality, while the two-stage exhibited superior water-flux distribution along the PVs. Additionally, optimal ratios of permeate flow rate and number of PVs were determined by energy recovery devices type, where the ratio of 1:2 was selected for the reverse osmosis system with a pressure exchanger and 2:1 for that with a Pelton turbine. Considering SEC and other operational aspects, the use of two-stage SWRO was feasible at a 50–70% recovery rate.

Keywords: *Seawater reverse osmosis; Staged configurations; Energy efficiency; Specific energy consumption; Design ratios.*

1. Introduction

A variety of water sources are recognized as potential water sources for human use in the era of water scarcity [1-3]. To avoid a negative public reaction on water reuse such as using wastewater and industrial effluents [4, 5], seawater is a more preparable option for human use [6], but an energy-intensive desalination process must be performed to utilize seawater as it contains a high concentration of salts [7]. This process is typically conducted by a pressure-driven seawater reverse osmosis (SWRO) process, where a hydraulic pressure higher than that of an osmotic pressure of feed is applied [1, 2, 8]. When the hydraulic pressure of the feed exceeds its osmotic pressure, freshwater is produced through SWRO membranes due to the salts being rejected [9, 10]. However, the recovery rate of typical single-stage (or single-pass) SWRO is limited to less than 50% due to the osmotic pressure of seawater [1, 2, 11]. When a high pressure is applied to achieve a high recovery rate, a large amount of water is produced from front SWRO elements, and the osmotic pressure of the rear feed is prone to exceeding its hydraulic pressure, resulting in no further water production.

To increase the recovery rate of the SWRO system, a two-stage design has been developed and implemented, where the concentrate of the first stage is fed into the second stage, and additional freshwater is produced [9, 11]. The two-stage SWRO system commonly utilizes a 2:1 ratio for the first-stage number of pressure vessels (PVs) compared to that of the second stage, which is similar to that of nanofiltration (NF) and brackish water reverse osmosis (BWRO) systems [9, 12, 13]. Using a two-stage SWRO system, water is produced at each stage by gradually increasing the hydraulic pressure and exceeding the feed osmotic pressure, and the recovery can be increased by up to 60–65%. The increased recovery allows for a reduction in plant size, particularly for the intake and pretreatment parts; thus, the costs for construction and operation can be reduced [9]. In contrast, the application of two-stage SWRO is uncommon as a high-pressure is required compared to that of a single-stage SWRO system.

Some SWRO desalination plants are configured as two-stage SWRO with a high-recovery rate operation (**Table 1**). In most two-stage SWRO plants, the second-stage SWRO is installed in addition to the existing first-stage SWRO to retrofit the plant and increase its capacity [9]. The retrofitted two-stage SWRO can increase the recovery rate to 50–60% depending on the design, and the required hydraulic pressure depends on the recovery rate

(70–90 bar). Because of the extremely high pressure of the feed at the second stage, equipment that is highly resistant to pressure should be installed [14, 15]. This results in an increase in equipment costs compared to those of a normal pressure operation. The capital cost also increases due to the installation of additional stages and other equipment [9]. Moreover, the specific energy consumption (SEC) of the two-stage SWRO process is high because of its high recovery rate [8, 16, 17]. As a low SEC is the recent focus of the desalination market as opposed to a high recovery rate, current SWRO desalination plants predominately adopt single-stage instead of two-stage.

Recently, theoretical studies have found that a staged reverse osmosis (RO) configuration can lower the SEC of a SWRO process closer to the theoretical minimum energy for separation. This is because two-stage RO can deliver high pressure to a small volume of feed in each stage [2, 18, 19]. The advantage of a two-stage SWRO design for SEC has been investigated in comparison with single-stage SWRO at the same recovery rate (e.g., 40%), unlike the real application recovery rate of two-stage SWRO (e.g., 60%). The results showed that two-stage SWRO consumes less energy than that of single-stage SWRO due to the reduction in the irreversibility of the high-pressure pump [2, 18, 20-22]. The theoretical background support the benefits of two-stage SWRO such as having a low SEC, increasing the possibility of the wider application of two-stage SWRO in current desalination markets.

Studies do not fully support the claim that two-stage SWRO is more feasible than single-stage SWRO. The theoretical analysis is only focused on energy consumption, and the more practical aspects of SWRO operation such as permeate quality and other operational issues are not considered. Moreover, when SEC is compared, the number of PVs for the two-stage RO is larger than that for the single-stage RO, which results in different equipment conditions. In addition, the SEC that is evaluated is not optimal, as the permeate flow rate and number of PVs are determined without considering optimization but using a ratio of 2:1 as the rule of thumb. The average water flux and recovery for each stage are not determined systemically. By applying the thermodynamic and simple RO models for SEC calculation, the feasibility of two-stage SWRO cannot be accessed.

Due to the disparity between the practical and theoretical SEC of two-stage SWRO, this study evaluates the applicability of a two-stage SWRO system for seawater desalination with regard to energy efficiency. As SEC is a critical factor in determining the application feasibility, the SEC of two-stage SWRO is compared to that of single-stage SWRO based on the recovery rate when the same number of PVs is employed. Permeate quality is also considered given that the permeate is utilized and is thus analyzed in association with water flux. To examine the validity of the current 2:1 ratio, practical designs for two-stage SWRO (e.g., ratios of the number of PVs and permeate flow rate for each stage) are analyzed at a given recovery rate. The SEC for single-stage and two-stage SWRO is also assessed at a high recovery rate to demonstrate the energy-efficiency of two-stage SWRO systems. To the best of our knowledge, this is the first study that provides a theoretical foundation for the use of an optimized staging RO configuration to improve the energy efficiency of seawater desalination using practical design aspects including permeate quality, water flux, and design ratios.

Table 1.

Two-stage SWRO desalination plants

Plant	Country	Plant capacity (m^3/d)	Overall SWRO recovery rate (%)	Hydraulic pressure (bar)[a]	ERD type	Reference
Curacao	Curacao[b]	10,200	58	N/A	PT	[15]
Fukuoka	Japan	50,000	60	N/A	PT	[23, 24]
Las Palmas Ⅲ	Spain	86,000	50	N/A	PX	[25]
Maspalomas Ⅱ		26,200	60	90	PT	[15, 26]
Rambla Morales		60,000	58	83	PT	[27]
Valdelentisco		140,000	50	77	PX	[28]
Kindasa	KSA	26,800	50	71	PT	[29]

[a] Second-stage SWRO. [b] Netherlands Antilles. KSA: Kingdom of Saudi Arabia. ERD: energy recovery device. PT: Pelton turbine. PX: pressure exchanger. TC: turbocharger.

2. Methods

2.1. Description of two-stage SWRO

In single-stage SWRO, approximately 40% of the feed flow rate is converted to the permeate flow rate, which represents 40% recovery rate (**Fig. 1a**). To increase the recovery rate, a second-stage SWRO is equipped in addition to the existing single-stage SWRO. Such a SWRO configuration is referred to as two-stage SWRO (**Fig. 1b**), and the SWRO system can achieve a 60% overall recovery rate (i.e., 40% from the single-stage and 20% from the second stage). The operation of the practical two-stage SWRO desalination plants (**Table 1**) can also be illustrated as **Fig. 1b**. However, the recovery of two-stage SWRO (**Fig. 1b**) is higher than that of single-stage SWRO (**Fig. 1a**). Thus, the energy consumption for two-stage SWRO is inherently higher due to the higher recovery rate [1]. Unlike two-stage SWRO in practice, two-stage SWRO in theoretical studies is operated with a 40% overall recovery rate as depicted in **Fig. 1c**. For the same recovery rate for single- (**Fig. 1a**) and two-stage (**Fig. 1b**) SWRO in previous research, two-stage SWRO is demonstrated to consume a lower amount of energy than that of single-stage SWRO [18-22]. This research targets two-stage SWRO in theory, and the feasibility of two-stage SWRO is examined considering practical design aspects such as permeate quality, water flux, and design ratio.

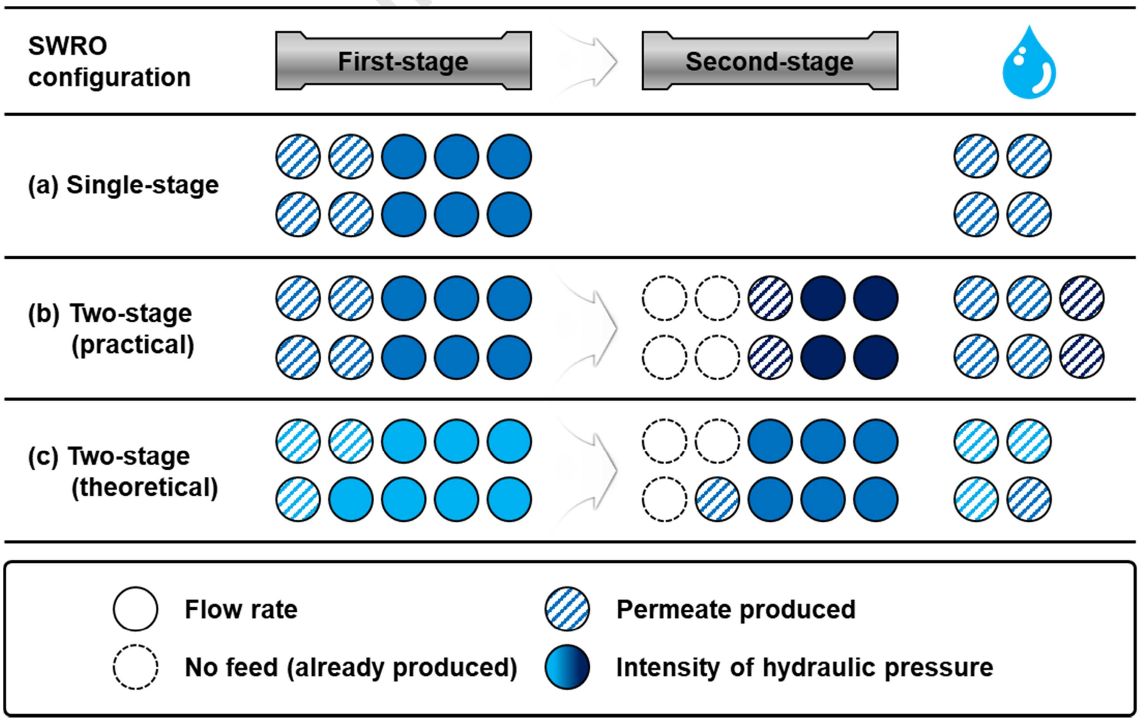


Fig. 1. Conceptualization of SWRO: (a) single-stage, (b) two-stage (practical), and (c) two-stage (theoretical).

2.2. Types of staged SWRO configurations

Staged RO configurations can be classified into two types: processes without circulation stream and those with it. Examples of the former are the single-stage and multi-stage processes, where the concentrate of the previous stage is supplied to the following stage as feed. In contrast, closed circuit desalination (CCD) and batch RO contain circulation streams, and they have not yet been applied as full-scale SWRO desalination plants [8]. To focus on the feasibility of commercially available technologies, only the staged RO configurations without a circulation stream were examined. **Fig. 2a** is a scheme of a single-stage SWRO, where the hydraulic pressure of the concentrate is delivered to a part of feed with a pressure exchanger (PX). A Pelton turbine (PT) can be used instead of a PX, but applying a PX is more beneficial for energy savings due to its high mechanical efficiency [30]. Similar to the single-stage SWRO in **Fig. 2a**, a two-stage SWRO can be configured with a PX, which recovers high pressure to a partial stream of feed supplied to the first stage (**Fig. 2b**). However, such a configuration is impractical as the pressure delivered from the concentrate is higher than that required for the first stage. Thus, a two-stage SWRO configuration employing PX can be alternatively expressed as in **Fig. 2c**, where the hydraulic pressure is delivered to a partial second-stage feed. To utilize the hydraulic energy in the concentrate to operate the first stage, a PT should be employed as an energy recovery device (ERD) (**Fig. 2d**). Two-stage SWRO is different from two-pass SWRO, in which the permeate from the first stage (pass) RO is fed to the second pass RO; thus, it is typically composed of both SWRO and BWRO [8].

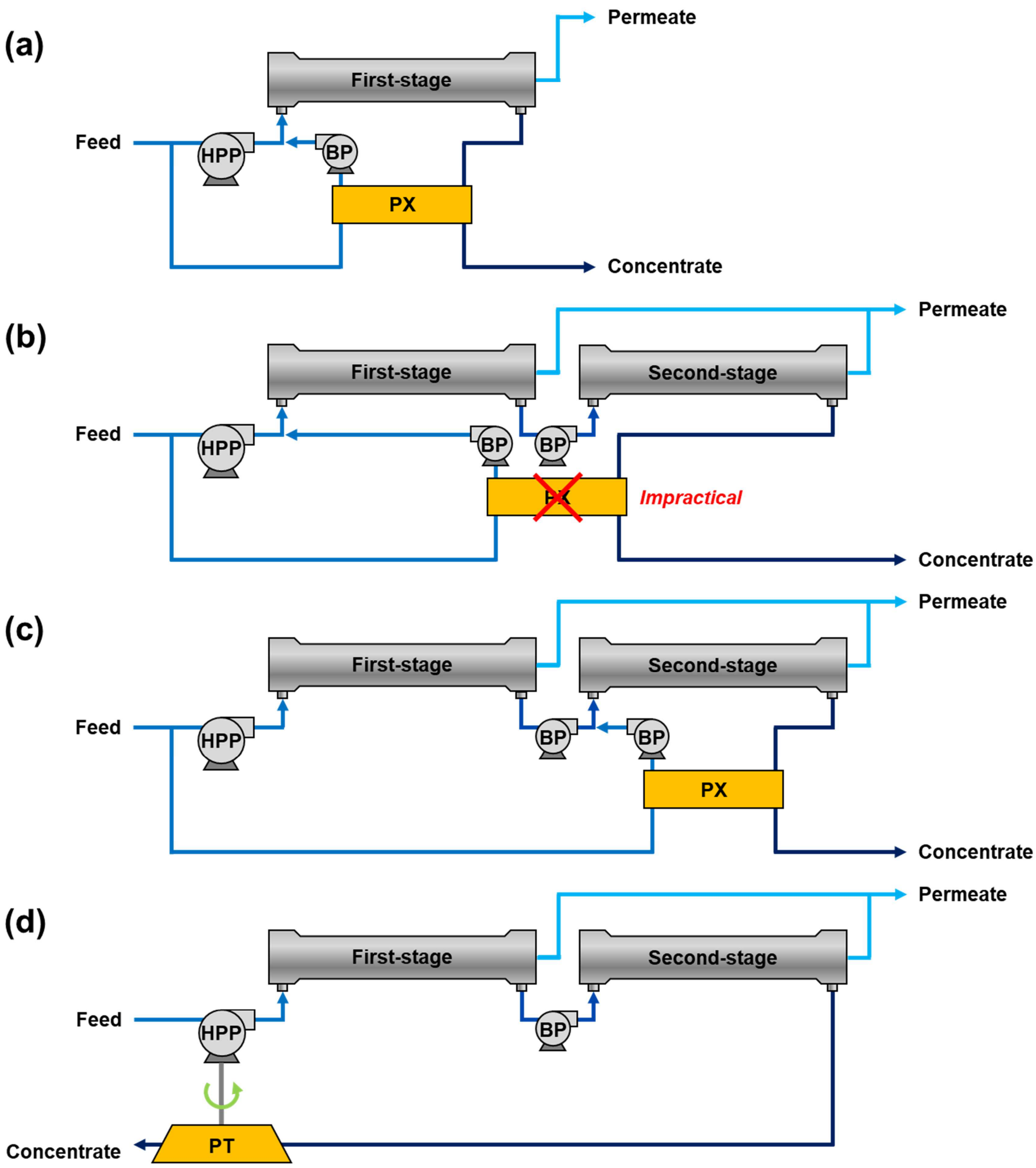


Fig. 2. Scheme of staged SWRO configurations for seawater desalination: (a) single-stage, (b) two-stage with PX (impractical), (c) two-stage with PX, and (d) two-stage with PT.

2.3. SWRO process modeling

A typical condition for seawater of 35,000 mg/L as total dissolved solids (TDS) and 25 ℃ was used in the simulation. A single type of SWRO membrane, SW400R, was manufactured from LG Chem and was employed to examine the effect of a staged RO design without considering the internally staged design (ISD). Water permeability (*A*) and salt permeability (*B*) were obtained as 1.52 L/m^2 h bar and 5.20 × 10^{-2} L/m^2 h, respectively [11]. The pump efficiency was 80% for both the high-pressure pump (HPP) and booster pump (BP), while those of the ERDs (e.g., PX and PT) were 95% [8, 11, 31-33]. It should be noted that the efficiency of the PT was both 95% and 90% in Section 4.3 to consider the real application of two-stage SWRO with a PT. The performance of the SWRO process was evaluated by a developed RO process program [8, 11], which calculates water and salt fluxes using Eqs. (1) and (2) as derived from the solution-diffusion model [34] (J: flux, P: hydraulic pressure, π: osmotic pressure, CPF: concentration polarization factor, $_w$: water, $_s$: salt, $_f$: feed, and $_p$: permeate).

$$J_w = A\left[(P_f - P_p) - (CPF \times \pi_f - \pi_p)\right] \tag{1}$$

$$J_s = B(CPF \times C_f - C_p) \tag{2}$$

The program demonstrated a high accuracy (R^2 = 0.9998) based on the results of the projection software provided by the membrane manufacturer (Q+ version 2.4), and the maximum differences in applied pressure and permeate quality in the recovery range were 0.7 bar and 2 mg/L, respectively (**Fig. 3**). Small differences may have resulted from the empirical coefficients by the manufacturer. When operating conditions violate the recommended design values by the manufacturer (e.g., hydraulic pressure > 82.7 bar, pressure drop > 1.0 bar, feed flow rate > 408 m^3/d, and water flux > 32.3 L/m^2 h), the developed program displayed a warning sign, which is depicted in **Figs. 5, 6,** and **9** with red dots.

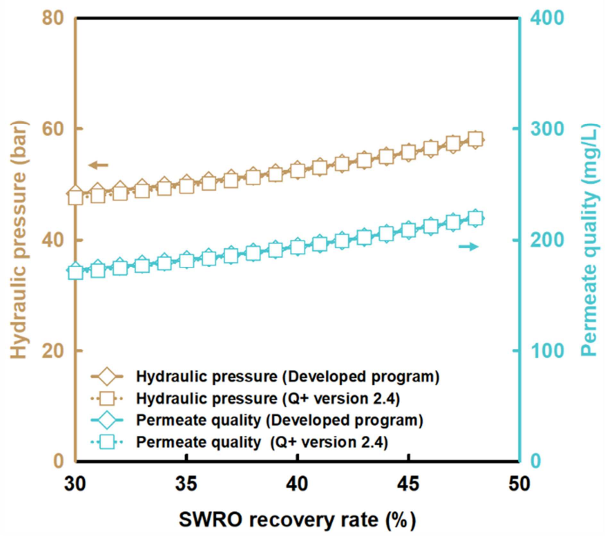


Fig. 3. Performance of the developed program and Q+ version 2.4.

2.4. Performance of SWRO

Permeate quantity and quality of the SWRO system, $Q_{p,system}$ *and* $C_{p,system}$, were evaluated using Eqs. (3) and (4), which integrate Eqs. (1) and (2) along membrane area A_m. Different equations were applied to calculate the energy consumption of the SWRO system, E_w, depending on the configuration ($_{single}$: single-stage, $_{two\_PX}$: two-stage (PX), and $_{two\_PT}$: two-stage (PT)) in Eqs. (5)–(7) [11, 35]. The feed and concentration are expressed as Q_f and Q_c, and the subscripted numbers 1 and 2 represent the first and second stage, respectively. The stream pressure for each stage is similarly expressed, and the pressures for the inlet and outlet of the SWRO system, P_{in} and P_{out}, were 1 bar each. In contrast, it was assumed that the mechanical efficiency of electric motor η_{motor} was 98%, and the pumps including HPPs η_{HPP} and BPs η_{BP} were both 80%. The efficiencies of PX η_{PX} and PT η_{PT} were both 95% under the basic conditions, but a 90% of η_{PT} was also applied to Section 3.4. Lastly, SEC of the system (SEC_{system}) was calculated in Eq. (8).

$$Q_{p,system} = \int_{x=0}^{x=L} J_w \, dA_m \tag{3}$$

$$C_{p,system} = \frac{\int_{x=0}^{x=L} J_s dA_m}{\int_{x=0}^{x=L} J_w dA_m} \tag{4}$$

$$E_{w,single} = \frac{(Q_{f,1}-Q_{c,1})(P_{f,1}-P_{in})}{\eta_{motor}\eta_{HPP}} + \frac{Q_{c,1}[(P_{f,1}-P_{in})-\eta_{PX}(P_{c,1}-P_{out})]}{\eta_{motor}\eta_{BP}} \tag{5}$$

$$E_{w,two\_PX} = \frac{Q_{f,1}(P_{f,1}-P_{in})}{\eta_{motor}\eta_{HPP}} + \frac{(Q_{f,2}-Q_{c,2})(P_{f,2}-P_{c,1})}{\eta_{motor}\eta_{BP}} + \frac{Q_{c,2}[(P_{f,2}-P_{in})-\eta_{PX}(P_{c,2}-P_{out})]}{\eta_{motor}\eta_{BP}} \tag{6}$$

$$E_{w,two\_PT} = \frac{Q_{f,1}(P_{f,1}-P_{in})}{\eta_{motor}\eta_{HPP}} + \frac{Q_{f,2}(P_{f,2}-P_{c,1})}{\eta_{motor}\eta_{BP}} - \frac{Q_{c,2}[\eta_{PT}(P_{c,2}-P_{out})]}{\eta_{motor}\eta_{BP}} \tag{7}$$

$$SEC_{system} = \frac{E_{w,system}}{Q_{p,system}} \tag{8}$$

2.5. Selection of design ratios for two-stage SWROs

An SWRO plant was designed with a capacity of 100,000 m^3/d, where 1200 PVs containing seven elements each were installed to maintain an average water flux of 13.35 L/m^2 h. For two-stage SWRO systems, both 1200 PVs and 1800 PVs were considered to examine SWRO feasibility, even when the number of PVs is the same as that of single-stage SWRO. However, the permeate flow rate and number of PVs for each stage (i.e., decision variables) must be determined to evaluate the performance of a two-stage SWRO system in terms of minimizing energy consumption. Thus, the objective function and constraints for a harmony search (HS) are given in Eqs. (9) and (10), respectively.

$$\textit{Minimize SEC} = f(\textit{Number of PVs (1st), Permeate flow rate (1st), Number of PVs (2nd), Permeate flow rate (2nd)}) \quad (9)$$

$$\begin{aligned} &\textit{Subject to} \\ &5 \le \textit{Number of PVs (1st)} \le 1200 \textit{ (or 1800)} \\ &1000 \le \textit{Permeate flow rate (1st)} \le 100000 \\ &\textit{Number of PVs (1st) + Permeate flow rate (2nd)} = 1200 \textit{ (or 1800)} \\ &\textit{Permeate flow rate (1st) + Permeate flow rate (2nd)} = 100000 \end{aligned} \quad (10)$$

As the objective function is not continuous nor differentiable, finding the optimal decision variables is an extremely complex endeavor when using conventional optimization techniques. Thus, HS as a metaheuristic algorithm was adopted to efficiently find the decision variables through its balancing of diversification and intensification [36, 37]. Because the best decision variables can be obtained within 500 iterations for this problem (**Fig. 4**), the HS algorithm was able to significantly reduce the iteration time compared to the original computation time required for optimization (i.e., 24,000). The parameters used in the HS are summarized in **Table 2**.

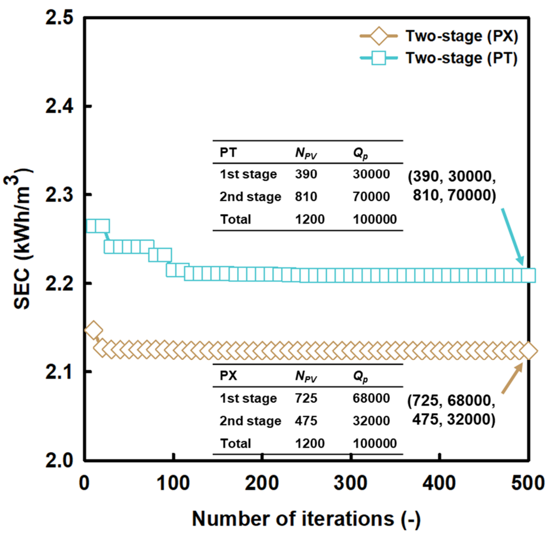


Fig. 4. SEC reduction by applying improved decision variable values for two-stage SWRO using HS. The target recovery rate was 45%. Q_p: permeate flow rate. N_{PV}: PV numbers.

Table 2.

Parameters used in the HS

Parameters	Value
Harmony memory size (HMS) [–]	10
Bandwidth (BW) for permeate flow rate [m^3/d]	1000
BW for number of PVs [–]	5
Harmony memory considering rate (HMCR) [–]	0.7
Pitch adjusting rate (PAR) [–]	0.3

3. Results and discussion

3.1. Specific energy consumption and recovery

The number of PVs for a typical two-stage SWRO design is 1.5 times greater than that for a typically single-stage SWRO design (2:1 ratio) [9]. However, the feasibility of the RO design can be evaluated fairly only when the number of PVs (or membranes) are the same. Thus, the SEC of single- and two-stage SWRO was compared separately when the number of PVs is 1.5 times greater (i.e., typical comparison) or the same (i.e., fair comparison). The SEC was evaluated using the optimal ratios for each case, which are further discussed in Section 3.

In **Fig. 5(a)**, two-stage SWRO consumed less energy than single-stage SWRO for a typical SWRO recovery rate. The SEC of single-stage SWRO was 1.99–2.15 kWh/m^3, and the lowest SEC was observed at a recovery rate of 38%. In contrast, two-stage SWRO with PX consumed 1.89–2.04 kWh/m^3 for permeate production, where the SEC was lower than that of single-stage SWRO for all recovery rates. However, the SEC for two-stage SWRO with a PT changed dramatically from 2.28 kWh/m^3 to 1.95 kWh/m^3 depending on the recovery rate, and the two-stage SWRO with a PT was more energy-efficient than that of single-stage SWRO at a recovery rate greater than 38%. Considering that SWRO plants are operated at a recovery rate of 40–45%, conventional two-stage SWRO configurations are feasible for a typical SWRO recovery rate. One study [21] reported that the two-stage design consumes less energy than a single-stage one when the overall recovery rate is over approximately 20% (different simulation settings resulted in different outcomes).

However, when the number of PVs is equal, a higher SEC was required to operate two-stage SWRO than that of single-stage SWRO. Single-stage SWRO SEC was unchanged as the same condition was applied to the system. In contrast, the SEC for two-stage SWRO increased when the same number of PVs were installed as that of the single-stage SWRO (**Fig. 5b**). Two-stage SWRO with a PX and PT exhibited SECs of 2.10–2.22 kWh/m^3 and 2.97–2.18 kWh/m^3, respectively; thus, the two-stage SWRO consumed more energy than that of the single-stage SWRO for a given recovery rate. This result is different from the claim that the two-stage configuration is more energy efficient compared to the single-stage. In fact, when the two-stage SWRO systems were equipped with the same number of PVs as that of the single-stage SWRO, the average water flux for the SWRO systems was also the same. In contrast, preceding theoretical works were only focused on the calculation of SEC without considering RO design aspects such as the average water flux. Thus, it can be concluded that the SEC reduction in two-stage SWRO designs is more affected by lower average water flux and not the inherent benefit of staged design (i.e., the reduction of irreversible work) for a typical SWRO recovery rate range. Two-stage SWRO is not beneficial in terms of energy consumption for such a recovery rate range.

An optimal recovery rate that minimizes SEC is affected by different RO designs. In particular, high feed flow rates for stages that are due to the design results increases the value of the optimal recovery rate. In two-stage SWRO with a PX, fresh feed is supplied separately to the first and second stages, and the feed for the second stage is a mix of the concentrate of first stage and fresh feed (**Fig. 2c**). Because the initial feed is divided and supplied to each stage, the feed flow rate for each stage is not significantly higher than that of the single-stage SWRO. Thus, the second-stage SWRO optimal recovery rate (40%) is relatively close to that of the single-stage one (38%) (**Fig. 5b**). In contrast, in the two-stage SWRO system with a PT, all the fresh feed is supplied to the first stage, and the concentrate of the first stage is then fed to the second-stage SWRO. However, the first stage is equipped with a smaller number of PVs, and the feed flow rate of the first stage is higher. As a larger amount of permeate is produced from the first stage than the second stage in a two-stage SWRO (PT), the optimal recovery rate was higher (over 50%) than that of the single-stage SWRO (**Fig. 5b**). The operation of two-stage SWRO systems is desirable when the recovery rate is higher than that of the optimal recovery rate.

While two-stage SWRO can consume less energy than single-stage SWRO when equipped with more membranes, two-stage SWRO are always infeasible compared to single-stage SWRO when the number of membranes is the same. The configuration of two-stage SWRO does not lower the energy consumption in the typical SWRO recovery rate range. Additionally, the optimal recovery varies depending on the SWRO system design, and the optimal recovery rate for two-stage SWRO with PT was higher than that of the typical SWRO recovery rate. Therefore, two-stage SWRO may be feasible at recovery rates higher than the typical one, which is examined in Section 3.4.

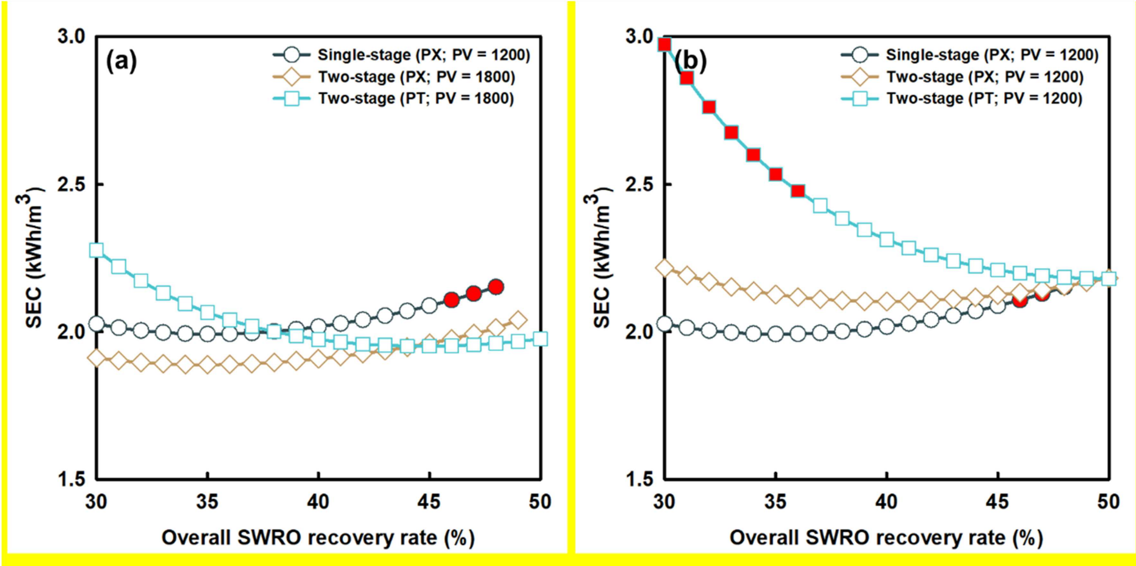


Fig. 5. SEC of staged SWRO designs when the number of PVs for two-stage SWRO designs were installed at a rate (a) 1.5 times higher than that of the single-stage SWRO design and (b) the same as that of the single-stage SWRO design. The red dots indicate when the SWRO systems exceeded the design constraints.

3.2. Permeate quality and water flux

Permeate quality is critical in operating SWRO plants, as it must meet water standards to be utilized. Because permeate quality is affected by water flux [11], it is important to determine the average water flux for SWRO systems. If permeate flow rate and number of PVs are the same for the entire system, then the average water flux for single-stage SWRO is determined directly, whereas is different for each state for a two-stage SWRO system. This profile is crucial as it may affect the permeate quality of the entire system. Additionally, the high-flux operation is vulnerable to fouling formation (e.g., colloidal fouling, organic fouling, and biofouling) on the membranes, which deteriorates their performance [11, 38, 39]. Thus, permeate quality and average water flux for two-stage SWRO were investigated.

Permeate quality was determined by the average water flux of the entire SWRO system, not by that of each stage individually. **Fig. 6a** presents permeate quality for the different staged SWRO configurations. When two-stage SWRO systems were equipped with 1800 PV, their permeate qualities were inferior to that of a single-stage SWRO system with 1200 PV. However, when the same amount of permeate was produced from the same number of PVs (i.e., average water flux = 13.35 L/m^2 h), the permeate quality of single-stage SWRO was

173–220 mg/L for a recovery rate of 30–50%, and that of two-stage SWRO with a PX and PT were 174-214 mg/L and 174-206 mg/L, respectively. Although each stage produced permeate with a different quality (**Fig. A1**), the mixed permeate (i.e., permeate from both the first and second stage) from two-stage SWRO was similar to that from single-stage SWRO, and it was slightly better. This reflects that permeate quality is affected by the average water flux of an SWRO system regardless of that of each stage and RO design.

Two-stage SWRO with a PX exhibited a similar average water flux for each stage, while two-stage SWRO with a PT was operated with an uneven average flux for the stages. For two-stage SWRO with a PX, fresh feed was supplied separately to each stage, and the stages were operated with similar average flux values (**Fig. 6b**). With an increase in recovery rate, the first stage produced water with lower fluxes (13.81–11.92 L/m^2 h) and the second stage with higher fluxes (13.20–14.15 L/m^2 h), with the difference between fluxes gradually increasing in response to an increase in recovery rate, which was not found to be significant. Because of the similar average water flux, each stage was loaded similarly without violating the design constraints. In contrast, in the two-stage SWRO system with a PT, the first stage was always operated with higher a flux than that of the second stage. The average flux for the first stage was 18.24–14.48 L/m^2 h, and that for the second stage was 6.84–11.59 L/m^2 h with an increase in recovery rate. Because the first stage was operated with an extremely high average flux for SWRO, the design constraint was violated at a lower recovery rate range, from 30% to 36%. However, the second stage lessened the burden of the first stage by producing water with a higher flux. Thus, the SWRO system was stable with its operation at a recovery rate higher than 37%.

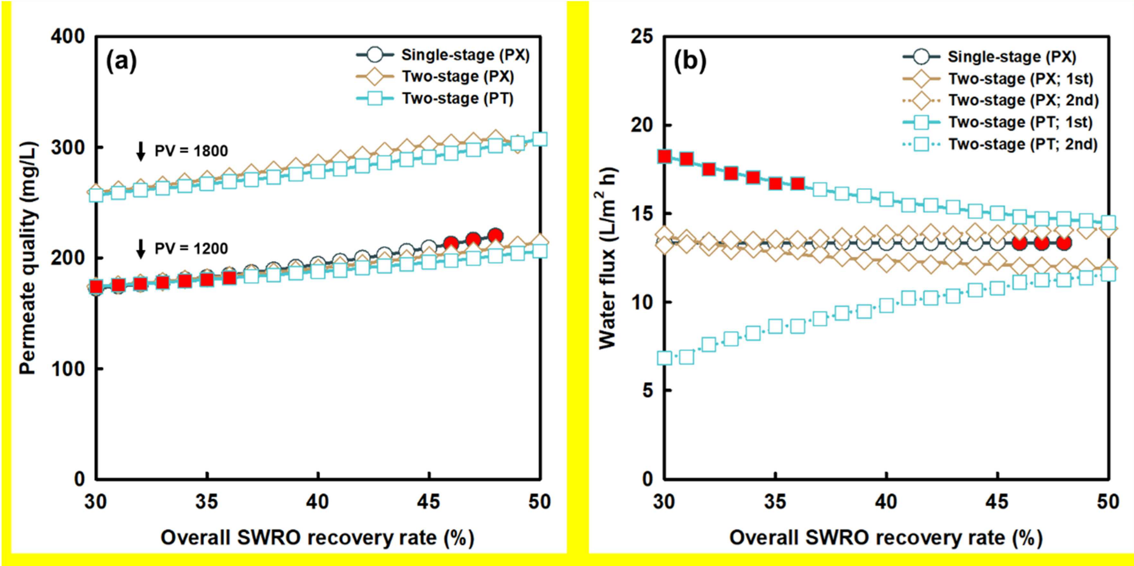


Fig. 6. Profile of (a) permeate quality of SWRO systems and (b) average water flux for each stage. The number of PVs was 1200 for each system in (b). The red dots indicate the situation when the SWRO system exceeded the design constraints.

Two-stage SWRO systems can distribute water fluxes more evenly compared to single-stage SWRO systems. While the first element of single-stage SWRO was operated with a water flux of 27.99 L/m^2 h at a 40% recovery rate, that of two-stage SWRO with a PX and PT was 20.93 L/m^2 h and 25.53 L/m^2 h, respectively (**Fig. 7a**). Due to a lower water flux at the first stage (i.e., a smaller amount of permeate over the target), the rest of the permeate was produced in the second stage. The water flux of the eighth element (i.e., the first element of the second stage) was 26.04 L/m^2 h and 17.49 L/m^2 h for two-stage SWRO with a PX and PT, respectively. With an increase in recovery rate, the amount of permeate produced increased, which induced a higher water flux along the PVs. At a 45% recovery rate (**Fig. 7b**), a water flux of 31.50 L/m^2 h was observed for the first element, which is near to the recommended water flux limit of 32.30 L/m^2 h. In contrast, the water flux was 22.07 L/m^2 h and 25.37 L/m^2 h for the first element, and 28.41 L/m^2 h and 19.97 L/m^2 h for the eighth element for two-stage SWRO with a PX and PT, respectively. Given that SWRO systems are operated with higher water fluxes at higher recovery rates, two-stage SWRO systems are favorable in a high-recovery operation due to the more even water flux distribution, which contributes to a reduced fouling propensity. Similarly, Voutchkov also mentioned that two-stage SWRO can be used to reduce fouling formation in the first stage when the feed contains a high concentration of foulant [9].

Permeate quality was similar regardless of RO design unless the average water flux of the entire SWRO system changed. Despite the average flux being the same for the entire SWRO system, each stage of the two-stage SWRO system was operated with a different average flux. The gap in average fluxes for the stages in the two-stage SWRO system with a PT in particular was high at a low-recovery condition, which burdened the first stage, while that in the two-stage SWRO with a PX was relatively small. However, a high average water flux does not necessarily indicate a high water flux for the first element of each stage; the water flux of the first element was higher in the single-stage SWRO. In short, two-stage SWRO systems are advantageous with regard to water-flux distribution.

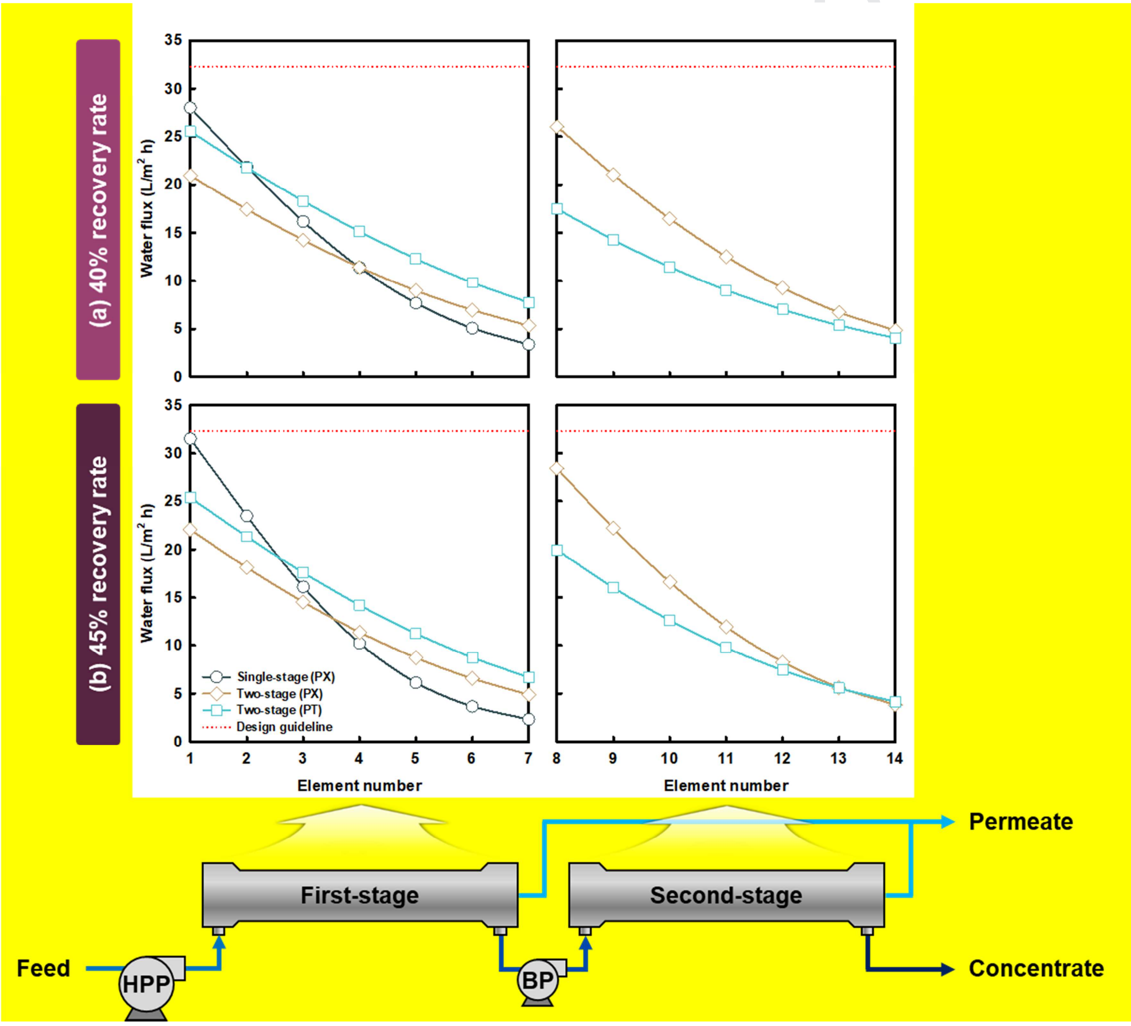


Fig. 7. The flux distribution of elements in a PV with different-staged SWRO designs. Two-stage SWRO systems can more evenly distribute water fluxes than can single-stage SWRO systems.

3.3. Optimal design ratios

Most two-stage SWRO designs follow a 2:1 ratio: where the number of PVs for the first stage to that for the second stage. The amount of permeate produced from the first and second stage is also in a ratio of 2:1. This is because two-stage SWRO systems are generally used to retrofit a single-stage plant operating at a 40% recovery rate at the first stage, and the overall recovery rate of the plant is increased up to 60% by installing the second stage, achieving an additional 20% of recovery [9]. Because the optimal design ratios for two-stage SWRO systems (e.g., number of PVs and permeate flow rate of each stage) have not been investigated, the best ratios minimizing SEC were examined considering overall SWRO recovery (i.e., the summation of the first and second stage).

While more PVs were installed in the first stage of the two-stage SWRO (PT) system, the second stage contains more PVs in the two-stage SWRO (PX) system. In two-stage SWRO (PX), the first stage was composed of 24–36% PVs, increasing overall SWRO recovery from 30% to 50% (**Fig. 8a**). The ratios of number of PVs were 24:76–36:64 (= 6:19–9:16). Thus, more PVs were situated in the second stage. In contrast, the first stage of two-stage SWRO with PT contained 57–61% PVs of the entire system in the recovery rate range of 30–50%, and the corresponding ratios of number of PVs were 57:43–61:39. Additional PVs were installed at the second stage instead of the first stage, increasing SWRO recovery. Overall, a 2:1 ratio for number of PVs is not the optimal ratio, and the ratio varies depending on the SWRO recovery rate and ERD in use.

Different amounts of permeate were produced from the first and second stages, and the use of different ERDs affects the permeate flow rate for each stage. When two-stage SWRO was equipped with a PX as the ERD, 25–32% of the permeate was produced from the first stage and the remaining permeate (i.e., 68–75%) from the second stage by changing SWRO recovery from 30% to 50% (**Fig. 8b**). The ratio for permeate flow rate was 25:75–32-68 (= 1:3–8:17), which reflects the greater permeate production at the second stage. In contrast, the first stage in two-stage SWRO (PT) produced less permeate (i.e., 63–78%) with an increase in recovery rate (i.e., 30–50%), but a larger permeate flow rate was obtained from the first stage compared to that of the second stage. The permeate flow rate ratio for the first and second stages was in the range of 78:22–63:27 (= 39:11–7:3). The optimal ratio for permeate flow rate for each stage when using different ERDs was not consistent with previous findings.

Two-stage SWRO with PX is primarily focuses on the second stage and that with PT on the first stage. Additionally, the optimal ratios for both number of PVs and permeate flow rate were not 2:1, and two-stage SWRO with PT exhibited values close to those of the general ratio. However, the optimal ratio differs depending on the ERD in use and SWRO recovery rate.

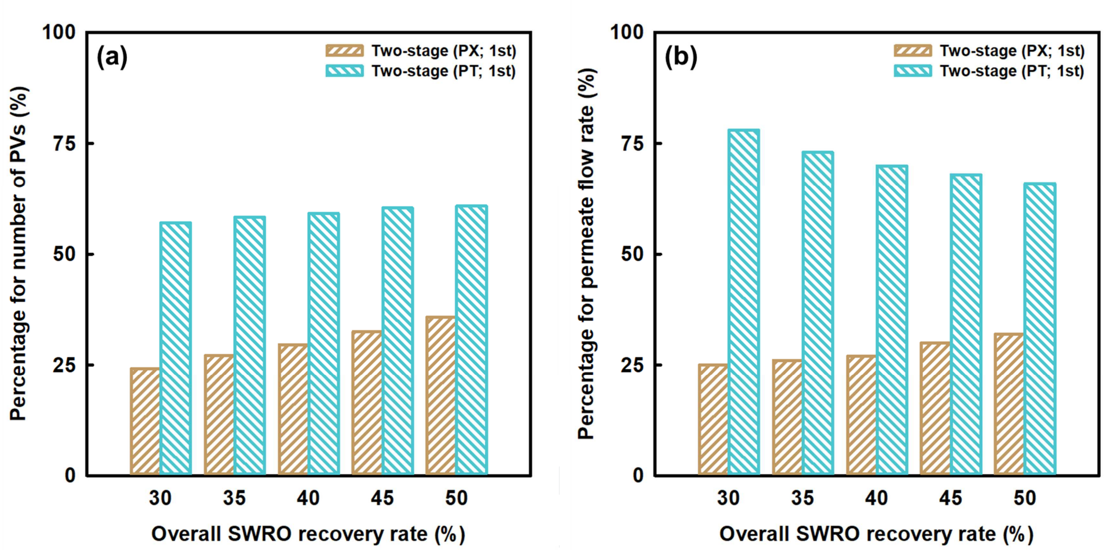


Fig. 8. Percentages for (a) number of PVs and (b) permeate flow rate. Only the percentages of the first stage over those of the entire system are illustrated.

3.4. Feasibility of two-stage SWRO systems

Although two-stage SWRO systems can distribute water fluxes more evenly than single-stage SWRO systems, they appear to not be advantageous in terms of SEC for an overall SWRO recovery rate under 50%. However, as the SEC values for two-stage and single-stage SWRO systems were similar at a 50% recovery rate (**Fig. 5b**), further investigation into SEC was required to find the feasibility of two-stage SWRO systems at a recovery rate higher than 50%.

Two-stage SWRO systems were more energy-efficient than single-stage SWRO systems when the recovery rate is higher than 50%. In **Fig. 9**, the SEC of single- and two-stage SWRO systems was presented for a 30–70% recovery rate. Single-stage SWRO consumed less energy compared to two-stage SWRO as discussed in **Fig. 5b**, but the SEC for single-stage SWRO was not obtainable over a 50% recovery rate. At that recovery rate, the hydraulic pressure cannot exceed the osmotic pressure, as the rate of osmotic pressure increase is higher than that of the hydraulic pressure increase [11]. Thus, only two-stage SWRO systems can be utilized for producing freshwater at a recovery rate higher than 50% (**Fig. 9**). Two-stage SWRO (PT) can be more energy-efficient than two-stage SWRO (PX) for a recovery rate greater than 50% depending on the mechanical efficiency of the PT. When the efficiency of the PT is lower than that of the PX, a recovery rate of 90% can be assumed instead of 95%, and two-stage SWRO with PT is feasible for a recovery rate over 55%.

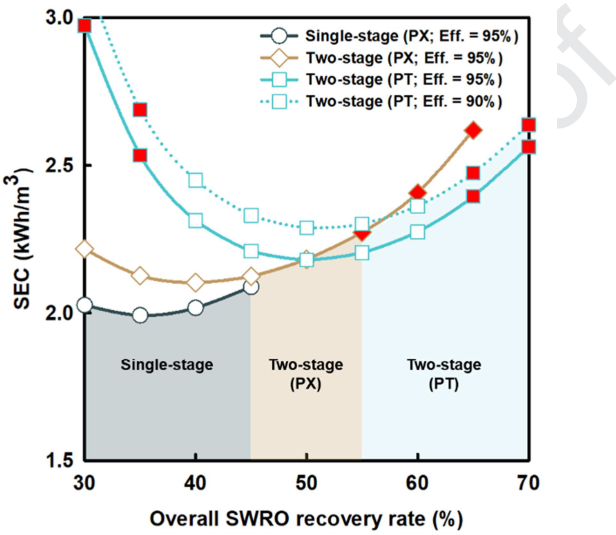


Fig. 9. The SEC of staged SWRO in a wider recovery rate range from 30% to 70%. The red dots indicate when the SWRO systems exceeded the design constraints.

The trends in SEC for two-stage SWRO systems can be explained by the irreversibility of pumps and the generation of mixing entropy. With the assumption an ERD efficiency of 95%, two-stage SWRO with PX was more energy-efficient when operating at a recovery rate below 50%, while that with PT exhibited a lower SEC at a higher recovery rate. Initially, HPPs in two-stage SWRO with PT require a higher pressure than that with PX as more water is produced in the first stage, which results in a greater generation of irreversible work in the HPPs. In contrast, in two-stage SWRO with PX, a partial feed stream is mixed with the first-stage concentrate (i.e., the mixing entropy is generated), and additional energy is required to re-separate the feed into the permeate and concentrate. At a typical SWRO recovery rate (< 50%), the effect of irreversible work is more significant, and two-stage SWRO with PX consumed less energy than that with PT. In contrast, as the feed is richer at a higher recovery rate, more energy is required to compensate for the entropic loss, resulting in a higher SEC for two-stage SWRO with PX. Therefore, the best design of two-stage SWRO differs depending on the recovery rate as illustrated in **Fig. 10**. In the feasible range, the ratio for both permeate flow rates and number of PVs was approximately 1:2 for two-stage SWRO with PX and 2:1 for that with PT.

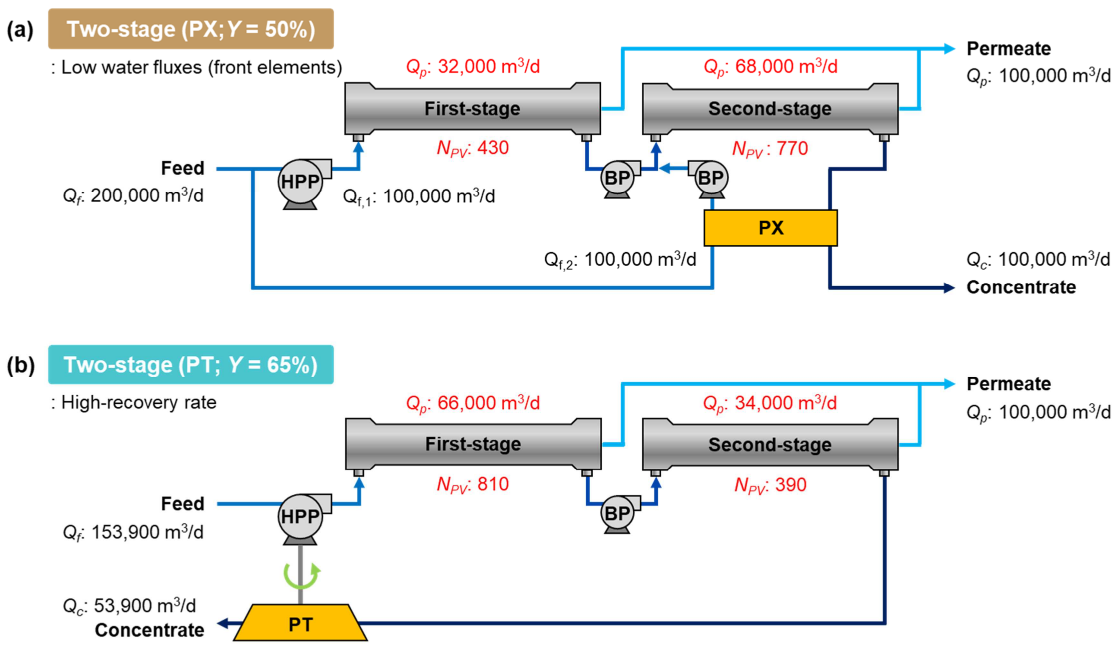


Fig. 10. The application of optimal two-stage SWRO designs (a) with PX at a 50% recovery rate and (b) with PT at a 65% recovery rate. Q_f: feed flow rate. Q_p: permeate flow rate. Q_c: concentrate flow rate. N_{PV}: PV numbers. Y: overall SWRO recovery.

Although two-stage SWRO systems exhibit their feasibility at high recovery rates, their operational issues must be addressed. In particular, high water flux and hydraulic pressure are major issues of the two-stage SWRO system. For a 55–60% recovery rate, only two-stage SWRO with a PX exceeded the design constraint due to the high-flux of the front elements in the first stage. This reflected that two-stage SWRO employing a PT distributes water fluxes more evenly, particularly at high recovery rates. In contrast, both two-stage SWRO systems violated the water flux and hydraulic pressure constraints at a recovery rate of over 65%, and the performance of two-stage SWRO with PT is only obtainable at a recovery rate of 70% under 100 bar of hydraulic pressure. For these cases, high pressure-resistant SWRO membranes and equipment should be installed to operate the system. Considering that several SWRO desalination plants using two-stage SWRO are equipped with such equipment and are operated with 71–90 bar depending on the recovery rate (**Table 1**), two-stage SWRO can be utilized and further optimized. However, scaling problems can occur at high-recovery operations over a rate of 60% [40].

The study results are summarized in **Table 3**. Two-stage SWRO systems exhibited high energy-efficiencies when operated at high recovery rates, and the types of ERDs used were different depending on the target recovery rate. The two-stage SWRO system with PX was feasible at a high recovery rate, while that with PT at an even higher recovery rate.

Table 3.

Summary of staged SWRO configurations

Type of stage	Single-stage	Two-stage (PX)	Two-stage (PT)
Recommended recovery [%]	< 50	50–55	55–70
Ratio of permeate flow rate [-]	N/A	32:68 = 8:17 ≈ 1:2 (at 50% recovery rate)	66:34 = 33:17 ≈ 2:1 (at 65% recovery rate)
Ratio of number of PVs [-]	N/A	36:64 = 9:16 ≈ 1:2 (at 50% recovery rate)	68:32 = 17:8 ≈ 2:1 (at 65% recovery rate)
Advantage(s)	• Simple design • Low cost	• High recovery rate • Low water flux for front elements at the first stage (only for moderate recovery rate)	• High recovery rate • Uniform water flux for both stages (only for high recovery rate)
Disadvantage(s)	• Low recovery rate • Biased flux distribution	• Easy violation of design constraints	• High-pressure operation (< 100 bar)

4. Conclusions

Current two-stage SWRO plants face high energy consumption and operational issues, making the two-stage configuration not preferred for SWRO. In contrast, superior energy efficiency of two-stage SWRO compared to that of single-stage SWRO has been fundamentally demonstrated in recent studies, providing the possibility of the further application of two-stage SWRO. However, the analyses were obtained using simple thermodynamic models, and the comparison of staged SWRO was skewed. Thus, this study explored the applicability of a two-stage SWRO system in terms of SEC while considering its practical design aspects. The main findings of this study are as follows:

- Two-stage SWRO consumed less energy than single-stage SWRO when more PVs (i.e., membrane modules) were employed. However, two-stage SWRO always exhibited greater energy consumption than that of single-stage SWRO for a typical SWRO recovery rate when the same number of PVs was applied.

- The permeate quality of single- and two-stage SWRO was similar when the number of PVs was the same, as permeate quality is affected by average water flux. In contrast, two-stage SWRO effectively distributed water fluxes compared to single-stage SWRO in spite of both exhibiting the same average water flux.

- The optimal design ratio for the number of PVs for each stage varied depending on the system configurations and operating conditions (e.g., recovery). The 1:2 ratio was more appropriate for two-stage SWRO with a PX, while a 2:1 ratio was maintained for that with a PT. The ratio of permeate flow rate for each stage was similarly 1:2 and 2:1 for two-stage SWRO with a PX and PT, respectively.

- The employment of two-stage SWRO can be advantageous at high recovery rate of over 50%. Two-stage SWRO with a PX was suitable for a 50–55% recovery rate, while that with a PT was a more suitable configuration for a 55–70% recovery rate.

It is expected that two-stage SWRO will be adopted and installed in plants that require a high-recovery operation. Additionally, as two-stage SWRO can distribute water flux effectively without violating design constraints, it can be implemented in plants with water-flux distribution problems including fouling propensity. Moreover, using the suggested optimal design ratios, conventional two-stage SWRO designs can be retrofitted and improved. Our study provides a fundamental basis for the use of energy-efficient staging RO configurations and practical guidelines for the optimization of two-stage SWRO systems under various operating conditions.

Acknowledgment

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Appendix A. Permeate quality of each stage

In two-stage SWRO, each stage produces permeate with a different quality as quality is significantly affected by water flux. When two-stage SWRO was equipped with a PX, the average water flux for the first and second stages was similar, and the permeate quality from them was also similar. In contrast, two-stage SWRO with a PT was operated with a high water flux for the first stage and a low one for the second stage, which resulted in an uneven permeate quality between the stages. The first stage produced high-quality permeate, and the second stage produced low-quality permeate. A larger amount of permeate was produced from the first stage, which can improve the permeate quality of the second stage when they are mixed. Although each stage produced permeate with different concentrations, the mixed permeate from two-stage SWROs exhibited a quality similar to that of single-stage SWRO, as the average water flux of the system was maintained.

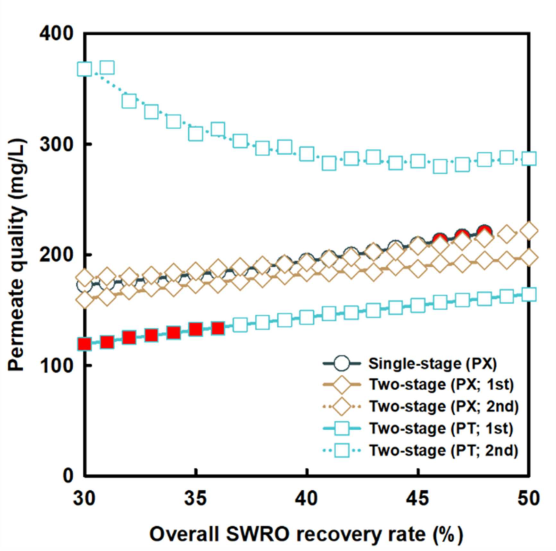

Fig. A1. Permeate quality of each stage depending on the type of ERD. The red dots indicate when the SWRO systems exceeded the design constraints.

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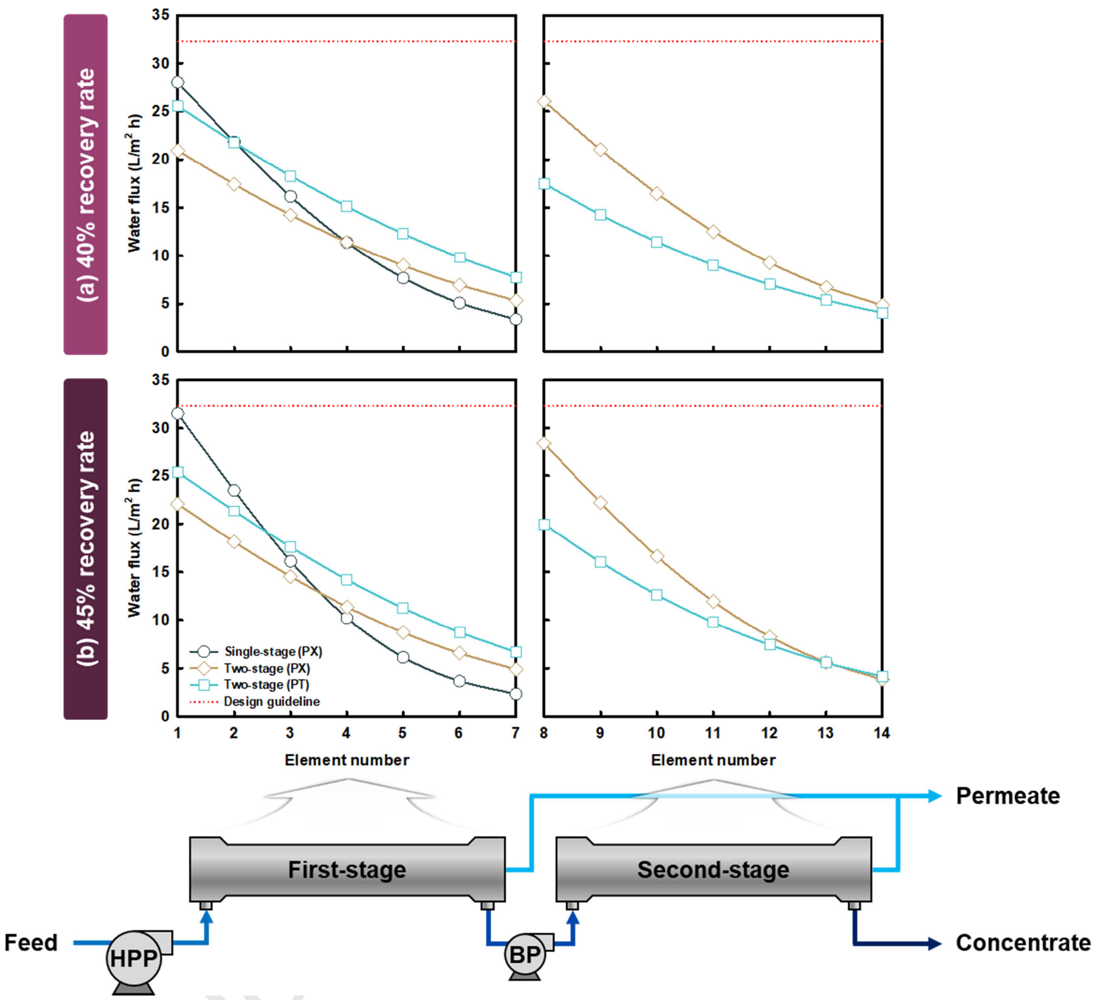

Fig. 7. The flux distribution of elements in a PV with different-staged SWRO designs. Two-stage SWRO systems can more evenly distribute water fluxes than can single-stage SWRO systems.

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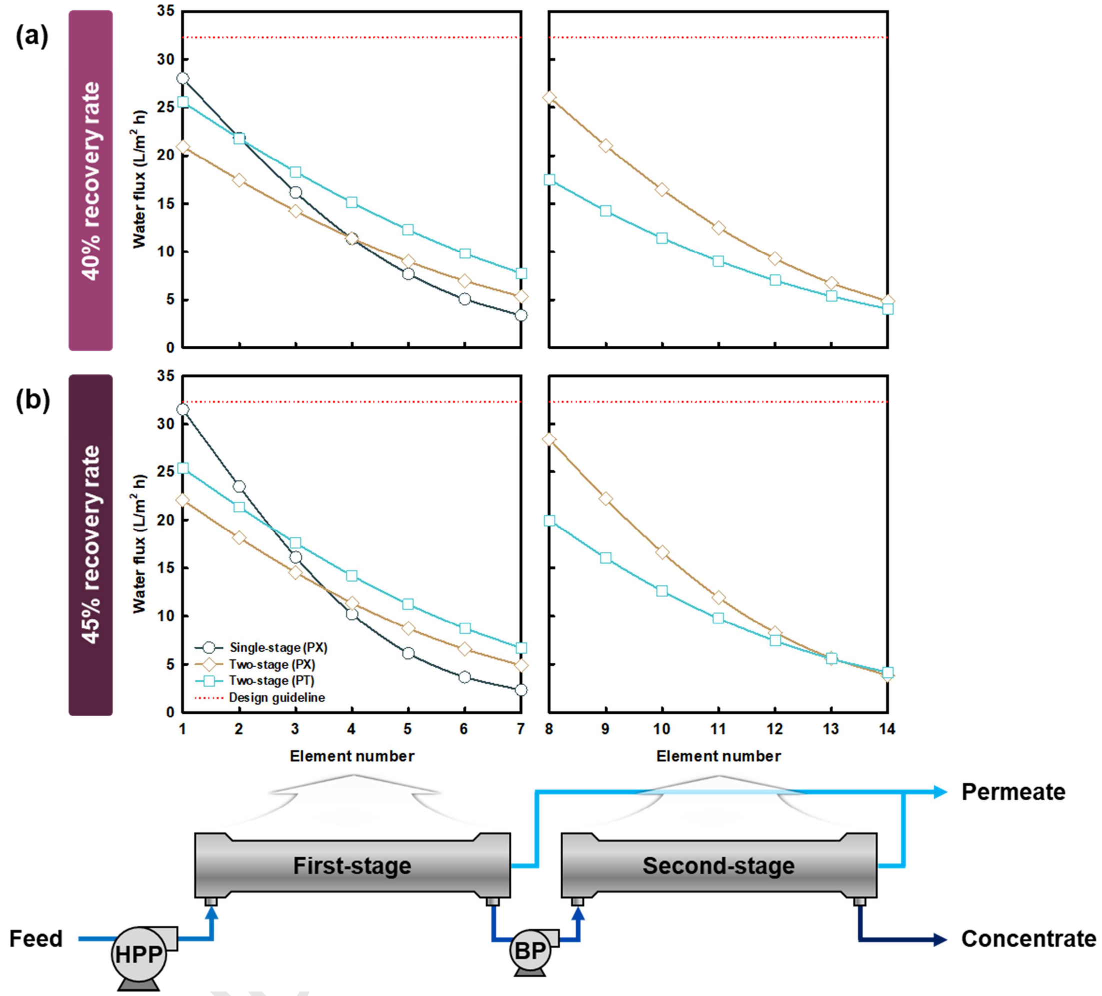

Fig. 7. The flux distribution of elements in a PV with different-staged SWRO designs at (a) 40% and (b) 45% recovery rate. Two-stage SWRO systems can more evenly distribute water fluxes than can single-stage SWRO systems.

Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: