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A comprehensive review of energy consumption of seawater reverse osmosis desalination plants

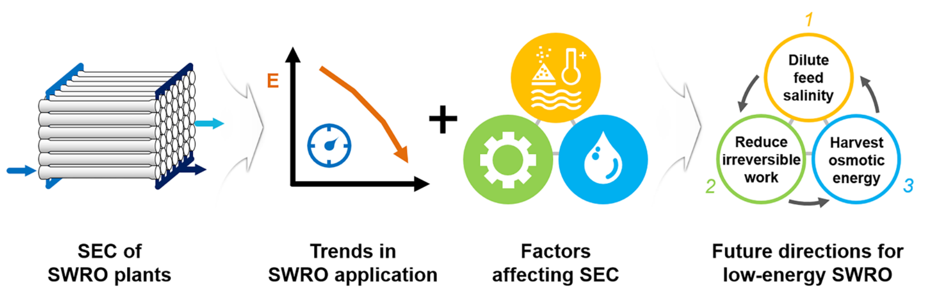
Jungbin Kim[a,2], Kiho Park[a,2], Dae Ryook Yang[b,1], Seungkwan Hong[a,*]

[a] School of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea
[b] Department of Chemical and Biological Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea

HIGHLIGHTS

- Critical review of energy consumption of seawater reverse osmosis plants.
- Collection of more than 70 datasets for large-size seawater reverse osmosis plants.
- Investigation of trends in the application of seawater reverse osmosis plants.
- Analysis of factors associated with energy consumption of seawater reverse osmosis.
- Future directions to reduce energy consumption of seawater reverse osmosis plants.

GRAPHICAL ABSTRACT



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ABSTRACT

High specific energy consumption (SEC) is the main barrier for the expansion of seawater reverse osmosis (SWRO). Therefore, the main objective of current SWRO research is to lower the SEC of SWRO plants. However, SEC of SWRO plants has not been systemically explored or analyzed, despite the need for information to develop appropriate strategies to reduce SEC. Therefore, this study aims to review and analyze SWRO plants for a comprehensive understanding of their SEC. First, trends in SWRO application are investigated using more than 70 datasets on large-scale SWRO. The analysis explains the increasing number of large-size SWRO plants, the SEC reduction by isobaric energy recovery devices (ERDs), and the use of different SWRO configurations to meet the energy and quality requirements. Factors associated with SEC (*i.e.*, feed conditions, target conditions, and equipment efficiency) are also analyzed. High salinity increases energy demand, whereas the temperature effect on energy consumption is not entirely clear. High-efficiency ERDs and pumps can reduce SEC, but overall SEC cannot be explained by these factors alone. SEC is also affected by target water quality and quantity. Moreover, specific SWRO designs can improve the system to efficiently achieve the established goals. Furthermore, future directions to develop low-energy SWRO plants are discussed.

* Corresponding author.
E-mail addresses: dryang@korea.ac.kr (D.R. Yang), skhong21@korea.ac.kr (S. Hong).
[1] Co-corresponding author.
[2] These authors equally contributed to this work.

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1. Introduction

With the increasing scarcity of conventional freshwater sources, a higher amount of energy is needed to provide clean water from alternative sources. Seawater is one of the emerging non-traditional water sources for human use. However, seawater desalination is an energy-intensive process. While the energy use of conventional treatments for surface water ranges between 0.2 and 0.4 kWh/m^3 [1,2], the theoretical minimum specific energy for seawater desalination (total dissolved solids (TDS) = 35,000 mg/L) is 1.07 kWh/m^3 for 50% recovery [1,3–5], and a significantly amount of additional energy is required to actually operate the system. It has been reported that the specific energy consumption (SEC) of seawater reverse osmosis (SWRO) process is 2.5–4.0 kWh/m^3 [1], which is significantly higher than its minimum specific energy. The SEC of a real-scale SWRO plant is even higher, approximately 3.5–4.5 kWh/m^3, including pre-treatment and post-treatment processes [6]. Because of the inherent high energy requirement for SWRO desalination, seawater is not commonly utilized over traditional surface water.

Despite its high-energy consumption, the application of SWRO technology is inevitable for water production in specific regions, where/when seawater is the only available water source. Middle East and North Africa (MENA) countries typically employ SWRO for water production because of typical water shortage. In these regions, the need for desalination is exponentially increasing with water demand [7], and the desalinated water is used not only for drinking but also for irrigation and industries [8]. Recently, SWRO can also be observed in regions outside the MENA, to fulfill the demand caused by reduced surface water sources due to drought. Studies have predicted that the security of currently available water sources will not be stabilized in the future [9,10]. As a result, many countries will extensively focus on seawater desalination to obtain freshwater in this new era of water scarcity.

However, high-energy consumption is an unavoidable issue associated with desalination plants when SWRO technology is used. This means a larger amount of fossil fuels and other energy sources would be used for water production, which imposes a negative impact on the environment [11]. Moreover, this elevated energy requirement can amplify the generation of greenhouse gases (*e.g.*, carbon dioxide; CO_2) contributing to climate change [12,13]. As a low carbon footprint is important in desalination, the Global Clean Water Desalination Alliance has been launched with a concept of "$H_2O - CO_2$" [14]. Likewise, the high-energy consumption of SWRO should be addressed to minimize environmental impacts and to allow for a sustainable exploitation of seawater. To find strategies for lowering current energy consumption, understanding energy use of SWRO plants is fundamentally required. In other words, information on current SWRO plants should be collected, including SEC values and the factors that contribute to SEC. Also, the factors affecting SEC should be thoroughly analyzed so that promising strategies can be implemented.

Whereas several review papers describe the range of SEC for SWRO plants, a study clearly explaining the SEC values of various SWRO plants has not been developed. In a previous study, the typical cost and SEC of an SWRO system (not the entire plant) were established according to feed types, but the SEC of the SWRO plant was not investigated [1]. Another study presented the energy consumption for different water sources [2], but it only provided an SEC range for SWRO plants. The SEC of SWRO has been theoretically analyzed, and strategies to lower it have been suggested [15]. However, specific values of energy consumption have not been provided, and the factors affecting SEC have not been elucidated. While basic principles and application aspects of reverse osmosis were elucidated in [16], a discussion on SEC was not provided. In this context, current energy consumption of SWRO plants is neither easily accessible nor well understood.

Even when SEC values are provided, it is difficult to determine the energy efficiency of SWRO plants without plant details. In fact, the SEC values alone do not reflect the efficiency of the plant. For example, SWRO plants treating high-salinity seawater are likely operated with high pressure, which results in high SEC [17]. Moreover, plants equipped with a high-efficiency energy recovery device (ERD) would consume less energy compared to those with a low-efficiency ERD. Thus, a clear understanding of the plants is required to analyze their energy consumption. Another drawback is the lack of consistency between the SEC analyses by different authors. For example, some studies present the energy consumption of the RO system, and not of the whole plant. In addition, some data are difficult to understand, as they indicate the energy consumption which is reduced by the use of renewable energy [18,19]. Nevertheless, it is essential to understand the SEC of SWRO plants and the factors associated with it, so that adequate alternatives to reduce the SEC can be provided.

In this study, the specifications and performance data of numerous SWRO plants were collected, and the SEC of these plants was reviewed and analyzed. First, the trends in SWRO application were investigated to establish the status of the SWRO technology and its energy use. The main objective of this study is to support the reduction of SEC in desalination plants. Therefore, the factors affecting the SEC of SWRO desalination plants were evaluated. Based on the results, future directions to reduce the SEC are discussed and elucidated.

2. Description of seawater reverse osmosis desalination plant

The typical processes of an SWRO desalination plant are illustrated in Fig. 1. Pre-treatment units are employed to remove large-size particles and solids before the SWRO because they can cause fouling and/or scaling on the surface of the RO membrane. Many chemical species and ions are dissolved in seawater, which has a TDS concentration of approximately 30,000–40,000 mg/L [20]. TDS should also be removed to produce freshwater. In SWRO, a semi-permeable membrane which allows water molecules to permeate while blocking solids molecules is employed for that separation. However, the osmotic pressure across the semi-permeable membrane becomes an obstacle to desalination. Therefore, the SWRO process requires high pressure to overcome the osmotic pressure of seawater, for which a high-pressure pump (HPP) is utilized. After the RO system, the desalted fresh water is obtained while concentrate is discharged from the RO train. In the concentrate, a considerable amount of pressure still remains. To improve the energy efficiency, the pressure in the concentrate should be recovered, for example, by ERDs [21]. The recovered pressure is utilized to increase the pressure of the feed stream. However, this pressure increase is not enough, and the feed stream pressure is supplemented by a booster pump (BP).

While most SWRO desalination plants adopt such common processes, their SEC differ depending on various factors. For example, the pre-treatment, which is mostly conducted by granular media filtration or membrane filtration, affects energy consumption. Despite its trivial effect, it can account roughly for 11% of the energy use in the plant [1]. Moreover, the characteristics of the feed water, particularly salinity and temperature, are critical because they are closely related to the minimum energy consumption for separation. Furthermore, the energy consumption of the RO system varies according to the target conditions, such as water quality and quantity. These factors are also associated with the performance of the RO membrane. Additionally, the efficiencies of the HPP, BP, and ERD significantly influence the total energy consumption, since the RO system is the most energy-intensive process in the plant (approximately 71%) [1].

3. Methods

3.1. Data collection

More than 70 datasets from large plants (capacity greater to or equal 10,000 m^3/d) were collected, including specifications and SEC (Table 1). Various sources were utilized, including scientific journals,

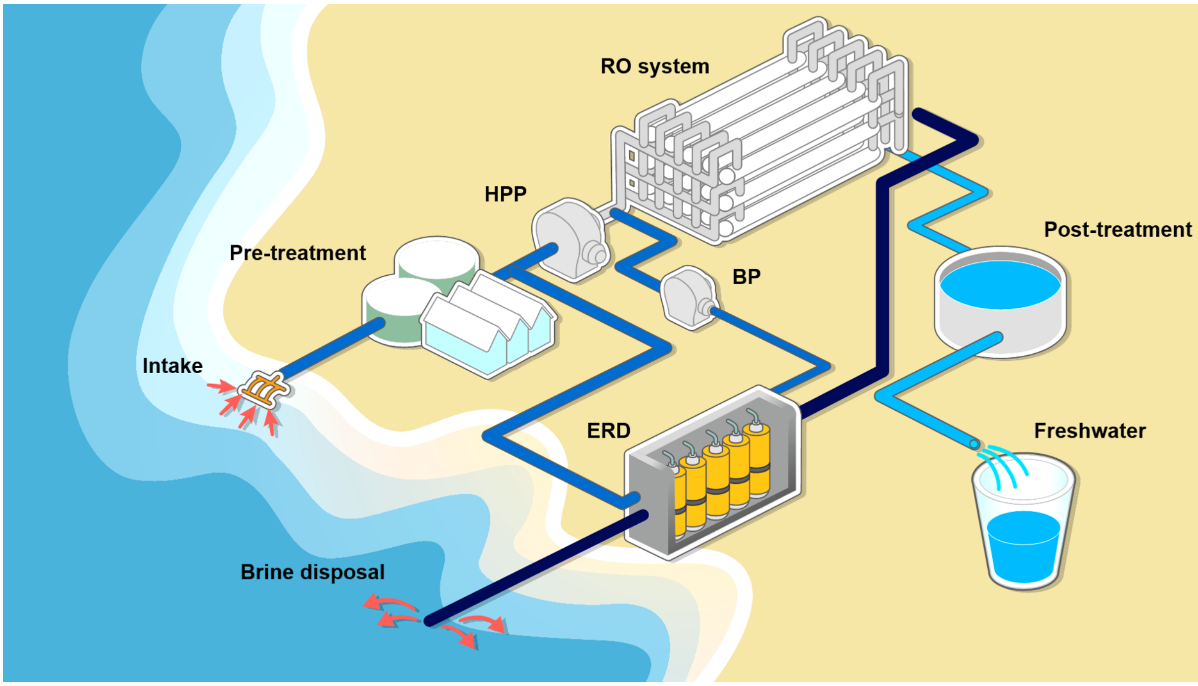

Fig. 1. Scheme of a typical SWRO desalination process. A pre-treated feed is supplied to the RO system with pressurization by HPP and BP, and the hydraulic pressure in the concentrate is recovered by ERD. RO: reverse osmosis. HPP: high-pressure pump. BP: booster pump. ERD: energy recovery device.

books, reports, conference proceedings, company catalogs, and websites. The data sometimes differed depending on the reference. Therefore, they were generally cross-checked against other sources. We assumed that scientific journals were the most reliable source of data. References authored by people relevant to a particular SWRO plant were also preferred. Moreover, actual operational data was preferred over design values.

3.2. Data processing

Countries were classified into regions, and the ones with land in more than one region were split by region. The commissioning year was based on the operation year with the corresponding capacity. Capacity was classified if normal and maximum capacity were specified, and it was rounded to the nearest tenth. Average values for feed TDS and temperature were used, and some feed data based on the seawater characteristics at the intake points or near the plants were collected. Feed TDS was rounded to the nearest hundred, and temperature to the nearest whole number. Product TDS was marked as before- and after-remineralization for two- or triple-pass RO. Some data on product TDS were expressed as conductivity, then converted to mg/L ($1\,\mu s/cm = 0.640\,mg/L$). Average recovery values were used and rounded to the nearest whole number. It was preferable to express SWRO and brackish water reverse osmosis (BWRO) separately, but they were expressed as an overall recovery when specific data were not accessible. Types of ERD were specified, although models may have varied. Work exchangers (WEs) and dual work exchanger energy recovery (DWEER) devices are basically same-principle isobaric work exchangers, but WE is specified when the model is not from Calder™. Because some data were misleading, plant SEC and RO SEC were distinguished. The SEC was an average rounded to one decimal place.

3.3. Auxiliary and trend line

Using the dataset, a trend line was expressed using linear regression. Prediction interval (PI) and confidence interval (CI) were provided with a typical 95% confidence. PI addresses the prediction accuracy of the targets, whereas CI considers that of the regression [22,23]. In addition, an ellipse, which can visually provide an interpretation of correlation among data, was generated with 95% confidence for each group [24]. Data points connected by a solid line represent the change of SEC by retrofit and expansion in the same plant. For the box plot, box and whisker represent quartiles, and the median is plotted as a band inside the box.

4. Trends in the application of seawater reverse osmosis

The trends in SWRO application were investigated using the data associated with the commissioning years (Table 1). The increasing plant capacity over the year depicts the increasing need for desalination. Moreover, the reduction of energy consumption can be explained by the development of ERDs. Lastly, the trends in RO configuration were analyzed by associating it with the requirements for the SWRO process.

4.1. Increasing large-scale seawater reverse osmosis

Membrane-based desalination was not included in the mainstream desalination field before the 2000s. In 1999, for example, only 10% of the world's seawater desalination capacity was provided by RO [142]. At that time, the capacity of desalination plants was small, and the plants used immature SWRO technologies. After successful experiences with SWRO operation, many large desalination plants were constructed with higher capacities after 2000 (Fig. 2). In particular, SWRO application increased dramatically in the MENA and Mediterranean regions. That was inevitable due to the dry weather and lack of freshwater sources in these regions. The Oceanian region has also produced a large amount of water through desalination. Australia, for example, has suffered a severe drought referred to as "Millennium Drought," [143] and installed "the big six" desalination plants for water supply. Thus, the number and capacity of desalination plants in those regions imply the importance of desalinated water.

Table 1
Specification of SWRO desalination plants. Different feed conditions, equipment, and RO configurations are employed in each plant, affecting the SEC of RO system and the plant.

Region	Country	Plant	Commissioning year	Capacity (m^3/d)	TDS (mg/L)		Temp. (°C)
					Feed	Product	
North Africa	Algeria	Beni Saf	2009	200,000	36,500	N/A	24
		Honaine	2011	200,000	35,900	N/A	21
		Skikda	2009	100,000	39,300	< 450	23
	Egypt	Marsa Matrouh (Baghoush)	2013	24,000	38,700	200	N/A
	Morocco	Jorf Lasfar	2014	75,800	38,000	N/A	30
	Spain (The Canary Islands)	Arucas-Moya	2009	15,000	37,100	< 400	25
		Las Palmas III	1989	36,000	N/A	1660	N/A
			1997	36,000		640	
			2001	57,800		790	
			2003	65,000		960	
			2006	79,000		700	
			2007	79,000		780	
			2009	85,000		330	
			2011	86,000		260	
		Lanzarote IV	1999	20,000	38,600	50[b]	21
		Maspalomas II	1987	16,400	39,400	380	N/A
			1999	20,600		300	
			2001	26,200		< 350	
North America	Mexico	Los Cabos	2006	17,300 (max. 20,700)	30,900	< 400	N/A
	USA	Carlsbad	2015	190,000	33,500	N/A	23
North East Asia	China	Caofeidian	2012	50,000	36,000	N/A	14
		Yuhuan Power Plant	2006	34,600	34,000	< 20[b,g]	24
	Japan	Fukuoka	2005	50,000	35,000	< 200[a]	20
	Korea	Gijang	2014	45,500	36,000	< 250[a]	19
Oceania	Australia	Adelaide (Port Stanvac)	2012	300,000	37,200	< 200[a]	18
		Gold Coast	2009	133,000	38,000	< 220[a]	23
		Melbourne (Victorian)	2012	450,000	37,100	< 300[a]	16
		Perth I (Kwinana)	2006	143,700	36,500	< 200[a]	20
		Perth II (Southern)	2013	306,000		< 200[a]	
		Sydney	2010	250,000	36,500	< 115[a]	20
South America	Chile	El Coloso	2006	45,360	36,500	< 400[pl]	17
		La Chimba	2003	52,000	36,000	N/A	17
South Asia	India	Nemmeli	2013	100,000	40,000	300	28
South East Asia	Singapore	Singspring	2005	136,400	31,600	< 250[a]	31
		Tuaspring	2013	318,500		N/A	
The Caribbean	Aruba[nl]	W.E.B. #2	2012	24,000	36,000	15[b]	28
	Curacao[nl]	Curacao	2000	10,200[ep]	37,900	< 40[b]	N/A

(continued on next page)

Table 1 (*continued*)

Region	Country	Plant	Commissioning year	Capacity (m^3/d)	TDS (mg/L)		Temp. (°C)
					Feed	Product	
The Mediterranean	Cyprus	Dhekelia	1998	40,000	41,800	N/A	25
			2004			350	
		Larnaca	2001	54,000[ep]	40,000	300[b]	23
	Spain	Aguilas-Guadalentin	2013	181,000 (max. 212,000)	39,500	< 400	20
		Alicante I	2006	66,000	38,000	< 500	21
		Alicante II	2008	65,000		< 400	
		Almeria City	2001	50,000	39,000	< 400	20
		Barcelona (Llobregat)	2009	200,000	39,700	< 130[b]	19
		Campo de Dalias	2015	97,200	39,800	N/A	19
		Carboneras	2005	120,000	38,000	< 400	22
		Rambla Morales	2006	60,000	N/A	N/A	N/A
		San Pedro del Pinatar I	2005	65,000	40,900	< 400	23
		San Pedro del Pinatar II	2006	65,000		N/A	
		Tordera	2002	28,000	37,500	< 500	N/A
			2010	57,600 (max. 64,000)			
		Torrevieja	2013	240,000	N/A	N/A	N/A
		Valdelentisco	2010	140,000 (retrofit)	39,000	< 400	21
	Malta	Ghar Lapsi	1983	18,600 (20,000 [g])	36,500	380	17
The Middle East	Bahrain	Al Dur	2012	218,000	47,000	< 200[a]	28
	Israel	Ashkelon	2005	330,000[ep]	40,700	< 80[b]	23
		Hadera	2010	350,000[ep]	40,700	< 270[a]	23
		Palmachim 1	2007	110,000	42,000	< 300[a]	25
		2	2010	150,000		N/A	
		3	2013	300,000		N/A	
		Sorek (Soreq)	2013	540,000	40,800	< 300[a]	27
	KSA	Kindasa	2006	26,800	42,500	< 250[a]	30
		Rabigh IWSPP	2009	168,000 (max. 192,000)	39,600	< 10[b]	29
		Sadara	2016	148,800 (max. 178,600)	< 45,000	< 40[b]	27
		Shuaibah III	2009	150,000	44,500	45[b]	30
		Shuqaiq II	2009	212,000	37,100	30[b]	29
		Yanbu	2006	50,400	46,400	< 500	28
	Oman	Sur	2009	80,000	39,700	123[a]	N/A
	Qatar	Ras Abu Fontas A3	2017	164,000	45,900	N/A	25
	UAE	Fujairah	2004	170,500	38,300	< 120[b]	29
		Ghalilah	2015	68,200	42,000	< 500	27
		Khorfakkan	2008	22,700	37,400	N/A	28
		Layyah	2008	22,700	37,400	< 450	28
		Palm Jumeirah	2005	64,000	42,000	N/A	28

(*continued on next page*)

Table 1 (*continued*)

Region	Overall RO configuration	SWRO		BWRO		ERD type	SEC (kWh/m^3)		Ref.
		Configuration	Recovery (%)	Configuration	Recovery (%)		Plant	RO system	
North Africa	Single-pass	Single-stage	45	–	–	PX	4.0	2.3[d]	[25,26]
	Single-pass	Single-stage	45	–	–	PX	4.4	N/A	[27–29]
	Single-pass	Single-stage	47	–	–	PX	3.6	N/A	[27,30,31]
	Single-pass	Single-stage	N/A	–	–	PX	3.1	2.2[d]	[32–34]
	Partial two-pass	Single-stage	45	Two-stage	87	PX	3.8	N/A	[35,36]
	Single-pass	Single-stage	45	–	–	PX	3.4	N/A	[37,38]
	Single-pass	Two-stage	45	–	–	FT	6.7	N/A	[39,40]
			45			PT	5.9	N/A	
			49			PT	5.1	N/A	
			51			PT	4.8	N/A	
			53			PT	4.6	3.5[d]	
			53			PT, PX	4.5	2.7[d] (PX)	
			51			PT, PX	4.3	2.7[d] (PX)	
			50			PX	4.1	2.3[d]	
	Partial two-pass	Single-stage	49	Two-stage	89	PT	< 4.8	3.8[e]	[41]
	Single-pass	Single-stage	40	–	–	FT	N/A	3.8[d]	[37,42]
		Two-stage	50			PT	N/A	3.4[d]	
		Two-stage	60			PT	3.8	N/A	
North America	Single-pass	Single-stage	49	–	–	PX	3.5	N/A	[31,43,44]
	SPSP	Single-stage	50 (overall)	Cascade[c]	N/A	PX	3.6	N/A	[45–47]
North East Asia	Single-pass	Single-stage	45	–	–	WE	4.0	N/A	[31,48,49]
	Full two-pass	Single-stage	45	Two-stage	85	PX	< 3.8	N/A	[31,50–52]
	Partial two-pass	Two-stage	60	N/A	85	PT	5.5	N/A	[31,53,54]
	SPSP	Single-stage	48	N/A	91	DWEER, TC	3.9	N/A	[55–57]
Oceania	Advanced SPSP[ad]	Single-stage	49 (overall)	Two-stage	N/A	PX	3.6	N/A	[58,59]
	SPSP	Single-stage	45	Two-stage	85	DWEER	3.5	3.0[e]	[31,60,61]
	Partial two-pass	Single-stage	48	Two-stage	90	PX	< 4.6	N/A	[62,63]
	Partial two-pass	Single-stage	45	Two-stage	90	PX	3.6	2.4[d]	[64,65]
	SPSP	Single-stage	45	Two-stage	90	PX	3.5	2.9[e]	[60,62,66–68]
	Partial two-pass	Single-stage	45	N/A	N/A	DWEER	< 3.9[w]	N/A	[60,69,70]
South America	Single-pass	Single-stage	50	–	–	PT	4.3[p]	3.4[d]	[71–73]
	Single-pass	Single-stage	52	–	–	PT	4.2	N/A	[31,74,75]
South Asia	Single-pass	Single-stage	45	–	–	PX	3.9	2.7[d,g]	[76–78]
South East Asia	Partial two-pass	Single-stage	45	Two-stage	90	DWEER	4.1	3.1[d]	[79–81]
	Partial two-pass	Single-stage	45	Two-stage	90	DWEER	4.0	N/A	[31,80,82]
The Caribbean	Full two-pass	Single-stage	43	Two-stage	88	PX	3.8	N/A	[83–85]
	Two-pass[uc]	Two-stage	58 (overall)	Three-stage	N/A	PT	4.2	2.6[d]	[42]

(*continued on next page*)

Table 1 (*continued*)

Region	Overall RO configuration	SWRO		BWRO		ERD type	SEC (kWh/m^3)		Ref.
		Configuration	Recovery (%)	Configuration	Recovery (%)		Plant	RO system	
The Mediterranean	Single-pass	Single-stage	N/A	–	–	FT	6.2	5.2[d]	[86,87]
			46			PX	5.3	N/A	
	SPSP	Single-stage	50	Two-stage	78	PT	4.4	N/A	[88,89]
	Partial two-pass	Single-stage	45	Two-stage	90	DWEER	4.6	2.9[d]	[90–93]
	Single-pass	Single-stage	45	–	–	PT	4.5	N/A	[37,94–96]
	Single-pass	Single-stage	43	–	–	PX	3.8	< 2.5[d]	
	Single-pass	Single-stage	45	–	–	PT	4.2	N/A	[31,95]
	Partial two-pass	Single-stage	45	Two-stage	85	PX	4.2	2.6[d]	[97–100]
	Partial two-pass	Single-stage	47	Two-stage	87	DWEER	4.0	N/A	[101–103]
	Single-pass	Single-stage	45	–	–	PT	4.3	N/A	[31,95,104–106]
	Single-pass	Two-stage	58	–	–	PT	3.6	N/A	[31,107,108]
	Single-pass	Single-stage	45	–	–	PT	4.2	N/A	[31,94]
	Single-pass	Single-stage	45	–	–	PX	3.8	N/A	
	Single-pass	Single-stage	45	–	–	PT	4.5	3.1[d]	[31,95,109]
						PX	N/A	2.6[d]	
	Two-pass[uc]	Single-stage	43 (overall)	Two-stage	N/A	PX	4.7	3.0	[110–112]
	Single-pass	Two-stage	50	–	–	PX	3.7	3.1	[113,114]
	Single-pass	Single-stage	33	–	–	N/A	6.3	N/A	[115]
The Middle East	Full two-pass	Single-stage	42	Two-stage	90	PT	5.4	4.7[e]	[116–118]
	SPSP	Single-stage	45	Cascade[c]	85, 85, 90	DWEER	< 3.9	3.0[d]	[79,119,120]
	SPSP	Single-stage	45	Cascade[c]	N/A	PX	4.0	2.7[d]	[69,79,121]
	SPSP	Single-stage	45	Cascade[c]	98 (total)	PT	3.5	2.9[d]	[79,122–124]
		Single-stage	N/A		N/A	PT, PX	N/A	2.7[d]	
		Single-stage	N/A		N/A	PX	N/A	2.5[d]	
	SPSP	Single-stage	45 (overall)	Cascade[c]	N/A	DWEER	< 4.0	2.7[d]	[69,79]
	Partial two-pass	Two-stage	50	Two-stage	90	PT	4.6	3.5[e]	[125,126]
	Full triple-pass	Single-stage	43	Two-stage	90, 90	PT	4.8	N/A	[31,100,107,127]
	Full/Partial two-pass[f]	Single-stage	45	N/A	90	PX	4.4	3.1[e]	[128,129]
	Full two-pass	Single-stage	42	N/A	90	PX	4.8	N/A	[31,35]
	Full two-pass	Single-stage	40	PCP[pcp]	90	PT	4.4	N/A	[130–132]
	Single-pass	Single-stage	39	–	–	PT	5.2[g]	N/A	[31,133]
	Two-pass[uc]	Single-stage	N/A	Two-stage	N/A	WE	3.6	N/A	[134,135]
	Two-pass[uc]	Single-stage	43 (overall)	Two-stage	N/A	PX	4.5	N/A	[136]
	Partial two-pass	Single-stage	43	Two-stage	90	PT	4.5	3.8[e]	[137]
	Single-pass	Single-stage	40	–	–	PX	< 3.0	N/A	[138,139]
	Single-pass	Single-stage	N/A	–	–	PX	4.0	N/A	[31,107,140]
	Single-pass	Single-stage	42	–	–	PX	4.0	N/A	[30,31,140,141]
	Full two-pass	Single-stage	35	Two-stage	90	DWEER	4.1	N/A	[35]

BVI: British Virgin Islands. DWEER: dual work exchanger energy recovery. ERD: energy recovery device. FT: Francis turbine. KSA: Kingdom of Saudi Arabia. PCP: Permeate circulation process. PT: Pelton turbine. PX: pressure exchanger. SEC: specific energy consumption. SPSP: split partial second pass. TC: Turbocharger. TDS: total dissolved solids. UAE: United Arab Emirates. USA: United States of America. WE: work exchanger. [a]After the remineralization process. [b]Before the remineralization process. [c]Additional BWRO passes following two-stage BWRO to meet water standards. [d]SEC of SWRO-ERD. [e]SEC of SWRO-ERD and BWRO. [f]Full two-pass required during the summer. [g]Design value. [m]Maximum capacity. [n]Normal capacity. [p]Pumping system requires additional 14 kwh/m^3 to transport water up the mountain. [w]Energy produced from the wind farm further reduced SEC to 3.2 kWh/m^3. [ad]Front and rear permeate are each split and treated by second-pass ROs. [ep]further expansion is not included. [nl]Netherlands Antilles. [pcp]Rear permeate from the BWRO second stage is circulated back to BWRO feed to improve water standards. [uc]Unclassified two-pass. [uk]British Overseas Territory. [pd] pilot data.

4.2. Energy recovery device with higher efficiency

Over the years, not only the capacity but also the energy efficiency of SWRO plants increased. Without ERDs, SWRO consumed high amounts of energy compared to other desalting technologies. However, ERDs significantly reduced the SEC of RO systems and allowed SWRO to become more competitive than thermal-based desalination. Therefore, ERDs are essential to reduce the SEC of an RO system, and efforts to improve ERD efficiency have been made (Fig. 3). Turbines were used in the first ERD applications. Francis turbines (FTs) were the earliest, followed by Pelton turbines (PTs). In these systems, a turbine is attached to a shaft that is common to the HPP and the electric motor. The turbine-type ERD is not highly efficient due to the double energy conversion, where hydraulic energy in the concentrate is converted to mechanical energy to rotate the shaft, and converted again to hydraulic energy in the feed [144,145]. To further improve energy efficiency, isobaric ERDs, such as for DWEER devices or PXs, are adopted. However, they can slightly increase feed salinity during the pressure exchange [146,147]. Fig. 3 clearly demonstrates that the development of ERDs significantly reduces the energy consumption of SWRO.

4.3. Reverse osmosis configurations for better energy efficiency and water quality

In typical SWRO operations, more than half of the feed is discharged as concentrate (*i.e.*, recovery < 50%). Therefore, attempts to increase SWRO recovery have been investigated. In the early 2000s, some plants adopted a two-stage SWRO process (Fig. 4a) in which the concentrate of a conventional single-stage SWRO is fed into the second stage. With increased recovery, the size of the plant can be reduced, and the volume of concentrate is lower [148]. However, a two-stage SWRO requires relatively higher SEC (Fig. 4a) due to its high-pressure operation, in which nearly 100 bars of pressure is applied in the second stage [42,148]. Moreover, some operational issues arise, as the second stage of the SWRO process is performed under high pressure. Because low SEC instead of high recovery is required for current SWRO plants, a two-stage RO configuration has rarely been applied in recent years, and BWRO is generally configured with two or more stages.

While attempts to increase the recovery rate are declining, the demand for high-quality product is increasing. Recent SWRO plants have adopted two-pass RO designs to reduce the TDS of the permeate from the first-pass RO (*i.e.*, SWRO) by using a second-pass RO (*i.e.*, BWRO) [6]. Furthermore, SWRO plants have been reported to use triple-pass RO for industrial water production [127]. However, extra energy is required to undertake an additional RO pass [6]. In this regard, two-pass RO should consume more energy than a single-pass RO. However, two-pass RO designs showed a lower SEC compared to single-pass RO in the early 2000s (Fig. 4**b**). That was because the two-pass RO plants during this period were equipped with isobaric ERDs, whereas single-pass RO plants were mostly equipped with turbine ERDs. Nevertheless, when isobaric ERD is used for both single- and two-pass RO, single-pass RO is more energy efficient, as shown since the mid-2000s (Fig. 4**b**).

5. Factors affecting energy consumption

The RO system accounts for the majority of the energy use in an SWRO plant. Therefore, there is a dependency between the SEC of the RO system and that of the plant, as depicted in Fig. 5. According to the trend line, the SEC of the plant is approximately 1 kWh/m^3 higher that of the RO system. Thus, it can be inferred that the energy consumption for pre- and post-treatment is close to 1 kWh/m^3 regardless of feed conditions and other factors. In this scenario, it is important to understand the factors affecting the energy consumption of an RO system, which ultimately relates to the SEC of the plants (Table 1).

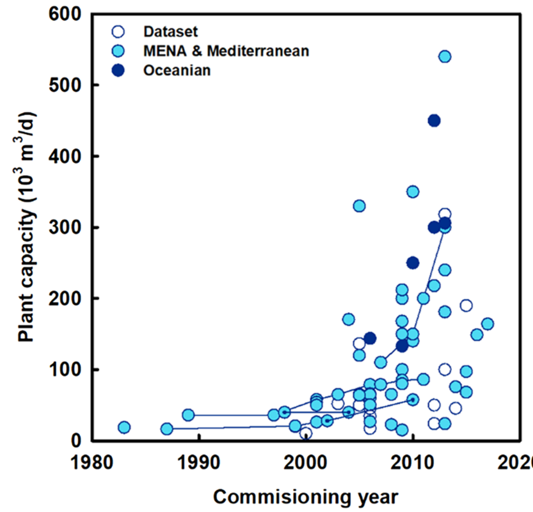

Fig. 2. Plant capacity of SWRO desalination plants over commissioning years. SWRO plants have been installed aggressively after 2000. MENA: Middle East and North Africa.

5.1. Feed conditions

5.1.1. Salinity

A feed with high salinity possesses high osmotic pressure. To produce fresh water from a high salinity feed, higher hydraulic pressure must be applied. Therefore, SEC increases with increased salinity [17]. Fig. 6**a** shows the relationship between feed salinity and SEC, and the tendency agrees with the common theory. The impact of salinity on SEC would be stronger than the one depicted in Fig. 6**a** if the temperature effect is not correlated. A low-salinity condition (approximately 35,000 mg/L) is shown for a wide temperature range, including low-temperature conditions (Fig. 7). The SEC data collected at low temperatures shows high SEC despite the low salinity. Meanwhile, in high-salinity conditions (above 40,000 mg/L), the temperature is also high, which lowers the SEC. Thus, a stronger relationship would be expected between salinity and SEC if the temperature effect was excluded.

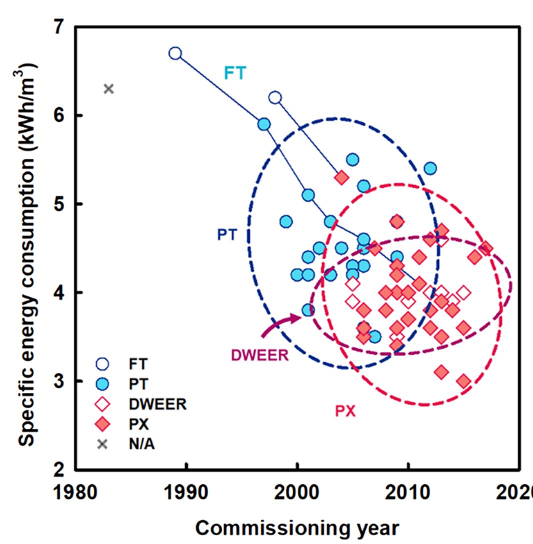

Fig. 3. SEC of SWRO desalination plants with the application of different ERD types. When a plant adopts two different types of ERDs, the ERD with the higher efficiency is then represented. DWEER devices include all kinds of work exchangers. FT: Francis turbine. PT: Pelton turbine. DWEER: dual work exchanger energy recovery. PX: pressure exchanger.

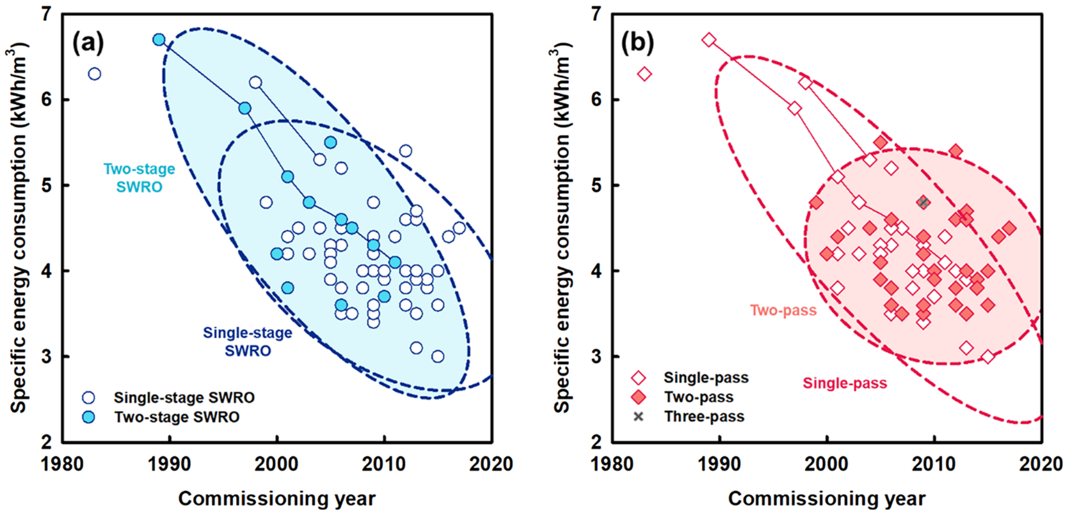

Fig. 4. SEC of SWRO plants according to the RO design: (a) SWRO stage and (b) overall RO pass. Two-stage design is adopted to increase overall recovery, while two-pass design is used to improve water quality.

5.1.2. Temperature

Whereas the feed salinity affects the osmotic pressure of the feed, the temperature changes the apparent membrane properties. When the water temperature increases, the water permeability coefficient (*A*) and the salt permeability coefficient (*B*) of the RO membrane also increase [6]. Because low hydraulic pressure is required for water production at a high *A* value, the SEC is reduced. Moreover, the minimum energy required for separation slightly increases with temperature increase, contributing to an SEC increase. As the SEC is more influenced by the increase of *A* than by the minimum energy increase, the SEC of the RO system is reduced with increasing temperatures [17]. However, the trend line of Fig. 6**b** does not corroborate this theory. It shows a weak correlation between temperature and SEC, due to the impact of salinity. Some points have high salinity at high temperature, and low salinity at low temperature (Fig. 7), hence their distorted SEC values. Therefore, the effect of temperature on SEC is not clearly shown in Fig. 6**b**. Although the effects of feed conditions are explained, they show a weak correlation when the effect of single factors on SEC are analyzed. Additionally, feed conditions alone cannot describe the SEC data. Other factors that influence SEC besides feed conditions should be also be considered.

5.2. Equipment efficiency

5.2.1. Energy recovery device

In Fig. 8, the SEC of SWRO desalination plants with different types of ERDs is presented. The plants with FTs obtain a high SEC over 6 kWh/m^3, but those with PTs obtained SEC in the range of 3.5–5.9 kWh/m^3. Moreover, isobaric ERDs show lower energy use than turbine ERDs. The plants with DWEER devices consume 3.5–4.6 kWh/m^3, and those with PXs exhibit a wider range, with energy use of 3.0–5.3 kWh/m^3. It is notable that a plant with PXs has been reported to consume less than 3 kWh/m^3 [138,139]. Such low SEC can be explained by the highly efficient RO system, in which a single pass is configured, high-performance membranes are accommodated, and PXs are employed as ERDs. Although ERDs reduce the SEC of only RO systems, the SEC of the plant also decreases with different ERD applications, because the SEC of plants has a linear relationship with the RO SEC (Fig. 5).

5.2.2. High-pressure and booster pump

The efficiency of the HPP and BP is one of the factors that determine the SEC of an RO system. The pump efficiency can be improved by increasing its size [149]. Thus, an SWRO plant with large capacity is advantageous in reducing RO SEC. Fig. 9 illustrates the correlation

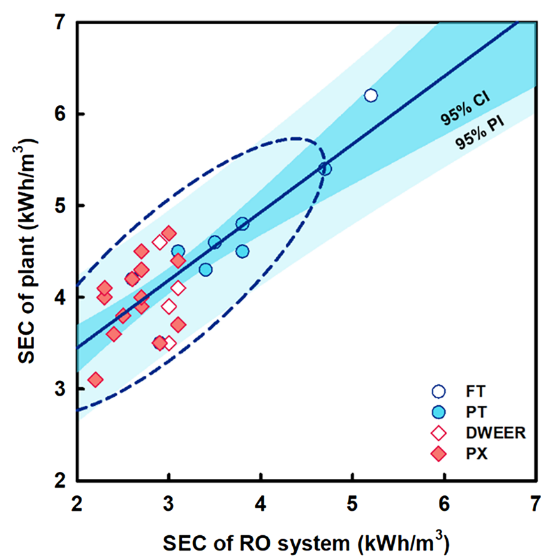

Fig. 5. Correlation between SEC of the RO system and of the plant. RO system is the most energy-intensive unit. Thus, the SEC of the plant depends on that of the RO system. FT: Francis turbine. PT: Pelton turbine. DWEER: dual work exchanger energy recovery. PX: pressure exchanger. PI: Prediction interval. CI: confidence interval.

between capacity and SEC of desalination plants. The trend line declines with increasing capacity, which is consistent with the common theory. However, large SWRO plants are not always energy efficient. In fact, the plants are composed of several pump stations (Fig. 10), and the pump efficiency is more influenced by the capacity of the pump stations than by the plant capacity (*i.e.*, the capacity of the RO system). In this regard, the plants with a capacity less than or equal to 100,000 m^3/d are analyzed to exclude the influence of the number of pump stations. Although certain SWRO plants have a low energy consumption even with small capacity, the number of SWRO plants that consume high amounts of energy is likely decreased by larger capacities. This reflects the impact of capacity on SEC reduction. Because a large pump is more efficient, there have been attempts to increase pump size without changing plant capacity. Pressure center design (or three-center design) is a corresponding design where the HPP, BP, and ERD are located in the middle of trains. By pressurizing the feed with large pumps in the middle of the RO trains, pump efficiency can be increased above that of a typical system [1]. This design has been developed by IDE

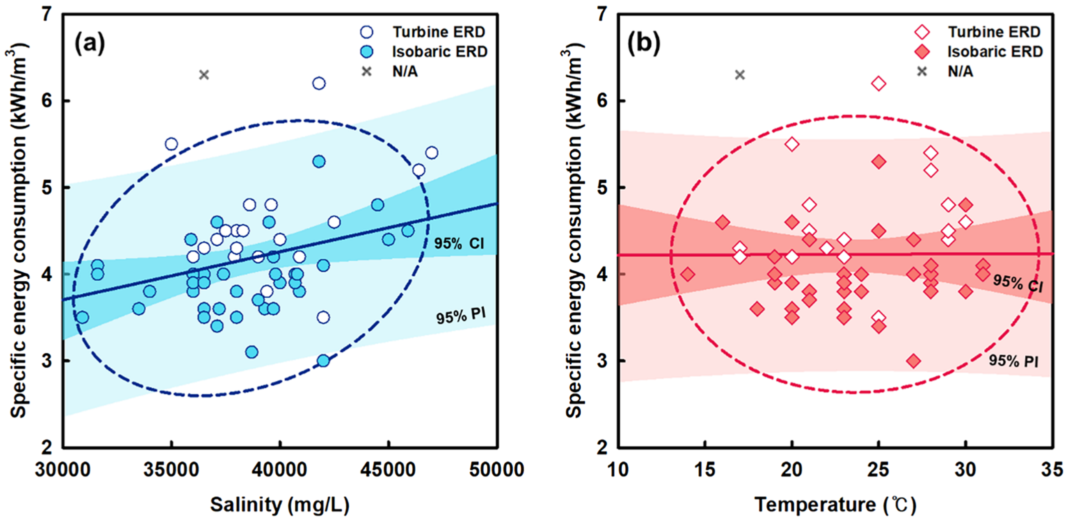

Fig. 6. Effects of (a) feed salinity and (b) temperature on the SEC of SWRO desalination plants. SEC increases with increased salinity but is not significantly affected by temperature. ERD: energy recovery device. PI: Prediction interval. CI: confidence interval.

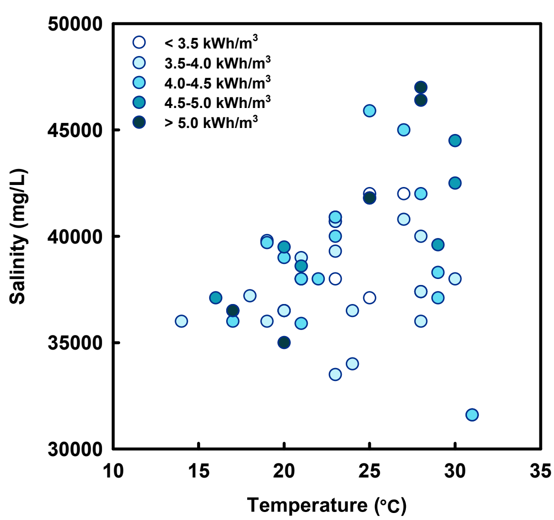

Fig. 7. SEC according to feed conditions. Low salinity (approximately 35,000 mg/L) is shown for all ranges of temperature, while high salinity (above 40,000 mg/L) occurs mostly in high-temperature conditions. High SEC is required when the salinity is high, and the temperature is low.

Technologies Ltd. and applied in many large-scale SWRO plants in Israel (Ashkelon, Hadera, and Sorek) [69,79,119–121].

5.2.3. Retrofit and expansion

SEC reduction by ERD retrofit and capacity expansion for a single plant is presented in Fig. 11. The ERD from the Dhekelia SWRO Plant in Cyprus was retrofitted from FT to PX, which reduced the SEC from 6.2 to 5.3 kWh/m^3 [86,87]. In the Canary Islands, Spain, the design of the Las Palmas III SWRO Plant changed drastically. Its capacity was 36,000 m^3/d in 1989 and reached 86,000 m^3/d in 2011, while its ERD was replaced from FT to PT, and from PT to PX. The SEC reduced from 6.7 kWh/m^3 (1989) to 4.1 kWh/m^3 (2011) [39,40]. Changes of SEC in the RO system and not the whole plant are presented in several references. The SEC of the RO system in the Tordera SWRO plant (Spain) reduced from 3.1 to 2.6 kWh/m^3 [31,95,109], and the one in the Palmachim SWRO plant (Israel) reduced from 2.9 to 2.5 kWh/m^3 [79,122–124]. Commonly, the energy reduction is mainly due to both capacity expansion and retrofit of ERD as PX.

5.3. Target conditions

5.3.1. Permeate quality

In general, two-pass design is applied to the RO system to improve water quality. An additional RO pass is installed to treat the permeate from the single-pass RO (Fig. 12**a**), thus configuring a two-pass RO (Fig. 12**b**). However, SWRO plants that produce high-quality permeate also exhibit high SEC. This is because the purer the obtained water, the higher the minimum energy required for separation. As shown in Fig. 13**a**, relatively low SEC is required to produce permeate quality of 300–500 mg/L (*i.e.*, moderate water quality), and the permeate is mostly produced from a single-pass RO (Fig. 12**a**) operation. Two-pass RO (Fig. 12**b**) is adopted to further improve the water quality. The permeate quality from two-pass RO is mostly 15–130 mg/L before remineralization and 115–300 mg/L after remineralization. It should be noted that remineralization is performed to add useful ions according to the purpose of the water product, because divalent ions are lacking in desalinated water [150,151]. Thus, a higher SEC is demanded to achieve better water quality. In particular, SEC is significantly higher

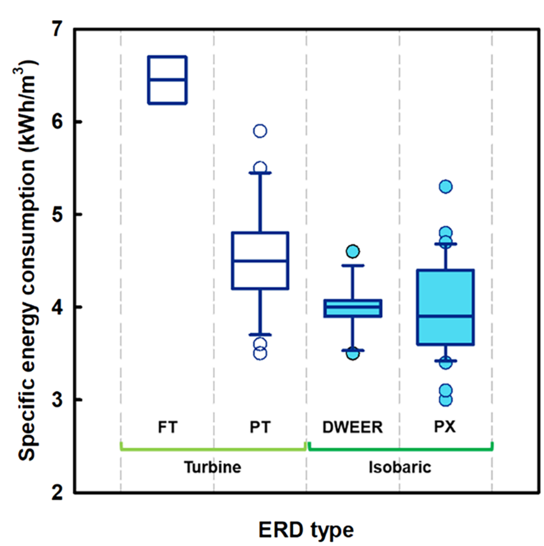

Fig. 8. SEC of SWRO plants according to ERD. Isobaric ERD showed better equipment efficiency compared to turbine ERD. ERD: energy recovery device. FT: Francis turbine. PT: Pelton turbine. DWEER: dual work exchanger energy recovery. PX: pressure exchanger.

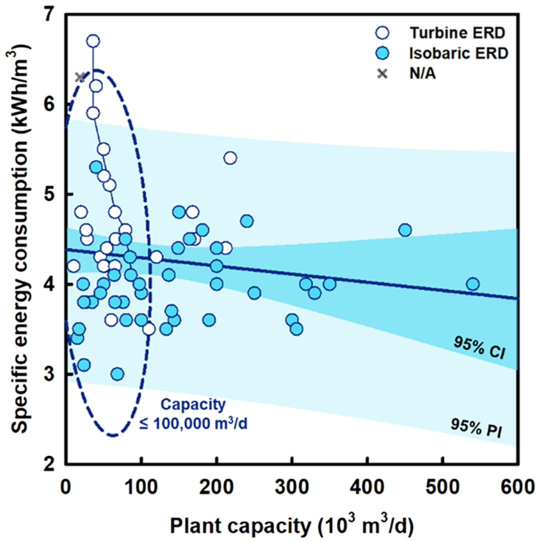

Fig. 9. Effect of capacity on SEC of SWRO desalination plants. Pump efficiency is more affected by the capacity of the pump stations rather than by the plant capacity. An ellipse was generated with 95% confidence, based on data for plants with a capacity less than or equal to 100,000 m^3/d. ERD: energy recovery device. PI: Prediction interval. CI: confidence interval.

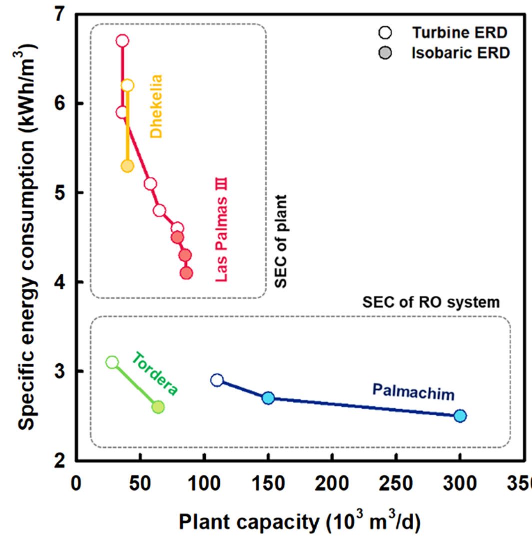

Fig. 11. SEC reduction through ERD retrofit and capacity expansion. By installing ERD with better equipment efficiency and increasing the capacity of pump stations, SEC of the plants is reduced. ERD: energy recovery device.

when the permeate quality is lower than 50 mg/L (before remineralization) due to the full two-pass RO operation (Table 1).

The use of different RO configurations affects not only permeate quality but also energy consumption. Fig. 13**b** presents SEC values according to RO configurations. It could be assumed from common sense that a single-pass RO would consume less energy compared to a two-pass RO. However, some single-pass SWRO plants, which were commissioned in the early 2000s and equipped with turbine ERDs, exhibit higher SEC. In other words, the use of immature desalination technologies including low equipment efficiency results in high energy consumption. For two-pass RO systems, SEC varies depending on the ratio of partial permeate treated by the second-pass RO. In split partial second-pass (SPSP) system, the front permeate of first-pass RO is directly sent to a permeate tank, while the rear permeate is treated by the second-pass RO before going to the permeate tank [6]. A lower mixing entropy is generated during permeate production under the split design (Fig. 12**b**). Therefore, SPSP RO consumes less energy compared to partial two-pass RO when treating the same volume at the second-pass RO [6]. In contrast, the full two-pass RO treats all the permeate of first-pass RO to produce high-quality water. Thus, a high energy consumption is unavoidable. The correlation between two-pass RO configuration and SEC is well depicted in Fig. 13**b**, particularly for a system adopting isobaric ERDs.

5.3.2. *Permeate quantity*

Recovery is a ratio that can be expressed as permeate flow rate per feed flow rate. A high recovery ratio can minimize the overall intake, pre-treatment, and brine disposal [152]. Thus, a high-recovery operation can reduce the costs of intake and brine disposal. However, the typical recovery range of the SWRO process is limited by the osmotic pressure of the feed. In fact, the osmotic pressure of the feed increases during the RO process [6]. Under high-recovery conditions, the osmotic pressure may reach the hydraulic pressure at the last elements. In this condition, water is not produced unless the pressure is increased

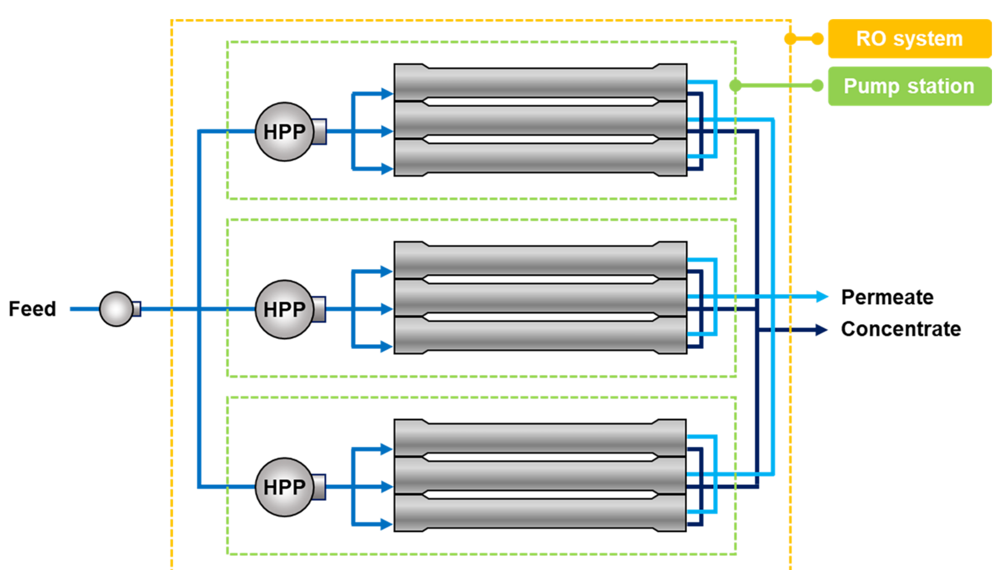

Fig. 10. Scheme of pump stations in the RO system. An SWRO plant is composed of several pump stations, and the plant capacity is equivalent to the summation of permeate produced from the pump stations. HPP: high-pressure pump.

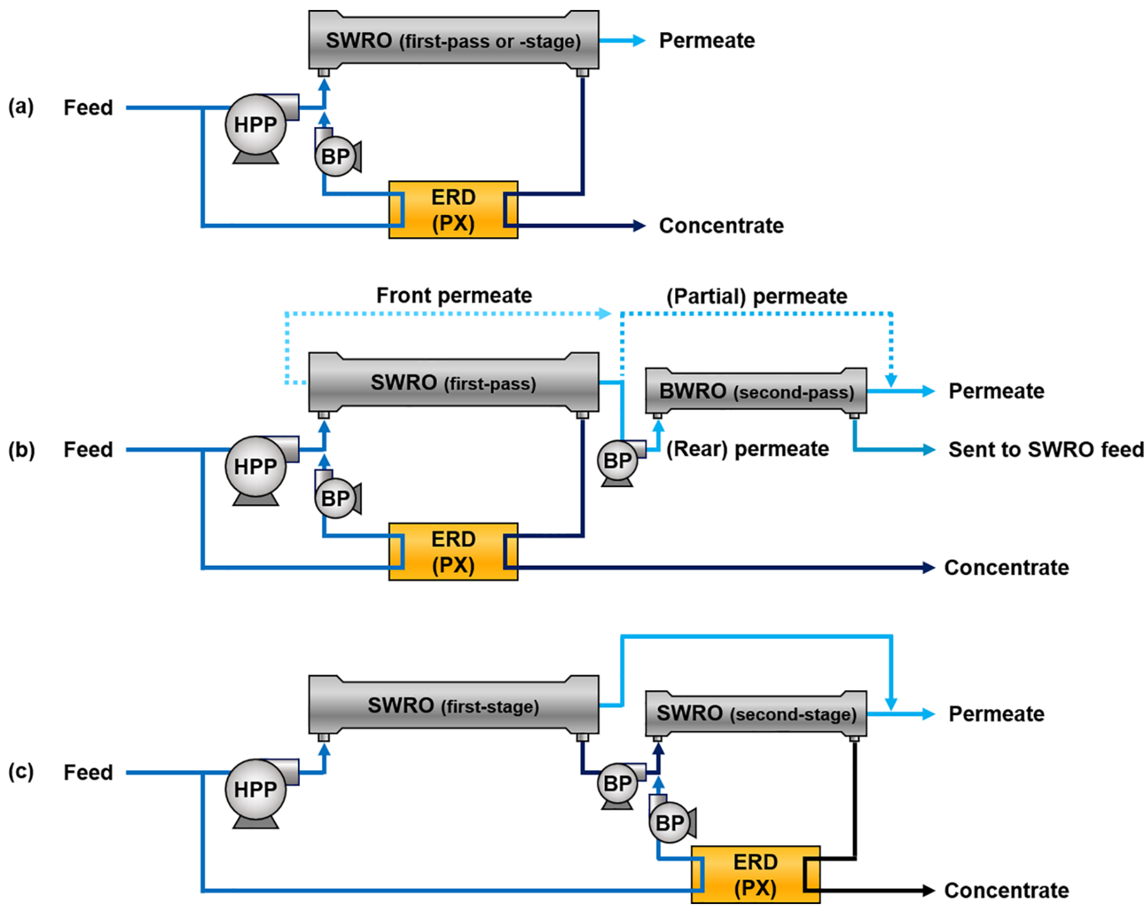

Fig. 12. Different RO configurations using PX as ERD: (a) single-pass or -stage (*i.e.*, SWRO), (b) two-pass (*i.e.*, SWRO + BWRO), and (c) two-stage RO (*i.e.*, SWRO + SWRO). HPP: high-pressure pump. BP: booster pump. ERD: energy recovery device. PX: pressure exchanger. SWRO: seawater reverse osmosis. BWRO: brackish water reverse osmosis.

[12,153,154]. Because high osmotic pressure limits the RO recovery, a feed with high salinity has limited potential for recovery (Fig. 14**a**). To achieve a recovery of over 50%, the hydraulic pressure of the feed must be increased, thus some SWRO desalination plants adopt a two-stage SWRO (Fig. 12**c**; Table 1).

Conversely, high recovery does not always guarantee low-energy consumption. Fig. 14**b** presents the SEC of desalination plants according to their SWRO or overall recovery. Single-stage SWRO plants (Fig. 12**a**) consume relatively low energy, with a recovery range between 40% and 50%. That is because there is an optimal recovery that minimizes RO SEC [12]. The optimal recovery differs based on the feed conditions, but it is formed near this range. For two-stage SWRO plants (Fig. 12**c**), the optimal recovery is near 60% because an additional 20% recovery is achieved in the second stage. If the recovery is small, or higher than the optimal recovery, the SWRO system consumes more energy. Therefore, it is important to operate the SWRO system with a recovery that properly satisfies the optimal SEC and cost.

6. Summary and future directions

In a water and energy crisis scenario, energy consumption is a crucial factor to consider for the installation of seawater reverse osmosis (SWRO) desalination plants. However, the energy consumption of SWRO is not systemically comprehended, and the available information is normally perceived without a critical view. Thus, specific energy consumption (SEC) of SWRO plants was investigated and analyzed using the collected datasets. Through the analysis of SWRO application trends, it can be observed that the size of SWRO plants is increasing while the energy consumption is decreasing. Moreover, the RO design is developed by focusing on low-energy consumption and high-water quality. Factors affecting SEC were analyzed, and future directions to lower SEC of SWRO plants are suggested.

- ***Dilute feed salinity***: Feed conditions (*i.e.*, salinity and temperature) affect energy use because they are associated with the thermodynamic minimum energy consumption for separation. As such, distinct feed conditions lead to different SEC, even if the same SWRO design and equipment are applied. In particular, the increase of feed salinity demands high energy for desalination, whereas a temperature increase reduces the SEC with a relatively weak effect. In other words, SWRO plants would consume less energy if the salinity is lower and the temperature is higher. Yet, feed conditions are site-specific variables, and it is difficult to handle their effects. However, a dilution method to reduce feed salinity has been recently developed, such as an osmotic dilution by forward osmosis (FO) integrating wastewater reclamation with seawater desalination. Despite the lack of thorough feasibility studies, this method would reduce the energy use of SWRO plants when the amount of energy reduced is higher than the amount consumed by the technique. Thus, further investigations should focus on the reduction of feed salinity considering the feed conditions.
- ***Reduce irreversible work***: With the development of high-efficiency apparatus, SEC of SWRO plants has been reduced over time. The use of energy recovery devices (ERDs), particularly isobaric ERDs, significantly reduces the SEC of plants, reaching 3 kWh/m^3. The most energy-efficient ERD is the pressure exchanger (PX), with a reported efficiency of over 95%. Advancements in ERDs could reduce the SEC, but the impact would not be significant considering the current

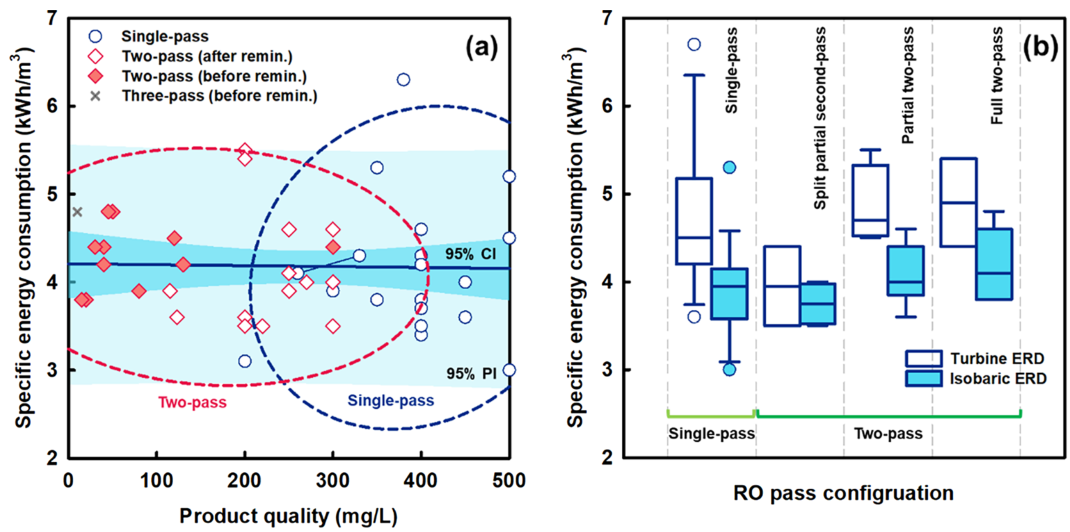

Fig. 13. SEC according to (a) product quality and (b) SWRO configuration. To improve product water quality, an additional RO pass is required, but more energy is used. TDS higher than 500 mg/L were excluded in (a). Unclassified two-pass is excluded in (b), where the plant adopts a two-pass RO but its specific configuration is not identified. Remin.: remineralization. PI: Prediction interval. CI: confidence interval.

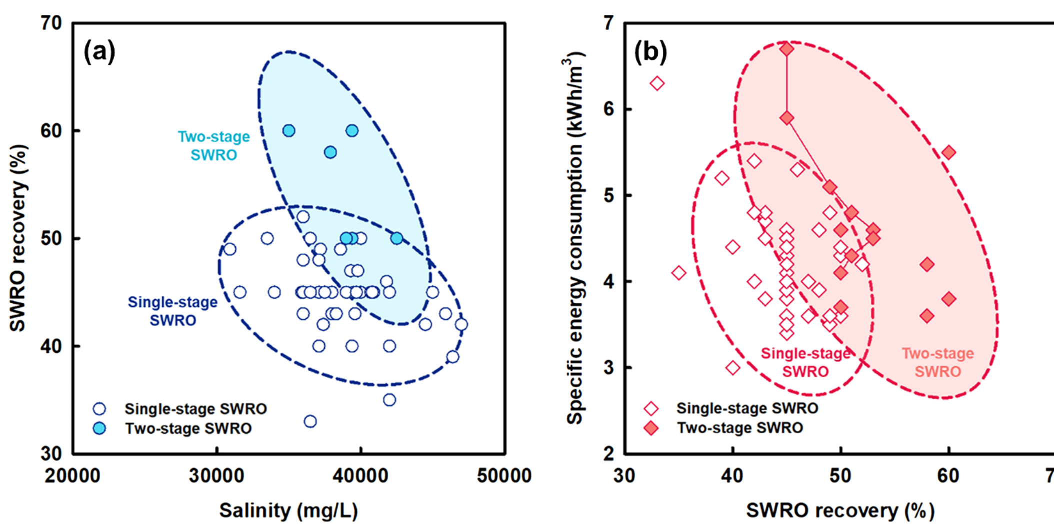

Fig. 14. (a) SWRO recovery according to feed salinity and (b) SEC of desalination plants by SWRO recovery. For two-pass ROs, overall recovery data was used if data for SWRO recovery alone was unavailable. Considering that the BWRO process has a high recovery of approximately 90%, an overall recovery would be slightly less than the SWRO recovery.

status of technological advancement. Moreover, the efficiency of pumps can be increased when their size is larger. Thus, an attempt to increase the capacity of pump stations has been implemented. However, due to the consequent need for several pump stations, maintenance, and other operational reasons, expanding the pump size is not an adequate suggestion to reduce SEC. Nevertheless, the energy consumed by pumps can be reduced by improving their efficiency and reducing irreversible work. Pumps demand energy for both reversible and irreversible work, but the irreversible work is not involved in the separation process. Therefore, strategies to reduce such wasted work should be developed and implemented to reduce SEC.

- ***Harvest osmotic energy***: SWRO plants should be operated to satisfy target conditions such as permeate quality and quantity, and more energy is required to improve the water quality and quantity. To produce a high-quality product, the use of two-pass reverse osmosis (RO) is inevitable, and SEC varies according to the type of configuration. To efficiently produce permeate with high quality, SPSP has been applied to two-pass RO configuration. Thus, the development of the RO configuration, which improves permeate quality with lower energy use, seems to be saturated. Nevertheless, two-stage RO configuration should be used to increase overall RO recovery, and the SEC of the RO system depends on the target recovery for operation. Therefore, optimizing the operation would reduce SEC of a two-stage RO system. In summary, the technological development has been widely focused on permeate production. However, utilizing the concentrate is not an attractive option. Nevertheless, the abundance of osmotic energy in the concentrate can reduce the energy consumption of SWRO plants once it is harvested. The use of technologies to harvest osmotic energy, such as pressure retarded osmosis (PRO) and reverse electrodialysis (RED), has yet to be demonstrated in current SWRO plants. Therefore, they must be technically developed for a feasible operation.

Given that current SWRO plants consume more energy than the thermodynamic minimum for separation, it is possible to further reduce the SEC of the plants. This can be achieved by improving the current SWRO technologies and developing novel desalination technologies.

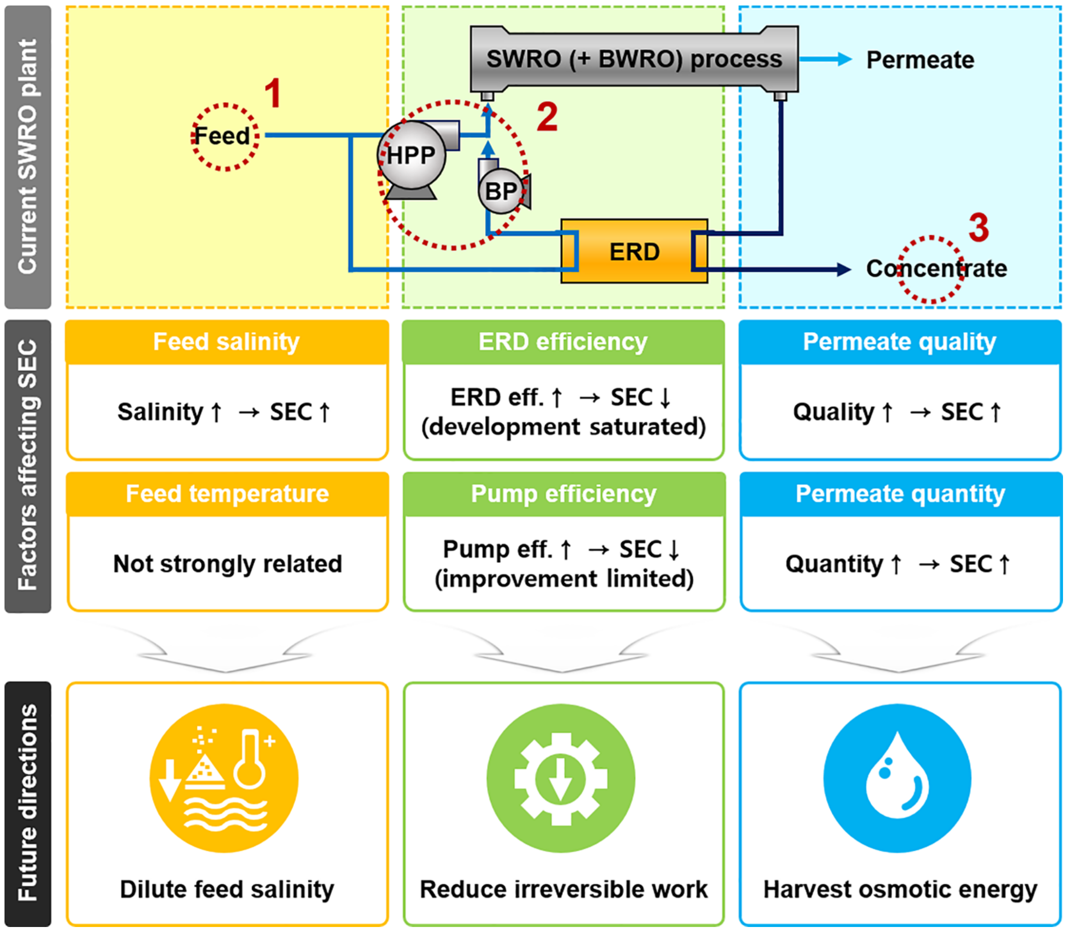

Fig. 15. Summary of SWRO process, factors affecting SEC, and future research suggestions. SEC of SWRO plant can be lowered by diluting feed salinity, reducing irreversible work, and harvesting osmotic energy.

Such technologies should feature lower feed salinity, reduced irreversibility of pumps, and recovery of the osmotic energy from the concentrate (Fig. 15).

Acknowledgement

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