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# Brine recovery using reverse electrodialysis in membrane-based desalination processes

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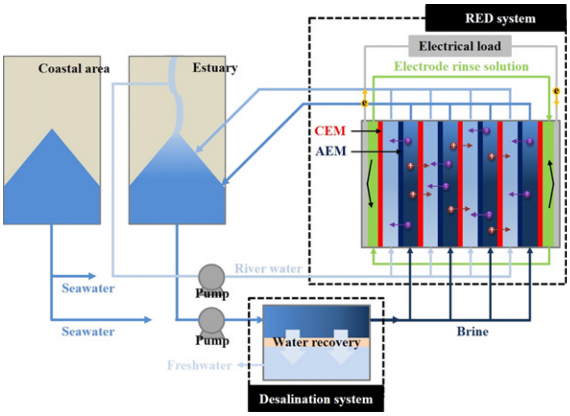
## HIGHLIGHTS

- We evaluated the influence of desalination brines on reverse electrodialysis (RED).
- We modified the RED model developed by Veerman et al.
- We obtained maximum powers of 1.48 and 1.86 W/m$^2$ with the RO and FO brines.
- Using RED, the SEC of the RO and FO processes can be reduced by 7.8% and 13.5%.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Power enhancement is a key issue in the commercialization of RED. In this paper, we report a method to improve the power generation using brines discharged from two different membrane-based desalination processes. We modified a RED model proposed by Veerman and co-workers, and this modified model was in agreement with experimental results. We considered river water and seawater as the diluted solutions for RED. The power density with RO (1.48 W/m$^2$) and FO (1.86 W/m$^2$) increased 1.5-fold and 2-fold, respectively, compared with that using seawater. When seawater was used as the diluted solution, the RED power decreased considerably. We characterized the RED performance using the intermembrane distance and the inlet flow rate. The power generated monotonously increased with decreasing compartment thickness and increasing flow rate. The net power had a specific optimal value because of a drastic growth in the pumping power. In our system, the optimal intermembrane distance was 0.1 mm (RO brine) and 0.3 mm (FO brine). We also computed the energy cost owing to RED. The results showed that the energy consumption could be lowered by ~7.8% from the typical value for RO. We found a drastic decrease for FO with the energy consumption lowered by ~13.5%.

## 1. Introduction

The energy crisis is one of the biggest issues in the world, which is mainly a result of limited fossil fuel sources. Many researchers have

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**Nomenclature**

| | |
|---|---|
| $D$ | diffusion coefficient [m$^2$/s] |
| $C$ | concentration [mol/L] |
| $F$ | Faraday constant [96,485 C/mol] |
| $I$ | current [A] |
| $J$ | molar flux [mol/m$^2$·s] |
| $L$ | length [m] |
| $P$ | power [W] |
| $Q$ | volumetric flow rate [m$^3$/s] |
| $R$ | resistance [Ω] |
| $R_g$ | universal gas constant [8.314 J/mol·K] |
| $T$ | ambient temperature [K] |
| $V$ | voltage [V] |
| $V_w$ | molar volume of water [mol/m$^3$] |
| $W$ | width [m] |
| $d_h$ | hydraulic diameter [m] |
| $h$ | membrane thickness [m] |
| $i$ | current density [A/m$^2$] |
| $n$ | porosity [−] |
| $p$ | power density [W/m$^2$] |
| $t$ | residence time [s] |
| $z$ | valence number [−] |

*Greek symbols*

| | |
|---|---|
| $\Delta p$ | pressure drop [Pa] |
| $\Lambda$ | molar conductivity [S·m$^2$/mol] |
| $\alpha$ | transference number [−] |
| $\beta$ | open ratio [−] |
| $\gamma$ | activity coefficient [−] |
| $\delta$ | intermembrane distance [m] |
| $\varepsilon$ | permittivity [F/m] |
| $\eta_{pump}$ | pump efficiency [−] |
| $\mu$ | viscosity [Pa·s] |

*Subscripts*

| | |
|---|---|
| $H$ | concentrated solution |
| $L$ | diluted solution |

developed and extensively studied various renewable energy resources, such as solar energy, wind energy, ocean energy, and geothermal energy to resolve this energy challenge [1–4]. Salinity gradient energy (SGE) is energy generated from mixing two solutions of different concentrations and has attracted significant attention owing to its estimated high potential of more than 15 PWh/year, which is of a similar magnitude as the worldwide electricity consumption in 2011 [5,6].

According to the power generating mechanism, SGE can be divided into three techniques: pressure retarded osmosis (PRO), capacitive mixing (CAPMIX), and reverse electrodialysis (RED) [7,8]. PRO employs semipermeable membranes to transport water by osmosis from the diluted side to the concentrated side. PRO requires mechanical parts, such as turbines or pressure exchangers, to convert osmotic energy into useful energy. CAPMIX can produce electrical power through repeated ion adsorption/desorption processes using carbon-based electrodes. To date, the power produced with CAPMIX is lower than with the other two competitive technologies owing to its relatively short history of development. RED uses ion exchange membranes (IEMs) to selectively deliver cations or anions. Electrical energy can be directly generated by redox reactions on electrodes. This method does not require moving parts and thus has high reliability. Membrane fouling issues also can easily be mitigated, compared with PRO. These advantages have made RED attractive, and recently, a 4 kW pilot plant constructed in Afsluitdijk, Netherlands is in operation [9].

There are still several issues that need to be addressed to allow wider commercialization of RED, including the high cost of IEMs and relatively low power density [7,10]. The cost of IEMs is gradually declining with their increased use in various applications, such as fuel cells, electrodialysis, and the redox flow battery [11–14]. Most studies on RED focus on the improvement of the power density, and various approaches have been actively conducted to enhance the power [15–21]. Długołęcki et al. [19] employed a secondary IEM as a spacer that played several roles, such as flow distribution and a support to block channels instead of non-conductive spacers made of polymer materials. They showed that the use of ion conductive spacers could lead to a tremendous increase in power compared with that obtained using existing spacers. Vermaas et al. [20] reported an improvement of RED power when a decreased intermembrane space was used because of the reduction of internal resistance in the working solutions. Güler et al. [21] compared the RED performance using various combinations of commercial and tailor-made IEMs, and reported important parameters for fabrication of optimal IEMs. Kim et al. [16] introduced a RED method using straight nanochannels fabricated by microelectromechanical systems (MEMS) instead of the existing polymer-based IEMs.

Another way to improve RED performance is to use highly concentrated brines in the desalination process. Desalination brines have high chemical potentials because of the ions that remain after water is eliminated from seawater. To date, there are only a few studies on using brines as the concentrated solution in a RED system [22–27]. These previous studies include a thermodynamic analysis of the mixing extent between 0 (no mixing) and 1 (perfect mixing) without consideration of the operating conditions of RED [23,24]. The other previous work was concerned with high concentrated brines (~5 mol/L) obtained from a solar pond, which are not feasible in desalination markets [25–27].

In this study, we demonstrated power enhancement of RED using brines discharged from two different membrane-based desalination processes: (1) reverse osmosis (RO), the most popular method in the desalination markets [28] and (2) forward osmosis (FO), a novel concept without energy-intensive high pressure processes [29,30]. The effects of desalination brines on RED performance were evaluated both experimentally and numerically. We modified the one-dimensional RED model developed by Veerman et al. [31] and successfully validated this modified numerical model with our lab-scale RED stacks. We characterized the maximum power density and net power density of RED according to the intermembrane distance and the inlet flow rate. We assumed two different realistic conditions for the diluted solutions using river water and seawater. We also analyzed the combined effects of integrating RED with the desalination processes. We found a reduction in specific energy consumption (SEC) owing to the chemical energy recovery using RED.

## 2. Material and methods

### 2.1. Process description

Fig. 1 shows the schematic diagram of the combined desalination and RED processes. We considered two different membrane-based desalination processes. RO produces freshwater using a high pressure above osmotic pressure [32,33], whereas FO naturally obtains freshwater by employing so-called draw solutions, which have higher osmotic pressures than seawater [34,35]. As we considered two locations (estuary and coastal area) for these desalination plants, we simulated both river water and seawater as the diluted solution for the RED processes.

We assumed the concentration of seawater (~35,000 mg/L total dissolved solids (TDS)) and river water (100–600 mg/L TDS) to be 0.6 and 0.01 mol/L NaCl, respectively [35]. In the RO process, the water recovery rate, which is defined as the outlet flow rate per inlet flow rate, is typically reported at ~50%, and we therefore fixed the concentration of the RO brine at two-fold that of seawater (1.2 mol/L) [23,24,36].