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On the present and future economic viability of stand-alone pressure-retarded osmosis

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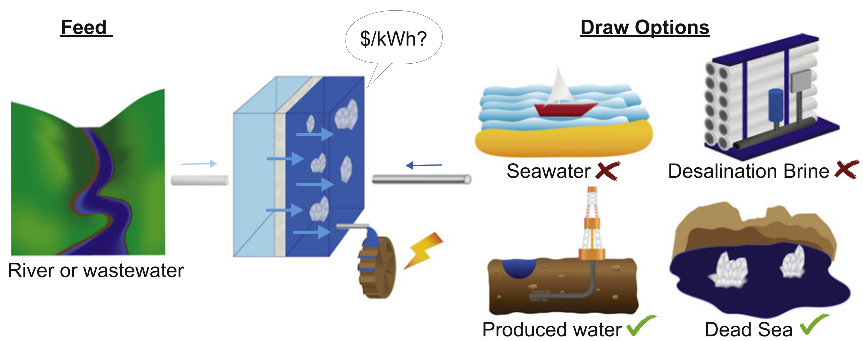
HIGHLIGHTS

- A comprehensive economic analysis was developed for wide range of salinities.
- Nonlinear optimization ensures that the results are general.
- A lower bound of the levelized cost of electricity (LCOE) was calculated.
- The lower bound LCOE identifies operating conditions which are not economically viable.
- Pressure-retarded osmosis is potentially viable only with extremely high draw salinities (>18%).

GRAPHICAL ABSTRACT



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ABSTRACT

Pressure-retarded osmosis is a renewable method of power production from salinity gradients which has generated significant academic and commercial interest but, to date, has not been successfully implemented on a large scale. In this work, we investigate lower bound cost scenarios for power generation with PRO to evaluate its economic viability. We build a comprehensive economic model for PRO with assumptions that minimize the cost of power production, thereby conclusively identifying the operating conditions that are not economically viable. With the current state-of-the art PRO membranes, we estimate the minimum levelized cost of electricity for PRO of US$1.2/kWh for seawater and river water pairing, $0.44/kWh for reverse osmosis brine and wastewater, and $0.066/kWh for nearly saturated water (26% wt) and river water, all for a 2 MW production system. Only a pairing of extremely high salinity (greater than 18%) water and freshwater has the potential to compete with wind power currently at $0.074/kWh. We show two methods for reducing this cost via economies of scale and reducing the membrane structural parameter. We find that the latter method reduces the levelized cost of electricity significantly more than increasing the membrane permeability coefficient.

1. Introduction

While the consequences of climate change are becoming increasingly felt globally, renewable sources of energy such as solar and wind power are being adopted at rapidly accelerating rates. This is predominantly due to drastic cost reductions which allowed these technologies to attain grid parity, or compete economically with retail rates of grid power by fossil fuels [1,2]. In 1955, Pattle [3] wrote that an untapped potential source of exergy is lost when seawater is mixed with river water and proposed a system for recovering this lost resource. About two decades later, Loeb invented two practical methods, pressure-retarded osmosis (PRO) and reverse electrodialysis (RED), to harness this untapped source of energy which involves the controlled mixing of two streams with different salinities [4,5] such

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as river water and seawater or desalination brine and treated municipal wastewater. While RED has been extensively studied from both energetic and economic point of views [6–8], PRO has been found to have a higher energy efficiency and power density than RED [9].

PRO has received substantial attention in the academic literature recently [10–12] and several researchers have studied integrating PRO with reverse osmosis systems to reduce the overall energy consumption for desalination [13,14]. But these studies were focused solely on energetic analyses of PRO and fewer studies have investigated the economic viability of this technology. However, just as attaining grid parity enabled and continues to enable widespread adoption of solar photo-voltaic and wind power, so too do economic considerations determine the viability of PRO systems. Given the significant academic and commercial interest in PRO, a comprehensive economic assessment is both imperative and timely.

In this study, we compute the minimum levelized cost of electricity ($LCOE_{min}$) in *US*$/kWh and the minimum overnight cost-of-capital (OCC_{min}) in *US*$/MW for a variety of draw and feed stream combinations. These figures of merit allow for a direct comparison between PRO and other energy sources including renewables, such as wind and solar, or fossil technologies, such as diesel and natural gas.

The novelty of this work lies in using lower bound cost estimates rather than attempting to precisely estimate costs. The aim therefore is to sharply characterize sets of operating conditions as economically unviable. In addition, we use a comprehensive optimization algorithm that enables exploration of a large space of operating conditions rather than being restricted to some arbitrarily set operating condition. Finally, the effect of system scale up on the economic viability is also considered. These factors are discussed in more detail in the following subsections.

1.1. Lower bound cost estimates

Firstly, we use lower bound cost estimates to determine the economic viability of stand-alone PRO. This is because accurately estimating capital cost (CapEx) and pretreatment cost data for PRO is difficult due to the lack of large scale PRO plants in existence. Previously estimated PRO system costs in the literature vary greatly due to selection of these values and it is unclear which are the most accurate. Instead of attempting to accurately determine the cost of a PRO system, we adopt simplifying assumptions whenever there is uncertainty which lead to the lowest possible cost - thereby providing a lower bound on the cost of electricity generated by PRO. One of our most important assumptions is that we use capital costs of modern seawater reverse osmosis (SWRO) plants of a similar size to estimate PRO CapEx. Although RO and PRO are similar, directly applying the RO CapEx to PRO may result in overestimation of the PRO CapEx. Whenever we believe there exists a difference between PRO and RO, we exclude the CapEx contribution from the specific item which is attributed to the difference (e.g., the intake system). We chose SWRO because the salinity of draw stream considered in this study is greater than or equal to seawater salinity. Because RO technology and construction methods are rather mature, using their capital cost should provide a lower bound cost to our PRO study.

1.2. Comprehensive model and optimization algorithm which explores a large set of process parameters

Secondly, our model is one of the most comprehensive to date due to consideration of all known loss mechanisms including internal and external concentration polarization, reverse solute flux, viscous losses in hydraulic pressure, and axial changes in concentration due to large system sizes. We also take into account the decrease in membrane permeability at high pressures ($>$ 45 bar) due to compaction - a critical, but poorly understood factor which must especially be considered when using high osmotic pressure draw streams to produce power.

In addition to our large set of explored draw and feed stream combinations, we use a four parameter non-linear optimization method to investigate a vast range of feed and draw velocities, applied hydraulic pressures, system sizes, and mass flow rate ratios. With our lower bound cost estimation method, we can clearly rule out a large set of infeasible operating regimes. Our optimization approach makes the results from our study general rather than being limited to one choice of parameters.

While we are not the first to explore the economic viability of PRO, most studies have focused on pairing seawater with freshwater (or river water level salinity) [15–18]. Kleiterp [15] investigated the commercial potential of PRO but used a zero dimensional model which does not take into account the decreasing driving force along the length of the PRO module. This choice of model significantly overpredicts the power density, which in turn results in an underestimate of the cost of electricity.

Skilhagen et al. [18] suggested that 5 W/m^2 is required for the feasibility of PRO but did not specify the details of their economic argument. Lee et al. [16] assumed a power density value and membrane cost without using a PRO model to study only the OCC. Ramon used an exceptionally low capital cost ($234 day/m^3 of permeate), less than a quarter of the cost of a typical SWRO plant ($>$$1000 day/m^3 [19]), which resulted in an electricity cost of $0.06/kWh USD.

Some papers studied solution pairings other than river water/seawater, but use unreasonable assumptions or scale-up factors that may not be accurate. Loeb [20] studied a large scale PRO plant which uses Dead Sea and RO brine as inlets and achieved US$0.058/kWh in 1998 (US$0.084/kWh in 2016 [21]). Loeb [22] also studied pairing 12% (by weight) salinity stream of the Great Salt Lake with nearby river water and achieved US$0.09/kWh in 2001 (US$0.12 kWh in 2001 [21]). However, both studies based capital cost on a brackish RO plant ($420 day/m^3), which is less than half the cost of a SWRO plant ($>$$1000 day/m^3 [19]) due to the absence of high pressure pumps in brackish water RO. Also Loeb used a scale-up cost factor which may not be accurately applied to PRO.

1.3. Future PRO economic viability

Finally, we study the future economic viability of PRO by pushing the limits of PRO membrane technology in our models. We first identify two potential methods of reducing the LCOE: harnessing economies of scale and improving membrane performance. We find that the $LCOE_{min}$ is reduced by 42% as the net power production is increased from 2 to 75 MW. Then we compute the $LCOE_{min}$ for PRO systems with up to an order-of-magnitude greater water permeability coefficient, lower solute passage, and smaller structural parameter while maintaining the salt permeability constant–all steps which have been proposed to prepare PRO for commercialization and real-world application [17,23,24]. We find that decreasing the structural parameter results in a more significant decrease in $LCOE_{min}$ than increasing the membrane permeability.

With these unique analyses, we conclusively demonstrate that PRO has potential to be economically viable only if extremely high draw salinity is used (at least above 18%). Therefore, we suggest that future PRO research be focused on challenges associated with implementing highly saline draw solutions.

2. Economic model to obtain a lower bound cost of energy from PRO

A representative PRO system is shown in Fig. 1. A counterflow[1] PRO module takes draw and feed solutions to produce power. After

[1] We investigate counterflow exchangers as opposed to parallel flow exchangers in this work because the latter configuration produces less power irrespective of operating conditions [25].