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A new reverse electrodialysis design strategy which significantly reduces the levelized cost of electricity

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ABSTRACT

We develop a framework for choosing the optimal load resistance, feed velocity and residence time for a reverse electrodialysis stack based on minimizing the levelized cost of electricity. The optimal load resistance maximizes the gross stack power density and results from a trade-off between stack voltage and stack current. The primary trade-off governing the optimal feed velocity is between stack pumping power losses, which reduce the net power density and concentration polarization losses, which reduce the gross stack power density. Lastly, the primary trade-off governing the optimal residence time is between the capital costs of the stack and pretreatment system. Implementing our strategy, we show that a smaller load resistance, a smaller feed velocity and a larger residence time than are currently proposed in the literature reduces costs by over 40%. Despite these reductions, reverse electrodialysis remains more expensive than other renewable technologies.

1. Introduction

A reverse electrodialysis stack consists of alternating layers of anion and cation exchange membranes sandwiched between two electrodes, which are connected in series to an external load resistor. Diluate and concentrate feeds are pumped between the layers, facilitating ion transfer along the membrane length and converting the chemical potential stored in the salinity gradient to electrical work. In the literature, aspects of the overall system performance have been improved through the introduction of smaller channel heights [1], profiled membranes [2], and ion conductive spacers [3].

Other improvements result from optimizing RED stack design parameters. Studies to date have focused on maximizing performance parameters such as stack power density [1,3–5], net power density (stack power density net of pumping power) [1,6], efficiency (or power per unit water) [4,5], and response product (efficiency times net power density) [7]. By contrast, our study represents the first cost-based optimization of RED stack design parameters. Specifically, we determine the optimal load resistance, residence time (length divided by feed velocity), and feed velocity based on minimizing the levelized cost of electricity produced. We show how the resulting cost-based design is different from the previous designs currently proposed in the literature. We also identify the important trade-offs involved in using this approach.

The optimal load resistance is explained by considering the trade-off between stack current and stack voltage. In literature, the load resistance is most often chosen by setting it equal to the equivalent stack resistance, as in traditional impedance or load matching, to maximize the power density delivered by the stack (the gross power density) [1,2,8]. This approach, however, is not optimal because of salinity variations along the stack [4,9]. We propose a more rigorous numerical maximization of the gross power density to determine the optimal load resistance and show, analytically, that the optimal load resistance is always smaller than the equivalent stack resistance. Additionally, we show that the load resistance which maximizes the gross power density also minimizes the levelized cost of electricity.

Another important trade-off is between power density and efficiency (or stack capital cost and pretreatment cost). Here, the relevant design parameters to consider are residence time, charge utilization, stack length, and feed velocity – two of which are independent. In a related study, Yip et al. [4] examined the effect of charge utilization on power density and efficiency separately, keeping the velocity large (effectively neglecting concentration polarization). We argue that the most complete and intuitive approach is to consider the effect of velocity (holding residence time constant) and residence time (holding velocity constant) on the levelized cost of electricity with concentration polarization considered. Framing the optimization in terms of velocity and residence time decouples the capital cost versus pretreatment cost trade-off from another important trade-off – concentration

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polarization losses versus pumping power losses. The result is a more intuitive understanding of the optimal RED stack design.

Based on the consideration of these trade-offs (see Fig. 1), we find that the optimal load resistance and the feed velocity are actually significantly smaller and the optimal residence time is significantly larger than values reported in the literature.

2. Methodology

Fig. 2 illustrates our recommended optimization approach for designing an RED stack. We design a step-wise approach for two reasons. First, the step-wise approach clearly quantifies the trade-offs in determining the optimal parameters. Second, the step-wise optimization simplifies the procedure for experimental validation by reducing the parameter space. We show that the loss in cost savings resulting from a step-wise optimization is negligible, and only one iteration is sufficient.

First we fix the residence time τ to an arbitrary value significantly larger than a critical residence time τ_c. While holding the residence time fixed, we minimize the levelized cost of electricity with respect to the superficial feed velocity and load resistance. Because the residence time is fixed, the stack length is implicitly varied as well. We show that this optimization step is equivalent to maximizing the gross power density with respect to the load resistance and maximizing the net power density with respect to the feed velocity. Then we fix the feed velocity and minimize the cost with respect to residence time and load resistance. Again, the stack length is implicitly varied in this step. Together, the optimal feed velocity and the residence time yield the optimal stack length.

In our analysis, we hold the diluate and concentrate channel heights constant and equal at 100 µm – the optimal channel height with respect to net power density identified by Vermaas et al. [1]. While smaller channel heights increase the gross power density, they also increase pumping power losses as well as manufacturing difficulty. Larger channel heights significantly reduce the gross power density, and the sensitivity of our results to channel height is explored in Section 6.1. We set the feed velocities equal and channel heights equal to simplify the system design. We suggest that the greatest cost reductions can be achieved through optimizing the load resistance, residence time, and feed velocity.

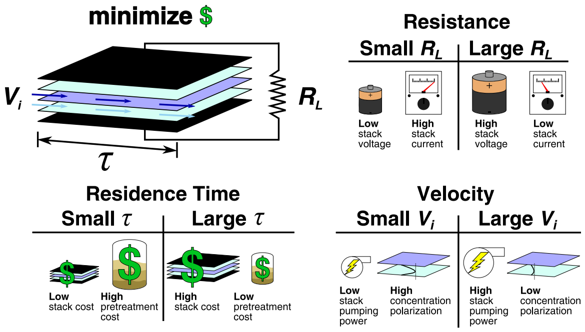

Fig. 1. The primary trade-offs associated with determining the optimal load resistance R_L, optimal inlet feed velocity V_i, and optimal residence time τ which minimize the levelized cost of electricity.

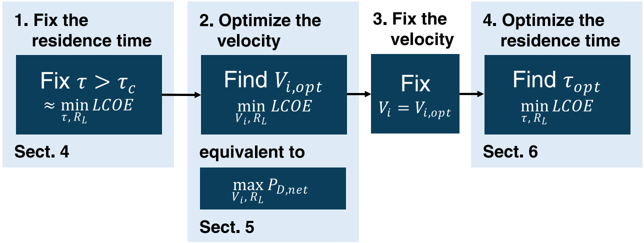

Fig. 2. An optimization method for RED stack design, where τ is the residence time and τ_c is the critical residence time, $LCOE$ is the levelized cost of electricity, R_L is the load resistance, and V_i is the superficial inlet feed velocity.

The first step in calculating the levelized cost of electricity for the optimization procedure is to model the net power density of the system – the gross power density less the pumping power density consumed in the pretreatment (PT) system and the stack. Our method is illustrated in Fig. 3. In Section 3, we show that the load resistance which maximizes the gross power density also minimizes the levelized cost of electricity. Hence, in modeling the gross power density we always maximize with respect to the load resistance.

The gross power density model itself is of an unsegmented-electrode RED stack, validated with experimental results from the literature. The model is one-dimensional, accounting for stream-wise variations in salinities, membrane potentials, and channel resistances along the stack. We base the model for pumping power consumed in the pretreatment system and stack on systems reported in the literature, and all equations were solved numerically using a quadratic approximation method in Engineering Equation Solver [10].

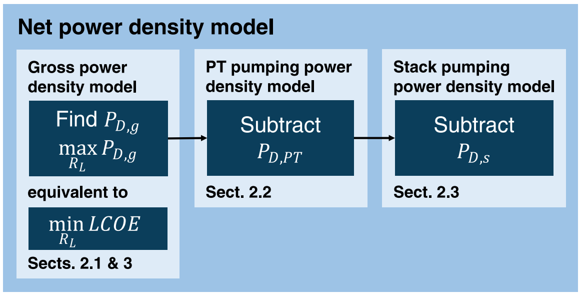

Fig. 3. The net power density of the system $P_{D,net}$ is the gross power density $P_{D,g}$ supplied by the stack, continuously maximized with respect to the load resistance R_L, less the power densities consumed in pumping the feed through the pretreatment system $P_{D,PT}$ and stack $P_{D,s}$.

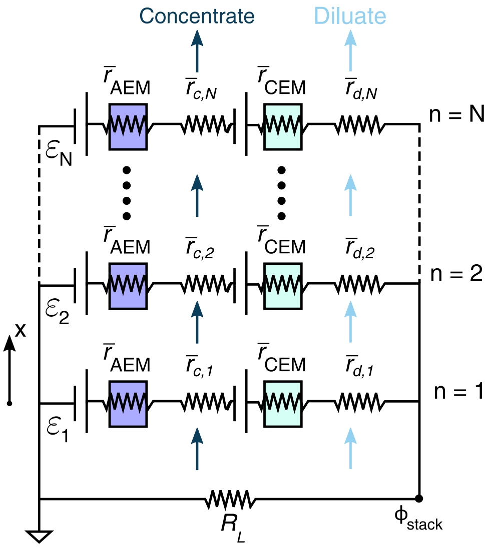

Fig. 4. A circuit model for the one-dimensional, unsegmented-electrode RED stack which accounts for streamwise variations in concentration.