On the potential of forward osmosis to energetically outperform reverse osmosis desalination

Ronan K. McGovern[a], John H. Lienhard V[a]

[a] *Center for Clean Water and Clean Energy, Massachusetts Institute of Technology, Cambridge, MA 02139*

Abstract

We provide a comparison of the theoretical and actual energy requirements of forward osmosis and reverse osmosis seawater desalination. We argue that reverse osmosis is significantly more energy efficient and that forward osmosis research efforts would best be fully oriented towards alternate applications. The underlying reason for the inefficiency of forward osmosis is the draw-dilution step, which increases the theoretical and actual energy requirements for draw regeneration. As a consequence, for a forward osmosis technology to compete with reverse osmosis, the regeneration process must be significantly more efficient than reverse osmosis. However, even considering the optimisation of the draw solution and the benefits of reduced fouling during regeneration, the efficiency of an optimal draw regeneration process and of reverse osmosis are unlikely to differ significantly, meaning the energy efficiency of direct desalination with reverse osmosis is likely to be superior.

Keywords: forward osmosis, seawater desalination, reverse osmosis

1. Introduction

Energy consumption accounts for approximately 20-35% of the total cost of water in reverse osmosis desalination of seawater [1], and a greater fraction when the price of electricity is high. In this context, forward osmosis, a technology with the benefit of operating at low pressures [2–9], has been promoted as an alternative to reverse osmosis. Indeed, seawater desalination is very frequently cited as a motivating application for the study of forward osmosis; 17 of the 20 most cited articles that include the words ‘forward’ and ‘osmosis’ within their titles on the Thomson Reuters Web of Science Database address seawater desalination [2, 4, 5, 8, 10–25]. This level of interest in forward osmosis for seawater desalination is surprising given that FO processes have higher theoretical and actual energy requirements than reverse osmosis, though this is seldom acknowledged [26] or analysed.

In this context, we perform an energetic comparison of reverse osmosis, the most energy efficient commercial desalination technology [1], and forward osmosis, an indirect means of desalination, consisting of two steps; the dilution of a concentrated draw solution, and, its subsequent regeneration (Fig. 1). We outline how the draw-dilution step of Fig. 1 influences the theoretical and actual energy consumption of draw-regeneration, we assess how efficient draw-regeneration need be for forward osmosis to compete with reverse osmosis, and we outline what efficiency might be achievable by the most efficient draw-regeneration systems.

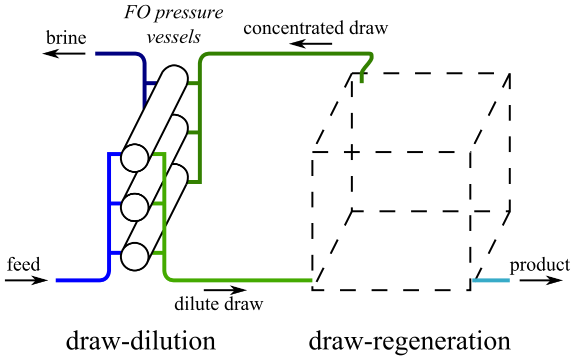

Figure 1: A two step desalination involving draw dilution by forward osmosis and a draw regeneration process

2. Thermodynamic limits upon draw regeneration

The minimum theoretical energy[1] required for the direct desalination of a feed stream depends upon the composition and the recovery ratio. For a seawater feed of 35,000 ppm total dissolved solids and a recovery of 50%, the theoretical energy requirement [27]

Email addresses: `mcgov@alum.mit.edu` (Ronan K. McGovern), `lienhard@mit.edu` (John H. Lienhard V)

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[1] The ‘minimum theoretical energy requirement’, which may also be termed the ‘minimum thermodynamic energy requirement’ or the ‘reversible work requirement’ will from here on, for brevity, be referred to as the ‘theoretical energy’.

of 1.05 kWh/m^3 places single-stage seawater reverse osmosis, with an energy consumption [1] of about 2.5 kWh/m^3, at a thermodynamic efficiency of about 42% (if pre-treatment, raw and treated water conveyance are excluded).

Since forward osmosis involves the initial transfer of water from the feed to a draw solution of higher osmotic pressure, the theoretical energy required for regeneration is different. Specifically, the theoretical energy required to remove an infinitesimal volume of pure water $\mathrm{d}V_p$ from a solution at an osmotic pressure of π is $\pi \mathrm{d}V_P$. On a volumetric basis, say in J/m^3 (equivalent to pascals), the minimum energy required is given by the osmotic pressure π. Thus, by first drawing water from a feed solution at π_F into a draw solution at π_D, the theoretical energy required to produce pure water increases by a factor of π_D/π_F.

The same arguments hold for a desalination process where a finite recovery (*e.g.*, greater than infinitesimal) of the feed stream is desired. Figure 2 illustrates a counter-flow draw dilution process where the relative mass flow ratio of the feed and draw are controlled to facilitate a driving osmotic pressure difference that is close to uniform. The feed salinity is a 35,000 ppm NaCl solution and the inlet draw osmotic pressure is 78.5 bar. The draw solution in this case is modelled as NaCl, though this is in-consequent as an almost identical osmotic pressure profile may be obtained with almost any draw solution[2] by tailoring the mass flow rate ratio. To calculate the theoretical energy for water production, the product of osmotic pressure and permeate production are integrated over the process:

$$E_T = \frac{1}{\dot{V}_P^{tot}} \int_0^{\dot{V}_p^{tot}} \pi(\dot{V}_P)\,\mathrm{d}\dot{V}_P \tag{1}$$

$$= \frac{1}{RR^{tot}} \int_0^{RR^{tot}} \pi(RR)\,\mathrm{d}RR \tag{2}$$

Figure 3 illustrates the effect of the mean osmotic pressure ratio (π_D/π_F — averaged over water permeation through the membrane) in Fig. 2 upon the theoretical energy required for draw solution regeneration. The theoretical energy penalty is the difference between the theoretical energy required for direct desalination and the theoretical energy for draw regeneration. Both the magnitude of this energy penalty, and the total theoretical energy required for draw solution regeneration depend only on the osmotic pressure of the draw solution and not on its chemical composition.

The magnitude of the energy penalty increases rapidly with an increasing osmotic pressure ratio. At a mean pressure ratio of 2.3 (mean osmotic pressure differential of 50 bar), the theoretical energy requirements for a forward osmosis process reach 2.5 kWh/m^3 — the *actual* energy requirement of energy efficient reverse osmosis plants. Therefore, if forward osmosis systems are to achieve energy efficiency that is comparable to RO, low osmotic pressure ratios during draw-dilution are a necessity.

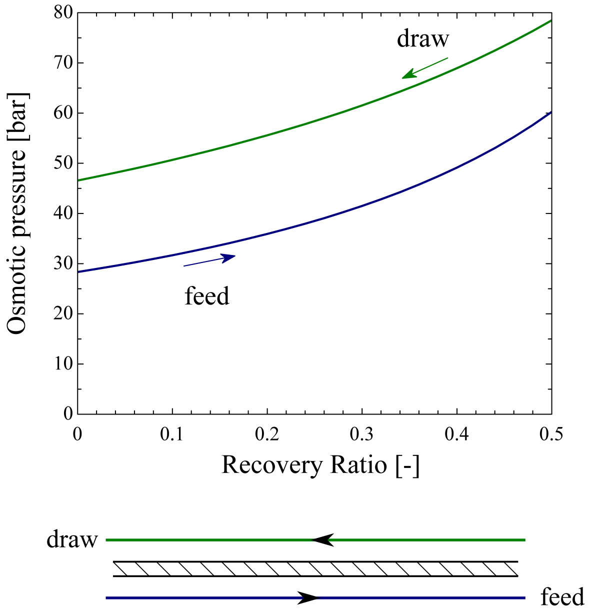

Figure 2: Counterflow feed concentration and draw solution dilution forward osmosis process. Feed stream of 35,000 ppm NaCl at 25°C. Draw solution of aqueous NaCl at an inlet osmotic pressure of 67.3 bar. Osmotic coefficients taken from Robinson and Stokes[28].

3. An energetic comparison of FO and RO

While reverse osmosis is typically electrically driven, the regeneration process in forward osmosis may also be thermally or chemically driven. Rather than delve into the amortised equipment (*e.g.* solar collectors or waste-heat exchangers) and fuel costs for various different direct desalination and draw regeneration processes, we compare FO and RO systems on the basis of their thermodynamic efficiencies. For the reverse osmosis process, the thermodynamic efficiency, η_R, is the ratio of the theoretical energy required to recover a defined portion of the feed water as a pure water product, E_T to the actual energy (or more strictly exergy [29]), E, required:

$$\eta_R^{RO} = \frac{E_T^{RO}}{E^{RO}} = \frac{\frac{1}{RR^{tot,RO}} \int_0^{RR^{tot,RO}} \pi_{sw}(RR)\,\mathrm{d}RR}{E}. \tag{3}$$

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[2] The saturation osmotic pressure of the draw must be above the maximum desired osmotic pressure

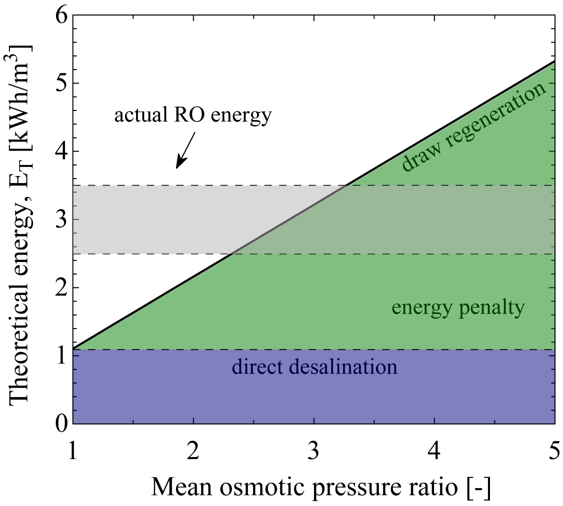

Figure 3: Effect of the mean osmotic pressure ratio upon the energy penalty imposed by draw solution dilution. Feed stream as in Fig. 2. Draw solution of aqueous NaCl with the inlet osmotic pressure and mass flow rate varied to achieve desired mean osmotic pressure ratio.

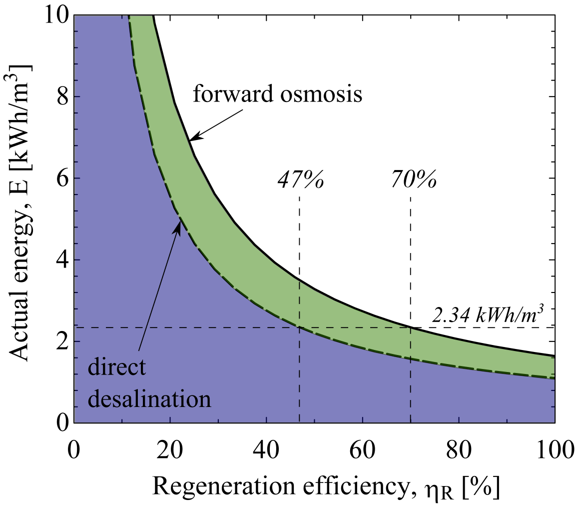

Figure 4: Effect of the efficiency of the draw regeneration process upon overall energy consumption. Feed stream of 35,000 ppm NaCl at 25°C and recovery ratio of 50% in all cases. Draw solution of aqueous NaCl with inlet osmotic pressure of 78.5 bar. The energy consumption of a typical single pass reverse osmosis system is indicated.

For a draw regeneration process η_R^{regen} differs only in that osmotic pressure of the draw solution, rather than of seawater, is integrated over the recovery ratio of the draw regeneration process:

$$\eta_R^{RO} = \frac{E_T^{regen}}{E^{regen}} = \frac{\frac{1}{RR^{tot,regen}} \int_0^{RR^{tot,regen}} \pi_{draw}(RR)\,\mathrm{d}RR}{E^{regen}}. \tag{4}$$

E^{regen} is the exergy required to drive the actual regeneration process, which for an electrically driven process equals the electrical energy required and for a thermally driven process is related, by the dead state temperature, T^0, and the temperature, T^{source}, at which heat, Q^{regen}, is supplied, by:

$$E^{regen} = \left(1 - \frac{T^0}{T^{source}}\right) Q^{regen}. \tag{5}$$

Thus, for a draw regeneration process, η_R^{regen} relates the theoretical energy required to restore the draw solution from its most diluted to its most concentrated state, to the actual energy required (again on a Second Law basis).

In our comparison, we parametrise the thermodynamic efficiency of both reverse osmosis and draw regeneration using η_R. We consider the desalination of a 35,000 ppm stream of NaCl, with RO and FO systems at a recovery of 50%. For the draw dilution process we consider a mean osmotic pressure difference of 19.4 bar (osmotic pressure ratio of approximately 1.5). This driving force is based on the net driving pressure for a typical seawater reverse osmosis system, Appendix A. A larger (smaller) osmotic pressure difference would result in a lower (higher) forward osmosis capital costs but higher (lower) theoretical and actual energy penalties. Setting the mean driving force in forward osmosis equal to that in reverse osmosis is perhaps conservative since flux is lower in FO (at the same driving pressure difference) due to concentration polarisation [12] and thus area requirements would be higher [30].

Figure 4 illustrates the actual energy consumption of the RO and FO systems. Whereas the theoretical energy penalty for a draw dilution desalination process is shown in Fig. 3, the actual energy penalty is shown, in green, in Fig. 4. The actual energy penalty is calculated as the theoretical energy penalty divided by the regeneration/direct-desalination efficiency. Its presence means that the actual energy consumption of forward osmosis is always above that of reverse osmosis if reverse osmosis and the draw regeneration process operate at the same efficiency.

To perform a more complete comparison we can compare the energy consumption for a forward osmosis system and a two-pass reverse osmosis system that includes pre-treatment, Table 3. Experiments suggest that forward osmosis exhibits lower rates of irreversible fouling than reverse osmosis [31] and thus might be expected to cope with lower levels of pretreatment. As a limiting case we can neglect pretreatment for forward osmosis and consider ultrafiltration pretreatment for reverse osmosis, estimating pumping power consumption of 0.1 and 0.3 kWh/m^3 respectively Appendix B. Assuming the FO draw regeneration process to be just as efficient as RO leads to an energy requirement of 3.48 kWh/m^3 for draw re-

Table 1: Comparison of two-pass reverse osmosis with forward osmosis assuming 47% efficiency for the first RO pass and for draw regeneration. 35,000 ppm NaCl feed @ 50% recovery.

Two-pass RO		FO	
	kWh/m^3		kWh/m^3
Ultra-filtration	0.16	Draw dilut.	0.10
RO - 1st Pass	2.34	Draw regen.	3.48
RO - 2nd Pass	0.50	-	-
Total	3.00	Total	3.58

generation, compared to 2.34 kWh/m^3 for the first pass of reverse osmosis (from Fig. 4). Thus, even allowing for the additional energy typically consumed in a second pass of reverse osmosis (0.5 kWh/m^3) [32, 33], the total energy consumption of reverse osmosis remains lower than forward osmosis.

4. An analysis of RO as a regeneration process for FO

According to Fig. 4, a single pass RO system must operate at an efficiency of η_R=47% to achieve a specific energy consumption of 2.34 kWh/m^3 (the energy consumption of a representative seawater RO process, see Appendix A). To match this performance, the regeneration portion of a forward osmosis system must achieve regeneration at an efficiency of η_R=70% — an increase of 23 percentage points. Since RO is currently the most energy efficient of desalination systems [27] (thermal regeneration systems are estimated to achieve about 6-8% efficiency[3] and, in the case of a thermally regenerated ammonia-carbon dioxide solution, energy requirements for a final reverse osmosis purification step may further reduce efficiency [35].) it is therefore important to analyse whether reverse osmosis, operating as a draw regeneration system, can significantly outperform reverse osmosis as a direct desalination system [36]. Five factors to consider include the possibilities of:

1. employing higher permeability nano-filtration membranes.
2. increasing permeability through optimisation of the draw solution composition;
3. increasing permeability by optimising temperature;
4. lower levels of fouling as a result of treating a clean draw rather than feed seawater; and
5. reducing feed flow rates per vessel (and thus energy consumption) due to lower fouling.

Although nano-filtration membranes offer superior permeability, they exhibit inferior solute rejection to reverse osmosis membranes. For example, the nominal $CaCl_2$ rejection of nanofiltration membranes is typically in the range of 89% [37], compared to normalised NaCl rejections of 99.8% [38] for RO membranes. Thus, the use of nanofiltration necessitates multiple passes of filtration [39] or draw solutes that are large in size [40]. Unfortunately, larger molecules (such as sucrose and glucose) typically exhibit lower diffusivities than NaCl, which result in stronger concentration polarisation and reduced flux in the draw dilution step. This is particularly true when the FO membrane is oriented in forward osmosis mode [41], as is typically necessary to minimise fouling [17, 42]. Thus, while large solutes such as glucose may allow the use of nanofiltration membranes, flux in the draw-dilution step is significantly reduced compared to using an NaCl draw solution of the same osmotic pressure [39].

An analysis of the effect of feed solution chemistry on the permeability of reverse osmosis membranes [43] revealed that permeability decreased with increasing ionic strength. Since the draw solution must be of higher concentration than the feed water, and thus typically of higher ionic strength, this suggests that RO regeneration is at a disadvantage compared to direct reverse osmosis treatment of the feed; at least if the draw solution is ionic. As previously discussed, non-ionic draw solutes (such as glucose and sucrose) are undesirable as they increase the membrane area required in the draw dilution step.

To analyse the effects of temperature, fouling and cross-flow optimisation upon energy consumption we perform comparative analyses of RO systems using membrane projection software [44]. Holding constant the feed composition and recovery ratio we vary the feed temperature, the fouling factor and the number of membrane elements per vessel one by one, as indicated in Table 2.

In FO-RO processes, since the draw solution is recirculated it can potentially be maintained at a temperature above that of the feed [45], with the objective of increasing membrane permeability. However, this effect is mitigated, particularly at temperatures above 25°C, by the increase in osmotic pressure with temperature [46]. Thus, the overall enhancement in efficiency in going from 25 to 40°C, 1.4% pts, is small.

When operating as a draw regeneration process, RO benefits from lower fouling rates than a direct seawater desalination process. The levels of fouling (flux reduced to 91% of nominal after 3 years [44]) might be

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[3] For seawater desalination at 50% recovery, Semiat et al. estimated energy requirements of 13 kWh/m^3, leading to an efficiency of 1.1/13 = 8% [34]. For 50% recovery of a 73,000 ppm NaCl feed stream in pure form, an actual auxilliary system power of 8.5 kWh/m^3 and an electrical input of 21 kWh/m^3 for mechanical vapor compression was reported by McGinnis [35]. Based upon a theoretical minimum requirement of 1.9 kWh/m^3 this suggests an efficiency of 6%. While the use of low temperature waste heat may reduce fuel costs, the capital costs of heat exchangers required to capture waste heat are typically prohibitive (see Appendix C).

Table 2: Influence of temperature, fouling and cross-flow optimisation on reverse osmosis efficiency, computed using membrane projection software [44] with a 35,000 ppm NaCl feed and operating at 50% recovery (see Appendix A).

	temp. [° C]	fouling factor [-]	membranes/ vessel [-]	average flux [lmh]	theoretical spec. energy [kWh/m^3]	actual spec. energy [kWh/m^3]	efficiency [-]
direct desalination	25	0.8	6	13.5	1.1	2.34	47%
temperature	40	0.8	6	13.5	1.1	2.27	+1.4% pts
fouling	25	0.91	6	13.5	1.1	2.30	+0.8% pts
cross-flow	25	0.8	5	13.5	1.1	2.33	+0.2% pts

considered similar to that of the second pass in a two pass RO system [45], rather than the levels of fouling seen when treating seawater from an open intake (flux reduced to 80% of nominal after 3 years [44]). A comparison of the energy consumption reveals that the improvement in efficiency, of 0.8% pts, remains small. While this analysis focuses on energy consumption it is true that there may be cost benefits if membrane replacement is reduced in hybrid FO-RO processes. However, the contribution of energy to the cost of water can be five times more important than the cost of membrane replacement, as seen in the analysis of Reddy and Ghaffour [47].

A further benefit arising from reduced fouling is a relaxation of the requirement for a minimum brine cross-flow velocity to reduce fouling [44] in the reverse osmosis unit used for draw regeneration. Holding the average flux constant, this would allow for operation with a larger number of shorter pressure vessels (fewer elements per vessel). The reduced viscous pressure drop within shorter vessels with reduced flow rates can allow for a slight reduction in feed pressure and energy consumption. However the improvement in efficiency, +0.2% pts, is small, in part due to the strengthening of concentration polarisation at lower cross flow velocities.

Ultimately, the draw-dilution step requires draw regeneration to be significantly more efficient (+23% pts) than direct reverse osmosis desalination if the overall energy consumption of forward osmosis is to be comparable. Though reductions in fouling and the optimisation of temperature can enhance the regeneration efficiency, these effects are an order of magnitude smaller than what is required. It appears, therefore, that forward osmosis is better suited to applications other than seawater desalination, particularly those where reverse osmosis cannot directly compete.

5. Comments on alternate forward osmosis applications

One implication of the energy penalty, imposed by draw dilution, is that forward osmosis research might increasingly focus on regeneration-free applications [48], *e.g.*, where the draw solution is a nutrient containing drink [49], a concentrated fertilizer [50], or a kill fluid for hydraulic fracturing [51]. Forward osmosis processes that dilute rather than concentrate the feed stream are a second option, whereby forward osmosis is used to dilute seawater feeds, prior to reverse osmosis desalination, by employing a low salinity 'impaired' source of water [52]. This dilution provides an energy benefit compared to direct desalination of seawater but an energy penalty compared to the direct desalination of the impaired stream. Perhaps the viability of pre-dilution will be decided by weighing the benefits of a dual-barrier FO-RO system versus the benefits of avoiding the energy penalty of draw-dilution in single-barrier RO desalination of the impaired stream [53].

Desalination applications where the osmotic pressures of feeds are too great for existing reverse osmosis technologies are also potentially promising for forward osmosis [54, 55]. Here, the alternatives to forward osmosis that desalinate feed streams directly are primarily evaporative technologies with efficiencies that draw regeneration processes can potentially surpass [35]. Meanwhile, evaporative technologies may well improve in efficiency [56, 57] and reverse osmosis may increase its reach in terms of osmotic pressure, perhaps through tiered processes [58], but until then forward osmosis may offer energetic advantages at salinities higher than seawater.

6. Conclusion

The draw dilution step in forward osmosis desalination systems places the draw regeneration process at a significant energetic disadvantage compared to direct desalination of the feed stream with reverse osmosis. Even with optimisation of the draw solution, and the benefit of reduced fouling in the regeneration step, the overall forward osmosis process is unlikely to approach the energy efficiency of reverse osmosis for seawater desalination. In this light, it appears best for forward osmosis research to focus fully on high salinity applications and applications that do not require draw regeneration, where reverse osmosis cannot compete.

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Appendix A. Seawater Reverse Osmosis Example

Basic input parameters for the base seawater reverse osmosis case are provided in Tab. A.3. A detailed list of parameters is provided in the Supplementary Electronic Information for this base case as well as the three other cases of Tab. 2.

Table A.3: Seawater reverse osmosis projection [44]

Feed source	open seawater intake
Feed TDS	35,000 ppm NaCl
Feed temperature	25°C
Recovery	50%
Membranes	SWC5
Elements/vessel	6
Pressure recovery	isobaric
Average flux	13.5 lmh
Net driving pressure	19.4 bar
Specific energy	2.34 kWh/m^3

Appendix B. Ultrafiltration and forward osmosis pumping power estimations

The maximum transmembrane pressure in ultrafiltration is in the region of 2 bar [59]. Assuming close to 100% recovery of water from the ultrafiltration unit and a pump efficiency of 70% this leads to power consumption of approximately 0.16 kWh/m^3 of product water from the entire system.

To estimate the pressure difference between the feed inlet and outlet and the draw inlet and outlet we employ the pressure difference of 0.6 bar between the feed inlet and the brine outlet in the RO base example of Appendix A. Assuming a pump efficiency of 70% this leads to an energy consumption of approximately 0.10 kWh/m^3.

Appendix C. Evaluation of heat exchanger costs in waste heat driven forward osmosis applications

Fuel costs may be minimal when low temperature waste heat is employed to drive a desalination process. However, the cost of heat exchangers required to capture waste heat is significant. This is largely because the lower the temperature of the heat source, the lower its exergy, and, consequently, the larger the amount of heat required and the higher the heat exchanger costs. For example, if we consider a draw solution regeneration process requiring E^{regen}=13 kWh of exergy per m^3 of product water desalinated (the electrical energy requirement computed by Semiat et al. for a thermally regenerated seawater forward osmosis process [34]), we can compute the heat exchanger size, p_{HX} [in kW$_t$/(m^3/day)] theoretically required for the process to be thermally driven by a heat source at temperature T^{source}:

$$p_{HX} = \frac{E^{regen}}{1 - \frac{T^0}{T^{source}}} \times \frac{\text{day}}{\text{hr}}, \tag{C.1}$$

where T^0 is the ambient temperature. The capital cost of the heat exchangers required can then be obtained by considering the cost of heat exchangers on a \$/kW$_t$ basis, which, according to a recent report, can fall roughly[4] within the range of \$500-2,000/kW$_t$ [60]. In Fig. C.5 we illustrate how the cost and size of the heat exchangers required depends upon the heat source temperature assuming, conservatively, a heat exchanger cost of \$500/kW$_t$. At low temperatures, the capital cost of heat exchangers becomes very large, in fact, much larger than the capital costs of multi-effect distillation plants [47] (or reverse osmosis plants for that matter, typically \$600-800/(m^3/day) [47]). Thus, unless low temperature draw regeneration (or desalination) processes can be developed with significantly lower exergetic requirements (or equivalently, significantly higher

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[4] This range depends in part on whether heat exchange occurs between two liquids, a liquid and a condensing fluid or a liquid and an evaporating fluid.

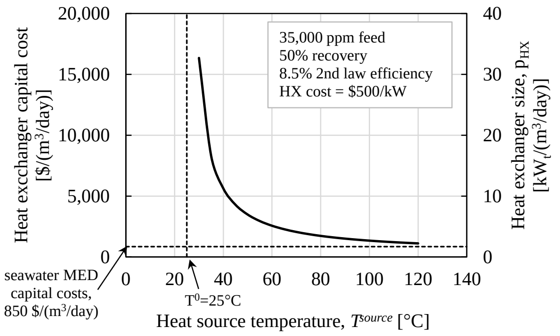

Figure C.5: When using low temperature heat sources to drive desalination the total heat input required, and thus heat exchanger size and costs, become very large. Here, heat exchanger costs are compared to typical capital costs for large scale multi-effect distillation systems [47].

2nd law efficiencies than existing thermal processes such as those documented by Mistry et al. [29]) heat exchanger costs pose a major barrier to desalination using waste heat.