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Economic framework for net power density and levelized cost of electricity in pressure-retarded osmosis

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ABSTRACT

Economic analysis is necessary to ascertain the practical viability of a pressure-retarded osmosis (PRO) system for power production, but high complexity and the lack of large scale data has limited such work. In this study, a simple yet powerful economic framework is developed to relate the lower bound of levelized cost of electricity (LCOE) to net power density. A set of simplifying assumptions are used to develop an inverse linear relationship between net power density and LCOE. While net power density can be inferred based on experimentally measured power density, LCOE can be used to judge the economic viability of the PRO system. The minimum required net power density for PRO system to achieve an LCOE of $0.074/kWh (the capacity-weighted average LCOE of solar PV in the U.S.) is found to be 56.4 W/m^2. Using this framework, we revisit the commonly cited power density of 5 W/m^2 to conclude that it is not economically viable because net power density would be even lower. Finally, we demonstrate that fundamental difference exists between power density and net power density, and as a result we recommend using net power density as a performance metric for PRO system.

1. Introduction

Given the rapidly increasing need for a non-intermittent source of renewable energy, pressure-retarded osmosis (PRO) has continued to receive significant interest even after the first commercial pilot plant by Statkraft stopped operation in 2014 [1]. Japan's Megaton Project has integrated PRO with seawater reverse osmosis (SWRO) to lower capital cost and harness the high salinity of RO brine [2]. In South Korea, PRO was integrated with RO and membrane distillation (MD) systems to process the brine at even higher salinity. These leading pilot plants and recent studies on PRO [3,4] suggest that the most popular salinity pairing of seawater and river water is not feasible and that a more saline draw stream is necessary to make PRO viable. Although these studies identified the need for high salinity, the power density needed for economic viability remains unclear. In 2008, Statkraft, the Norwegian company that constructed a PRO power production pilot plant producing 2–4 kW of electricity, reported that a power density of at least 5 W/m^2 is necessary for PRO to be economically viable [5]. Since then, this number has been widely quoted in the literature [6-11], yet the economic basis for this value of minimum power density remains unclear. Using a new economic framework, we revisit the minimum power density for PRO and conclude that 5 W/m^2 is an order-of-magnitude lower than the required power density for economic viability.

Most PRO studies report power density to quantify the performance of PRO because it is an easily measurable quantity. We will sometimes use "module power density" to differentiate power density from net power density. To our knowledge, 60 W/m^2 is the highest module power density achieved in the literature [12], using a coupon-sized system. Coupon-sized experiments do not account for the streamwise variations of salinity found in larger, commercial-scale elements, and consequently their power densities are significantly higher than can be achieved at a practical scale. Also, net power density, which accounts for the necessary power input to the pumps, was not reported by Straub et al. [12]. As will be discussed in Section 5, the net power density even for a coupon sized system is much lower than the module power density.

Although the power density is a metric that accounts for both the energy production (related to OpEx) and the membrane area (related to CapEx), maximizing the power density directly may not correspond to minimizing the overall cost. This ambiguity arises because a clear relationship between the power density and an economic metric is missing in the literature. The economic framework developed in the present study directly relates the levelized cost of electricity (the most widely used economic metric for power production) to net power density. Using this model, we can calculate the minimum required net power density to achieve the target LCOE. Another way to use this

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Nomenclature

i	Interest rate
n	Payback period
A_m	Membrane area, m^2
w_d	Draw salinity, w/m^2
$\tilde{C}'_{CapEx}(A_m, w_d)$	Total capital expenditure as a function of A_m and w_d, \$
$\tilde{C}'_{m}(A_m, w_d)$	Total membrane cost as a function of A_m and w_d, \$
$\tilde{C}'_{labor}(A_m, w_d)$	Total labor cost as a function of A_m and w_d, \$
$\tilde{C}'_{chem}(A_m, w_d)$	Total chemical cost as a function of A_m and w_d, \$
$\tilde{C}'_{parts}(A_m, w_d)$	Total parts replacement cost as a function of A_m and w_d, \$
$\tilde{C}_{CapEx}(A_m, w_d)$	Total capital expenditure as a function of A_m at w_d^{min}, \$
$\tilde{C}_{m}(A_m, w_d)$	Total membrane cost as a function of A_m at w_d^{min}, \$
$\tilde{C}_{labor}(A_m, w_d)$	Total labor cost as a function of A_m at w_d^{min}, \$
$\tilde{C}_{chem}(A_m, w_d)$	Total chemical cost as a function of A_m at w_d^{min}, \$
$\tilde{C}_{parts}(A_m, w_d)$	Total parts replacement cost as a function of A_m at w_d^{min}, \$
C_{CapEx}	Proportionality constant for linear approximation of capital expenditure, \$/m^2
C_m	Membrane cost per unit membrane area, \$/m^2
C_{labor}	Proportionality constant for linear approximation of labor cost, \$/year-m^2
C_{chem}	Proportionality constant for linear approximation of chemical cost, \$/year-m^2
C_{parts}	Proportionality constant for linear approximation of parts replacement cost, \$/year-m^2
CRF	Capital recovery factor
L_m	Membrane life, years
$LCOE_{CapEx}$	Capital expenditure per unit membrane area, \$/m^2
$LCOE_m$	Membrane cost per unit membrane area, \$/m^2
$LCOE_{labor}$	Labor cost per unit membrane area, \$/m^2
$LCOE_{chem}$	Chemical cost unit membrane area, \$/m^2
$LCOE_{parts}$	Parts replacement cost per unit membrane area, \$/m^2
$\dot{W}_{module}$	Module (gross) power output, W
$\dot{W}_{net}$	Net power, kW
$\dot{W}_{pump}$	Pump power consumption, W
$\dot{W}_{pt}$	Pretreatment power consumption, W
$\dot{W}_{aux}$	Auxiliary power consumption, W
$P_{den,module}$	Module (gross) power density, W/m^2
$P_{den,net}$	Net power density, W/m^2
$P_{den,pump}$	Pump power density, W/m^2
t_{op}	Operating days of a year, hr/year

model, when a laboratory measurement of the net power density is available, is to calculate the minimum LCOE based on scaling up the laboratory PRO system.

2. Economic analysis

The goal of this section is to develop a direct relationship between LCOE and net power density that does not depend on a particular use case or system design (e.g., salinity or area) of the PRO system.

2.1. Breakdown of CapEx data

Since no commercial PRO plant is operating as of 2017, the capital expenditure (CapEx) for a full PRO plant is difficult to estimate. Therefore, we benchmark using CapEx data for reverse osmosis plants. This approach is similar to that of Loeb [13,14] in that SWRO data was used to approximate the PRO cost. However our approach is different in that we do not attempt to accurately model the PRO cost with SWRO cost because significant uncertainty may arise in doing so. Instead, whenever SWRO and PRO have fundamental difference, we exclude such cost factors so that the resulting cost is lower than an actual cost would be.

A detailed breakdown of CapEx and operating expenditures (OpEx) data for SWRO CapEx is available from DesalData.com [15]. Each CapEx value from DesalData.com is given as a function of pure water production capacity of the RO plant (\$-day/m^3), which we convert to a per-membrane area basis by using an average RO water flux of 14 L/m^2-hr [16]. From the CapEx data, we exclude the membrane cost because the membrane replacement cost is taken into account by the OpEx. In this paper, we assume that PRO membranes have the same price as RO membranes, which makes the resulting PRO cost lower than the actual cost, assuming that a PRO membrane is likely to be more expensive than an RO membrane. We also exclude intake and outfall cost. This is to account for the possibility that a PRO plant can be added to an existing SWRO plant, in which case the intake and outfall systems are already present.

In typical SWRO with 50% recovery (with the salinity range of 35–70 g/kg), the highest pressure is around 70 bar. For PRO system operating with similar salinity range (e.g., draw solution is the SWRO brine and diluted to 35 g/kg), the highest pressure involved is lower. Typically, the draw stream is pressurized to half the osmotic pressure difference at the inlet condition[1]. Hence, the cost of pressure vessels and pumps was excluded to avoid SWRO CapEx overestimating the PRO CapEx. Finally, we also excluded the CapEx associated with the pretreatment system because the best practice for pretreatment is not well-understood for PRO operation. Note that these assumption are consistent in that they all tend to lower the cost of PRO thus giving a *lower bound* on PRO's cost. All these exclusions resulted in 31% reduction in CapEx (averaged over plant capacity) relative to SWRO CapEx. This CapEx level should, therefore, serve as a lower bound for the CapEx of PRO.

2.2. Lower bound of LCOE

Both CapEx and OpEx contribute to LCOE. The OpEx contribution can be further broken down into labor cost, chemical and parts replacement costs[2].

$$\begin{aligned} \text{LCOE} &= \text{LCOE}_{\text{CapEx}} + \text{LCOE}_{\text{OpEx}} \\ &= \text{LCOE}_{\text{CapEx}} + \text{LCOE}_{\text{m}} + \text{LCOE}_{\text{labor}} + \text{LCOE}_{\text{chem}} + \text{LCOE}_{\text{parts}} \end{aligned} \tag{1}$$

We can work with each term separately starting with the $LCOE_{CapEx}$. In most infrastructure projects, a loan is made so that the CapEx can be paid in annual installments over some period of time. The annuity of the CapEx (i.e., constant yearly payment) can be calculated using the capital recovery factor (CRF), which is obtained by dividing the annuity by the sum of the annuity over the loan period (n) in present value. In other words, the annuity is the product of the total CapEx and CRF. A 25 year loan period and 8% interest rate [17] were used to evaluate the CRF. CRF can be calculated as:

[1] The choice of 50% of inlet osmotic pressure difference is not theoretically justified unless the system size is very small. See Section 5 for detail.

[2] Operating expenditures related to pretreatment energy cost or other energy input are captured in $\dot{W}_{net}$. So we should not double count these.