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Pilot study of emerging low-energy seawater reverse osmosis desalination technologies for high-salinity, high-temperature, and high-turbidity seawater☆

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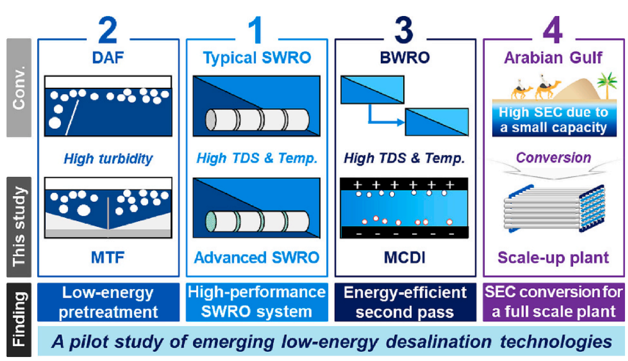
HIGHLIGHTS

- A pilot-scale SWRO desalination plant was used to investigate low-energy technologies.
- Developed SWRO membranes significantly decreased feed TDS under normal pressure.
- MTF reduced feed turbidity effectively and consumed lower energy compared to DAF.
- MCDI demonstrated potential as a substitute for BWRO in two-pass RO systems.
- The SEC of SWRO desalination plants was evaluated as 3.11 kWh/m^3 through scale-up.

GRAPHICAL ABSTRACT



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ABSTRACT

The increasing impact of climate change has worsened drought conditions, leading to a surge in the demand for seawater desalination. However, current seawater reverse osmosis (SWRO) desalination technologies are not energy-efficient for handling the high-salinity, high-temperature, and high-turbidity seawater found in the Arabian Gulf. Therefore, a pilot-scale SWRO desalination plant was established to evaluate the new desalination technologies. The pilot plant tested high-performance SWRO membranes, meshed tube filtration (MTF) as a low-energy pretreatment for the high turbidity induced by algal blooms, and membrane capacitive deionization (MCDI) to improve permeate quality. The high-performance SWRO membrane demonstrated exceptional salt rejection and produced permeate quality in the range of 250–455 mg/L from the feed with salinities of 47,500–53,500 mg/L. MTF was effective in controlling turbidity, and the energy consumption was reduced by 77 % compared to the existing pretreatment process. Furthermore, MCDI exhibited similar levels of energy efficiency as brackish water reverse osmosis and may have the potential for future deployment by enhancing process development. Based on the pilot plant results, it is expected that a 100,000–200,000 m^3/d SWRO desalination plant will have a specific energy consumption of 3.11–3.13 kWh/m^3 for final product water quality at or below 200 mg/L.

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1. Introduction

Seawater desalination is considered a sustainable technology for freshwater production to meet increasing water demands [1–3]. While some countries have recently built seawater desalination plants to address water shortage issues during the era of climate change, countries in the Middle East and North Africa (MENA) region traditionally rely on seawater desalination because of the lack of surface water sources. Recently, the use of seawater desalination has rapidly increased in the MENA region; in particular, the Gulf Cooperation Council (GCC) countries will account for 40 % of the world's contracted desalination plant capacity in 2021 [4]. Thus, securing and expanding the water supply in GCC countries is crucial.

GCC countries have transitioned from using thermal desalination methods to membrane-based ones and are now implementing independent water projects (IWPs) instead of independent water and power projects (IWPPs). Traditionally, the GCC region has preferred to use thermal-based desalination methods such as multi-stage flash and multi-effect distillation for the treatment of high salinity seawater. The utilization of hot water from power plants via thermal-based desalination methods is also advantageous [5]. However, with advancements in membrane desalination technologies, the use of seawater reverse osmosis (SWRO) desalination plants in GCC countries has become dominant due to the higher energy efficiency of SWRO. According to the United Arab Emirates (UAE) Water Security Strategy 2036, the UAE plans to increase the proportion of municipal water supplied by SWRO desalination from 14 % in 2016 to 52 % by 2036. Similarly, numerous initiatives have been implemented to produce water through SWRO desalination in GCC countries. SWRO desalination is a vital approach for providing freshwater and offers an alternative to thermal-based desalination methods. Because SWRO desalination is now preferred over thermal-based desalination, the IWP format has increased in water plant bidding systems over the IWPP format [6,7].

SWRO desalination plants located in the Arabian Gulf region exhibit higher specific energy consumption (SEC) due to high-pressure SWRO operations, extensive pretreatment processes, and the implementation of brackish water reverse osmosis (BWRO). The Arabian Gulf is connected to the Indian Ocean by the Strait of Hormuz, and its water body is not sufficiently replenished with freshwater or seawater because it is a semi-enclosed body of water with limited exchange with the open ocean [8]. However, desalination plants in the region continuously discharge high-salinity concentrate, which increases the salinity of seawater in the Arabian Gulf [9]. SWRO plants in the Gulf of Oman are fed with seawater at 37,000–38,000 mg/L, whereas those in the Arabian Gulf after the Strait of Hormuz operate with seawater at 42,000 mg/L (Fig. 1a). The total dissolved solids (TDS) of the northern Arabian Gulf was 45,000 mg/L (Fig. 1b), and near the seashore of the southern Arabian Gulf, it ranged from 46,000 to 53,500 mg/L, with seasonal variations (Fig. 1c). Therefore, the SWRO plants in this region operate at higher pressures to overcome the high osmotic pressure of the feed. In addition, BWRO is often employed after the SWRO process to improve the purity of the SWRO permeate, and such a two-pass reverse osmosis (RO) system (i.e., SWRO with BWRO) consumes more energy [2,10]. Furthermore, algal blooms are a significant concern in the operation of SWRO plants in this region, and dissolved air flotation (DAF) is commonly used as an additional pretreatment method before ultrafiltration (UF) or dual media filtration (DMF) to reduce high turbidity [11]. SWRO desalination plants equipped with DAF and two-pass RO systems exhibit 3.6–5.4 kWh/m^3 in the Arabian Gulf seawater as a result of the aforementioned factors (Fig. 1b and c).

A Korean research consortium comprising distinctive research institutions and companies has been working on developing advanced desalination technologies since 2016 to reduce the SEC of SWRO desalination plants in the Arabian Gulf. The consortium has established three technological directions for this purpose. First, the consortium developed new SWRO membranes that exhibited superior rejection and water flux compared with other commercial SWRO membranes [12]. Second, a low-energy pretreatment process called meshed tube filtration (MTF) was developed to handle the turbidity induced by algal blooms with

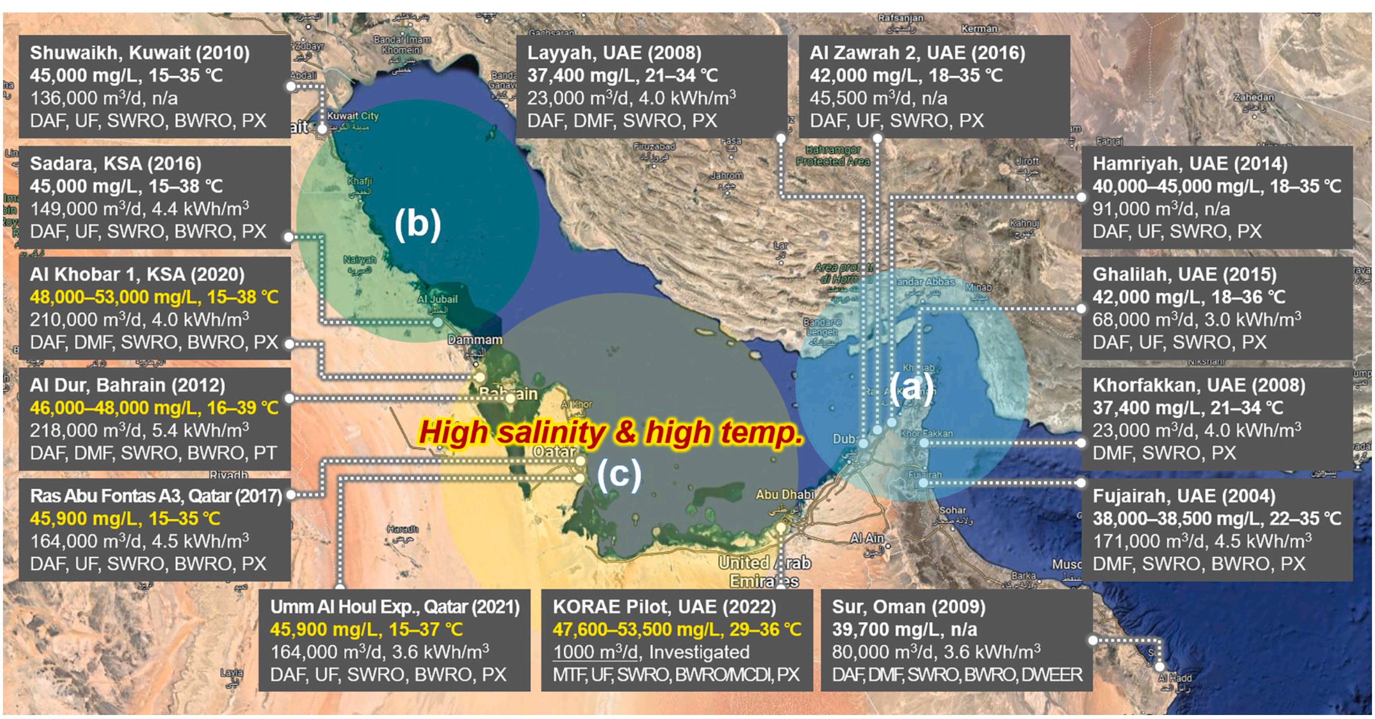

Fig. 1. SWRO desalination plants installed in the Arabian Gulf [2,11,16]. The area is classified with the feed TDS of (a) 37,000–42,000 mg/L, (b) 45,000 mg/L, and (c) 46,000–53,500 mg/L. DAF: dissolved air flotation. DMF: dual media filtration. MTF: meshed tube filtration. UF: ultrafiltration. SWRO: seawater reverse osmosis. BWRO: brackish water reverse osmosis. MCDI: membrane capacitive deionization. PX: pressure exchanger. PT: Pelton turbine. DWEER: dual work exchanger energy recovery.

Table 1
Water quality analysis for seawater. TSS: total suspended solids. TOC: total organic carbon. EC: electrical conductivity. TDS: total dissolved solids.

Parameter		Unit	Sampling date		
			July 27, 2022	September 29, 2022	November 17, 2022
pH		–	8.08	7.96	8.0
Turbidity		NTU	0.74	0.92	1.04
TSS		mg/L	<5	<5	<5
TOC		mg/L	2.7	2.18	1.57
EC		μS/cm	69,140	63,660	64,530
TDS		mg/L	49,800	45,850	46,450
Ions	Na^+	mg/L	13,731	13,948	13,120
	K^+	mg/L	467	565	579
	Ca^{2+}	mg/L	561	505	561
	Mg^{2+}	mg/L	2021	1807	1773
	Cl^-	mg/L	26,588	25,879	26,588
	SO_4^{2-}	mg/L	2776	2545	2586
	HCO_3^-	mg/L	149	156	151
	Others	mg/L	3507	445	1092

lower energy consumption than DAF [13,14]. Finally, a large-scale membrane capacitive deionization (MCDI) system was developed to replace the BWRO system and improve SWRO permeate quality with higher energy efficiency [15]. The research group aimed to achieve a 3.3 kWh/m^3 of SEC when the test result is converted to the plant at 100,000 m^3/d, with a design salinity of 42,000 mg/L and a temperature of 30 °C, which is an average seawater condition for the Arabian Gulf [8]. A 1000 m^3/d (i.e., SWRO permeate) SWRO desalination pilot plant was constructed using technologies developed in 2021 and operated in 2022.

This pilot study evaluated the feasibility of emerging desalination technologies for reducing the SEC of SWRO desalination plants. First, the high-performance SWRO membranes were operated under high-salinity and high-temperature seawater conditions to investigate their ability to reject salt and reduce SEC. In addition, the performances of DAF and MTF were compared in terms of turbidity control and SEC reduction to explore the potential of low-energy pretreatment that could respond to high turbidity induced by algae. Moreover, the performances of BWRO and MCDI in terms of salt rejection and SEC were compared to assess the practicality of the electrochemical processes that alternate with second-pass RO. Finally, the SEC of full-scale SWRO desalination plants was evaluated based on the pilot plant results for future applications of the newly developed technologies. This study provides practical insights into emerging technologies for SWRO desalination and suggests a scheme for future low-energy SWRO desalination plants.

2. Material and methods

2.1. Site conditions

The pilot plant is located on an island in Abu Dhabi, UAE, where the feed TDS and temperature of SWRO are 47,600–53,500 mg/L and 29–36 °C, respectively, from July 2022 to November 2022. Table 1 presents the results of the laboratory seawater analysis. It should be noted that the TDS presented in Table 1 differs from the TDS converted from electrical conductivity (EC) using a factor. The island is surrounded by shallow seawater with high tidal activity, which significantly affects seawater temperature and salinity. During high tide, water is released from the ocean and salinity decreases with the feed of seawater from a large ocean. By contrast, the evaporation of seawater is accelerated during low tide when extensive heat generates salt ponds near the island and the salinity of seawater around the island increases without mixing with fresh seawater feed. This results in large fluctuations in feed salinity (Fig. 2a); however, the temperature and turbidity values remain relatively stable throughout the day (Fig. 2b and c). Considering the site specifications, this is an ideal location for conducting seawater desalination research fed with high-salinity and high-temperature seawater, which is of significant concern for SWRO operations in GCC countries.

2.2. Plant construction and operation

This project was conducted by a consortium of Korean research institutions and companies. Korea University is in charge of managing the entire construction and operation process. The University began civil work, including foundation, intake pipeline, and cable installation, in April 2021. Daewoo E&C managed the overall plant construction work, and the plant equipment and materials were shipped from the Republic of Korea to the UAE. In addition, companies specializing in unit processes participated in the construction. The MTF process was managed by Keosong Construction [13,14], the UF system was supplied by Samsung Engineering, SWRO membranes were developed and provided by LG Chem, and the MCDI system was managed by Siontech. The overall construction was completed in October 2021, and commissioning began in June 2022. The SWRO pilot plant was operated by K-water from July 2022 to November 2022, including a period of extreme feed conditions, such as high temperature and high salinity (i.e., August and September). However, MCDI was only operated by Siontech. During the operation period, three performance tests were conducted to ensure that the operating conditions were reasonable and system performance, specifically the water quality, met the specified criteria. While the plant was operating for four months, there were several instances in which the operation had to be temporarily halted to change the sensors, replace spare parts, and address water leakage issues.

2.3. Overall desalination process

The pilot plant is located in the UAE, where seawater conditions are high in salinity and temperature compared with other regions. The plant consists of pretreatment, an RO system, and posttreatment, similar to other SWRO desalination plants (Fig. 3) [2]. Novel processes were implemented along with conventional ones to validate the feasibility of the newly developed process. The capacity of the plant is designed to be 1000 m^3/d (i.e., SWRO permeate), but the final product can be slightly reduced to 965 m^3/d depending on the use of second-pass RO, such as BWRO or MCDI.

After intake (Fig. 3a), both the DAF and MTF units were installed in a pretreatment system coupled with a UF unit to effectively handle high-turbidity seawater. The MTF is mainly used in the pilot study with a capacity of 2755 m^3/d (Fig. 3b); however, the DAF was installed as a contingency measure with the same capacity (Fig. 3c). In the Arabian Gulf, DAF is widely used in SWRO desalination plants to prevent membrane fouling during algal blooms. MTF was developed to reduce algal content, similar to DAF, where turbidity is reduced by polypropylene-meshed tubes situated in cages [13]. The UF system was used to further improve the feed quality (Fig. 3d), and a recovery of approximately 93 % was achieved at an operating pressure of <1 bar. A cartridge filter (CF) was also utilized to ensure feed quality for SWRO

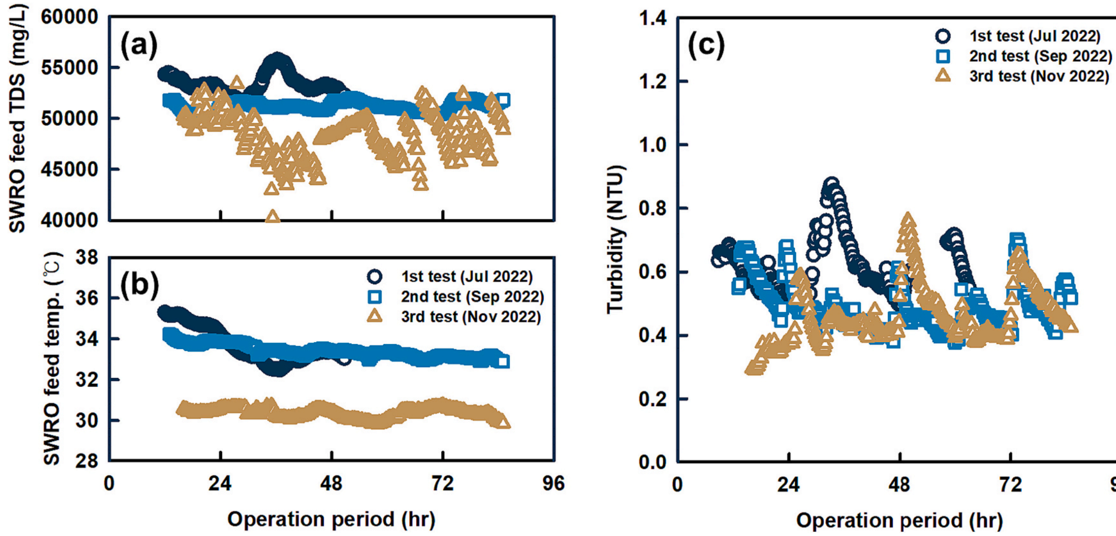

Fig. 2. Change of (a) SWRO feed TDS, (b) SWRO feed temperature, and (c) seawater turbidity during three performance tests in July, September, and November 2022. The SWRO feed TDS during the third test fluctuated owing to the circulation of SWRO permeate to the SWRO feed tank.

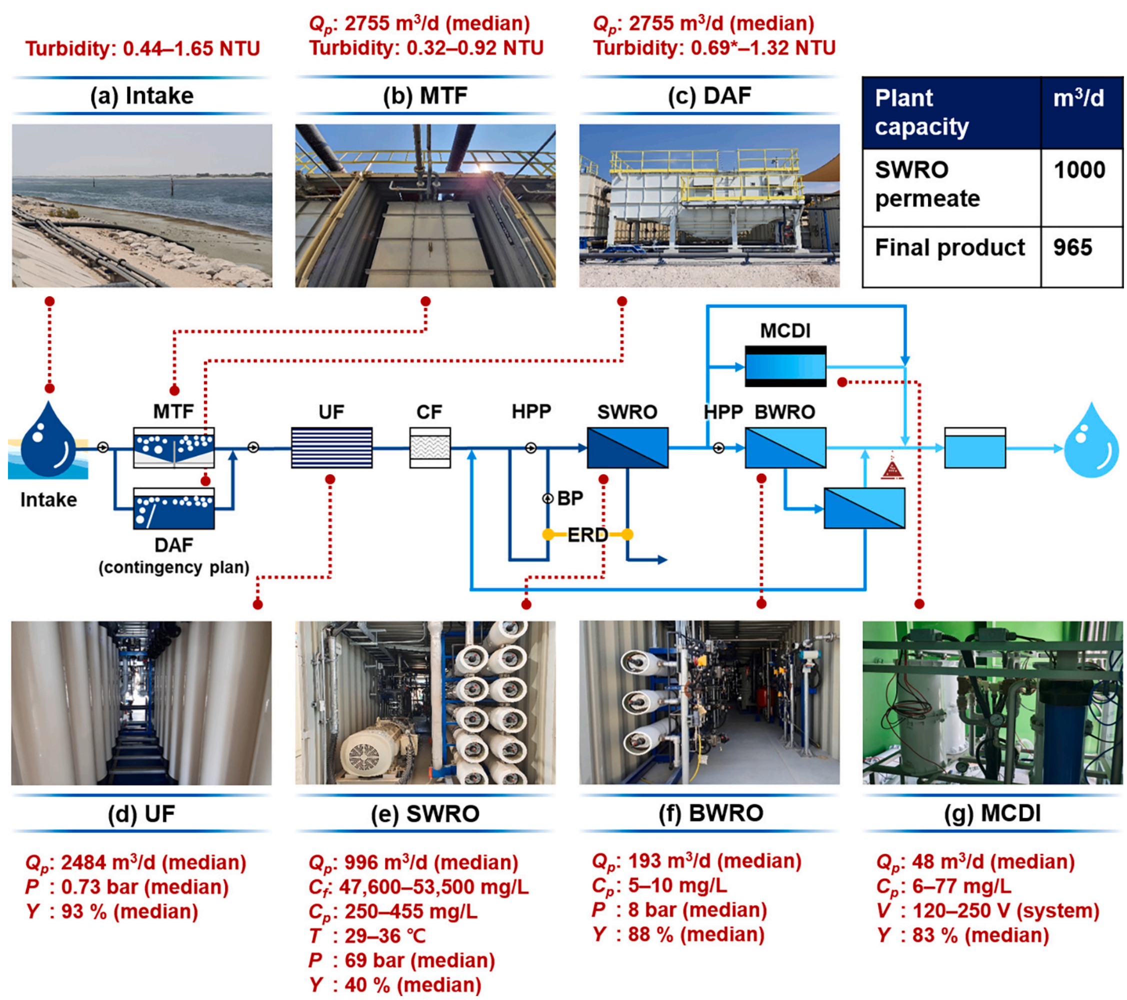

Fig. 3. Configuration of the SWRO desalination pilot plant: (a) Intake, (b) MTF, (c) DAF, (d) UF, (e) SWRO, (f) BWRO, and (g) MCDI. Operating conditions and performances are summarized for each process. MTF and DAF are installed to evaluate and compare their respective performances, while MCDI and BWRO are set up and compared for their performance. The lower limit of DAF effluent could be higher than that of seawater turbidity if DAF was not utilized when the seawater turbidity reached its lowest point. Q_p: permeate or effluent flow rate, P: operating pressure, Y: recovery, C_f: feed salinity, C_p: permeate or effluent salinity, T: temperature, V: applied voltage.

operation.

For the SWRO process, new high-rejection and high-flux SWRO membranes were developed and applied as an outcome of the research project (Fig. 3e). The installed SWRO membranes (LG SW 440 R G2) were developed to exhibit both a high flow rate and high rejection under basic test conditions. Compared to other commercial SWRO membranes, the developed membranes exhibited high water permeability *A* and low salt permeability *B* (Fig. 4; Table A1). These membrane characteristics enable relatively low-pressure SWRO operation and high-quality permeate production. A single-stage SWRO configuration was adopted with a designed capacity of 1000 m^3/d, whereas the capacity for the real operation was 996 m^3/d. The SWRO system comprised 11 pressure vessels (PVs), each equipped with seven SWRO elements. The designed SWRO recovery was limited to 40 % owing to the high TDS of the feed [17], and its designed water flux was 13.26 L/m^2 h [18]. SWRO can produce a higher amount of permeate if the feed salinity is reduced [2]. A pressure exchanger (PX) called the PX-Q300, manufactured by Energy Recovery Inc., was utilized as an energy recovery device (ERD).

The RO system is a partial two-pass system in which a partial stream of SWRO permeate is sent to the product tank, and the remainder is treated by second-pass RO [10]. Second-pass RO is typically referred to as BWRO, but MCDI is also installed to reduce the TDS of the SWRO permeate [15,19]. The ratios of the SWRO permeate utilized for the BWRO feed, MCDI feed, and bypass were designed to be 23.5 %, 6 %, and 70.5 %, respectively. The pilot study investigated the feasibility of MCDI over BWRO under brackish feed conditions (e.g., SWRO permeate) with 85 % recovery. The BWRO system employed three PVs, each equipped with three BWRO membranes from LG Chem, specifically the BW 440 ES model. The BWRO configuration was a two-stage BWRO with a 2:1 array, with a capacity of 193 m^3/d (design capacity:200 m^3/d) and 88 % recovery (Fig. 3f). Similarly, the capacity of MCDI was 48 m^3/d (design capacity:50 m^3/d), with 83 % recovery (Fig. 3g). MCDI operates in a dual mode to continually produce water, with one module adsorbing salts and the other desorbing salts. While a single MCDI cell in the lab-scale is operated under 1.23 V [20,21], the applied voltage for a pilot-scale MCDI system, which is composed of multiple MCDI cells, was 120–250 V overall depending on targeting salt rejection. The product was further processed by remineralization and sent to a storage tank.

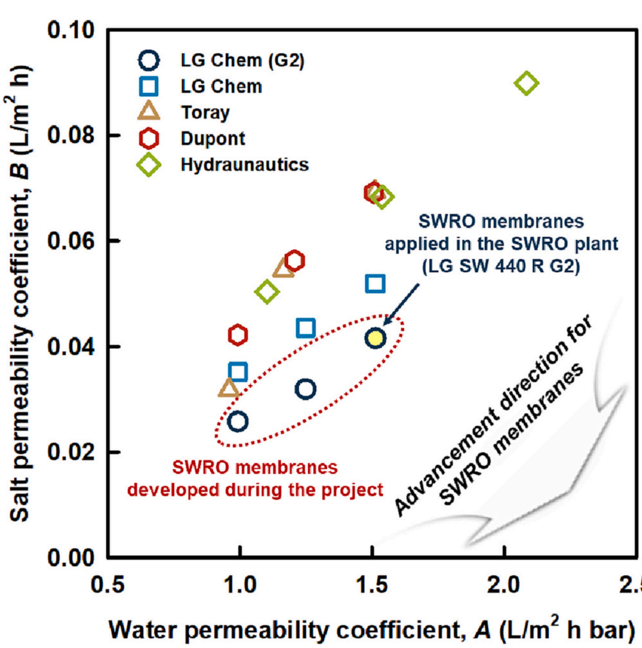

Fig. 4. Comparison of water permeability coefficient *A* and salt permeability coefficient *B* of commercial 8-inch SWRO membranes (Table A1) obtained by the methods in [10,18].

2.4. Project goal

The purpose of the pilot plant was to ensure optimal performance of the developed low-energy unit processes. The absolute SEC value of the pilot plant was not a criterion for the evaluation (Table 2a). This is because the pilot plant is expected to exhibit a relatively high SEC owing to extreme seawater conditions and the small capacity of the SWRO pump [2]. Instead, the consortium aims to achieve an SEC of 3.3 kWh/m^3 at the 100,000 m^3/d capacity design (Table 2b), assuming a feed condition of TDS of 42,000 mg/L and a temperature of 30 °C corresponding to an average seawater condition in the Arabian Gulf [8]. The target TDS of the final product was set at 200 mg/L to meet the final water quality requirements for commercial use. Therefore, a systematic methodology is required to convert pilot plant results into a determinant of project success.

2.5. Data acquisition

Real-time operational data, including turbidity, EC, temperature, flow rate, pressure, pH, electrical energy consumption, and other variables, were collected. For certain parameters that could not be measured in real time, laboratory tests were conducted by collecting multiple samples during the performance testing. Several spikes were observed in the real-time data due to hot weather conditions, which were eliminated by displaying the data range within the interquartile range of the box and whisker plot. The median was selected as the representative value of the data.

The TDS was calculated based on the correlation between the EC and TDS levels. In the temperature of 25 °C, the EC of seawater and brine is generally 45,000–60,000 μS/cm, and the factor of 0.7 is multiplied to convert EC to TDS [22]. Although the EC of seawater was higher than this range, the same factor of 0.7 was applied to convert the real-time EC to TDS values. Further, the factor of 0.55 was multiplied by EC to evaluate the TDS of freshwater, such as SWRO permeate, BWRO permeate, and MCDI effluent [22]. The TDS value after conversion was similar to the TDS value obtained in laboratory tests.

While the electrical energy consumption was monitored, the SEC was not obtained directly during the SWRO operation. To calculate the SEC, the electrical energy consumption per unit time was divided by the flow rate of the final product [10,23,24]. The final product is the summation of the SWRO permeate that does not pass the BWRO and the BWRO permeate [10]. The flow rate change due to MCDI operation was not considered for the SEC evaluation of the pilot plant because the MCDI was installed to compare the results with BWRO.

2.6. SEC conversion for full-scale SWRO plants

Using the operational data from the pilot plant, it was possible to project the performance of a full-scale SWRO desalination plant under specific feed conditions to achieve the target goal (Table 2b). However, the detailed design of an SWRO desalination plant may vary when the plant capacity is increased. This may involve the use of pumps with larger capacities and higher efficiencies. Furthermore, changes in feed salinity and temperature can significantly affect the operating pressure of SWRO. Therefore, it is necessary to consider calibration equations for both pump efficiency and operating pressure to ensure the performance of a full-scale SWRO desalination plant.

Employing larger-capacity pumps can improve pump efficiency. For full-scale SWRO desalination plants, using pumps with larger capacities and fewer pumps can decrease the SEC for each unit process. The efficiency of a pump η_{pump} can be determined by analyzing 226 commercial hydraulic pumps and assessing their capacity [25]. Eqs. (1) and (2) can be used to determine the pump efficiency depending on the pump capacities (i.e., feed flow rate of the pump $Q_{f,pump}$).

$$\eta_{pump} = 1.3196 \times \ln Q_{f,pump} + 73.05 \left(Q_{f,pump} > 13,300 \text{ m}^3/\text{d}\right) \quad (1)$$

Table 2
Evaluation criteria with different goals: (a) pilot-scale and (b) full-scale plants. The performances of full-scale plants are evaluated based on the conversion result utilizing the data from the pilot plant.

Type		(a) Pilot-scale plant (this study)	(b) Full-scale plant (imaginary)
Capacity [m^3/d]		1,000[a]	100,000
Feed conditions	TDS [mg/L]	47,600–53,500	42,000
	Temperature [°C]	29–36	30
Process		MTF, UF, SWRO, and BWRO/MCDI	Intake, MTF, UF, SWRO, BWRO/MCDI, and posttreatment
Criteria	SEC [kWh/m^3]	n/a	≤3.3
	TDS [mg/L]	≤500[b], ≤200[c]	≤200[c]

[a] Capacity of SWRO permeate. The capacity of the plant considering BWRO/MCDI operation was 965 m^3/d.
[b] SWRO permeate.
[c] Final product.

$$\eta_{pump} = 9.2234 \times \ln Q_{f,pump} – 1.999 \ \left(Q_{f,pump} \le 13,300 \ \mathrm{m^3/d}\right) \tag{2}$$

The SWRO operating pressure P_{SWRO} is affected by changes in feed salinity and temperature among operating parameters. By using the RO simulation software Q+ developed by LG Chem, operating pressures under a water flux of 13.24 L/m^2 h were obtained using the SWRO membranes applied in the pilot plant (LG SW 440 R G2). A fitting curve was obtained with R^2 = 0.9991 as a function of feed TDS TDS and temperature T in Eq. (3).

$$P_{SWRO} = 5.314 + \left(1.331 \times 10^{-3} \times TDS\right) + \left(-1.517 \times 10^{-1} \times T\right) \tag{3}$$

The electrical energy consumption of a unit process per unit time, $E_{w,unit}$ can be evaluated using Eq. (4). This calculation considers the number of pumps N_{pump}, pump pressure P_{pump}, and the feed flow rate of the pump $Q_{f,pump}$ used in the process. Pump efficiency η_{pump} is determined using Eqs. (1) and (2), whereas the motor efficiency η_{motor} is assumed to be 95 %. While $E_{w,unit}$ for the major processes involved in the SWRO process is calculated, the energy consumption of other equipment per unit time α including chemical injection pumps and pumps used for clean-in-place procedures is assumed 15 % of SWRO energy consumption [26]. The intake depth is assumed to be 20 m. The SEC for each process SEC_{unit} and the entire plant SEC_{plant} are evaluated using Eqs. (5) and (6), respectively: In both cases, the electrical energy consumption was divided by the flow rate of the plant's final product $Q_{p,plant}$.

$$E_{w,unit} = \frac{N_{pump} P_{pump} Q_{f,pump}}{\eta_{pump} \eta_{motor}} \tag{4}$$

$$SEC_{unit} = \frac{E_{w,unit}}{Q_{p,plant}} \tag{5}$$

$$SEC_{plant} = \frac{\sum E_{w,unit} + \alpha}{Q_{p,plant}} \tag{6}$$

However, MCDI is not a pressure-driven process, and its energy consumption cannot be calculated using Eq. (4). Thus, it was assumed that the energy consumption of MCDI was the same as that of BWRO. This assumption was made during the evaluation of the SEC of the plant.

3. Results and discussion

3.1. High-performance SWRO membranes

SWRO membranes play a crucial role in determining the desalination plant performance. When the feed seawater exhibits high salinity and temperature, it is imperative to use high-performance SWRO membranes. This is because moderate salt rejection by the membranes may lead to an increase in permeate salinity, particularly when operating under extreme feed conditions. In addition, a high-pressure operation is necessary to obtain a certain amount of permeate under high-salinity seawater conditions, which results in higher energy consumption. To address this issue, a study was conducted to evaluate the effectiveness of newly developed SWRO membranes when subjected to high-salinity and high-temperature feed conditions.

The SWRO membranes produced permeate with a lower TDS than the commercial SWRO membranes. Because of the extremely high salinity (i.e., 47,500–53,500 mg/L) and high temperature (i.e., 29–36 °C) of seawater, the TDS of SWRO permeate is expected to be high. Based on the simulation results, the permeate salinity range for existing SWRO membranes (e.g., LG SW 440 R, TM820V-440, and SW30XLE-440i) with a permeate flow rate of 9900 GPD at the basic conditions is 409–536 mg/L. In contrast, the newly applied SWRO membranes (LG SW 440 R G2) produced permeate of 348–420 mg/L during the first test (July 26–28, 2022), in which the temperature was 33–35 °C (Fig. 5a). Although the temperature increased during mid-August, the salinity did not deteriorate; instead, it remained at approximately 450 mg/L. The permeate salinity decreased from approximately 450 to 300 mg/L owing to the cooling temperature until early November. Although the TDS of the permeate fluctuated in November owing to the batch-mode operation for SWRO, the overall TDS of the permeate was distinctly lower (250–455 mg/L) than that of other commercial SWRO membranes. Owing to the high-quality (i.e., low-TDS) permeate, the amount of SWRO permeate treated by BWRO or MCDI process can be lowered, which significantly contributes to reducing capital expenditure (CAPEX) and operating expenditure (OPEX) for two-pass SWRO configurations. Moreover, the flow rate of the final product can increase as less BWRO concentrate is generated. Because of the smaller BWRO or MCDI systems and higher RO system recovery, the SEC of the RO system can be reduced.

The operating pressure of the SWRO system was maintained at approximately 70 bar to treat high-salinity seawater. High-rejection membranes are often operated at high pressures to compensate for low flow rates, owing to the tradeoff between salt rejection and water flow rate in membrane performance [18]. The developed SWRO membranes exhibited high salt rejection but were operated at approximately 70 bar to achieve 40 % recovery (Fig. 5b). The SWRO membranes used in the pilot plant demonstrated operating pressures comparable to those of other commercial SWRO membranes [17]. By contrast, a relatively high SEC was recorded because of the low efficiency (63 %) of small high-pressure pumps (HPP) for SWRO. The SEC of the SWRO system with ERD was maintained at approximately 4.0 kWh/m^3 for the 100-day operation, and the SEC data in November fluctuated owing to the issues of several meters.

Although the developed SWRO membranes could produce high-purity permeate, they did not directly reduce the SEC of the SWRO system. However, this contributes to the reduction of CAPEX and OPEX in the BWRO system, which is necessary for treating high-salinity feed to meet the final product criteria. Furthermore, the SEC of the plant can be lowered because of the higher recovery operation of the BWRO owing to the SWRO feed with reduced salinity.

3.2. Low-energy MTF as a pretreatment for turbidity control

DAF is a pretreatment process that reduces turbidity and algal content before the use of DMF or UF. SWRO desalination plants located in

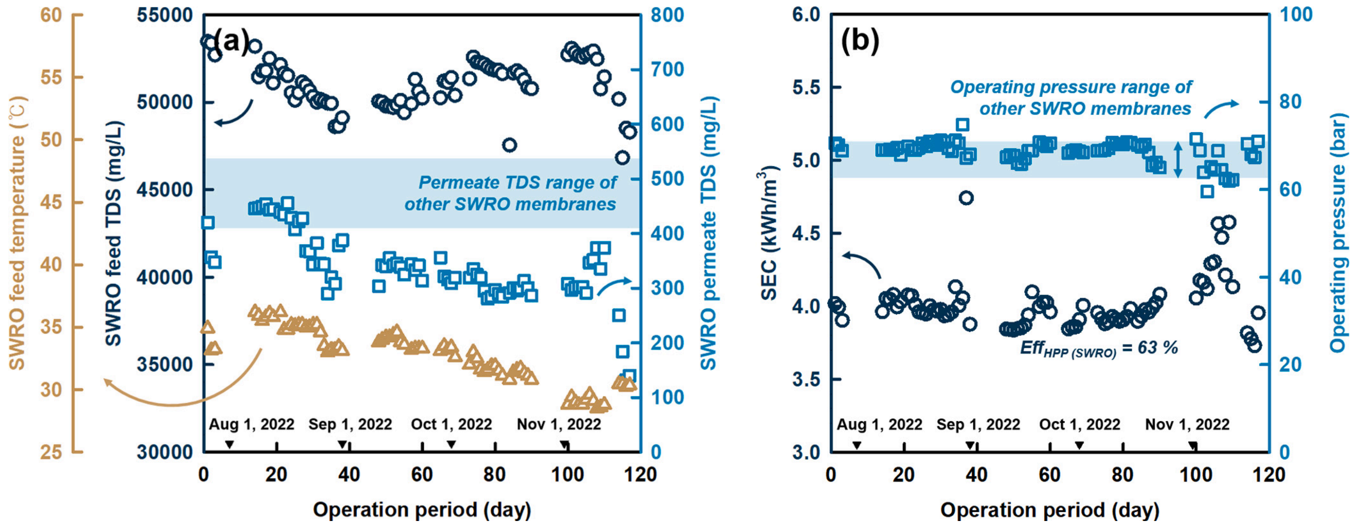

Fig. 5. Operation results of SWRO system: (a) TDS of permeate and (b) operating pressure and SEC. Because the efficiency of HPP for SWRO is 63 % owing to the small size of HPP on a pilot scale, a relatively high SEC was observed compared to other full-scale SWRO plants. Performances of other types of SWRO membranes were obtained from LG Q+ Projection Software V3.2.0.4, where the feed TDS and temperature are 47,500–53,500 mg/L and 33 °C, respectively.

the Arabian Gulf have been equipped with DAF since 2008–2009 in response to harmful algal blooms [11]. Algal blooms can cause severe biofouling of SWRO membranes and plant shutdowns. However, the SEC of DAF in SWRO desalination plants is 0.3–0.4 kWh/m^3 [26], which increases approximately 10 % of the plant's energy use. An MTF was developed and installed to alter the use of the DAF, and both the MTF and DAF were tested.

Turbidity was more effectively reduced by MTF than by DAF. The MTF was equipped with meshed tubes in the cage, and turbidity was reduced during filtration. When the turbidity of feed was 0.44–1.65 NTU (Fig. 6a), MTF can reduce to turbidity as 0.32–0.92 NTU (i.e., 43 % reduction; Fig. 6b). On the other hand, DAF can reduce turbidity to 0.69–1.32 NTU (i.e., 16 % reduction), which exhibited poor performance compared to MTF (Fig. 6b). However, the plant operation results would be limited to demonstrate the advantages of MTF as turbidity-control (i.e., algae-response) pretreatment owing to the low turbidity of the feed and no occurrence of algal bloom; TOC and turbidity was 2.18–2.70 mg/L and 0.44–1.65 NTU, respectively, during the operation. It has also been reported that DAF systems often do not exhibit proper performance under normal feed conditions in which the turbidity is <5 NTU [26]. The results demonstrated the possibility of using MTF instead of DAF for turbidity control.

The reduction in energy consumption for the MTF process was significant compared with that for DAF. MTF uses aeration pumps to circulate feed from the middle of the system, and less energy is consumed [13]. The operation results showed that MTF exhibited SEC of 0.04–0.08 kWh/m^3, and it does not exceed 0.1 kWh/m^3 (Fig. 6c). By contrast, DAF consumes a large amount of energy owing to the use of recirculation pumps and other equipment for air saturation and diffusion [26]. SEC of DAF was 0.23–0.35 kWh/m^3, which is similar to the reported SEC of DAF in SWRO desalination plants as 0.3–0.4 kWh/m^3 [26]. Compared with DAF, MTF consumed 77 % less energy. Given that the process was applied at a pilot scale, the energy efficiency of the MTF process can be further improved.

Overall, the MTF exhibited turbidity reduction with energy efficiency over DAF in SWRO desalination. Although the performances of MTF and DAF were not evaluated under high-turbidity conditions with algal blooms, the MTF process exhibits the potential to be used as a pretreatment process for turbidity control with low energy consumption. For further commercialization, the durability of the meshed tube should be improved to maintain its performance during occasional operations.

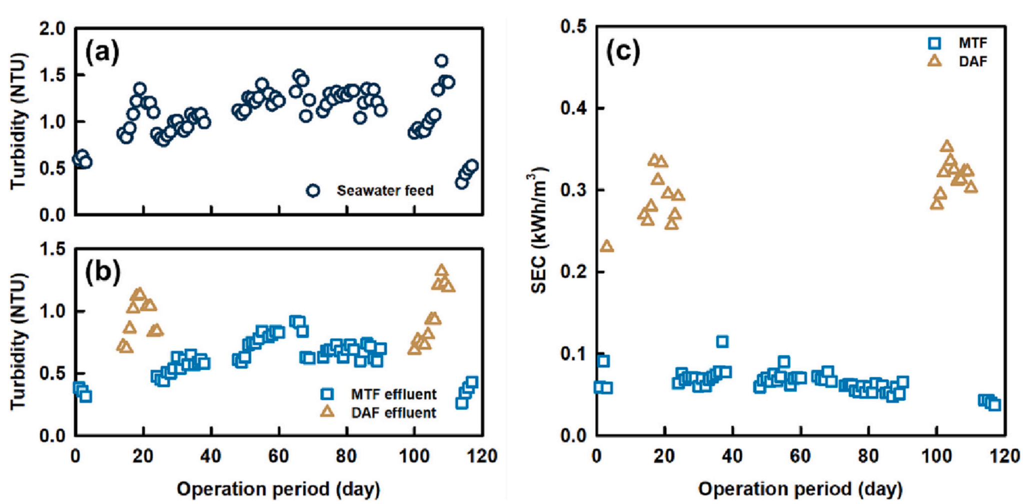

Fig. 6. Operation results of DAF and MTF: (a) turbidity of seawater, (b) turbidity of DAF and MTF effluents, and (c) SEC of DAF and MTF. SEC of the unit process is calculated considering the flow rate of the final product of the plant.

3.3. Possible application of MCDI alternating second-pass RO

BWRO systems are widely used in SWRO desalination plants to treat SWRO permeate at low TDS levels [27]. If the feed salinity is high, BWRO is necessary to improve the quality of the SWRO permeate. Numerous studies have evaluated the potential of MCDI as a replacement for BWRO. Although some controversy exists [28,29], multiple studies have established that MCDI exhibits a higher energy efficiency than BWRO when addressing the TDS of SWRO permeate [15,30–32]. Nevertheless, a direct comparison of these two technologies in an actual SWRO desalination process has yet to be conducted. Therefore, the performances of BWRO and MCDI were compared in a pilot-scale study after SWRO.

MCDI was able to reduce the TDS of the SWRO permeate to a moderate level. When the TDS of the SWRO permeate was between 250 and 455 mg/L, BWRO produced permeate of 5–10 mg/L (Fig. 7a). Because the BWRO system was operated in the cross-flow mode, the BWRO permeate quality and quantity remained constant without significant fluctuations. High-purity BWRO permeate is often mixed with SWRO permeate to control the TDS of the final product, and the RO configurations used in the Arabian Gulf are partial two-pass or split partial two-pass RO. In contrast, MCDI produced an effluent concentration of 6–77 mg/L, which corresponded to 87 % rejection (Fig. 7a). Fluctuations in the TDS of the MCDI effluent were observed owing to the dual-mode operation. When the MCDI module began to absorb salts, the valve was opened to transport the effluent from the MCDI module to the product pipeline. However, after desorption, the remaining salts moved to the production pipeline when the valve was opened. If a mixing tank is installed after the MCDI process, moderate-quality water with less fluctuation will be produced. In addition, the MCDI product could be utilized without mixing it with the SWRO permeate to increase the TDS to a desirable level.

MCDI exhibits the potential to achieve a lower SEC than BWRO through process improvements. Because the capacities of BWRO and MCDI were 200 m^3/d and 50 m^3/d, respectively, the SEC of the MCDI system excluding the pump was multiplied by four times and compared with that of BWRO. While the MCDI system exhibited 0.01–0.03 kWh/m^3 excluding a pump, the BWRO system consumed 0.10–0.12 kWh/m^3 to operate the system with a hydraulic pressure of 8 bar. However, because the MCDI system requires a pump to transport the feed to the system at 1–2 bar, the SEC for MCDI with a pump was measured to be 4–5 times higher than that without a pump. Therefore, the current MCDI system exhibited the SEC of 0.09–0.11 kWh/m^3 owing to the use of the pump (Fig. 7b). On the other hand, the SEC of BWRO can be corrected from 0.11 to 0.10 kWh/m^3, considering that BWRO system can exhibit the same salt rejection using 90 % of the feed flow rate compared to MCDI. Overall, the SEC of BWRO and MCDI was similar, considering the current constraints of the technologies, which are often neglected in academic research.

By comparing the BWRO and MCDI technologies, it was found that BWRO exhibited excellent and stable salt rejection compared to MCDI with a similar SEC. However, MCDI can replace BWRO in two-pass SWRO desalination plants by modifying the process designs. The effluent from the MCDI should be collected with a moderate detention time to avoid mixing high-purity water with discharged water. In addition, the MCDI system can reduce the energy consumption required for pumping operations by placing the system at a lower level to enable feed intake through natural flow. These advances could potentially allow the use of MCDI in SWRO desalination plants.

3.4. Conversion of SEC in full-scale plants

The purpose of constructing and operating a pilot plant was to verify whether the operational parameters of the unit processes satisfied the predicted levels. Owing to the differences in plant design and equipment, the performance of a pilot-scale SWRO plant may differ from that of a full-scale SWRO plant. Furthermore, if the feed conditions at the pilot and full-scale plants differ, corrections are required to accurately predict performance. The target SEC of the research project is 3.3 kWh/m^3 at a capacity of 100,000 m^3/d, with feed TDS and temperature of 42,000 mg/L and 30 °C, respectively. The performance of full-scale SWRO plants was evaluated based on the operational results of the pilot plant.

In full-scale SWRO desalination plants, the SEC of the SWRO system is reduced to 2.34 kWh/m^3. The feed conditions of the pilot plant, with a median TDS of 51,200 mg/L and a median temperature of 33 °C, represent extreme conditions for SWRO operation. These conditions result in a higher operating pressure and higher salt passage to the SWRO permeate compared to other desalination plants. However, changing the feed TDS and temperature to 42,000 mg/L and 30 °C, respectively, reduced the operating pressure from 68.46 bar to 56.67 bar. Increasing the pump capacity also improved the efficiency of the

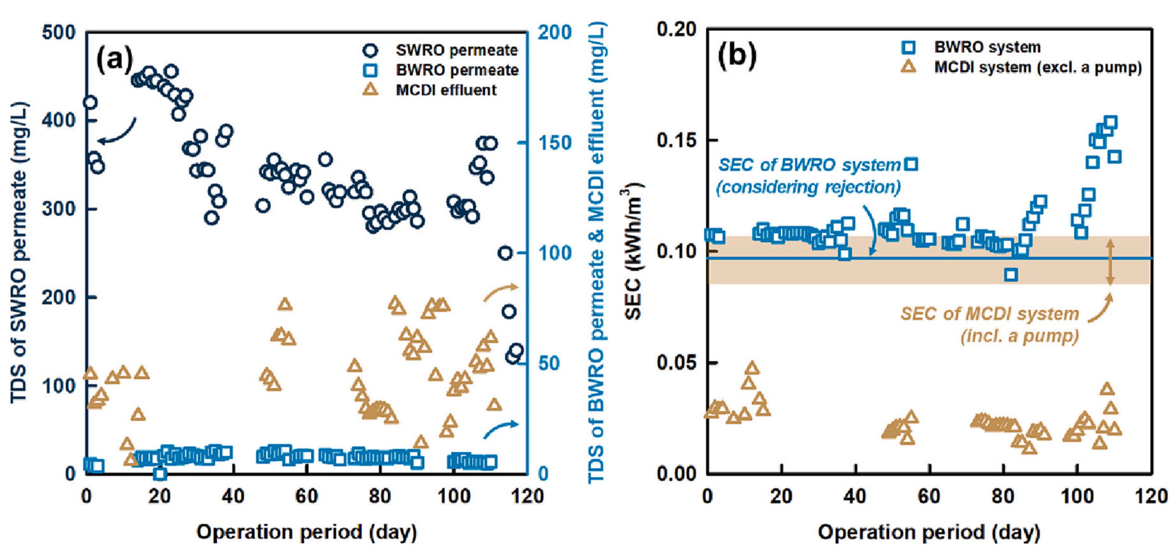

Fig. 7. Operational results of BWRO and MCDI: (a) TDS of BWRO permeate and MCDI effluent, and (b) SEC of BWRO and MCDI (excluding a pump). The SEC of the MCDI system (excluding a pump) was calculated by multiplying its energy consumption by four to produce the same amount of permeate or effluent as BWRO. Notably, the SEC of the MCDI system, including a pump, was four to five times greater than that of the system without a pump. Furthermore, BWRO can reduce the feed flow rate by 10 % compared to MCDI, considering its superior rejection.

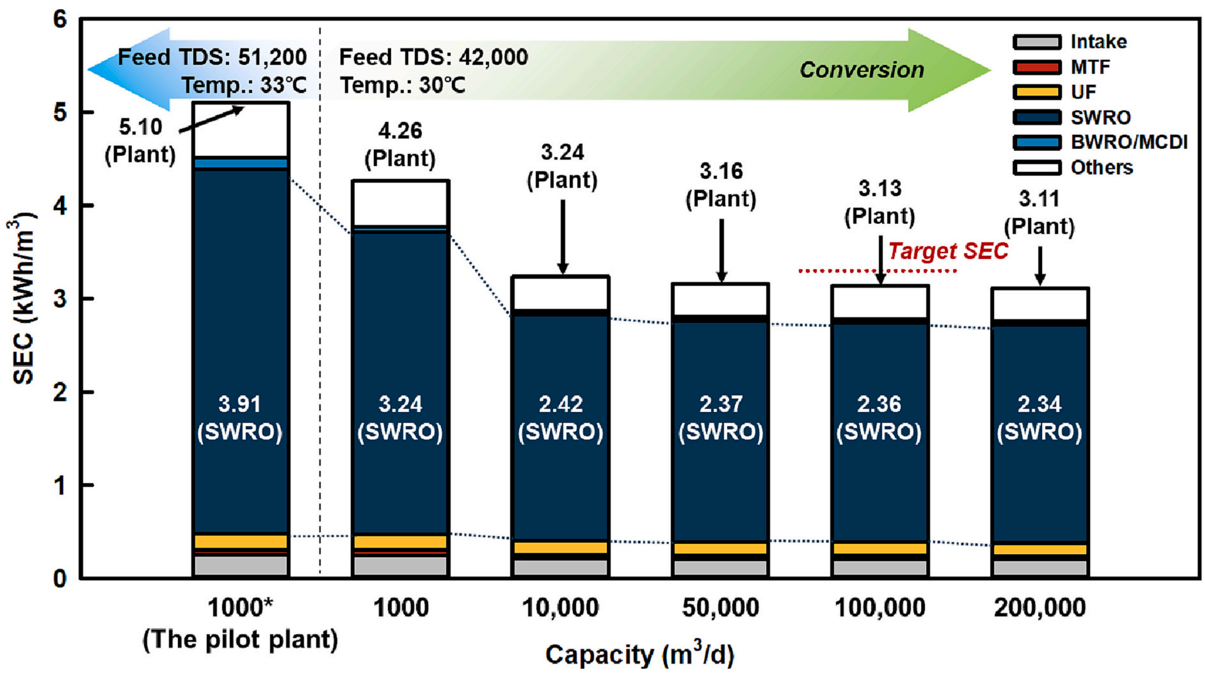

Fig. 8. SEC of SWRO desalination plants based on capacity. The capacity of the pilot plant is designed to be 1000 m^3/d, but it can be reduced to 965 m^3/d after considering BWRO/MCDI operation. It is assumed the intake depth is 20 m, and SEC of MCDI and BWRO are the same in current technical status.

high-pressure pump from 63 % to 83–87 %. Overall, the SEC of the SWRO system (including ERD) that initially exhibited 3.91 kWh/m^3 could be reduced to 2.36 and 2.34 kWh/m^3 for a plant capacity of 100,000 and 200,000 m^3/d, respectively (Fig. 8).

The implementation of a high-performance SWRO system is crucial for reducing the SEC of a plant in the presence of a two-pass RO configuration. The SEC was calculated by dividing the total energy consumption per unit time by the final product flow rate. To decrease SEC, the final product flow rate should be increased while minimizing the total energy consumption. The applied SWRO membranes produced SWRO permeate with low TDS, enabling the BWRO system to handle a smaller portion of the SWRO permeate and treat it at a higher recovery rate. For the conversion feed condition, the split ratio for the SWRO permeate (i.e., the feed flow rate for BWRO/MCDI) was reduced to 16 %, and the BWRO/MCDI recovery was increased to 90 % to achieve a final TDS of <200 mg/L. Therefore, the application of advanced SWRO would reduce the energy consumption of BWRO and increase the amount of the final product [10]. The overall plant SEC is reduced from 5.10 to 4.26 kWh/m^3 with the change of feed conditions and further reduced to 3.11 kWh/m^3 at a capacity of 200,000 m^3/d (Fig. 8). It was predicted that an SWRO plant with a capacity of 100,000 m^3/d could exhibit 3.13 kWh/m^3 and meet the target SEC of 3.3 kWh/m^3 under the given conditions.

Overall, the technologies developed for SWRO desalination could effectively reduce the plant SEC. Although energy-efficient pretreatment (i.e., MTF) and MCDI can reduce plant SEC, high-performance SWRO membranes are the most effective equipment for lowering plant SEC. If the water permeability and salt selectivity of SWRO membranes can be improved, an improved energy efficiency of SWRO plants can be obtained [33].

4. Conclusions

An SWRO desalination pilot plant was constructed in the Arabian Gulf (i.e., high-salinity, high-temperature, and high-turbidity seawater) to evaluate new low-energy SWRO-related technologies. High-performance SWRO membranes, MTF as low-energy pretreatment, and MCDI as a low-energy electrochemical process were investigated for four months under high salinity (i.e., 47,600–53,500 mg/L) and high temperature (i.e., 29–36 °C) feed conditions. Based on the operative results, the primary findings can be summarized as follows.

- The developed SWRO membranes exhibited excellent salt rejection and produced high-quality permeate (250–455 mg/L) under extreme feed conditions. Despite the tradeoff between salt rejection and water permeability, the operating pressure was maintained at nearly 70 bar, similar to the operating pressure of other SWRO membranes. Subsequent processes after SWRO, such as BWRO or MCDI, are expected to benefit from receiving high-purity SWRO permeate.
- The performances of the DAF and MTF were compared in response to high turbidity caused by algal blooms. MTF reduced the turbidity of the feed by 43 %, with an SEC of <0.1 kWh/m^3. Although MTF exhibited higher performance than DAF, the effectiveness of MTF should be studied further in the event of high turbidity caused by algal blooms in the Arabian Gulf.
- An MCDI system was investigated in the field to replace BWRO in SWRO desalination plants. The MCDI reduced the TDS of the SWRO permeate to a moderate water level, with 87 % rejection. The SEC of MCDI was comparable to that of BWRO, and the energy efficiency of MCDI could be improved by modifying the system configuration.
- The SEC of the full-scale SWRO desalination plant was calculated based on the results of the pilot-scale SWRO desalination plant. Although the pilot plant exhibited a relatively high SEC owing to the extreme feed conditions and small capacity, full-scale SWRO desalination plants could exhibit 3.11 kWh/m^3 by applying the developed technologies in the Arabian Gulf.

Because SWRO systems consume the highest portion of energy in SWRO desalination plants, the advancement of SWRO membranes is the key to achieving low-energy seawater desalination. Improvement in energy efficiency during pretreatment and SWRO permeate polishing will further contribute to the SEC reduction in SWRO desalination plants.

CRediT authorship contribution statement

Jungbin Kim: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Seungkwan Hong:** Conceptualization, Validation, Investigation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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.

Data availability

The authors do not have permission to share data.

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Appendix A. 8-inch SWRO membranes

Table A1
Comparison of commercial 8-inch SWRO membranes with a membrane area of 440 ft^2. The results are obtained at the standard test conditions (i.e., 32,000 mg/L NaCl, 5 mg/L boron, 25 °C, 800 psi, pH 8, and 8 % recovery). *A*: water permeability coefficient, *B*: salt permeability coefficient.

Manufacturer	Type	Permeate flow rate (GPD)	Salt rejection (%)	*A* (L/m^2 h bar)	*B* (L/m^2 h)	Remarks
LG Chem	LG SW 440 SR G2[a]	6600	99.89	0.99	2.58×10^{-2}	
	LG SW 440 GR G2[a]	8250	99.89	1.25	3.19×10^{-2}	
	LG SW 440 R G2[a]	9900	99.88	1.51	4.16×10^{-2}	Current study
	LG SW 440 SR	6600	99.85	0.99	3.52×10^{-2}	
	LG SW 440 GR	8250	99.85	1.25	4.35×10^{-2}	
	LG SW 440 R	9900	99.85	1.51	5.20×10^{-2}	
Toray	TM820K-440	6400	99.86	0.96	3.18×10^{-2}	
	TM820M-440	7700	99.8	1.16	5.45×10^{-2}	
	TM820V-440	9900	99.8	1.51	6.93×10^{-2}	
DuPont	SW30XHR-440i	6600	99.82	0.99	4.22×10^{-2}	
	SW30HRLE-440i	8200	99.8	1.21	5.63×10^{-2}	
	SW30XLE-440i	9900	99.8	1.51	6.91×10^{-2}	
Hydranautics	SWC4 MAX	7200[b]	99.8	1.10	5.04×10^{-2}	
	SWC5 MAX	9900[b]	99.8	1.54	6.83×10^{-2}	
	SWC6 MAX	13,200[b]	99.8	2.09	8.99×10^{-2}	

[a] SWRO membranes were developed during the project.
[b] 10 % recovery.

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