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Reverse osmosis (RO) and pressure retarded osmosis (PRO) hybrid processes: Model-based scenario study

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HIGHLIGHTS

- A model-based scenario study assessed the RO–PRO hybrid processes.
- A cost analysis evaluated RO–PRO hybrid systems.
- RO plays a crucial role to determine water and energy production (WERR).
- PRO plant size plays a minor role to determine WERR value.
- The use of RO as PRO draw solution is beneficial to augment power generation.

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ABSTRACT

We conducted a scenario study on a promising RO–PRO hybrid system to alleviate water and energy demands. We utilized a previously validated reverse osmosis (RO) process model and modified a model of a pressure-retarded osmosis (PRO) process to properly consider the spatial distribution of concentration and velocity based on a mass balance principle. Using the models, we compared four different RO–PRO hybrid configurations based on the water and energy return rate (WERR). Subsequently, the comparison of the water production rate and energy production rate confirmed the results that RO plays a dominant role to determine the WERR value. Hybrid systems that use seawater as a feed water for RO are more energy price sensitive. That is, a decrease in the RO plant size considerably diminishes the WERR values; however, the PRO plant size plays a minor role to determine the WERR value. Research and available literature on RO–PRO hybrid processes are in a relatively early stage; this study is a preliminary step to evaluate further advances in hybrid systems that can eventually alleviate water and energy demands.

1. Introduction

Climate change may affect precipitation levels and alter the global hydraulic cycle [1]; subsequently, aggravate regional freshwater accessibility could face drastic changes. Membrane technology, such as reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD), is widely recognized as a promising potable water-production process due to its ability to desalinate saline water (such as seawater and brackish water), which is the most abundant global water source [2]. Among the membrane processes, RO is one of the most dominant technologies in the seawater desalination and water treatment market since it has the lowest geographical restrictions as well as is a proven, reliable, and established process [3,4]. Relatively high energy consumption (due to pressurizing and environmental pollution by concentrated brine disposal) hinders the further development of RO [5]. Therefore, maximizing the efficiency of RO processes would tremendously alleviate freshwater demands.

Membrane technology can reduce energy demands as well as alleviate water demands. Pressure-retarded osmosis (PRO) has re-emerged as an energy production process that uses the chemical potential difference of two solutions [6]. The theoretical feasibility of electricity generated by mixing fresh and salt water was proposed in the 1950s [7] and the PRO process was suggested in the 1970s [8,9]. However, at the beginning of the PRO process, studies revealed that the PRO membrane was insufficient to produce water to operate a hydro turbine because the porous support substrate of the PRO membrane had a higher internal resistance against the solute transport within its inside and

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subsequently resulted in severe internal concentration polarization (ICP) [10–12]. The development of a membrane with a relatively low membrane structure parameter (i.e., an indicator of ICP) has renewed interest in the PRO process [13,14]. Statkraft opened a PRO prototype pilot plant in 2009 with a target of 5 W/m^2 in net specific power to show the possibility of a practical use of PRO [15]. The current progress in the PRO process as a renewable energy source can help alleviate future energy demands.

RO and PRO are promising processes to alleviate water and energy demands; subsequently, the enhancement of these two processes can potentially help ease water scarcity and energy stresses. The efficiency of these two processes is strongly dependent on the concentration of solutions (i.e., feed water for RO and feed/draw water for PRO). Low-saline water induces the low osmotic pressure as a feed solution in RO and requires low energy consumption. In PRO, a greater difference in the concentration of feed and draw solutions generates more energy. It would be beneficial to hybridize the two processes due to the reliance of the two membrane processes on the concentration of solutions. For instance, the hybrid configuration (where the concentrated brine of RO is utilized as a draw solution of PRO) may enhance the power generation in PRO. Furthermore, the PRO dilutes the concentration of the brine and eventually reduces the cost of post-treatment for brine disposal. It is important to investigate the feasibility of RO–PRO hybrid processes under various conditions that include feed and draw solution concentrations as well as applied pressures in the RO and PRO in order to maximize the benefits of the two membrane processes.

This study assesses the commercial feasibility of RO–PRO hybrid systems using a numerical approach. Four possible combinations of the two processes were considered and compared based on the water and energy return rate (WERR), which is the conversion of water produced by RO and energy generated by PRO to commercial value so that two different processes with different engineering purposes can be impartially compared. For the numerical model, a well-validated RO model was employed in previous literature. In addition, the previously validated PRO model was modified to account for a spatially variant concentration and velocity in large PRO systems. RO and PRO models were used to simulate various conditions by varying electricity/water prices and the plant size ratio of RO to PRO.

2. Materials and methods

2.1. SWRO–PRO hybrid processes

Fig. 1 illustrates the four proposed possible hybrid configurations in this study. These configurations were determined by considering the sequence of each system and the influent concentration. The brine of the RO process can be utilized as PRO influent without the need for additional pre-treatment when the RO process is located prior to the PRO

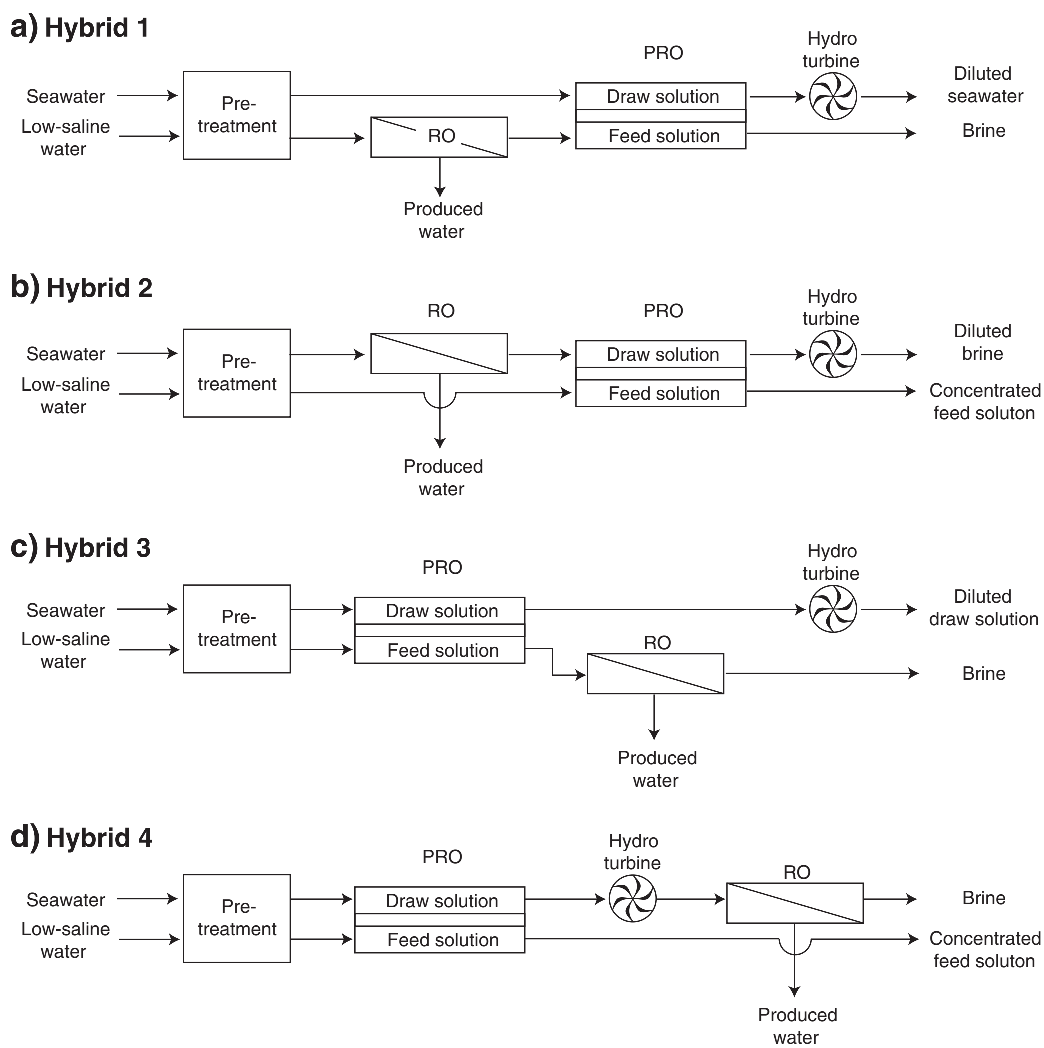

Fig. 1. Schematic of four possible RO–PRO hybrid configurations. (a) Hybrid 1 (RO → PRO mode): low-saline water is supplied as a RO feed. (b) Hybrid 2 (RO → PRO mode): seawater is supplied as a RO feed. (c) Hybrid 3 (PRO → RO mode): concentrated low-saline water is supplied as a RO feed. (d) Hybrid 4 (PRO → RO mode): diluted seawater is supplied as a RO feed.