Item title: Two-stage reverse osmosis: optimal element configuration and energy savings

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TWO-STAGE REVERSE OSMOSIS: OPTIMAL ELEMENT CONFIGURATION AND ENERGY SAVINGS

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Abstract

RO desalination can help to ensure secure water resources now and in the future, but the process remains energy intensive. Improving RO's energy efficiency is thus an important step towards achieving a sustainable water supply. While innovations in membrane and pump technology are not likely to substantially decrease the energy consumption of the RO process, improved system designs have real potential to bring RO closer to its thermodynamic performance limit. Two-stage systems can substantially lower RO energy consumption.

In a fixed size two-stage reverse osmosis (RO) system with eight membrane elements, the elements can be shared between the two stages in seven distinct element configurations. In this work, we investigate the optimal element configuration (system design) of a two-stage RO system. We isolate the energetic benefits of staging by comparing the energy consumption of a two-stage RO system to that of a single-stage RO system with the same system size and freshwater productivity. The optimal element configuration will place at least half of the elements in the first stage; the exact configuration depends on feed salinity, recovery ratio, and membrane permeability.

Previous studies on the energetic benefits of two-stage RO have not accounted for both the system size and the effects of concentration polarization. We evaluate systems with an average system flux comparable to today's systems and account for frictional losses and the effects of concentration polarization. This results in a more realistic evaluation of the energetic benefits of two-stage RO.

More energy can be saved by adding a stage when the thermodynamic least work of separation is larger. Therefore, energy savings from adding a second stage grow as recovery ratio increases. Significant energy can be saved with high salinity feeds at relatively low recovery ratios. We find that significant energy can be saved with the simplest two-stage RO design, at a system flux similar to today's RO plants and accounting for the effects of concentration polarization.

We perform a brief economic analysis to compare the relative capital expenses to the reduction in specific energy consumption (SEC) associated with a two-stage RO plant. We find that two-stage RO is probably not viable for seawater desalination at today's typical recovery ratios. If recovery ratios can be pushed up to 60%, two-stage RO could become viable with favorable financing terms and high cost of electricity.

I. MOTIVATION

A large portion of the costs associated with reverse osmosis is due to the capital costs and energy consumption [1]. While innovations in membrane and pump technology are not likely to substantially decrease the energy consumption of the RO process, improved system designs have real potential to bring RO closer to its thermodynamic performance limit [2]. Two-stage systems can substantially lower RO energy consumption [3].

Previous work has shown that there is potential to save energy in the RO process via staging [3-8]. However, most of these studies do not impose a restriction on the system size [3-7]. Other studies on staged RO do not model frictional losses or the effect of concentration polarization [8]. To our knowledge, no studies have investigated the optimal element configuration of a two-stage RO system.

In this work, we explore the effects of element configuration on the energy consumption of a two-stage RO system. We compare the energy consumption of an optimized two-stage seawater system to that of a single-stage RO system with the same size and freshwater production. We seek a realistic evaluation of the energetic benefits of staging by modeling frictional losses, concentration polarization, and using average system fluxes similar to today's RO plants. Finally, we investigate the potential for staged RO to save energy in the desalination of high-salinity feed streams, such as produced water resulting from oil and gas production.

II. MODELING

We implemented a mass-balance model of a spiral wound membrane element in MATLAB. The model predicts the required feed pressure needed to achieve the desired recovery ratio for a given feed flow rate and system size. The specific energy consumption of the RO process is then calculated using the feed pressure and feed flow rate.

The model accounts for frictional losses and the effects of concentration polarization. Each membrane element is divided into up to 32 cells, and we perform a mass balance between the feed channel of each pair of successive cells. We assume perfect rejection of salt. This is reasonable, given the performance of today's most permeable membranes. Since salt cannot pass through the membrane, it builds up on the surface of the membrane. This 'concentration polarization' reduces the permeate flux. We model the permeate flux and concentration polarization (CPF) by the Eqs. 1-3:

$$J_v = A(P - \pi_m) \tag{1}$$

$$w_{s,m} = \mathrm{CPF}w_{s,f} \tag{2}$$

$$\mathrm{CPF}{=}e^{J_v/k} \tag{3}$$

where J_v is the permeate flux, A is the membrane permeability, P is the feed pressure, π_m is the osmotic pressure at the membrane surface, $w_{s,m}$ is the salt concentration at the membrane surface, CPF is the concentration polarization factor, $w_{s,f}$ is the salt concentration in the bulk feed stream, and k is the mass transfer coefficient.

We validated our model by comparison to the Q+ Projection Software from NanoH2O (recently acquired by LG). We calculated the feed pressures required to achieve various recovery ratios with our model and compared to results from Q+. Figure 1 shows that our model is in good agreement with the Q+ model. Both models account for frictional losses and concentration polarization, but our model can obtain results beyond the operating regime of the Q+ model.

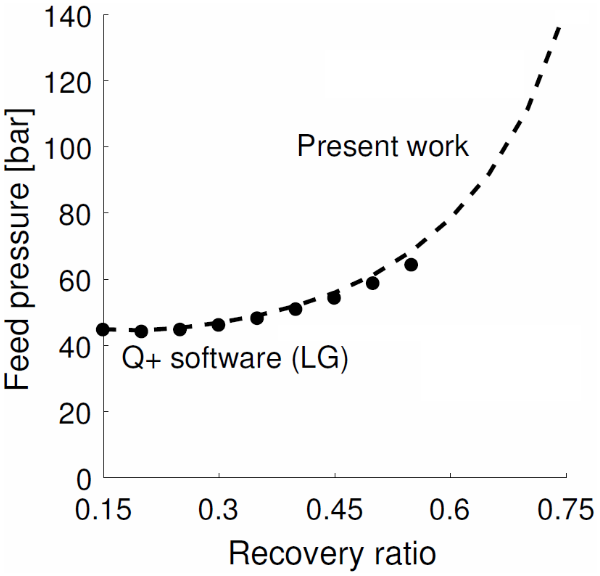

Figure 1: Feed pressure at fixed flux as a function of recovery ratio, comparing the present model to the Q+ software.

Feed streams are approximated by aqueous NaCl solutions. We used the equations developed by Pitzer et al. in order to capture the nonlinear behavior of osmotic pressure at high salinities [4,9]. Mass transfer coefficients and pressure losses were determined using correlations developed specifically for flow in spiral wound membranes [10,11].

III. OPTIMAL ELEMENT CONFIGURATION OF A TWO-STAGE SEAWATER RO SYSTEM

We use the numerical model presented in Section II to investigate the optimal element configuration of a two-stage seawater RO system.

Table 1: Configurations and parameters used to compare single-stage RO to two-stage RO at fixed membrane area and fixed flux.

	Single-stage RO	**Two-stage RO**	
Feed salinity	35	35	g/kg
Recovery ratio	0.7	0.7	-
System flux	15	15	L/m^2-h
Total membrane elements	8	8	-
Pump efficiency	0.85	0.85	-
Pressure exchanger efficiency	0.92	0.92	
Capital costs	1 pressure vessel, 1 high pressure pump, 1 booster pump, 1 pressure exchanger,	2 pressure vessels, 2 high pressure pumps, 2 booster pumps, 2 pressure exchangers	

We sought to make a fair and realistic comparison between the two-stage seawater RO system and a single-stage RO system. Therefore, we keep the system average flux and system size (total membrane elements) constant, as shown in Table 2. The total energy saved by moving to a two-stage RO system must be weighed against the additional capital costs required by the second stage.

The energy consumption of a two-stage RO system can vary depending on the intermediate and final feed pressures (system operation). We show all possible energy consumptions of every element configuration in Figure 2. The black bars represent energy consumptions greater than the corresponding single stage system. Gray bars represent energy consumption smaller than the corresponding single stage system. Every single element configuration can consume either more or less energy than the single stage system.

Extreme element configurations (one or seven elements in the first stage) can consume more than twice the energy of the single-stage system if operated poorly. If operated in an optimal manner, the extreme configurations could consume less energy than the single stage system. The optimal element configuration places five elements in the first stage and three elements in the second stage, achieving an energy savings of 0.95 kWh/m^3 at an energy consumption of 2.7 kWh/m^3. Very similar energy consumptions can be achieved with four or six elements in the first stage. Smart system operation can compensate for a poor system design.

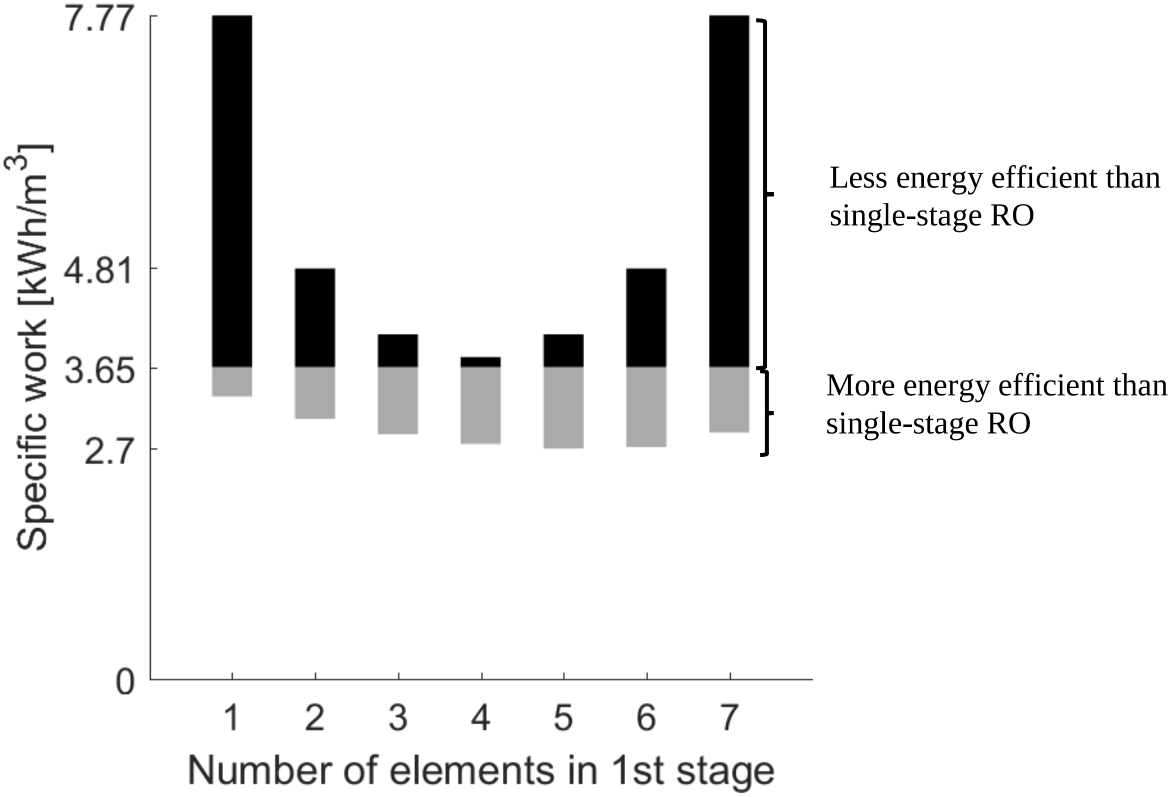

Figure 2: Specific energy consumption of a two-stage RO system under various operating conditions. The system can consume more (black bars) or less (gray bars) energy than a corresponding single-stage system of the same size and freshwater productivity, depending on the system design and operation. For this seawater RO system (J_{sys} = 15 L/m^2-h, $w_{s,f}$ = 35 g/kg, RR = 0.7), the optimal element configuration places five elements in the first stage. Similar energy consumption can be achieved with four elements in the first stage.

IV. TWO-STAGE RO WITH HIGH-SALINITY PRODUCED WATER

In this section we consider the energetic benefits of adding a second stage to a RO system treating high-salinity produced water. Produced water can be up to nine times as saline as seawater [12]. In this example, we model produced water with an aqueous NaCl solution ($w_{s,f}$ = 95 g/kg). We use pump and pressure exchanger efficiencies of 100%, establishing a lower bound for the energy saved by adding a second stage [13].

In Figure 3, we show the energy saved by moving from a single-stage RO system to an optimized two-stage RO system for seawater and produced water feeds at various recovery ratios. All systems have eight total membrane elements and an average system flux of 15 L/m^2-h. For the seawater feed, an energy savings of 1 kWh/m^3 is not achieved until the recovery ratio is greater than 0.7. For the produced water feed, an energy savings of 1 kWh/m^3 can be achieved at a much lower recovery ratio.

Larger energy savings is not equivalent to a lower energy consumption. For a fixed feed salinity, the thermodynamic least work of separation increases with recovery ratio. The single-stage RO and optimized two-stage RO energy consumptions will also increase with recovery ratio. We simply present the energy that would be saved by moving to a two-stage system at specific operating conditions.

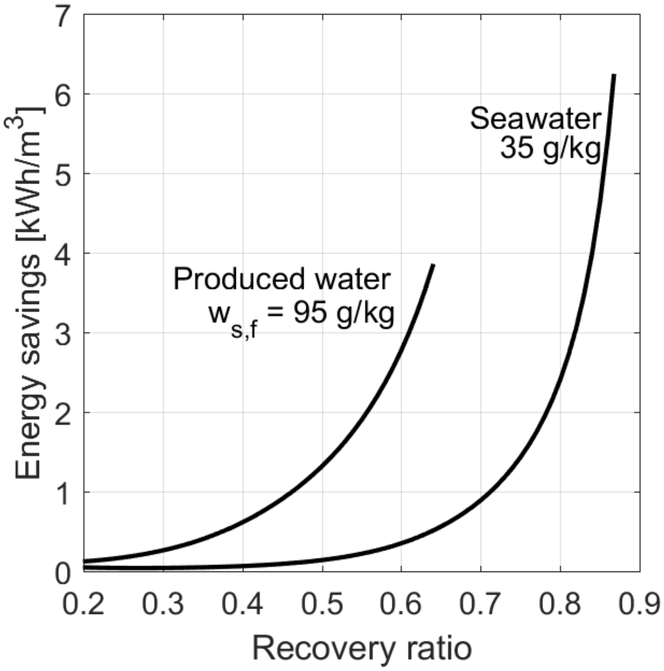

Figure 3: Energy saved by moving from a single-stage RO system to an optimized two-stage RO system of the same size (8 membrane elements) for different feed salinities as a function of recovery ratio. The potential to save energy grows as the thermodynamic least work of separation grows (i.e. at higher salinity). Significant energy can be saved with a produced water feed at relatively lower recovery ratios when compared to a seawater stream.

V. ECONOMIC VIABILITY OF TWO-STAGE RO

In this section we assess the economic viability of a two-stage SWRO plant. Our baseline is a single-stage SWRO plant with a capacity of 10,000 m^3/d, operating at a recovery ratio of 0.5 and system flux of 15 L/m^2-h. We compare the baseline case to a two-stage SWRO plant with an equal capacity, recovery ratio, and system flux. We estimate the additional capital and operating expenses associated with the components needed to add a second stage. These additional expenses must be outweighed by the energy savings associated with a two-stage RO system. We calculate those energy savings and then determine regions where the two-stage RO plant might be economically viable based on local electricity prices.

In this analysis, we hold the number of membranes constant in both the single-stage case and the two-stage case. Thus, capital expenses and replacement costs associated with membranes are assumed to be the same between both systems. In reality, the membrane replacement costs for the two-stage system may be slightly lower than the single-stage case due to a more uniform flux distribution.

Additional pressure vessels, pumps, motors, and pressure exchangers are required for the second stage. Their costs are outlined in Table 2 [14]. The high pressure pumps for the second stage must be designed to handle a high suction pressure and thus are more expensive than the high pressure pumps in the first stage.

Table 2: Summary of capital expenses for a second stage. The number of each component required is based on a capacity of 10,000 m^3/d system operating at an overall recovery ratio of 0.5 and a first-stage recovery ratio of 0.27.

	Cost [$]	Capacity [m^3/d]	Number	Total Cost [$]
Pressure Vessels	1,945	-	94	182,830
High pressure pump	75,000	1000	7	525,000
Booster pump	17,000	720	10	153,000
High pressure motor	12,000	-	7	84,000
Booster motor	4,000	-	10	40,000
Pressure exchanger	24,000	1000	10	240,000
Total Cost [$]				**1,241,830**
EAC [$]				**111,405.40**

Many of these components must be replaced throughout the lifecycle of the plant. The replacement costs are annualized and outlined in Table 3 below. All components are assumed to have a replacement rate of 0.1 as in [14].

Table 3: Summary of replacement costs for second-stage components.

	Replacement rate	**Capital expense [$]**	**Replacement Cost [$]**
Pumps	0.1	695,000	69,500
Motors	0.1	124,000	12,400
Pressure exchangers	0.1	240,000	24,000
Total Cost [$]			**105,900**

Next, we calculate the equivalent annual cost of the capital expenses according to Eq. 4:

$$\text{EAC}=\frac{i(1+i)^n}{(1+i)^n-1}C_{CAPEX} \tag{4}$$

where i is the annual interest rate, n is the expected plant life in years, and C_{CAPEX} is the total capital costs of the plant. In this analysis, we use an interest rate of 7.5% and a plant lifetime of 25 years. These financing terms are less than ideal in order to slightly overestimate the expenses of adding a second stage.

We then add the equivalent annual cost to the annual replacement costs to determine the total annual costs of owning and operating the two-stage plant RO relative to the single-stage RO plant. The energy savings achieved by the two-stage RO plant when operating at a recovery ratio of 0.5 are relatively low (0.12 kWh/m^3), so the price of electricity would have to be 48 ¢/kWh in order for the two-stage RO plant to be viable. Very few, if any, places in the world pay such high prices for electricity. This suggests that at current performance parameters, two-stage RO is not currently an economically viable option for seawater desalination.

In Table 4, we look at the required electricity price for a two-stage RO plant at recovery ratios higher than typically seen in today’s SWRO plants. At a recovery ratio of 0.55, the required electricity price falls to 27 ¢/kWh. At this point, two-stage RO might become an option in regions with the highest electricity prices, such as Italy and Brazil.

At even higher recovery ratios (RR=0.6) the required electricity price falls to 15 ¢/kWh. Two-stage RO might become an option in Japan at that point. At even higher recovery ratios (RR=0.65), the required electricity price is only 8 ¢/kWh, well within reach of many regions around the world. As the recovery ratio increases, the brine flow decreases and thus fewer booster pumps, motors, and pressure exchangers are required. This leads to far capital and replacement costs. The reduction in SEC associated with two-stage RO also starts to grow faster at higher recovery ratios.

Table 4: The required electricity price for a two-stage RO system to be economically viable based on the annual additional costs of a two-stage RO system relative to the baseline single-stage system and the resulting reduction in SEC, at various recovery ratios. If RO systems can be pushed to slightly higher recovery ratios, two-stage RO may become an attractive option in many regions around the world.

Recovery Ratio	**Annual cost of a second stage [$]**	**Energy savings [kWh/m^3]**	**Break-even electricity price [¢/kWh]**	**Viable regions**
0.5	220,000	0.12	48	N/A
0.55	209,000	0.21	27	Islands
0.6	192,000	0.35	15	Italy, Brazil, Japan
0.65	167,000	0.57	8	Italy, Brazil, Japan, Israel, USA

VI. CONCLUSIONS

The optimal element configuration of a two-stage RO system will place at least half the elements in the first stage; the exact configuration will depend on the feed salinity, recovery ratio, and membrane permeability. System operation can compensate for a suboptimal element configuration. In most cases, placing half the elements in each stage will result in energetic performance relatively close to the global optimum.

Energy saved via staging increases with the thermodynamic least work of separation. Therefore, significant energy could be saved with a high-salinity produced water feed at lower recovery ratios than a seawater feed.

We identify the operating conditions where the energetic benefits of adding a second-stage to a single-stage RO system are greatest. Some of the most promising regimes can only be achieved after additional membrane development, to enable operation at higher pressures or to avoid scaling at high salinities.

We find that significant energy can be saved with the simplest two-stage RO design, with four elements in each stage, even when accounting for frictional losses, concentration polarization, and component inefficiencies. More complex two-stage system designs, not explored in this work, could yield additional savings.

A simple economic analysis suggests that two-stage RO systems are not currently viable for seawater desalination, due to the small reduction in SEC at relatively low recoveries (RR=0.5). If RO systems can be pushed to slightly higher recovery ratios (RR=0.65), two-stage RO could become an attractive option in many regions around the world.

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VII. ACKNOWLEDGEMENT

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