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Economic analysis of desalination technologies in the context of carbon pricing, and opportunities for membrane distillation

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HIGHLIGHTS

- Carbon tax increases water cost by 16% to 28%, with RO being least sensitive.
- With waste heat and carbon tax, MD is the most cost effective technology.
- Direct contact MD was shown to concentrate RO brine up to 361,000 mg/L TDS.
- MD cost can be as low as \$0.57 per m^3 water treated.
- We proposed a cost effective MD mode for harnessing low grade heat (<50 °C).

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ABSTRACT

The economics of membrane distillation (MD) and common seawater desalination methods including multi effect distillation (MED), multistage flash (MSF) and reverse osmosis (RO) are compared. MD also has the opportunity to enhance RO recovery, demonstrated experimentally on RO concentrate from groundwater. MD concentrated RO brine to 361,000 mg/L total dissolved solids, an order of magnitude more saline than typical seawater, validating this potential. On a reference 30,000 m^3/day plant, MD has similar economics with other thermal desalination techniques, but RO is more cost effective. With the inclusion of a carbon tax of \$23 per tonne carbon in Australia, RO remained the economically favourable process. However, when heat comes at a cost equivalent of 10% of the value of the steam needed for MD and MED, under a carbon tax regime, the cost of MD reduces to \$0.66/m^3 which is cheaper than RO and MED. The favour to MD was due to lower material cost. On low thermally, high electrically efficient installations MD can desalinate water from low temperature (<50 °C) heat sources at a cost of \$0.57/m^3. Our assessment has found that generally, MD opportunities occur when heat is available at low cost, while extended recovery of RO brine is also viable.

1. Introduction

Desalination is a means of producing fresh water from saline or brackish water by removing dissolved salts to make it suitable for human use, agricultural and industrial or manufacturing purposes [1]. With water shortages emerging across the world, communities are turning to desalination as a solution to reliable water supply. Cost and energy reductions for desalination are therefore considered an important factor to minimise the environmental impact of desalinated fresh water supply especially in arid and semi arid regions where there is little alternative. Commercial technologies for desalination include membrane separation processes such as reverse osmosis (RO) and electrodialysis (ED), as well as thermal processes, specifically multi effect distillation (MED), multi stage flash (MSF) and vapour compression distillation (VCD). These technologies are the most widely used desalination processes with MSF and RO dominating the market for both brackish and sea water with a total share of about 78% [2].

The techno-economic performance of these processes favours RO due to the continual advances made to reduce energy consumption and lower cost of water produced [3,4]. While most authors report RO as the less expensive process to recover fresh water these studies do not take into account imminent rises in energy prices. RO uniquely relies on electricity to operate, while the thermal processes can utilise waste heat or solar thermal energy more conveniently [3–6].

The US Bureau of Reclamation Desalination Roadmap 2003 [7] indicated that in RO, energy consumption accounts for 44% of the produced water cost, and fixed charges account for 37%. Together, these account for over 81% of the total desalination cost [7,8]. Similarly, it

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is known that for thermally driven desalination processes MSF and MED, the capital cost of the large metallic evaporators is very high, in the range of 40% to 50% of the total cost of water produced [1–9]. These systems thus conform to very different economics, and it is of interest to know where they fit economically under rising energy prices and the recent emergence of carbon pricing. Furthermore, alternative desalination processes that are not commercialised (or widely used) may be more economical from the perspective of capital and energy costs. They may also be easier to use and can potentially utilise a low grade heat source making them of considerable interest. One commercially emerging desalination technology that has different cost metrics and can harness waste heat sources is membrane distillation.

Membrane distillation (MD) is a thermally driven membrane process and may find an economically feasible niche amongst the commercialised desalination processes (MSF, MED and RO) which are considered to be technologically mature and therefore have very little space for major performance improvements [2]. The advantages of MD over commercialised desalination technologies are as follows [6]: (i) lower operating temperatures and vapour space required than MSF and MED (ii) lower operating pressure than RO (iii) more than 99.9% theoretical salt rejection (iv) the performance is not limited by high osmotic pressure or concentration polarisation. Four MD configurations have been identified: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD) and sweep gas membrane distillation (SGMD) [5]. The DCMD configuration was selected in our experimental work because of its simplicity and high water flux.

To date the commercial uptake of MD has not been significant and further work is needed to uncover real opportunities. Furthermore, other emerging technologies which are still in the research and development phase such as forward osmosis and freeze/thawing [1] indicate that despite the variety of commercial desalination systems, there is still a driver for more diversity in desalination options. In order to foresee the 'economic niche' of these emerging technologies, a cost analysis is needed to understand how they will fit within the desalination industry. The emerging technology that is the focus in this economic assessment is MD.

A desalinated water cost model for MD, like the benchmark RO and MED systems, is sensitive to several economic and technical factors such as energy source, plant capacity, salinity, and design features [5]. Among those factors, energy source and plant capacity have a dominating influence in addition to feed seawater salinity for the RO process [5–11]. The energy requirement of desalination has an important effect on the overall process economics that is more prone to suffer from variation in the cost of fossil fuels [12].

An extensive study of membrane distillation by Obaidani et al. [3], reports exergy analysis, sensitivity study and economical evaluation carried out to assess the feasibility of the direct contact membrane distillation (DCMD) process with heat recovery. They estimated a water cost of \$1.17/m^3, which is comparable with the cost of water produced by conventional thermal processes, i.e. \$1.00/m^3 for MED and \$1.40/m^3 for MSF [10]. The study also reveals that there is a high possibility of significant savings when a low-grade thermal energy source is used. The study claims that the cost is competitive with the cost of water produced by RO, which is about \$0.5/m^3 [11].

The Memstill project presented in 2006 by Hanemaijer et al. [13] claims to have the potential to reduce the cost of existing desalination technologies for seawater and brackish water, by replacing MSF and MED modules by an air gap MD module. The process proposes to reduce the desalination costs to \$0.26/m^3 using low grade thermal steam or heat as the driving force. Similarly, in a recent (2012) study by M.R. Qtaishat and F. Banat [14], the costs in sourcing the heat from solar energy was explored. The economics were found to be dependent on the cost and efficiency of the solar panels indicating that waste heat for MD is currently a more economically viable concept.

Despite these costing reports in literature, it is uncertain what desalinated water by any technology will cost in a carbon constrained society. In 2012, Australia implemented a \$23 per tonne carbon cost. A variable price will commence in 2015 when the Australian Government converts this to an Emission Trading Scheme [15]. With policies coming into practice to tax carbon emissions, the economics of each desalination process is therefore undergoing change particularly with the concept of MD using waste heat. Therefore one of the purposes of this work is to explore how carbon taxing will influence the cost of desalination and how the waste heat concept can give opportunities for MD.

1.1. Membrane distillation progress and technological challenges

MD is a hybrid of membrane and thermal desalination. The MD process classically uses membranes that are hydrophobic and microporous. The driving force is a vapour pressure difference across the membrane. The vapour evolved from the feed solution passes through the pores of the membrane and is collected as the condensate. Liquid water is prevented from passing the membrane thus creating a desalination effect over a very small space. Due to the convenient containment of the liquid surface using the membrane, higher packing densities bring it in line with state of the art RO compactness. This is typically achieved via different MD configurations, which are DCMD, VMD, AGMD and SGMD, which have been well described in the literature [16–19].

The standard thermal energy required to operate an MD system is 628 kWh/m^3 [20]. This value equates to a performance ratio (PR), or gain output ratio (GOR) of 1, being the mass ratio of water produced to the amount of steam energy (i.e., latent heat) fed to the process. This can be compared with state-of-the-art MED requiring about 2 kWh/m^3 of electric energy and 60 kWh/m^3 thermal energy as shown in Table 1. In the last few years, MD has emerged with numerous commercially oriented devices and novel process integrations to try to match MED thermal efficiencies. The most notable organisations specialising in MD modules or high efficiency systems are: Fraunhofer ISE (AGMD), Memstill and Aquastill (AGMD), Scarab (AGMD), Memsys (vacuum enhanced multi effect AGMD) [20]. The thermal energy required through Memstill's trials, is as low as 56 to 100 kWh/m^3 of water produced (GOR up to 11.2). This is the lowest value reported from real testing (or highest GOR), but to achieve this, the water must be heated to 80–90 °C.

In addition to high energy requirements, the other technological challenges of MD include module design, membrane fouling and scaling. These are well described in the literature [16,17,21–23]. Attractive advantages of MD are related to the possibility of overcoming the RO limit of around 70,000 mg/L (due to trans-membrane flux independent from feed concentration), process intensification and also its ability to operate at relatively low temperatures [7,17]. This enables MD to be a compact operation for further recovery of RO brines at low pressure, and reduce discharge volumes in areas where this is a significant cost (e.g. inland groundwater desalination).

Despite the potential of MD, it has not been significantly implemented since it was patented in the late 1960s. Research intensity picked up in the 1980s [5] due to rising water, energy and environmental issues. We have previously explored polymer and ceramic membranes for desalination, and explored MD in dairy processing and industrial process integration [24–28]. While MD researchers have already focussed on relative technology costs, process optimisation, module design and fouling, this paper presents results on a niche operation of extended RO recovery, as well as the relative price of MD under a carbon tax and in a modified operational mode.