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# The cost effectiveness of electrodialysis for diverse salinity applications

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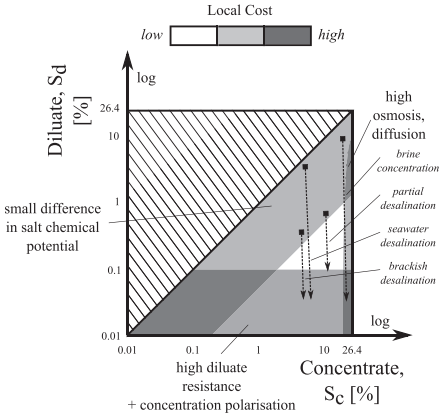
## HIGHLIGHTS

- Thermodynamic measures of efficiency and productivity are defined for ED.
- A cost metric is defined on the basis of free energy changes.
- Productivity and cost are constrained by limiting current density at low feed salinity.
- All three metrics are constrained by chemical potentials for high salinity feeds.
- Partial desalination of moderate to brackish waters lies in the sweet spot for ED.

## GRAPHICAL ABSTRACT

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## ABSTRACT

We provide a thermoeconomic assessment of electrodialysis indicating that the technology is most productive and efficient for the partial desalination of feed streams at the higher end of the brackish range of salinities. After optimising the current density to minimise the sum of energy and equipment costs, we demonstrate that at low feed salinities the productivity, and hence equipment costs, of electrodialysis are hampered by the limiting current density. By contrast, at higher feed salinities both productivity and efficiency are hampered by the reduced chemical potential difference of salt in the diluate (low salinity) and concentrate (high salinity) streams. This analysis indicates the promise of further developing electrodialysis for the treatment of waters from oil, gas and coal-bed methane as well as flue-gas de-sulphurisation, where the partial desalination of streams at the high-end of the brackish range can be beneficial.



## 1. Introduction

Electrodialysis involves the transfer of ions from a low salinity stream to a higher salinity stream — from diluate to concentrate. Together, the diluate salinity, the difference between diluate and concentrate salinity, and the ratio of concentrate-to-diluate salinity capture, via their effects on salt and water transport, the influence of salinity on cost. Our objective is to demonstrate that these three factors determine the influence of salinity on the cost-effectiveness of electrodialysis, and furthermore, that they have driven and will drive the selection of applications for which ED is worthy of development.

Recently, significant attention has been paid to the development of new electrical desalination methods [1–4], some of which report experimentally measured energy consumption close to reversible [2,4–6] and some of which report extraordinarily high salt removal rates per unit area [2,6]. Given the early stage of development of these technologies, there are interesting questions around their cost competitiveness at larger scales and, of interest in the present context, the range of

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salinities for which they are most economical. By analysing the effect of salinity upon the cost effectiveness of electrodialysis, a precedent is established allowing similar analyses to be conducted for emerging technologies as system models are developed.

No existing unified framework is available to explain, in a general sense, how diluate and concentrate salinities affect the cost of electrodialysis — though literature does provide certain distinct insights into the effects of salinity. At low diluate salinity, salt removal is restricted by the limiting current density and ohmic resistance is high. For brackish water desalination [7,8], and to a lesser extent salt production [9], the limiting current density effectively sets the size of equipment required. For the purification of higher salinity streams such as seawater [10] or produced water [11], currents are lowest (and, we surmise, capital costs highest) in the final stages of purification. High diluate resistance results in elevated energy consumption for brackish desalination, particularly due to the dominance of solution resistances over membrane resistances. Indeed, the challenges posed by a low diluate salinity are largely responsible for the development of narrow membrane channels [12], ion-conductive spacers within diluate channels (electrodeionisation) [13,14], hybrid designs combining ED with reverse osmosis [15–17], and theories to understand and possibly extend the operation of ED into the overlimiting current region [18]. With a large salinity difference between diluate and concentrate salinity, back diffusion of salt and water transport by osmosis degrades performance. In brackish desalination applications, this effect, coupled with the risk of scale formation at high concentrations, limits the recovery of feed water as a purified product. In concentrative applications, osmosis and diffusion serve to reduce the maximum concentration achievable in combination with the effect of water transport by electro-osmosis [19–22].

Our objective is to draw together the above insights and propose a unified framework explaining the influence of salinity upon the cost of electrodialysis.[1] Rather than modelling, in detail, a variety of electrodialysis processes, our approach is to consider a short cell pair that can represent a portion of any electrodialysis process.

## 2. Methodology

By understanding how the performance and cost of a short cell pair depend upon diluate and concentrate salinity, we can understand how overall systems will perform across different salinity ranges. Fig. 1 illustrates how the process in a two stage brackish water desalination system may be represented on a salinity map, and furthermore, how a short cell pair at any point in the system is represented by a point along the process path. Our approach consists of mapping the cost of this short cell pair process over the entire range of diluate and concentrate salinities. The consequent map of cost then allows us to assess the cost effectiveness of diverse ED processes.

To construct a map of cost we consider a numerical model of a short cell pair that allows us to parametrise diluate and concentrate salinity. We first establish a metric for the cost of separation. We then present a model for local salt transport, water transport and cell pair voltage. Finally, coupling these cost and cell pair models, and optimising for current density, we parametrise diluate and concentrate salinity to numerically investigate how they influence the 'Local Cost'.

### 2.1. The 'Local Cost' of separation

In a detailed analysis, costs associated with membrane replacement, chemical usage, the replacement of miscellaneous parts and pretreatment might be considered [23]. In this analysis we focus upon equipment and energy costs and determine the cost per unit time of operating an incremental cell pair as follows:

$$\text{Cost per unit time} = \frac{K_Q \delta A^{cp}}{CAF} + K_E \delta P. \tag{1}$$

Equipment costs are formulated as the product of a specific equipment cost per unit cell pair area $K_Q$ and the incremental cell pair area $\delta A^{cp}$ (with $\delta$ signifying an increment), together divided by the capital amortisation factor $CAF$ — which allows for a return on the investment in equipment:

$$CAF = \frac{1}{r}\left[1-\left(\frac{1}{1+r}\right)^{\tau}\right]. \tag{2}$$

Energy costs in Eq. (1) are formulated as the product of electricity price, $K_E$, and the incremental power consumption of the cell pair $\delta P$. Pumping power costs, typically smaller than stack power consumption in brackish [7] and salt production applications [9], are not considered as we focus on the trade-off between stack power and system size. Relative to stack power consumption, pumping power is most significant at low diluate salinity where the current density and hence the stack power density is small. That pumping power is a low fraction of total power at low salinity thus suggests that this should also be the case at higher salinities [7,24].

Setting pumping power aside, power consumption in the cell pair is therefore given by the product of cell pair voltage, $V^{cp}$, current density, $i$, and incremental cell pair area:

$$\delta P = i V^{cp} \delta A^{cp}. \tag{3}$$

Given the incremental cost of operating a cell pair we next establish a basis upon which this cost can be made specific. We consider costs on the basis of the rate of change in free energy of process streams. For a short (infinitesimal) cell pair, this rate of change is given by:

$$\delta G = \delta \dot{N}_s \Delta\mu_s + \delta \dot{N}_w \Delta\mu_w \tag{4}$$

where $\delta \dot{N}_s$ and $\delta \dot{N}_w$ are incremental molar flow rates of salt and water through the membranes, respectively, and $\mu$ denotes chemical potential, which takes the form of:

$$\mu_s - \mu_s^0 = RT\ln(\gamma m) \tag{5}$$

$$\mu_w - \mu_w^0 = RT\phi M_w \nu m \tag{6}$$

for salt and water respectively, with $R$ the universal gas constant, $T$ the temperature, $\gamma$ the mean molal salt activity coefficient, $m$ the molal concentration of salt, $\nu$ the number of moles of dissociated ions per mole of salt (2 for NaCl), $\phi$ the osmotic coefficient, $\mu_s^0$ the chemical potential of salt in its reference state and $\mu_w^0$ the chemical potential of water in its reference state.

The cost basis of free energy change, rather than water removal (e.g., \$/m$^3$ of water) or salt removal (e.g., \$/kg of salt), is based on the thermodynamic consideration that the difficulty of salt (or water) removal depends upon salinity. The difficulty of salt removal, as measured by the change in chemical potential in Fig. 2a, is greater when salt is removed (say into a saturated solution) from a lower salinity stream. By contrast, the removal of water (in pure form) is more difficult from a higher salinity stream.

[1] A similar approach might also be applied to analyse power generation with reverse electrodialysis technology, but here we focus upon electrodialysis.