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Conceptual designs of integrated process for simultaneous production of potable water, electricity, and salt

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HIGHLIGHTS

- Integrated process for the production of potable water, electricity, and salt
- Process simulation analysis for the integrated process system
- The effects of different water sources and temperature in the process are studied.
- The design proposed represents a feasible option for the production of water, electricity, and salt

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ABSTRACT

The main aim of this study was to conduct preliminary analysis on the performance of two conceptual designs that integrate the production of potable water, electricity, and salt. We used reverse osmosis (RO), pressure-retarded osmosis (PRO), and electrodialysis (ED) to produce potable water, electricity, and salt, respectively. The objective of the analysis is to observe how the relative positions of RO and PRO in the integrated process affect the five key parameters, i.e. the total dissolved solids (TDS) of potable water, permeate rate, the total energy requirement of the RO and ED units, net delivered power, and salt potential. We simulated each integrated design using previously validated mathematical expressions of RO, PRO, and ED. We found that the net delivered power is higher when the RO unit is located before the PRO unit. The same sequence also results in lower energy requirement for producing potable water, although the permeate rate is smaller than that of the rival sequence. On the other hand, the salt potential is not affected by the relative positions of the RO and PRO units.

1. Introduction

The fast-growing population of earth generates many crises such as dearth in energy and clean water sources. This situation forces us to anticipate smart solutions to solve those problems. The oceans of the earth may provide the desired solution to these problems. The oceans contain most substances required for the sustenance of human life. Marine life of the oceans provides a great source of foods, they are mined for minerals e.g. NaCl and desalinating seawater using reverse osmosis (RO) technology has become a common practice to produce potable water of late [1] desalination process. Moreover, there has been recent reports that seawater can also be exploited to produce electricity by taking advantage its high salinity through pressure-retarded osmosis (PRO) [2–4].

Clean water and salt are commonly produced from sea water in separate plants. Each of these standalone plants produces at least one valuable by-product that is wasted. RO can effectively desalinate sea water, but the remaining concentrated brine, which contains valuable salt ions, is discharged back into the ocean despite being harmful to marine life [5]. The solar salt production process utilizes massive areas to facilitate evaporation of water. On the other hand, producing electricity from sea water using PRO method is an emerging trend. The first and only PRO power plant were initiated by Statkraft in 2009, but it recently

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closed due to the economic infeasibility [6]. However, the termination of this plant does not imply that there is any future for electricity generation using the PRO technology.

Since clean water, salt, and electricity can all be produced from sea water, it would be logical to produce them in one plant using a single source of sea water. Wan and Chung [7] proposed the possibility to integrate the production of energy and clean water from sea water as these are interlinked and interdependent. McGovern et al. [8] treated the concentrated brine from an RO process by integrating it with a salt production unit i.e. electrodialysis. However, to the best of our knowledge, there is no open literature that investigates the combined production of salt, clean water, and electricity in one integrated process.

Herein, we conduct a preliminary analysis of conceptual process designs that integrate the RO, PRO, and ED units to produce potable water, electricity, and salt, respectively. The merits and demerits of each design were analyzed both qualitative and quantitatively. The analysis results should provide a rough guideline on selecting proper integrated PRO-RO-ED design under different conditions. However, optimizing the operating conditions for each presented design is beyond the scope of our study.

Seawater desalination using RO is a technology that is widely used for overcoming the current and future water scarcity [9]. In this process, sea water is subjected to pressure high enough to push the water molecules through a semi-permeable membrane, so that it can be collected as clean water in the permeate stream.

PRO was first introduced by Loeb [10] and has been a subject of investigation ever since [11–14]. A low-pressure stream of fresh water is introduced into a module while seawater is pressurized and sent to the same module. A semi-permeable membrane separates the two streams in that module. The sea water draws the fresh water through the semipermeable membrane due to its higher osmotic pressure. The volume flow at the high-pressure side of the membrane thus increases. This high-pressure stream with sufficiently large volume flow is then used to rotate a hydro-turbine to generate power [15].

The RO and PRO processes can be integrated into one plant using a single source of sea water feed in an interchangeable sequence. In a PRO-RO sequence, the discharged dilute sea water from the PRO unit can be reused as the feed for the RO unit. If the sequence is reversed i.e. in an RO-PRO sequence, the concentrated brine from the RO unit can be reused as the feed for the draw solution in the PRO unit.

Irrespective of the sequence chosen, the concentrated brine from the PRO-RO process or the dilute sea water from RO-PRO process retains valuable ions that can be further processed to produce salt. In this study, we use electrodialysis (ED), a mature technology that was originally used to produce potable water from brackish water sources [16]. Nevertheless, from a different perspective, ED can be used to pre-concentrate sea water with Na^+ and Cl^- ions, thereby separating it from the other salt ions.

There are two possible scenarios for integrating the PRO and RO processes. First, we qualitatively examined each scenario to assess its feasibility both from the process and economic points of view. Second, we simulated the two integrated designs to quantitatively judge how much potable water, net electricity, and potential salt they can produce. The results suggest that the selection of properly integrated design would depend on the desired major product because each design has its own advantages over the others.

2. Design considerations for integrated potable water, electricity and salt production

2.1. Sea water reverse osmosis (SWRO) for clean water production

RO is a relatively new process compared to distillation and electrodialysis for desalinating sea water to produce potable water [17]. In this process, sea water has to be pressurized, high enough to overcome the natural osmotic pressure of fresh water on the other side of the semi-permeable membrane. Under this high pressure, the water molecules in sea water are pushed through the membrane. The sea water that loses water molecules is discharged from the membrane as the retentate stream containing concentrated brine. The water molecules that escape from sea water are collected in the permeate stream. The process flow diagram of a sea water desalination plant using RO membrane is illustrated in Fig. S1.

The energy consumed in an SWRO plant is mostly for operating the high-pressure pumps for pressurizing the sea water. Recent advances in the SWRO technology include the development of an energy recovery device (ERD) that helps reduce the energy requirement of this plant [18]. ERD is designed to transfer the pressure energy in the high-pressure concentrated brine to the incoming low-pressure sea water, thereby decreasing the need for high-pressure pumps. There are two categories of ERD used in SWRO plants: centrifugal (e.g. hydraulic turbochargers) and isobaric devices (e.g. pressure exchanger) [19]. There are numerous reports that present comparative studies to determine the most efficient ERD [18–20]. Pressure exchanger, one of the latest advancements in ERD is considered the most efficient device for recovering the pressure energy [21]. However, efficiency is not the only contributing factor because there are several other variables that play different roles in selecting the most appropriate ERD in SWRO plants [17].

2.2. Pressure retarded osmosis for generating power from sea water

PRO is the most appropriate method for generating power to achieve process integration. It uses sea water as one of the feed sources and the discarded stream from a PRO unit can be reused as the feed for the salt production unit. Thus, sea water utilization can be maximized to produce power and salt. The schematic for power generation using PRO is illustrated in Fig. S2.

There are two feed sources for generating power using PRO: high-pressure sea water and fresh water e.g. river water. Both water streams are diverted into a chamber separated by a semipermeable membrane that divides the chamber into a high-pressure side and a low-pressure side. The fresh water (feed solution) has higher osmotic pressure than the sea water (draw solution). Consequently, some volume of the fresh water is drawn through the membrane and mixes with sea water. This mixing creates a high-pressure solution with a volume large enough to rotate a hydro turbine that generates power. Some fraction of this mixture flows to a pressure exchanger, an energy recovery unit where the pressure of the incoming sea water is increased without using an additional high-pressure pump. Pressure exchanger makes the PRO unit cost-effective by substantially reducing the power required for pressurizing sea water [15]. Between the two rejected streams of PRO unit, the dilute sea water contains valuable components that can be further processed to produce salt.

2.3. Electrodialysis for salt production

Electrodialysis (ED) is a membrane-based separation that uses ion exchange with an electrical potential difference as the driving force [16]. One of the original applications of ED is to produce potable water from brackish water. The brine or dilute sea water produced as the by-product of this water purification technique will be more concentrated with salt ions e.g. Na^+ and Cl^- and can be further processed to purify the salt.

The membrane used in ED is a cation- or anion-selective one. In the ED unit, the cation- and anion-selective membranes are stacked alternately as can be seen from Fig. S3 [22]. If the membrane is cation-selective, it will let the cations from the solution to penetrate the membrane and stop the anions from passing through. On the other hand, anion-selective membranes allow the transfer of anions but inhibit the transfer of cations. As a result, one compartment will contain a stream of dilute ion concentration (diluate) while the next one will contain a stream