Desalination 369 (2015) 140–148

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

# Increasing the power density and reducing the levelized cost of electricity of a reverse electrodialysis stack through blending

Adam M. Weiner *, Ronan K. McGovern, John H. Lienhard V

*Center for Clean Water and Clean Energy, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139 USA*

ARTICLE INFO

*Article history:*
Received 8 January 2015
Received in revised form 22 April 2015
Accepted 24 April 2015
Available online 16 May 2015

*Keywords:*
Reverse electrodialysis
Salinity gradient power
Renewable energy
Power density

ABSTRACT

We increase the power density of a reverse electrodialysis (RED) stack by blending the low salinity feed with a higher salinity stream before the stack entrance. This lowers the capital cost of the system and the resulting levelized cost of electricity, enhancing the viability of RED renewable energy generation. Blending increases the power density by decreasing the dominating electrical resistance in the diluate channel as well as the effective resistance caused by concentration polarization, but not without sacrificing some driving potential. To quantify this trade-off and to evaluate the power density improvement blending can provide, a one-dimensional RED stack model is employed and validated with experimental results from the literature. For a typical stack configured with a feed velocity of 1 cm/s, power density improvements of over 20% and levelized cost of energy reductions of over 40% are achievable, provided the salinity of the available river water is below 200 ppm. Additional cost reductions are realized through back-end blending, whereby the diluate exit stream is used as the higher salinity blend stream. Also, improvements from blending increase for higher feed velocities, shorter stack lengths, and larger channel heights.



## 1. Introduction

The objective of this study is to quantify the viability of blending as a design approach for improving the power density of future RED stacks installed at promising locations around the world. An examination of these locations suggests that salinity gradient power production through reverse electrodialysis (RED) could potentially provide 1 TW of clean, uninterrupted power globally [1]. However, the future competitiveness of RED as a renewable energy technology will depend upon the achievement of significant reductions in capital cost, through lower membrane prices and higher power densities [2].

As shown in a recent study of the financial feasibility of reverse electrodialysis [2], capital cost – driven by the gross power density of the stack – is the dominant contributor to the levelized cost of electricity produced by RED. Thus, raising the power density represents the greatest potential for enhancing RED viability.

One effective method for raising the power density is by reducing the electrical resistance through the stack. As evidenced by Fig. 1, significant improvements may be made by reducing the dominant diluate or low conductivity stream resistance $\overline{r}_d$. This reduction may be accomplished in any of the following three ways: by reducing the height of the diluate channel; by reducing the spacer shadow effect; or by increasing the diluate conductivity through blending a high salinity stream with the river water feed [3]. Both reducing the diluate channel height and reducing the spacer shadow effect have been studied extensively in the literature and can significantly improve the power density [4–6]. However, neither method is free from trade-offs. Reducing the diluate channel height increases the required pumping power [4], which lowers the net power density; such reduction may also be limited by manufacturing considerations. Similarly, reducing the spacer shadow effect increases the effective concentration polarization resistance [6].

Although raising the diluate conductivity through blending has its own set of trade-offs, it significantly reduces both the diluate and effective concentration polarization surface resistances, and should be given careful consideration. With blending, a fundamental trade-off is made between minimizing the diluate resistance and maximizing the driving potential for charge transport by optimizing the diluate salinity. As shown in Fig. 2, by blending a portion of the higher salinity stream with the river water before the RED stack entrance, the salinity of the river water may be increased. Optimization of the amount of blending allows the power density of the stack to be maximized.

Currently, there are many studies in the literature illustrating the trade-off between diluate resistance and driving potential, but there are no studies devoted to quantifying the power density gains made through blending. Weinstein and Leitz [8] and Lacey [9] modeled and computed the optimal diluate concentration in a zero-dimensional RED stack (a stack of infinitesimal length) with a seawater concentrate stream. Similarly, Veerman et al. [10] showed that the local power density in a one-dimensional stack (a stack of finite length) initially increases and reaches a maximum with respect to increasing local

* Corresponding author.
*E-mail addresses:* aweiner@alum.mit.edu (A.M. Weiner), mcgov@alum.mit.edu (R.K. McGovern), lienhard@mit.edu (J.H. Lienhard V).

http://dx.doi.org/10.1016/j.desal.2015.04.031
0011-9164/

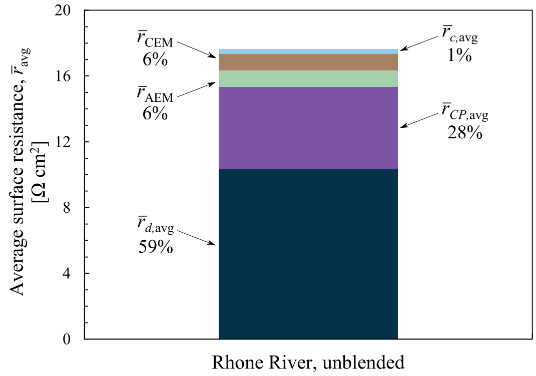


**Fig. 1.** Total resistive losses through a typical RED stack include contributions from the concentrate channel $\bar{r}_c$, anion and cation exchange membranes $\bar{r}_{AEM}$ and $\bar{r}_{CEM}$, effect of concentration polarization $\bar{r}_{CP}$, as well as from the diluate channel $\bar{r}_d$. Reduction of the diluate channel and effective concentration polarization surface resistances holds the greatest potential for improving RED power density. The case shown assumes a diluate feed from the Rhone River (339 ppm salinity [7]), a channel height of 100 μm, stack length of 10 cm, and feed velocity of 1 cm/s. Here, each contributing surface resistance is averaged over the RED length.

diluate concentration within the stack. The same trade-off is found in using electrodialysis for desalination. McGovern et al. [11,12] showed that removing salt from higher diluate salinity feeds significantly reduces the capital cost, because the resistance is lower.

Other studies have examined different feed waters for salinity gradient power generation, but none have considered blending the feed water as a design approach [2,13,14]. As an example, Daniilidis et al. [2] experimentally investigated RED power density and efficiency across a wide range of feed water salinities beyond river and seawater applications showing that power density continues to increase at very large salinity gradients despite reductions in permselectivity.

In a 2009 study of the various power output limitations in an RED stack, Dlugolecki et al. [3] mentioned blending as a possible means for reducing the resistance of the diluate channel, without specifically quantifying the potential power density improvements. The study cites early RED work by Weinstein and Leitz [8] from whose results it may be inferred that blending 600 ppm river water with seawater in a stack of infinitesimal length[1] could improve RED power density by upwards of 30%. Since Weinstein and Leitz's zero-dimensional study, significant advancements have been made in improving RED technology and stack design and in understanding and modeling the loss mechanisms as well. Absent from the current literature is a quantification of blending improvements since this progress.

In our study, we analyze the viability of blending in the context of the current modeling methods. First, we analyze blending using a one-dimensional model which accounts for streamwise variations in salinity. In Section 3.2, we show that, when inflowing river water is at 600 ppm, blending results in a minimal power density gain. Second, we analyze blending using a model which includes concentration polarization effects. We show in Section 4.1 that blending also reduces the effective concentration polarization resistance.

We also analyze the viability of blending in the context of recent designs. As an example, RED membrane resistances have decreased by over 90% since early RED development and no longer dominate resistive losses (see Fig. 1). Additionally, channel heights have decreased tenfold. We then extend the study by quantifying how blending may impact future stack configurations (see Section 4.3), concluding that improvements increase with shorter residence times and larger channel heights.

Lastly, we propose and analyze a blending configuration in which the diluate feed is recycled, see Fig. 3. In this configuration (termed back-end blending with diluate recirculation), recycling of the diluate feed reduces pretreatment system capital, operating, and energy costs — an additional benefit. We briefly analyze and discuss the cost advantages over front-end blending in Section 3.3.

## 2. Methods

To quantify the gross power density improvements achieved through blending, we model a single-cell RED stack accounting for salinity variations in the streamwise direction. We model three stack designs proposed in the literature, each characterized by different feed velocities — 0.5 cm/s [15], 1 cm/s [4], and 1.25 cm/s [16]. All three designs have 100 μm channel heights and 10 cm stack lengths. For each design, we maximize the gross power density with respect to the load resistance and inlet diluate salinity. We then compare this power density to the power density achieved with unblended river water (with the load resistance optimized) to evaluate the gross power density improvement.

To quantify the cost advantages of back-end blending over front-end blending, we model the RED net power density and levelized cost of electricity for the front-end and back-end blending cases, noting that for fixed velocities, the pumping power will be the same. As in the gross power density case, we repeat this analysis for three different feed velocities, keeping the stack length fixed.

### 2.1. Gross power density model

The RED gross power density model is based on the approach taken by Weiner et al. [15]. As in [15], we fix the diluate and concentrate channel heights $h$ and set them equal, as well as set the diluate and concentrate inlet feed velocities $V_i$ equal. This simplifies the stack design. Fig. 4 shows the cell pair circuit diagram, which is divided into $N$ discrete segments for modeling stream-wise variations in electromotive force (EMF) $\varepsilon_n$, diluate resistance $\bar{r}_{d,n}$, and concentrate resistance $\bar{r}_{c,n}$. The variations result from changes in salinity along the length due to salt and water transport across the membranes. For this analysis, we model 20 stack segments ($N = 20$). Additionally, we neglect variations in membrane resistance as well as the existence of ionic shortcut currents [17].

The local EMFs $\varepsilon_n$ are computed from the local chemical potential differences across the membranes [18]:

$$\varepsilon_n = \frac{t_s}{F}\left(\mu^s_{c,n} - \mu^s_{d,n}\right) + \frac{t_w}{F}\left(\mu^w_{c,n} - \mu^w_{d,n}\right) \tag{1}$$

where $t_s$ is the salt transport number, $t_w$ is the water transport number, $F$ is Faraday's constant, $\mu^s_{c,n}$ is the local salt chemical potential at the membrane surface on the concentrate side, and $\mu^s_{d,n}$ is the local salt chemical potential at the membrane surface on the diluate side. Blending reduces the difference between $\mu^s_{c,n}$ and $\mu^s_{d,n}$, driving the local EMFs down. This detrimental effect is a trade-off against reduced stack resistance brought about by the increased diluate salinity.

We model concentration polarization using a convection-diffusion approach [19] (diluate example shown):

$$C_{d,m,n} - C_{d,n} = \frac{2h}{\mathrm{Sh}_{d,n}} \frac{j_{D,n}}{F} \frac{\left(\overline{T}_{cu} - t_{cu}\right)}{D_{\mathrm{NaCl}}} \tag{2}$$

where $C_{d,m,n}$ is the local diluate concentration at the membrane (an input to $\mu^s_{d,n}$), $C_{d,n}$ is the local diluate concentration in the bulk, $j_{D,n}$ is the local current density (see Eq. (8) below), $h$ is the channel height, $t_{cu}$ is the counter-ion transport number (≈0.5 for anions and cations), and $D_{\mathrm{NaCl}}$ is the diffusion coefficient of salt through the bulk. $\overline{T}_{cu}$ is the

[1] An infinitesimal stack model does not account for streamwise variations in concentration as the diluate and concentrate travel through the RED channels. The present results are based on a one-dimensional model that incorporates the strong influence of streamwise changes.