ULTRAPERMEABLE MEMBRANES FOR BATCH DESALINATION: MAXIMUM DESALINATION ENERGY EFFICIENCY, AND COST ANALYSIS

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Abstract

Reducing the energy consumption of membrane desalination is critical to reducing its cost of water and minimizing desalination's CO_2 emissions. Hybrids of reverse osmosis (RO) with ultrapermeable membranes promise to address the efficiency, rejection, and fouling issues. In a batch reverse osmosis (BRO) process, salinity is varied over time so that the applied pressure better matches osmotic pressure, increasing efficiency. In this paper, the impact of ultrapermeable membranes in BRO are modelled, and a cost analysis is performed. The results show energetic advantages for the BRO over the best continuous RO configurations. Batch RO systems offer significant cost savings, and saves more energy than the use of ultrapermeable membranes in continuous RO systems. The two combined, BRO and ultrapermeable membranes, has the potential for the most efficient desalination systems yet proposed. However, low membrane cost is needed for ultrapermeable membranes to be viable.

I. INTRODUCTION

Ultrapermeable membranes have a higher water flux at a given driving pressure difference than conventional RO membranes [
1]. The possibility of reduced energy consumption has been considered in detail [2], showing that modest energy savings are achievable in steady flow RO systems, especially for brackish water, and that reduced system size is a strong possibility. However, concentration polarization limits the flux achievable in current configurations, for example, to only about four times what is typical for today's seawater RO [3]. Meanwhile, batch reverse osmosis (BRO) desalination systems have recently shown to be the most efficient membrane desalination configuration due to their matching of applied pressure to osmotic pressure [4-6]. By combining BRO with ultrapermeable membranes (U-BRO), the highest potential efficiencies for desalination can be reached. However, while BRO systems have cost savings, ultrapermeable membranes are more costly, and at present largely an immature laboratory technology.

In this study, modelling is done for the energy savings of batch RO versus alternatives, and a thorough cost analysis is performed for several RO configurations and a thermal technology for comparison.

II. METHODOLOGY

In this study, energy models are created to compare the energy needs and exergy destruction of several potential significant RO processes: steady single-pass reverse osmosis, batch reverse osmosis, and batch reverse osmosis with ultrapermeable membranes [6]. For fair comparisons, the design parameters, such as membrane properties and pump efficiency, are matched between models [7]. Performance is also compared with varied membrane permeability to capture the impacts of improved membranes. The numerical models are 1-D discretized systems solved as simultaneous differential equations in MATLAB [8, 9]. The details of the models are thoroughly described in other work [6, 10], and so are not covered here.

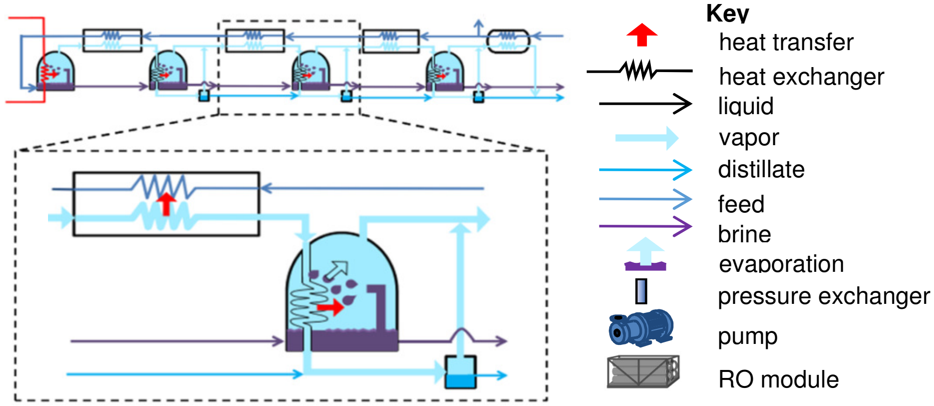

Fig. 1. Schematic diagram of multi-effect distillation (MED). Right: key for figures

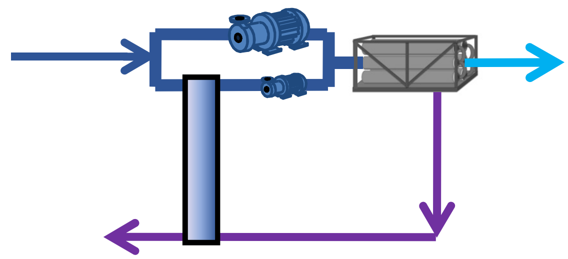

Fig. 2. Schematic diagram of a reverse osmosis (RO) system, with brine pressure recovery

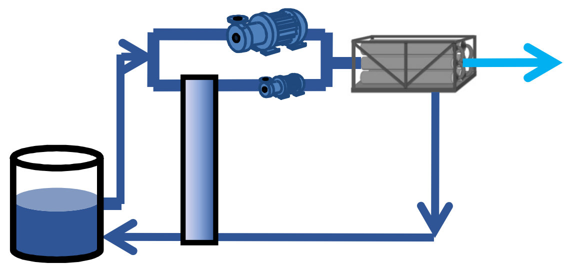

Fig. 3. Schematic diagram of a batch reverse osmosis (BRO) system, which uses a low pressure tank, and a high pressure recirculating flow loop which ramps up pressure over time, following the increase in osmotic pressure as salinity increases. Brine is not ejected until the end of a cycle.

The model used includes a 1D discretized system that includes time varying pressure, concentration polarization, membrane permeability, full aspects of inefficiencies in pressure exchangers [10, 11], and other details. This is most detailed BRO model published yet, and the details and expanded results are included in the paired paper in these proceedings [10]. In this system, the pressure is set for constant flux (to maximize efficiency).

Several key equations relevant to salinity and ultrapermeable membranes relevant here are described below [6, 12].

The membrane flux $J_w$is a function of the membrane area A, driving pressure ΔP, and osmotic pressure at the membrane $\Delta\pi_\mathrm{m}$:

$$J_w = A(\Delta P - \Delta\pi_\mathrm{m})$$

The osmotic pressure at the membrane is impacted by concentration polarization:

$$\Delta\pi_\mathrm{m} = \Delta\pi \exp\left(\frac{J_\mathrm{w}}{k\rho}\right)$$

Where k is the solute mass-transfer coefficient [m/s] and ρ is the density.

For the same overall flux, the driving pressure is described by:

$$\Delta P = \frac{J_\mathrm{w}}{A} + \Delta\pi.$$

At high salinity, $\Delta\pi$ is higher overall relative to $\frac{J_\mathrm{w}}{A}$ compared to in the case of low-salinity desalination. As a result, there is a greater opportunity to achieve an improvement in energy consumption by increasing A for a low salinity stream, compared to a high salinity feed stream.

The pump efficiency was 80%, and the average membrane flux was 14.5 LMH. The ultrapermeable membranes are assumed to have a permeability of 10 LMH, which has been achieved for graphene oxide RO membranes [13]. Meanwhile, the standard membranes are assumed to be 1 LMH. Mass transfer coefficient k is assumed to be a constant value of 2e-5 m/s [14]. All scenarios were assumed to have the same permeate quality.

III. RESULTS

The modeling analyzed energy savings of ultrapermeable membranes applied to batch RO. More detailed results from the model, and a full explanation, are given in an accompanying paper [10].

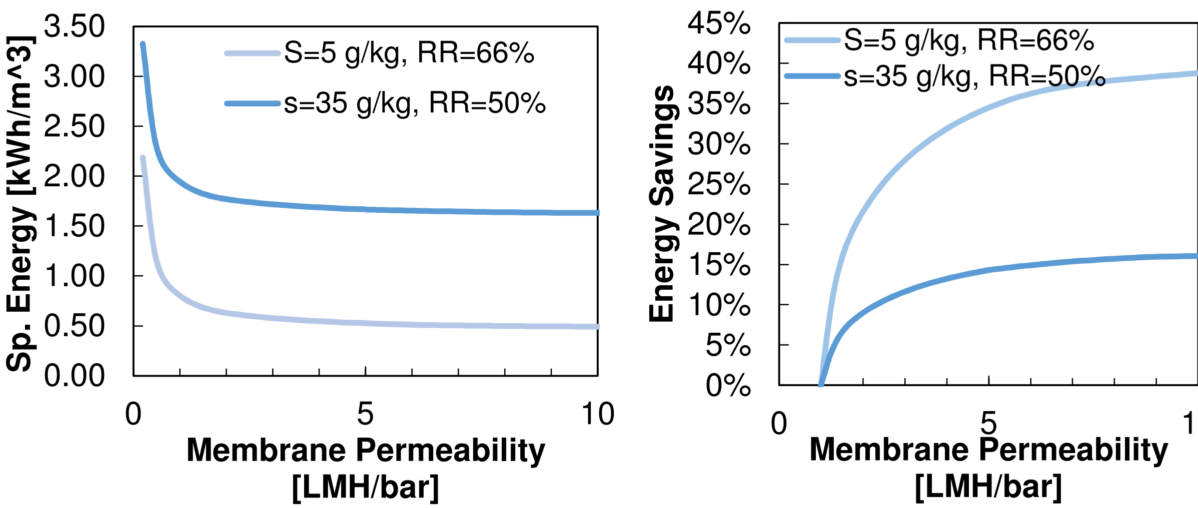

Fig. 4. Energy consumption in batch reverse osmosis based on permeability at high (seawater) and low (brackish) salinity. Left: total energy use, right: energy savings of BRO and U-BRO with increased membrane permeability, compared to a BRO system with membrane permeability of 1 LMH/bar.

Overall, the low salinity cases had a significantly larger benefit from the ultrapermeable membranes, and the return on permeability decayed less quickly. For seawater salinity, most of the savings (~13%) from ultrapermeable membranes were achieved by 4 LMH/bar permeability, while gains for low salinity (37%) did not diminish until about 7 LMH/bar. At these permeability values, a 10% increase in permeability results in less than a 2% gain in energy savings. Here the standard seawater RO permeability values were chosen at 1 LMH/bar [2], which represents many existing systems reasonably well [2, 15]. However, newer state-of-the-art modern membranes have reached 2 LMH/bar [16, 17].

Notably, high permeability polymeric membranes have achieved above 2 LMH/bar, so the benefits of the ultrapermeable membranes may be less worthwhile for high salinity desalination. However, for brackish water, relevant to water reuse, treatment of agricultural wastewater, etc., high permeability membranes offer significant gains and are worth considering.

The energy results for batch RO are impressive. For low permeability (1 LMH/bar) membranes at seawater salinity, the energy requirement was 1.94 kWh/m^3. Considering that the least work for this standard (seawater at 50% recovery) is 1.06 kWh/m^3, this yields a thermodynamic (second law) efficiency of 54%. For the high permeability case, the energy demand is 1.63 kWh/m^3, or an efficiency of 65%. Such a system, when implemented, would be the most efficient reverse osmosis system ever demonstrated.

For a lifetime cost assessment, cost analysis was performed for several combinations of reverse osmosis, and a comparison to the best thermal technology competitor: multi effect distillation (MED). MED was chosen for its relatively high efficiency and good scaling resistance due to the lack of membranes and the use of film evaporation rather than boiling.

For the analysis, data on plant costs by size were taken from review papers that synthesized plant cost data from several dozen sources. Lines of best fit were added to the ranges of cost and size for RO and MED plants, and the size of the plant dictated by this proposal was calculated with those fits. This figure was then combined with past analysis that used data to estimate overall costs by sub component for both RO variants [18-24] and MED [19-22, 24-26] breaking out capital costs, operating costs, and energy costs in detail.

The overall cost figures were broken down into capital costs, operating costs (excluding energy), and energy costs using the fractions identified by previous studies for both RO variants [26] and MED [23, 27]. Parts of the cost that only apply to the existing RO plant (e.g. pretreatment and intake) were adjusted. The cost of consumables was small. Compared to conventional seawater RO, BRO is anticipated to have a modest reduction (15%) in membrane replacement cost due to inherent osmotic backwashing, the potential biocidal benefits of salinity cycling, and reduced salt nucleation [28, 29]. Steel and equipment costs increased due to the need for tanks, additional pressure vessels and larger pressure exchangers relative to conventional RO. Figure 6 compares the cost breakdown of BRO versus MED.

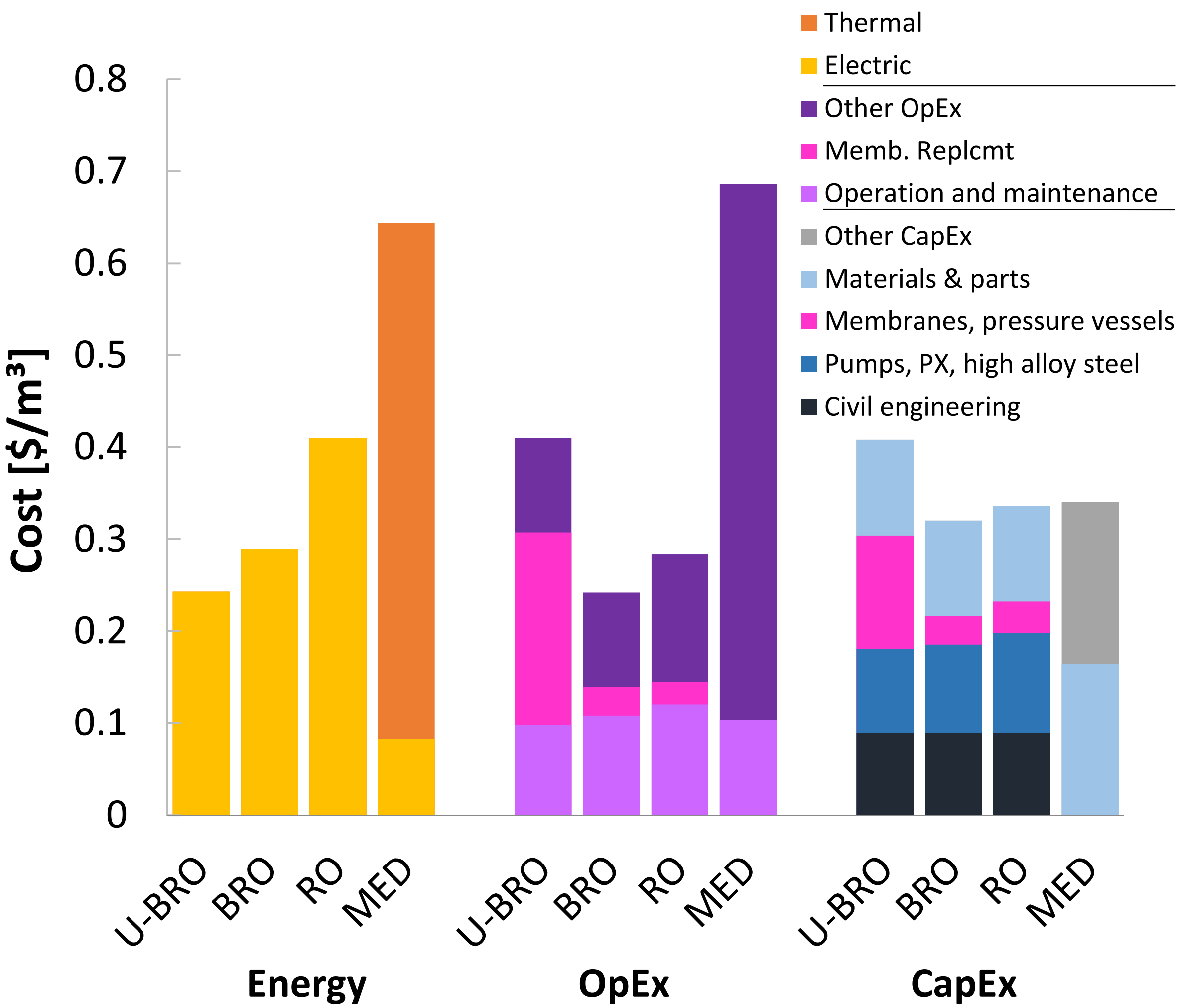

Fig. 5. Relative costs of different components in variants of RO and also MED. Calculated for a system size of 4,000 m^3/day. Includes ultrapermeable membrane batch RO (U-BRO), batch RO (BRO), standard single stage RO (RO), and Multi-effect distillation (MED)

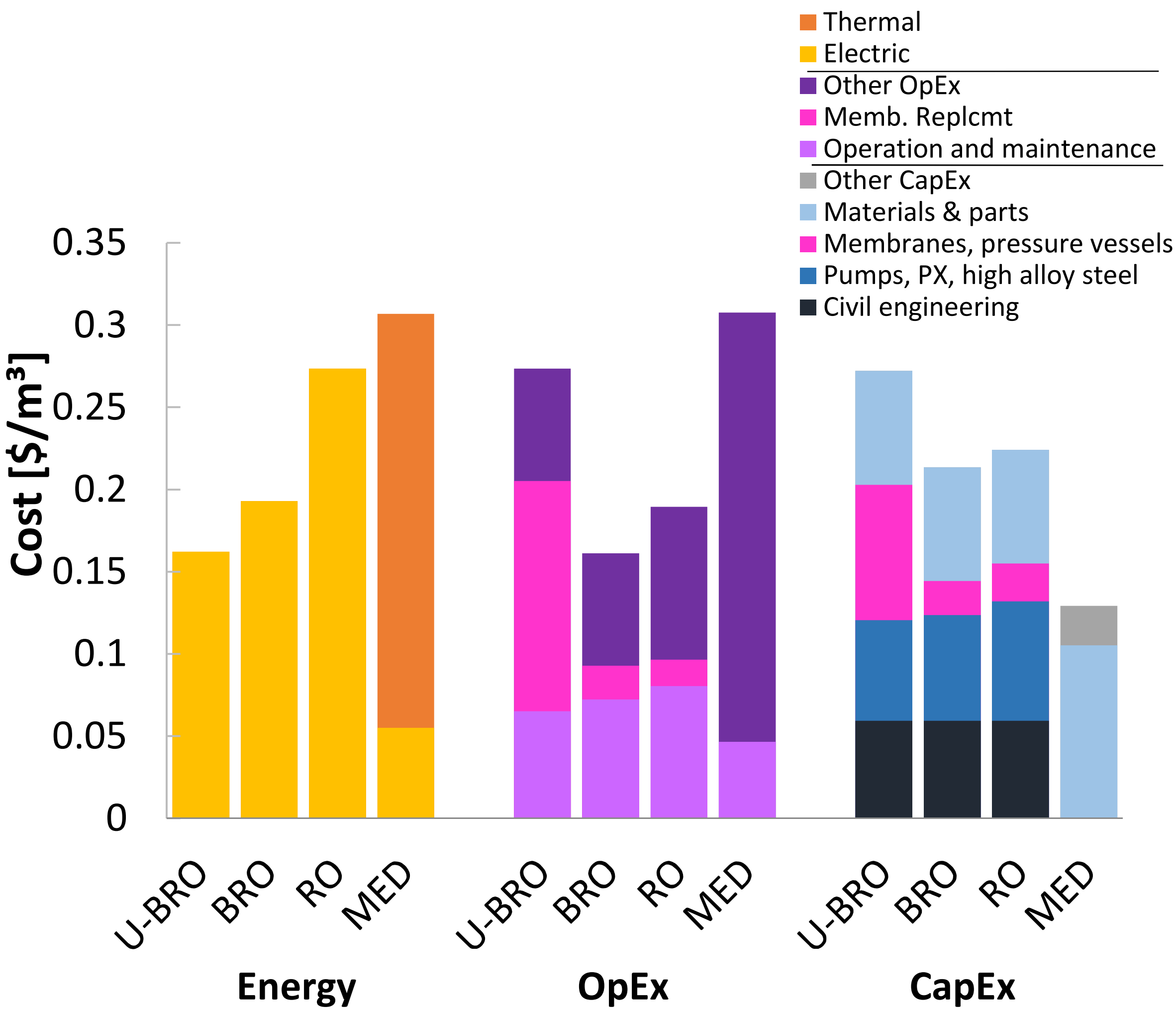

Fig. 6. Relative costs of different components in variants of RO and also MED. Calculated for a system size of 100,000 m^3/day.

Capital costs are similar and substantial for each technology. For BRO, there are expensive pressure vessels, while for MED there remains a large investment in copper piping. The operating costs are higher for MED due to an allowance for piping replacement in heat exchangers, and a larger number of components needing replacement. However, the real cost driver overall is energy: in MED paired with a power plant, the exergy of the fuel (which can burn at very high temperature) is largely used up in the cycle so using it at below 100°C has a small impact on energy produced by the plant. However, when natural gas (or a more expensive option like solar thermal) is used for the heating, there is no such synergy, and MED requires 67 $kWh_{thermal}/m^3$ plus ~1 $kWh_{electric}/m^3$. Batch RO only requires about 1.77 $kWh_{electric}/m^3$.

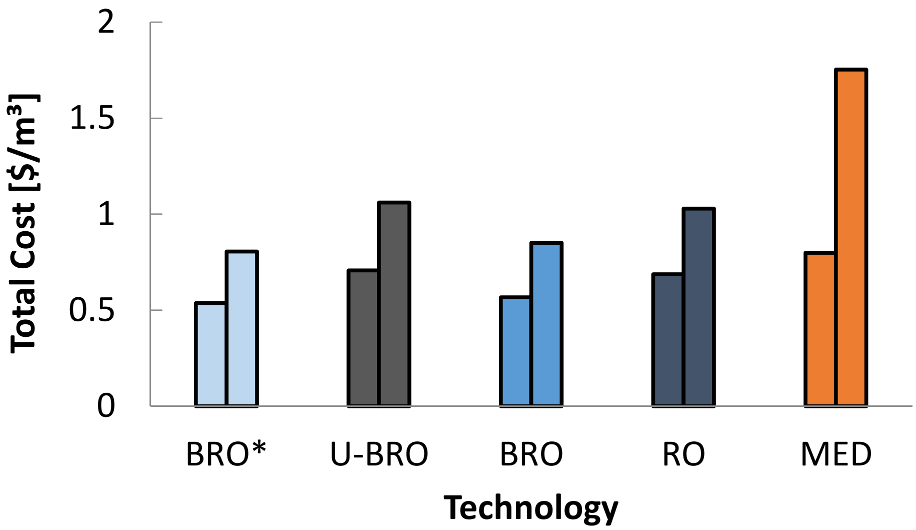

Fig. 7. Total costs by technology for seawater desalination. A large and small system were modelled for each technology: bars on left: system size of 100,000 m^3/day, bars on right: system size of 4,000 m^3/day. BRO* refers to BRO with no additional membrane costs, while U-BRO assumes 10x membrane costs.

As seen in Fig. 7, BRO is the cheapest technology for seawater desalination. BRO assuming no added membrane costs is lower, but assuming high costs of membranes (10x more expensive) as in ultrapermeable BRO (U-BRO), the ultrapermeable membrane case is less cost effective than even traditional RO. As expected, MED is much more price sensitive to system size, and has dramatic cost increases at the smaller size. Notably, the cost for thermal energy is based on data from MED systems that are tied to powerplants, and use low temperature steam . If natural gas was used without powerplant pairing at current average US prices [30], the thermal energy cost would be a dominating $1.42/$m^3$, calculated assuming a GOR of 12. It's critical to note that these numbers are averages from reviews, and that the total costs may vary by location, as will the relative performance of MED compared to the RO technologies.

IV. CONCLUSIONS

Overall, ultrapermeable membranes combined with batch reverse osmosis provided the lowest energy consumption of these options, but also lower than past modelling for achievable desalination systems. This energy demand for batch RO with ultrapermeable membranes was 1.63 kWh/m^3 (65% thermodynamic efficiency) for seawater at 50% recovery. However, the predicted high cost of ultrapermeable membranes means that traditional batch reverse osmosis (BRO) systems are cheapest overall. For ultrapermeable systems, the cost of the ultrapermeable membranes must not exceed 2.4 times that of traditional membranes to be cost effective. Larger increases of permeability are significantly more beneficial for lower salinity applications.

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VI. ACKNOWLEDGEMENTS

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