Journal of Membrane Science 469 (2014) 326–335

Contents lists available at ScienceDirect

Journal of Membrane Science

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

The benefits of hybridising electrodialysis with reverse osmosis

Ronan K. McGovern [a,*], Syed M. Zubair [b], John H. Lienhard V [a]

[a] Center for Clean Water and Clean Energy, Massachusetts Institute of Technology, Cambridge, MA 02139, United States
[b] King Fahd University for Petroleum and Minerals, Dhahran, Saudi Arabia

ARTICLE INFO

Article history:
Received 10 March 2014
Received in revised form
17 June 2014
Accepted 20 June 2014
Available online 1 July 2014

Keywords:
Reverse osmosis
Electrodialysis
Hybrid

ABSTRACT

A cost analysis reveals that hybridisation of electrodialysis with reverse osmosis is only justified if the cost of water from the reverse osmosis unit is less than 40% of that from a stand-alone electrodialysis system. In such cases the additional reverse osmosis costs justify the electrodialysis cost savings brought about by shifting salt removal to higher salinity, where current densities are higher and equipment costs lower. Furthermore, the analysis suggests that a simple hybrid configuration is more cost effective than a recirculated hybrid, a simple hybrid being one where the reverse osmosis concentrate is fed to the electrodialysis stack and the products from both units are blended, and a recirculated being one hybrid involving recirculation of the electrodialysis product back to the reverse osmosis unit. The underlying rationale is that simple hybridisation shifts salt removal away from the lowest salinity zone of operation, where salt removal is most expensive. Further shifts in the salinity at which salt is removed, brought about by recirculation, do not justify the associated increased costs of reverse osmosis.

1. Introduction

Based on a comparison of the cost of water, we establish guidelines for choosing between stand-alone electrodialysis (ED) and hybrid electrodialysis-reverse osmosis (ED-RO) systems. By modelling the energy and equipment costs of electrodialysis as a function of product salinity we demonstrate the opportunity to reduce costs by shifting salt removal to higher salinity. Hybridisation of electrodialysis with reverse osmosis allows such a shift. Therefore, we model hybrid electrodialysis-reverse osmosis systems to establish when the benefits of hybridisation outweigh the costs of the reverse osmosis unit. We frame our models such that the decision between hybrid and stand-alone systems is based upon a cost ratio between reverse osmosis and electrodialysis systems, and consider this as a variable in our analysis.

Our interest in hybrid ED-RO systems is to further minimise the environmental impact and economic cost of brackish desalination, of which the latter has grown at an estimated annualised rate of 12% over the past 10 years [1] (see Appendix A). Brackish desalination involves the treatment of waters of slight (1,000–3,000 ppm total dissolved solids, TDS) to moderate salinity (3,000–10,000 ppm TDS) [2] present in naturally saline inland aquifers or coastal aquifers that have become subject to the intrusion of seawater [3] (see Fig. 1).

From environmental and cost perspectives, the ratio of water recovered to that withdrawn, known as the recovery ratio, *RR*, is an important consideration. A higher recovery ratio allows the following benefits: a reduction in the size of the desalination plant intake; a reduction in the volume of brine produced, which requires disposal to the sea, surface waters or confined aquifers below the aquifer from which water is withdrawn [5]; and a reduction in the rate of aquifer recharge required, which might be done continuously with treated waste water [4] or periodically with water sourced from another location during periods of low demand [6]. Conversely, a higher recovery ratio results in the production of higher salinity brine, which, depending upon the degree of dispersion and/or dilution employed at the point of disposal, can have adverse effects on plant and animal life [7]. We focus on scenarios where the benefits of reduced volumes outweigh those of increased salinity and consider technologies offering high recovery ratios.

Electrodialysis is well suited to applications requiring high recovery ratios for at least three reasons. Firstly, electrodialysis is a salt removal rather than a water removal technology, and so the majority of the feed water is easily recovered as a product. This is in contrast to reverse osmosis, where high recovery ratios require multiple stages in a continuous process (Fig. 2a) or longer process times in a semi-batch (or batch) process [8]. Secondly, electrodialysis is capable of reaching brine concentrations above 10% total dissolved solids (TDS), which is beyond the osmotic pressures reachable by current reverse osmosis systems [9,10]. Thirdly, seeded precipitation of scalants in the ED process can in some

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

http://dx.doi.org/10.1016/j.memsci.2014.06.040
0376-7388/

cases circumvent the barrier on water recovery imposed by the solubility of feedwater solutes; this has been demonstrated by recirculating the electrodialysis concentrate loop through a crystalliser [9,11,12] or a combination of a crystalliser and an ultrafiltration unit [10].

Although ED enjoys the advantage of high water recovery, costs increase with the amount of salt removal required (Fig. 2b). This is particularly true at low salinity where salt removal rates, which scale with the electrical current, are limited by the rate of diffusion of ions to the membrane surface. This phenomenon, known as the limiting current density, as well as the high electrical resistance of solutions at low concentrations, increases the costs of electrodialysis at low salinity. Thus, it is the synergy of ED providing high recovery and RO providing final high product purity that gave rise to analyses of hybrid ED–RO systems. The technical feasibility of these systems has already been demonstrated [10,12–16], but there are a limited number of studies benchmarking hybrid ED–RO systems against other technologies. To date, one study has compared hybrid ED–RO to a reverse-osmosis-mechanical-vapour-compression system and concluded that the hybrid system has lower upfront capital costs and lower operational costs [13].

In summary, electrodialysis can offer the benefit of higher recovery relative to reverse osmosis systems. Although the cost of water from a reverse osmosis system operating at lower recovery may be smaller, when brine disposal costs are taken into account, electrodialysis can be more cost effective [17]. In this paper we focus on scenarios where, overall, ED is more cost effective than RO and analyse the question of when it is preferable to hybridise electrodialysis with reverse osmosis rather than operate with electrodialysis alone. We also compare simple hybrid and recirculated hybrid system configurations.

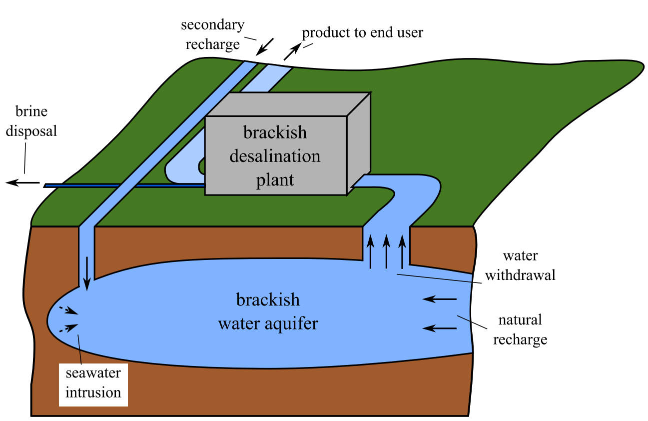

Fig. 1. The supply of freshwater and mitigation of seawater intrusion with brackish desalination and secondary recharge. Based on an aquifer management system proposed by Koussis et al. [4].

2. The rationale for hybridising electrodialysis with reverse osmosis

The rationale for hybridising electrodialysis with reverse osmosis is to relax the product purity requirements on the electrodialysis unit. Later, we will demonstrate how these requirements can be relaxed by comparing simple hybrid and recirculated hybrid designs to a stand-alone ED system, Fig. 3. First, to understand why the relaxation of product purity requirements can reduce ED costs, we focus on the stand-alone ED system and consider the dependence of the specific cost of water on product purity.

We consider a steady-state 1-dimensional model for the performance and cost of a stand-alone electrodialysis system. The total system area is divided, in the direction of the flow, into 20 stacks within which salt and water transport are approximated as uniform. These stacks serve the numerical purpose of discretisation and do not relate to the number of stacks within a real system. The key salt, water and charge transport equations, which are based on the approach of Fidaleo and Moresi [18] and McGovern et al. [19], are then applied to each stack. Membrane properties, flow rates and cell pair parameters are also taken from Fidaleo and Moresi [18] and are

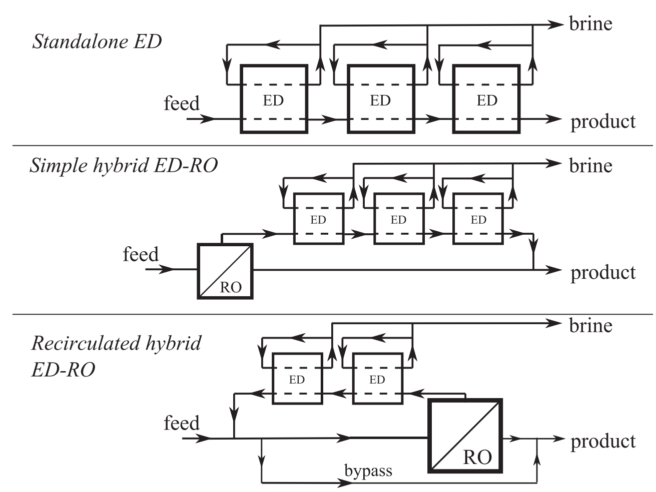

Fig. 3. Stand-alone and hybrid ED configurations. The relative size of electrodialysis (ED) and reverse osmosis (RO) units is intended to illustrate the relative quantities of membrane area required in each, assuming the final product flow rate from all systems is the same.

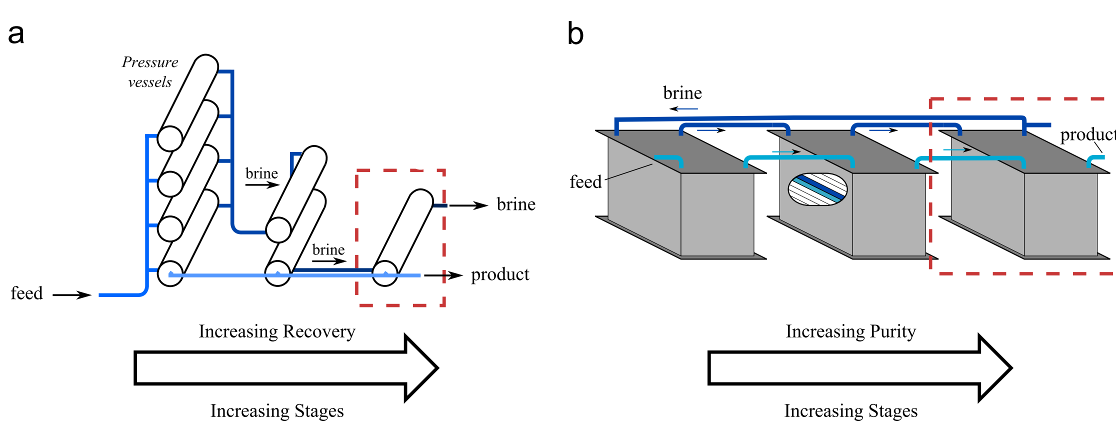

Fig. 2. The ability of electrodialysis to achieve high recovery and reverse osmosis to achieve high purity points towards an opportunity for hybridisation. (a) Reverse osmosis and (b) electrodialysis.