Front. Environ. Sci. Eng. 2023, 17(2): 16
https://doi.org/10.1007/s11783-023-1616-1

RESEARCH ARTICLE

Salinity exchange between seawater/brackish water and domestic wastewater through electrodialysis for potable water

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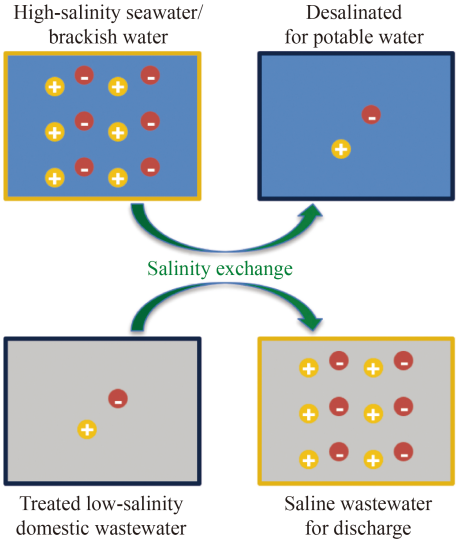
HIGHLIGHTS

- Present a general concept called "salinity exchange".
- Salts transferred from seawater to treated wastewater until completely switch.
- Process demonstrated using a laboratory-scale electrodialysis system.
- High-quality desalinated water obtained at ~1 mL/min consuming < 1 kWh/m^3 energy.

GRAPHIC ABSTRACT



ARTICLE INFO

Article history:
Received 28 May 2022
Revised 3 July 2022
Accepted 15 July 2022
Available online 31 August 2022

Keywords:
Desalination
Potable water reuse
Ion-exchange membrane
Salinity gradient energy
Wastewater discharge

ABSTRACT

Two-thirds of the world's population has limited access to potable water. As we continue to use up our freshwater resources, new and improved techniques for potable water production are warranted. Here, we present a general concept called "salinity exchange" that transfers salts from seawater or brackish water to treated wastewater until their salinity values approximately switch, thus producing wastewater with an increased salinity for discharge and desalinated seawater as the potable water source. We have demonstrated this process using electrodialysis. Salinity exchange has been successfully achieved between influents of different salinities under various operating conditions. Laboratory-scale salinity exchange electrodialysis (SEE) systems can produce high-quality desalinated water at ~1 mL/min with an energy consumption less than 1 kWh/m^3. SEE has also been operated using real water, and the challenges of its implementation at a larger scale are evaluated.

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Special Issue—Frontier Progresses from Chinese-American Professors of Environmental Engineering and Science (Responsible Editors: Xing Xie, Jinkai Xue & Hongliang Zhang)

1 Introduction

Providing safe, reliable, and affordable water to the ever-growing population remains one of the greatest challenges of our time (Mekonnen and Hoekstra, 2016). However, to harness the majority of Earth's water, i.e., seawater, which makes up 98 % of the total water supply,

the salt must be removed through desalination processes (Liu et al., 2015; Subramani and Jacangelo, 2015). In the desalination market, thermal desalination technologies account for about 30 % of the world's desalination plants in operation, but the majority of desalination plants (about 64 %) are based on reverse osmosis (RO) (Volfkovich, 2020). Over the past two decades, RO has significantly improved with the development of higher permeability membranes, nanocomposite membranes, the installation of energy recovery systems, and the use of more efficient pumps (Elimelech and Phillip, 2011). These improvements have led RO to dominate the global desalination market over competing technologies as it operates with less energy consumption (Fritzmann et al., 2007; Semiat, 2008; Qasim et al., 2019; Kurihara, 2021). Nevertheless, despite all the progress made on standard desalination techniques, energy consumption still remains the major obstacle preventing the implementation of more desalination plants worldwide.

Aside from commercialized membrane-based techniques, recent investigations on electrochemical processes have shown another promising technology that can lower the energy consumption and cost of desalinating seawater (Kalogirou, 2005; Al-Karaghouli et al., 2010; Galama et al., 2014). Specifically, electrodialysis (ED) transfers salt ions from a dilute solution to a concentrated solution through alternating anion/cation exchange membranes. This is powered by an electrical field exerted by an external voltage applied on two end electrodes (Sadrzadeh and Mohammadi, 2009; Galama et al., 2014; Bitaw et al., 2016; Luo et al., 2017). Generally, it is accepted that ED is primarily suitable for desalinating brackish water, while RO is favored more for seawater desalination (Pilat, 2001; Spiegler and El-Sayed, 2001; Youssef et al., 2014; Eke et al., 2020; Elsaid et al., 2020). ED is considered to be the most cost-effective for desalination using feed streams containing 5,000–10,000 mg/L total dissolved solids (TDS), but has not been shown to be suited for desalinating seawater (Vanoppen et al., 2016). Because of this, electrodialysis research has been mainly directed toward hybrid desalination processes aiming to improve energy consumption. Pellegrino et al. studied an intimate proximity combination RO-ED system utilizing internal recycling between the alternating ED flow channels and identified up to 20 % energy savings in some conditions (Pellegrino et al., 2007). Galama et al. looked at desalinating seawater using a combination of electrodialysis (as a pre-desalination technique) and brackish water reverse osmosis (BWRO) instead of the standard, one-step seawater reverse osmosis (SWRO) (Galama et al., 2014). When using the same feed solution, this combination approach of electrodialysis and BWRO was found to potentially lower the energy cost significantly when compared to just SWRO. Despite these potential improvements with hybrid approaches, RO is still the fastest growing method for desalinating seawater, and continues to outperform ED due to the high cost of ED's ion-exchange membranes and RO's total lower water production costs. (Semiat and Hasson, 2012; Patel et al., 2021; Patel et al., 2022). However, unlike RO, which focuses on moving water with high mechanical energy consumption and alternating current systems, electrodialysis relies mainly on moving ions utilizing electrical energy and direct current, making it not only possible to adjust the salt concentration of the produced water, but also potentially more sustainable and suitable for combination with renewable energy sources (Kalogirou, 2005; Al-Karaghouli et al., 2010; Fernandez-Gonzalez et al., 2019).

Besides desalination, direct potable reuse (DPR) is increasingly being considered as a largely "untapped" process, where we could use already present water resources to help mitigate the exponentially growing demands (Leverenz et al., 2011; Grant et al., 2012). DPR refers to the introduction of purified water, reclaimed from municipal wastewater after advanced treatment, directly back into a municipal water supply, without flowing through an environmental buffer such as a reservoir or aquifer first (Leverenz et al., 2011; du Pisani and Menge, 2013; Guo and Englehardt, 2015; Englehardt et al., 2016). DPR offers the potential to significantly reduce the cost and energy consumption of current water supply systems if implemented widely (Leverenz et al., 2011; Englehardt et al., 2016). Despite a few DPR plants showing success and feasibility, development and implementation still face several challenges, including the lack of general principles and guidelines for process design, limited economic and performance data, lack of regulatory structure, and most importantly, a lack of public acceptance (Pecson et al., 2017; Lefebvre, 2018; Ghernaout et al., 2019). Many studies highlight the current negative public perceptions associated with water reuse and especially the public resistance to adoption of potable reuse projects (Dolnicar et al., 2011; Diego, 2013). Reasons for the public's hesitation to water reuse can stem from a lack of knowledge, a lack of transparency and education, as well as limited community outreach programs, or sometimes traditions and religious beliefs (Baggett et al., 2006; Marks, 2006). Further studies concluded that the public discriminates between desalinated and recycled water, finding desalinated water preferred (49 % acceptance) over recycled (only 20 % acceptance) when used for drinking (Dolnicar and Schäfer, 2006; 2009).

Because of the above-mentioned challenges associated with conventional desalination technologies and DPR, the development of more cost-effective, energy-efficient, and publicly accepted processes to produce potable water is warranted. This has begun to be tackled by several authors who investigated different approaches to using both impaired water and seawater for desalination processes. Many studies discuss the potential for forward osmosis (FO)-RO hybrid processes that can obtain lower energy consumption with integrated water reuse when

compared with standard approaches (Yangali-Quintanilla et al., 2011; Valladares Linares et al., 2014; Blandin et al., 2016). Others have looked at electrochemical approaches combined with RO using impaired water/secondary treated effluents as the low-salinity feed and seawater as the high-salinity feed. For example, Li et al. investigated different combinations of reverse electrodialysis (RED)-RO approaches using high concentration seawater/brine and low concentration treated secondary effluent/impaired water, finding the potential to substantially reduce the specific energy consumption and provide better control for the discharging of brine in comparison to conventional SWRO (Li et al., 2013). Vanoppen et al. studied the pre-treatment techniques optimal for feeding secondary treated wastewater to a combined RED-RO desalination process (Vanoppen et al., 2019). Roman et al. investigated the organic micropollutant adsorption and transport in the RED system desalinating seawater using treated wastewater as the low-salinity stream (Roman et al., 2019; 2020). In this study, we present a general concept we refer to as "salinity exchange", where salts in high-salinity seawater or brackish water are transferred to low-salinity treated wastewater until their salinity values approximately switch. Due to the natural salinity gradient energy harvested during a salinity exchange process, lower total energy consumption can be achieved (Skilhagen et al., 2008; Achilli et al., 2009). The end products are wastewater with increased salinity, which can be discharged to the ocean, and desalinated seawater, which can be further treated to produce potable water. Because of the high-salinity treated wastewater produced, salinity exchange will be most applicable in coastal regions where seawater is regularly available and treated wastewater is commonly discharged into the ocean. The main advantages of this new process include 1) lower energy consumption than conventional desalination technologies due to the salinity gradient energy harvested *in situ*, 2) no brine generation since the end products are only desalinated seawater and high-salinity treated wastewater, and 3) drinking desalinated seawater is much more cognitively appealing than the DPR of treated wastewater. The authors have successfully demonstrated this concept through salinity exchange electrodialysis (Fig. 1). Laboratory-scale SEE systems have been operated under various conditions to 1) verify the advantages of the salinity exchange process, 2) compare its feasibility against state-of-the-art RO, and 3) identify the challenges for the application of salinity exchange in practical drinking water production.

2 Experimental section

2.1 Configuration of the SEE

The electrodialysis cell was purchased from Fumatech (Fig. S1). It consists of 10 pairs of ion exchange membranes (IEMs, i.e., 10 anion exchange membranes and 10 cation exchange membranes), each with an effective area of 36 cm^2. The IEMs are separated by 0.027-cm thick spacers to form 20 chambers. The chambers were alternately filled with high-salinity (Stream I) and low-salinity (Stream II) feeds, making the total effective volume for salinity exchange ~20 mL. The two side chambers are both equipped with a Ti mesh electrode and filled with electrode rinse solution (0.05 mol/L $K_3Fe(CN)_6$, 0.05 mol/L $K_4Fe(CN)_6 \cdot 3H_2O$, and 0.25 mol/L NaCl) that circulates through the two electrode chambers.

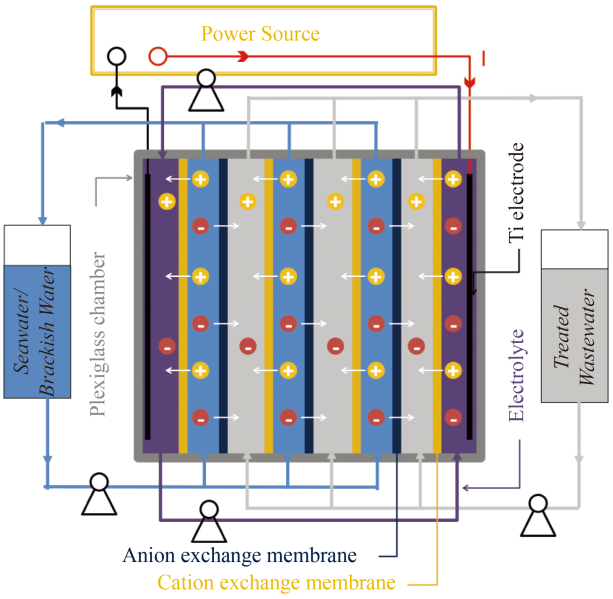

Fig. 1 Operation of a salinity exchange electrodialysis (SEE) system.

2.2 Feed water streams

In most experiments, the system used synthetic NaCl solutions to model both the salinities of seawater and treated wastewater. High concentration (0.1–0.6 mol/L) NaCl solutions were prepared to represent seawater and brackish water (Stream I), and low concentration (0.01–0.03 mol/L) NaCl solutions for treated wastewater (Stream II), according to typical values of salinity in these waters (Yip and Elimelech, 2012). The natural seawater was collected from the coast of Tybee Island beach in Savannah, Georgia. The treated domestic wastewater was collected from the secondary clarifier at a domestic wastewater treatment plant near Atlanta, Georgia. Both samples were vacuum filtered using filter paper (with pores larger than 5 μm) to eliminate any large particulate matter. Microfiltration of the real seawater was also performed (with 0.2-μm pore filter paper) as a pre-treatment to reduce the total bacterial content.

2.3 Operation of the salinity exchange electrodialysis cell

During SEE operation, the default conditions included a feed solution flow rate of 200 mL/min, Stream I NaCl

concentration of 0.6 mol/L, Stream II NaCl concentration of 0.01 mol/L, applied current density of 1 mA/cm^2, and an operating time of 9 h. The flow rate for the electrode rinse solution was fixed at 100 mL/min. The system was also tested for a range of flow rates, current densities, feed concentrations, and complex water matrices. Constant current was applied using an electrochemical workstation (VMP3 multi-channel potentiostat) to control the rate of ion transfer. The device was operated under room temperature (~25 °C) and the voltage across the 10 membrane pairs was monitored. Salinity exchange was conducted between 200 mL of feed solutions (ranging from 0.6 to 0.01 mol/L) over seven different applied current densities (0.1, 0.2, 0.5, 1, 2, 5, 10 mA/cm^2). All varying feed concentrations were tested under default 1 mA/cm^2 applied current density.

2.4 Characterization

The SEE system was assessed according to the energy consumption and Coulombic efficiency with respect to a set target treating capacity and set quality of water to be produced. Conductivity was measured using an Orion Versa Star Pro conductivity probe (Thermo Scientific) for all feeds and final water produced. The salinities were converted from mS/cm to g/L using a standard curve (Fig. S2). The volumes for all feed and final streams were measured for water transfer and final conductivities were corrected accordingly. The voltage was set to record every 10 mV or 20 s by the potentiostat.

2.5 Data analysis

For our synthetic NaCl solutions under constant pressure and temperature, the theoretical energy generation for phase 1 and minimum energy consumption for phase 2 were calculated separately based on the free energy of mixing and separation. The real energy generation and consumption were calculated by integrating the measured operating power over time. Due to the overpotential and water transport observed for all experiments, details on how endpoints for phases 1 and 2 were determined are described in Supplementary material Text 1. The theoretical energy generation for phase 1 and minimum energy consumption for phase 2 were compared to the real energy generation and consumption to determine the energy generation/consumption efficiencies. The total energy consumption was calculated and normalized based on the total mols of ions transferred for each operating condition. After assessing the water leakage, the energy consumption was also normalized to the volume of desalinated water produced. Finally, the Coulombic efficiency was calculated for each tested condition to determine how efficiently the current was used to move ions (Supplementary material Text 1 for additional details).

3 Results and discussion

Salinity exchange between Stream I (200 mL NaCl solution, ~0.6 mol/L, representing seawater) and Stream II (200 mL NaCl solution, ~0.01 mol/L, representing treated domestic wastewater) was achieved using an electrodialysis cell. SEE was operated at a current density of 1 mA/cm^2 for 9 h. During this process, we were able to observe water transport across the ion-exchange membranes as osmosis and/or electro-osmosis, which was also reported in other electrodialysis processes (Supplementary material Text 3 for additional discussion) (Indusekhar and Krishnaswamy, 1985; Galama et al., 2014). As a result, the volume of Stream I first increased and then decreased, while Stream II first decreased and then increased. The final volumes of Streams I and II were measured at 176 and 226 mL, respectively. As shown in Fig. 2(a) using the dashed arrows and gold triangles, the salinity of Stream I decreased from 32 to 0.42 g/L, while the salinity of Stream II increased from 0.70 to 36 g/L, demonstrating an almost complete salinity exchange (salinity values are corrected according to the final volumes of the two streams. Supplementary material Text 2 for details).

Fig. 2(a) also shows the voltage profile of the SEE operation. Based on the theoretical entropy change linked to the salinity, the SEE process should generate energy in the first half phase (Phase 1 shaded portion on left) and consume energy in the second half phase (Phase 2 shaded portion on right) of operation (Brauns, 2010; Li et al., 2013; Cipollina et al., 2016; Luo et al., 2017). However, due to the system's ohmic resistance, the net energy generation was only observed in the first 3.5 h of the total 9h operation, as indicated by the negative voltage shown in Fig. 2(a) (Phase 1). The observed water transport also diluted Stream I in Phase 1, shortening the energy generation. The Coulombic efficiency, indicating how much current flow was used to move ions, was calculated as 95 %, which is within the high range (80 %–100 %) according to previous literature (Sadrzadeh and Mohammadi, 2009).

The energy generation/consumption of the two phases of SEE operation were first assessed separately. According to the salinity values of the streams before and after SEE, the theoretical energy generation in Phase 1 and consumption in Phase 2 were 369 and 380 J, respectively. Determined by the voltage profile in Fig. 2(a), the practical energy generation and consumption in these two phases were calculated as 178 J and 481 J, which resulted in energy efficiencies of 48 % and 79 %, respectively. For the whole SEE process, the overall energy consumption was 303 J, or 0.48 kWh/m^3 if normalized to the volume of water desalinated (176 mL). Such an energy consumption is about half of that for just

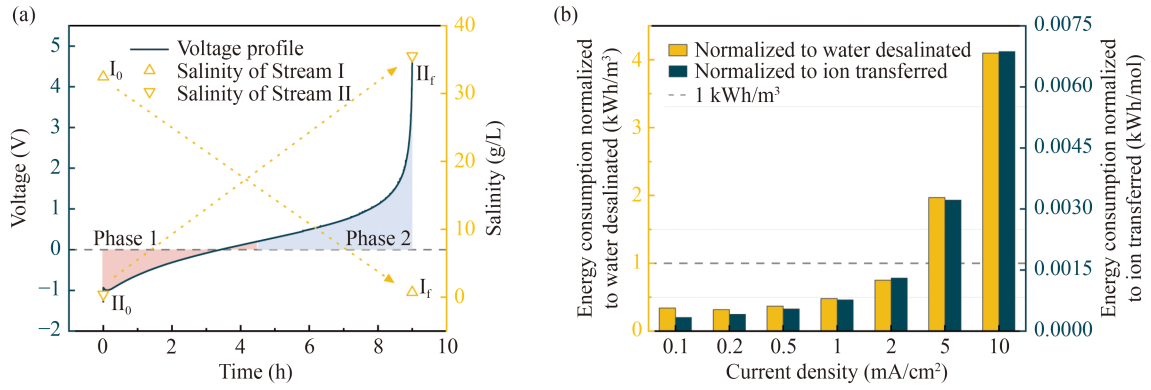

Fig. 2 Demonstration of the SEE process with simulated seawater (0.6 mol/L NaCl) and domestic wastewater (0.01 mol/L NaCl). (a) Voltage profile and salinity change of the two streams in a typical SEE operation and (b) energy consumption of the SEE process at different current densities. In (a) the blue curve represents the measured voltage over time with the shaded portions above and below representing the energy generation and consumption phases.

the state-of-the-art RO process (~1 kWh/m^3), an order of magnitude less than the total conventional SWRO process (3–5 kWh/m^3 including pre- and post-treatment), and lower than the thermodynamic limit of seawater desalination (0.78 kWh/m^3) (Rajindar, 2015; Singh and Hankins, 2016). If normalized to the moles of ions transferred during the SEE process, the specific energy consumption (SEC) is calculated as 0.00077 kWh/mol (2.7 kJ/mol), around an order of magnitude lower than that for conventional electrodialysis for seawater desalination (~0.0055 kWh/mol (~19.8 kJ/mol)) (Galama et al., 2014).

After the success of SEE operation with low energy consumption was demonstrated, the system was tested using a range of current densities (0.1–10 mA/cm^2) to decrease/increase the rate of salinity exchange (Fig. S3). Under all current conditions, the system achieved near-complete salinity exchange. Fig. 2(b) shows the overall energy consumption normalized to either the volume of water desalinated or moles of ions transferred for each tested current density (salinity exchange rate). As the current controls the speed of ion transfer, with higher current (higher salinity exchange rate), the reversal of salinity is achieved more quickly, but the overpotential for driving ions, i.e., the energy consumption, is higher. As shown in Fig. 2(b), the SEE process consumes less than 1 kWh/m^3 of desalinated water at applied current densities of 0.1–2 mA/cm^2. For current densities higher than 2 mA/cm^2, the energy consumption was > 1 kWh/m^3. Although the ion transfer continued to follow along the concentration gradient, when applying a higher ion transfer rate, it was predominantly driven by the exerted electrical field. Therefore, energy consumption was observed throughout the whole process. A separate energy analysis was also conducted for the two phases of the SEE operation at different current densities (Fig. S4). Generally, smaller current densities (i.e., lower salinity exchange rates), required lower energy consumption and showed higher energy efficiencies. However, lower current densities produced a more significant water transport across the ion-exchange membrane (Supplementary material Text 3), leading to less volume of desalinated water produced (Fig. S4). The Coulombic efficiency also slightly decreased when lower current density was applied, comparable to previous studies reporting similar relationships (Sadrzadeh and Mohammadi, 2009; Galama et al., 2014). The relationship between Coulombic efficiency and current density is reliant upon the concentration gradient over the membrane and the back diffusion of ions (Galama et al., 2014). Because we have more back diffusion of ions at lower current density, the Coulombic efficiency is impacted accordingly (Fig. S4).

Previous work found that at lower applied current densities, the osmotic water transport increases significantly (Indusekhar and Krishnaswamy, 1985; Galama et al., 2014). This agrees with our findings that the water loss is directly correlated with the applied current density, which indicates the appropriate time to transport ions in solution. Because of this, higher current densities resulted in the least amount of water loss as the time to transport ions was much less. We also observed the water transport in SEE tapering off at ~10% total volume for higher current densities (above 1 mA/cm^2). Previous literature supports this observation as studies have found water transport to decrease with increasing current and approach a limiting value (Indusekhar and Krishnaswamy, 1985) (Supplementary material Text 3 for further details).

To determine whether similar performance of SEE could be maintained with lower pumping energy required, the system was also tested under different circulation flow rates for the two streams (Fig. S5). Briefly, when the circulation flow rate was lower, the SEE process produced similar volumes of desalinated water, but the Coulombic and energy efficiencies all decreased to

various degrees, and the energy consumption increased (Fig. S6). When the flow rate decreased from 200 to 50 mL/min, the energy consumption increased 25% from 0.48 to 0.60 kWh/m^3. The lower flow rate here contributed to less complete mixing and a higher mass transfer resistance, resulting in the increasing energy consumption which, nevertheless, is still lower than that of the state-of-the-art RO (~1 kWh/m^3).

To simulate the salinity exchange between brackish water and treated domestic wastewater, the SEE system was tested with an initial NaCl concentration of Stream I varied from 0.1 to 0.6 mol/L (Fig. S7). Under all conditions tested, the system achieved near complete salinity exchange. When the NaCl concentration of Stream I decreased from 0.6 to 0.1 mol/L, the desalinated water produced increased from 176 to 194 mL since less ions were needed to be transferred, allowing a shorter process time, limiting any undesired water transport (Fig. S8). The Coulombic efficiency also increased (Fig. S8), due to higher permselectivity of the ion-exchange membranes at lower salt concentrations, as discussed by Fan and Yip (2019). However, a lower initial NaCl concentration in Stream I resulted in a lower conductivity and higher overpotential. This caused the energy efficiencies of both phases in SEE operation to decrease (Fig. S8), and the overall energy consumption normalized to the ion transferred increased significantly from 0.00077 kWh/mol (2.7 kJ/mol) at 0.6 mol/L to 0.0019 kWh/mol (6.7 kJ/mol) at 0.1 mol/L (Fig. 3(a)). Nevertheless, since Stream I with a lower initial NaCl concentration required a smaller amount of ion transfer to complete salinity exchange with Stream II, the energy consumption normalized to water desalinated is significantly lower, 0.21 kWh/m^3 at 0.1 mol/L vs 0.48 kWh/m^3 at 0.6 mol/L.

The SEE system was also tested with varying the NaCl concentration of Stream II from 0.01 to 0.03 mol/L, simulating domestic wastewater with different salinity (Fig. S9). Under these conditions, the performance of the SEE showed negligible impact (Fig. 3(b), Fig. S10).

Conventional electrodialysis desalination of seawater was also tested using the same device with both feed streams set as 0.6 mol/L NaCl solution. Since conventional electrodialysis cannot transfer salts using salinity gradient energy, it required more energy consumption to achieve the same level of desalination as SEE. For current densities 1 and 2 mA/cm^2, conventional electrodialysis required more than double the energy consumption of SEE, and for all three current densities tested, the energy consumption was much higher than 1 kWh/m^3 (Fig. 3(c)). We also observed more water transport in conventional

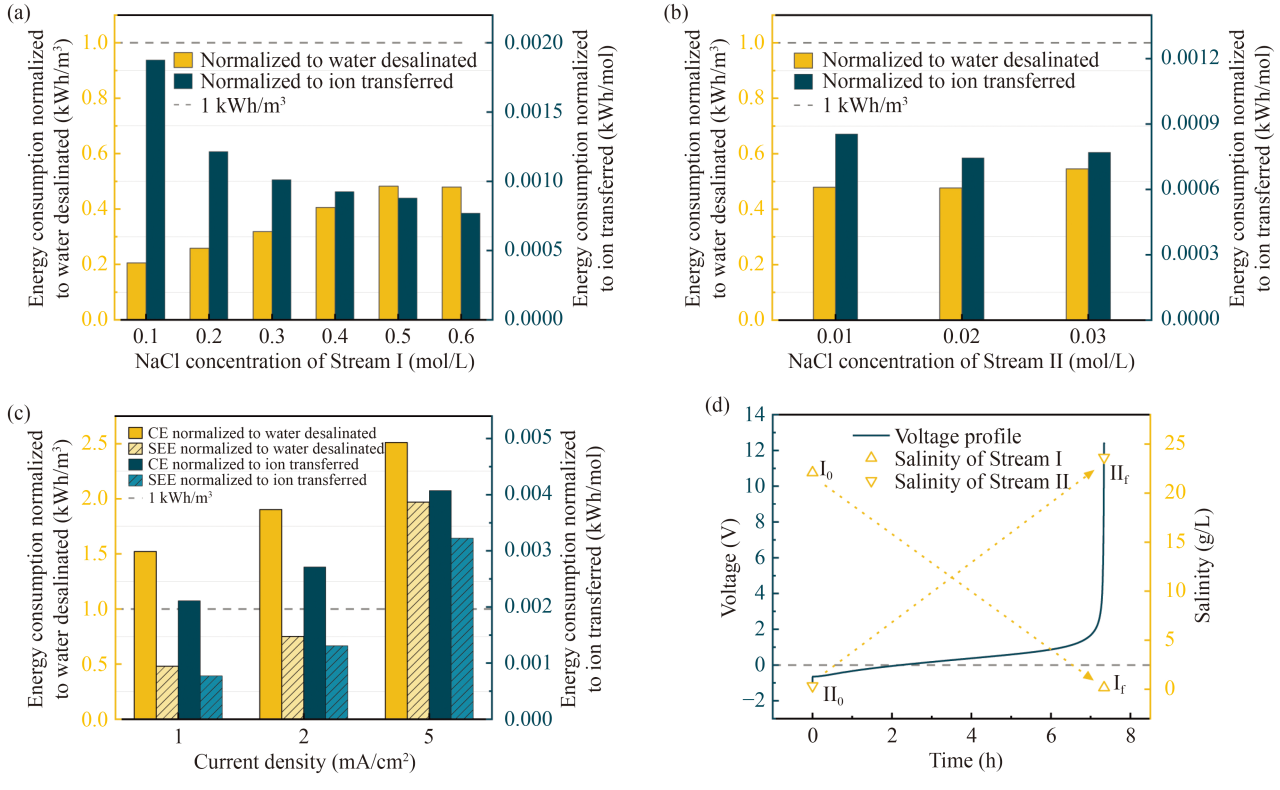

Fig. 3 Performance of SEE process with different feed streams. (a) Energy consumption of the SEE process with various initial NaCl concentrations of Stream I (0.1–0.6 mol/L) and a fixed initial NaCl concentration of Stream II (0.01 mol/L), (b) energy consumption of the SEE process with a fixed initial NaCl concentration of Stream I (0.6 mol/L) and various initial NaCl concentrations of Stream II (0.01–0.03 mol/L), (c) energy consumption of conventional electrodialysis (CE) processes with both streams of 0.6 mol/L NaCl at different current densities, and (d) SEE demonstrated with treated domestic wastewater and seawater.

electrodialysis compared with SEE (Fig. S11), thought to be caused by the larger unfavorable osmotic pressure difference, but to be expected as the water recovery efficiencies aligned with previous studies (typically 50 %–60 %) (Seto et al., 1978; Thampy et al., 1988). Overall, although high-quality water production with conventional seawater desalination through electrodialysis was achievable under the same current density applied, SEE consumes less energy and produces potable water more efficiently.

To demonstrate success in practical applications, the SEE system was tested using natural seawater (Stream I) and treated municipal wastewater (Stream II). The default conditions for SEE operation were used, and an effluent salt concentration lower than 0.015 mol/L (~0.9 g/L) was considered potable. In a ~7 h SEE operation (shown in Fig. 3(d) using the dashed arrows and gold triangles), the salinity of the seawater decreased from 22 to 0.17 g/L. Although the initial salinity for the collected seawater was lower than predicted due to measurable dilutions observed from land drainage at the coastal areas of GA, our goal of complete salinity exchange with real water was still achieved (SMCAPHA et al., 2005; Johnson et al., 1974). The water recovery maintained a high value > 90 %, while the Coulombic efficiency was 76 %. The energy consumption per volume of treated water produced was 0.59 kWh/m^3 and per mol of ions transferred was 0.0014 kWh/mol (5.1 kJ/mol). Although these numbers are slightly higher than that reported above with synthetic water streams, they are also much lower than that for state-of-the-art RO, demonstrating the success of SEE with real water application.

The low-energy consumption of salinity exchange processes is mainly attributed to the harvest of salinity gradient energy (Skilhagen et al., 2008; Achilli et al., 2009; Vanoppen et al., 2016). Salinity gradient energy results from the change in entropy when two solutions with different salinities are mixed (e.g., fresh water and seawater) (Ramon et al., 2011; Logan and Elimelech, 2012). The extraction of salinity-gradient energy can be achieved through membrane-based technologies, such as pressure-retarded osmosis (PRO) and RED (Logan and Elimelech, 2012; Gilstrap, 2013). Recent studies have explored harnessing salinity gradient energy with RED utilizing the mixing of municipal wastewater effluent and seawater for clean, non-polluting, and sustainable energy production (Nam et al., 2019). However, it is still very challenging to efficiently store the recovered salinity gradient energy and result it commercially viable. The beauty of the salinity exchange process introduced here is that we can utilize the recovered salinity gradient energy in situ, which gives us the opportunity to subsidize the large energy needed for desalination. Unlike conventional RO or electrodialysis processes for seawater desalination that have a minimum energy consumption to overcome the thermodynamic limit, the salinity exchange process, theoretically, may not need to generate or consume any energy. When manipulating the ratio of the feed streams, there is a tradeoff between the energy generation/consumption and the capacity of desalinated water to be produced, and adjusting these can result in a more thermodynamically favorable process. Rather than overcoming the thermodynamic barrier, the main energy consumption in the salinity exchange process is in terms of electrochemical overpotential to move the dissolved salts.

Another main advantage of the salinity exchange process is the absence of brine generation. Because the removed salt is directly "diluted" by the low-salinity treated wastewater, the waste stream does not generate any brine, avoiding any unwanted environmental and ecological concerns associated with conventional desalination processes. In addition, the quality of potable water produced by salinity exchange can be easily treated to meet drinking water standards. The water produced by most conventional desalination technologies is actually "too clean" for human health as minerals are required to be added back into the desalinated water before human consumption. Such an inefficient and energy-wasting step is not needed for the potable water produced by salinity exchange since the ion concentration can be well controlled. Finally, when we compare the DPR of treated domestic wastewater with desalinated seawater, the latter is more cognitively appealing (Dolnicar and Schäfer, 2006; 2009).

Producing potable water through salinity exchange will be most applicable in coastal areas where seawater is readily available and wastewater is typically discharged to the ocean after treatment regardless. In the U.S., more than 1,400 coastal wastewater treatment plants serve over one-third of the population, discharging approximately 10 billion gallons of treated effluent per day; hence, the potential impact of salinity exchange can be significant.

In this study, we have successfully demonstrated the salinity exchange concept using SEE systems. Since electrodialysis is a membrane-based process, the properties of the ion-exchange membranes (IEMs) are critical to the SEE performance. Upon material advances in the future, IEMs with higher ionic conductivity will enable faster salt transfer (i.e., higher water production rates) with much lower energy consumption. IEMs are already expected to block most of the emerging contaminants in wastewater from migrating to the desalinated seawater, so it is not of high concern, although potential cross-contamination of small and charged pollutants and fouling limitations at larger scales should be investigated in future studies.

4 Conclusions

In this paper, we demonstrate the successful operation of SEE for potable water production with much less energy

consumption compared to conventional RO and electrodialysis for seawater desalination. Due to the salinity gradient energy harvested, the salinity exchange process not only achieved the predicted lower energy consumption, but also without any brine generation. SEE operated successfully under various influents of different salinities through a wide range of operating parameters. At the lab scale, SEE can produce high-quality desalinated water at 1 mL/min with an energy consumption maintained under 1 kWh/m^3. SEE was also operated successfully using water from natural sources to demonstrate its potential for practical application.

Acknowledgements This work was supported by the U.S. Department of Interior Bureau of Reclamation (No. R19AC00101). The authors acknowledge Sydney Taylor-Klaus for helping in seawater collection.

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s11783-023-1616-1 and is accessible for authorized users.

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