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Does Pressure-Retarded Osmosis Help Reverse Osmosis in Desalination?

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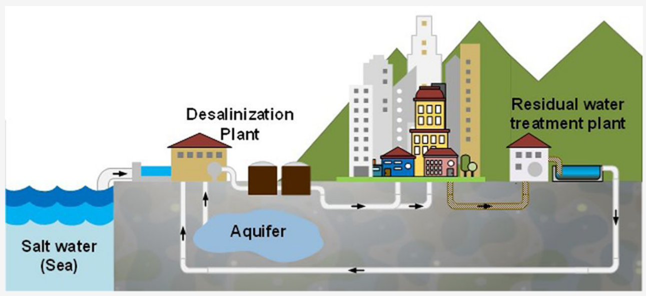
ABSTRACT: In a recent study [Parra, A. et al. *Ind. Eng. Chem. Res.* **2019**, *588* 3060−3071], the design of reverse osmosis (RO) systems for desalination of water at different concentrations was studied and optimal solutions were obtained. Equipped now with a powerful tool to solve the problem, we explore its use to determine if RO coupled with a pressure-retarded osmosis (PRO) unit can improve its economics. We present different configurations and different scenarios of RO integrated with PRO. Possible changes in electricity cost and water and salt permeability effects were also studied. We studied different scenarios of seawater desalination aided by recycled fresh water from users, as well as the limited use of low-salinity water from wells, and we present four configurations of RO-PRO aside from the pure RO case. For the cases we studied, the cost parameters we used, and the scale of the production that we chose, we conclude that PRO does not help RO, that is, the stand-alone RO always shows a lower cost per unit permeate.



1. INTRODUCTION

Reverse osmosis (RO) is one of the most popular options for desalination, and under certain cost conditions, it is the technology of choice. In a previous article,[1] we presented a design procedure to design an optimal multistage reverse osmosis system for desalination purposes, where we made a review of different solution strategies and the many difficulties to solve the design-optimization model, locally or globally.

Obtaining a cost-effective design (number of units, stages, membrane modules, and pressures) requires special attention because the cost performance of RO desalination is very sensitive to the design parameters and operating conditions.[2] Besides, the models are very complex and some of them, inaccurate. Because of these difficulties, RO systems have been designed by manufacturers using traditional empirical approaches and heuristics.[3] We discussed all relevant previous work and the methodologies used to synthesize the RO network in our previous study.[1] Summarizing, many authors solve the problem of synthesizing a reverse osmosis network (RON) using mixed-integer nonlinear programming (MINLP) or nonlinear programming (NLP)[3] approaches. Among these attempts, we have MINLP approaches using several starting points being used,[4] outer approximation within gPROMS,[5] the "what's Best" Mixed-Integer Global Solver for Microsoft Excel by LINDO Systems Inc.,[6] an MINLP technique with several starting points obtained from an ad hoc preliminary simulation,[7] a special initialization using SBB and SNOPT solvers, and also an attempt to use the global optimizer BARON.[8]

Results from our previous work indicate that our methodology robustly renders optimal solutions for this complex mixed-integer nonlinear model with less computational effort (we use local solvers initialized by genetic algorithm solutions), that is, always converging to a local optimum.[1] The influence of the number of reverse osmosis stages for different inlet flows and concentrations was studied, finding that the configuration featuring two RO stages presents the lowest total annualized cost (TAC), even when the capital charge factor is reduced. The effect of the number of membrane models was also investigated, finding that increasing the maximum number of membranes allowed in a commercial pressure vessel does not have an advantage over the TAC values obtained.

For a two-stage RO network, the total annualized cost increases with an increase in the feed flow. Conversely, it presents little variations for different feed salt concentrations at a fixed inlet flow, indicating that a reverse osmosis plant could have an adaptation capability for variations in the inlet concentration without major effects on the TAC. Indeed, such small differences in TAC for a large range of feed concentrations allow for concluding that an average TAC for each flow is a good representation of all.

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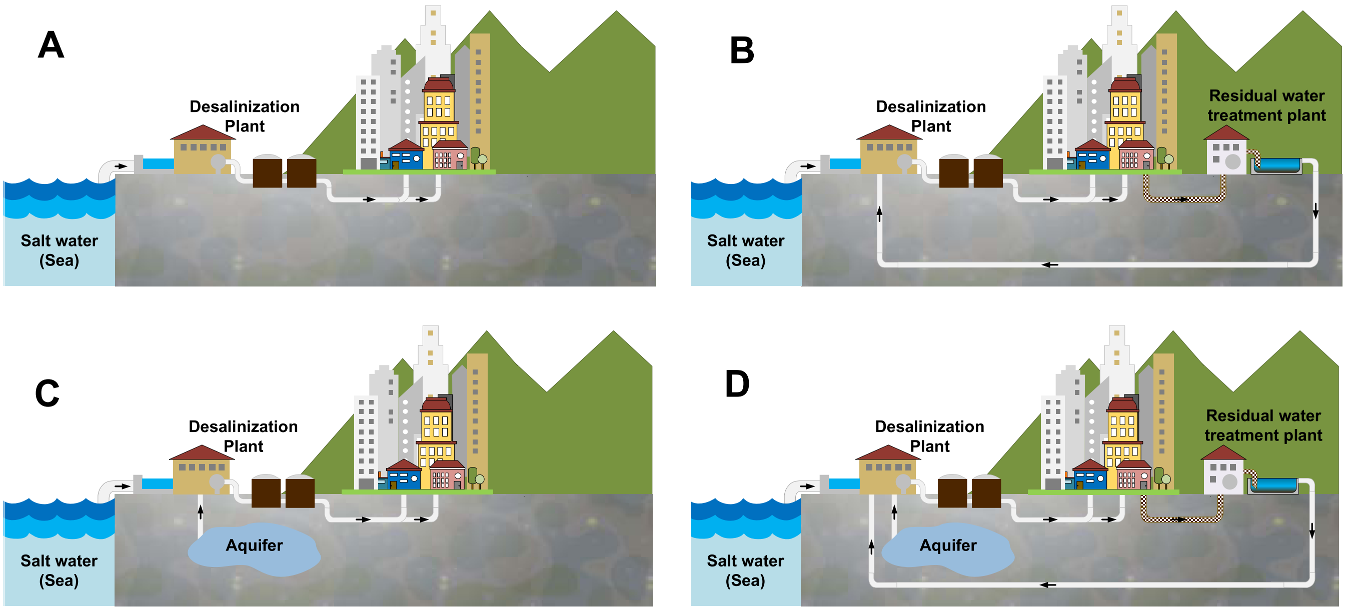

Figure 1. Studied scenarios for RO-PRO integration.

Given the good economics presented by prior work, one wonders if the performance of RO can be improved. Literature combing suggests that pressure-retarded osmosis (PRO) can be used as an aid to RO. PRO is a technique to generate power from a salinity gradient resulting from the difference of chemical potential between solutions. It uses a semipermeable membrane that separates two streams of different salinities (a low-salinity solution and a high-salinity prepressurized solution), allowing for water from the low-salinity solution to pass to the high-salinity-solution side. The additional volume increases the flow, which can be depressurized by a hydroturbine to produce power.[9] Thus, PRO can aid a RO network using the brine reject of RO as the high-salinity stream. Also, for the low-salinity stream, different authors proposed the use of river water,[10] wastewater retentate,[11] treated sewage,[12] and others.

Prante et al.[13] concluded that the RO-PRO system can theoretically achieve 40% energy reduction and also suggested that the manufacturing of next-generation membranes should focus on improving water permeability. The authors did not show the effect of this study on TAC. Long et al.[14] studied a closed-loop hybrid electrical energy storage system consisting of an RO module and a PRO module. The round-trip energy efficiency of the proposed system, defined as energy recovered divided by the energy input, reaches 38.27%. Almansoori et al.[15] studied the design problem of the RO-PRO integrated system for water and power production in desalination applications. The network design-optimization problem was solved using a MINLP procedure with the maximization of the total annual profit for water and power production. The process layout uses the arrangement of RO and PRO stages with recycled streams to increase the salinity gradient in the PRO stages. However, this is an undesirable condition for the RO operation because it increases the osmotic pressure and therefore reduces the water recovery of the RO stages. Another finding shows that some of the RO stages have salinity gradient generation points without meeting the final water product demand. Altaee et al.[16] evaluated three design configurations for power generation and/or seawater desalination using seawater and impaired water as salinity gradient resources. They conclude that decreasing the forward osmosis (FO) membrane cost tips the scales in favor of the forward osmosis and reverse osmosis hybrid (FO-RO) design while decreasing the energy cost favors the RO-PRO design. Wan et al.[17] compared the energy consumptions of RO without a pressure exchanger, RO with a pressure exchanger, and RO with pressure exchangers and PRO using fresh water or wastewater as the feed solution in PRO, all using specific configurations. They show that the energy consumption of the RO-PRO integrated process is the lowest among all of the cases. Nevertheless, effects on the TAC were not reported. Park et al.[18] presented results of a hybrid pilot plant seawater reverse osmosis with pressure-retarded osmosis (SWRO-PRO), using RO brine as the draw solution and the permeate as the feed solution. They found that the capex of the hybrid system is larger than the SWRO stand-alone plant, and they also report that for different energy-saving conditions, the draw and feed solution flow rates and the cost of energy affect the break-even point.

Kurihara et al.[19] found that it is possible to attain an energy reduction of 10% by adding a PRO system to the "Megaton water system" as a renewable energy recovery system (ERS) using high-salinity brine from the RO plant and reclaimed water as draw and feed solutions, respectively. In turn, Choi et al.[20] presented a performance evaluation and economic analysis of the RO-PRO hybrid process. They conclude that the RO-PRO hybrid process can be economically competitive with the RO process when electricity is expensive, the PRO membrane cost is cheap, and the power density and PRO recovery process are high, which is the expected result at first glance. Senthil et al.[21] studied six different RO-PRO hybrid configurations. Of these, the one that mixes the diluted PRO draw outlet with the feed water of RO brings down the net specific energy consumption by 49% as compared to standard RO desalination. Wan et al.[22] performed a technoeconomic evaluation of various RO-PRO and RO-FO integrated processes, and they conclude that closed-loop PRO can significantly reduce the Capex and Opex of seawater

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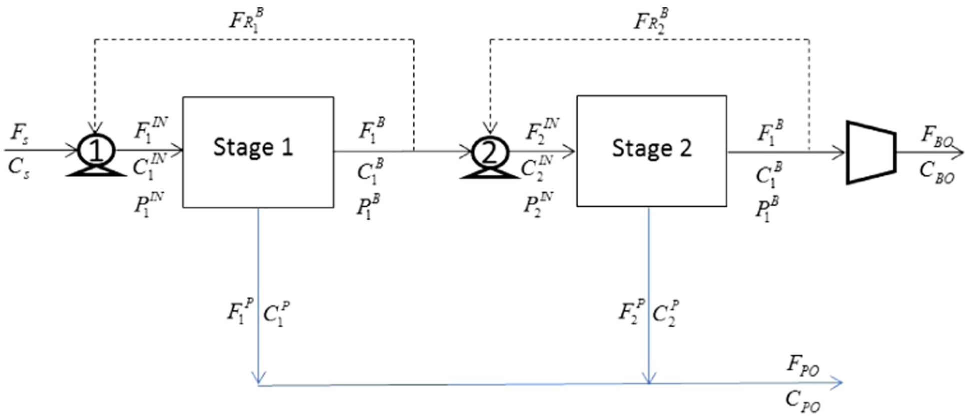

Figure 2. RO superstructure (two-stage reverse osmosis network), configuration 1.

desalination. Li et al.[23] developed a RO-PRO optimization, and they conclude that a high water recovery in RO-PRO enhances the driving force in PRO but reduces the feed rate at the same time, limiting the volume gain ratio to the system level. Recently, Blankert et al.[24] proposed a RO-PRO hybrid that can take advantage of fluctuating energy prices. This is accomplished by producing high-quality water from effluent when energy is cheap and generating electricity from the salinity difference between brine and effluent when energy is expensive. However, their hybrid RO-PRO concept is only feasible as an improvement to a PRO system when there is a limited demand for purified effluent.

Hitherto, we covered literature related to technoeconomic studies performed in the open literature. There are several other articles that study related issues, but they do not directly discuss the issue we study in this work, such as membrane properties, laboratory experiments, and other systems that are not strictly a combination RO-PRO.

All of the studies above discussed RO-PRO hybrid processes and reported a reduction in the net specific energy consumption. Nevertheless, they do not include the equipment costs, making it difficult to determine whether there is an advantage after all. To address this shortcoming, in this work, we test how PRO can aid a RON for four specific configurations and minimize the total annualized cost (TAC) for each case. As in the previous study, we formulate the problem as a mixed-integer nonlinear model that we solve using a combination of genetic algorithm, followed by a rigorous MINLP procedure that guarantees local optimality;[1] for both membrane types, RO and PRO modules, concentration polarization was modeled to avoid the overestimation of the recovery (RO) and energy production (PRO).

2. USAGE OF SCENARIOS AND RO-PRO CONFIGURATIONS

Figure 1 presents four possible scenarios to consider for the RO-PRO process integration. The first scenario (A) corresponds to a plant taking water from the sea and delivering potable water to a city. In the second scenario (B), the plant takes water from the sea, delivers the potable water to a city, and the wastewater from the city is returned to the desalination plant, passing through a residual water treatment plant. In the third scenario (C), the plant takes water from the sea and from an aquifer nearby. Finally, the fourth scenario (D) integrates all of the studied scenarios, that is, the plant takes water from the sea and from an aquifer, the potable water is delivered to a city, and the wastewater from the city is returned to the plant, passing previously through a water treatment plant.

Figure 2 shows the reverse osmosis network with two stages employed for all of the tested configurations. The RO system is composed of two RO stages, pumps, and turbines. Each stage consists of a set of parallel pressure vessels. Figure 2 also presents the brine recycles for each stage. The feed flow enters a high-pressure pump and is sent to the first RO stage, where it is separated into two streams: permeate and brine. Brine leaving the first RO stage feeds the second RO stage, but a fraction can be recycled. Recycling increases the velocity through the membrane module and thus reduces the concentration polarization. The final brine from the second stage goes to a turbine to recover the residual energy. The permeates from stages 1 and 2 are mixed to get the final permeate. This arrangement is referred to as configuration 1.

Figure 3 presents a reverse osmosis network with two stages, pumps, and a turbine (configuration 2) assisted by PRO. In

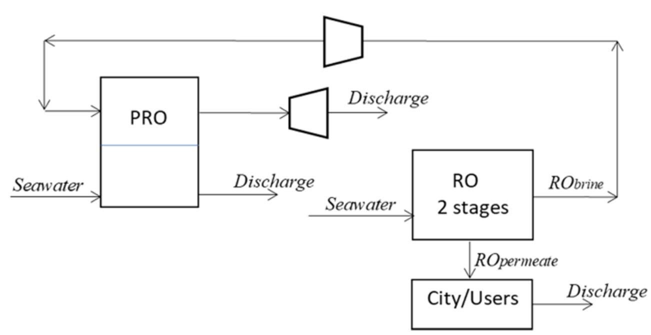

Figure 3. RO-PRO superstructure, configuration 2.

this configuration, the pressure-retarded osmosis unit uses the brine stream coming from the second RO stage after passing through the turbine. This acts as a draw solution (the one with high osmotic potential), which is contacted with some pretreated seawater stream as a feed solution (low salinity potential) on the other side of the membrane. This arrangement is referred to as configuration 2.

Figure 4 presents an RO network where the PRO also uses brine from the second stage after pressure conditioning by turbine as the draw solution as in configuration 2, but this time the pretreated seawater stream is divided into two: one serving the PRO unit as the feed solution and the other by-passed the PRO unit to be recombined with the low-salinity-side PRO output solution. The combined stream enters the RO first

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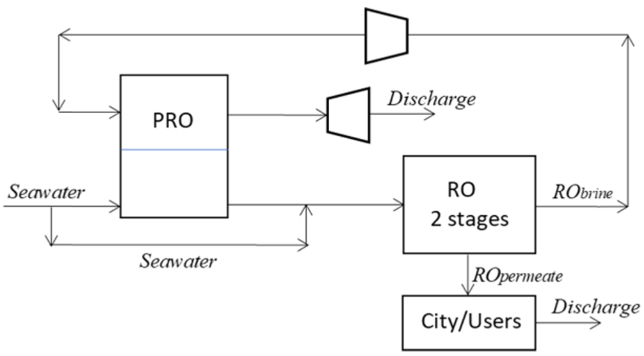

Figure 4. RO-PRO superstructure, configuration 3.

stage. The difference with configuration 2 is that the two RO stages are fed by a combination of saline water feed and PRO saline outlet. In this regard, the PRO unit receives a higher saline concentration. This arrangement is referred to as RO-PRO configuration 3.

Both configurations 2 and 3 use the same brine stream as the draw solution (the one leaving the second RO stage). However, RO-PRO configuration 3 presents an efficient way to integrate the PRO unit as an energy recovery system (ERS) because a fraction of the seawater intake needed for the single RO network is used as a low-salinity feed for the PRO unit, sharing the pretreatment and pumping systems and just increasing slightly the salt concentration of the RO first-stage feed flow without affecting the overall performance.

Figure 5 shows configuration 4, where the RO system is fed with the mix between a low-salinity stream and the seawater.

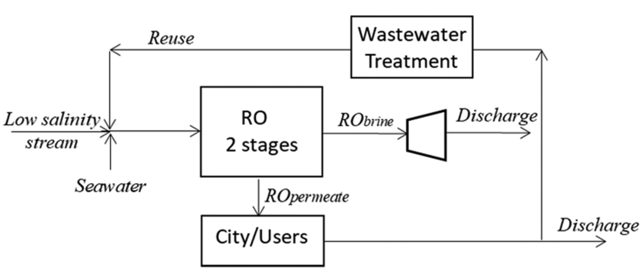

Figure 5. RO superstructure with low-salinity feed (two-stage reverse osmosis network), configuration 4.

Therefore, this superstructure is the same as configuration 1 with an additional low-salinity feed. The low-salinity stream could be obtained from a residual water treatment plant or an aquifer (Figure 1).

Figure 6 presents RO-PRO configuration 5; this superstructure is similar to configuration 2. Indeed, brine from the RO system is the draw solution for the PRO unit. However, instead of using saline water, the feed solution for the PRO unit is a stream with lower salt concentrations than that of the seawater inlet. Therefore, this superstructure is the same as configuration 4 with the PRO system.

In all configurations, the PRO unit consists of a parallel membrane module arrangement where both entering flows (draw and feed solutions) are distributed equally to the N_{PRO} vessels, as presented in Figure 7.

Table 1 shows the relation between scenarios and networking configurations. Configurations 1, 2, and 3 can be employed in scenario A because they do not need a low-salinity flow in their operation. Configurations 4 and 5 can be

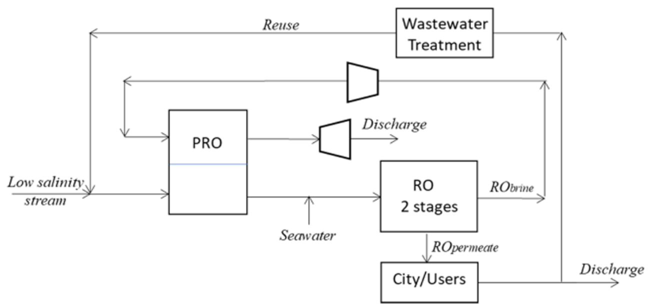

Figure 6. RO-PRO superstructure, configuration 5.

used in scenarios B, C, and D because for these scenarios the water from the residual water treatment plant and aquifers could be employed as low-salinity fed. A comparison of the performance of any configuration can be developed only for the same studied scenario. Therefore, on one hand, it is possible to compare configurations 1, 2, and 3 between them, and, on the other hand, it is possible to compare configurations 4 and 5.

3. MATHEMATICAL MODEL

Our final model is a mixed-integer nonlinear rigorous model, which we solve using the same procedure outlined by Parra et al.,[1] that is, using DICOPT, initialized by the results of a genetic algorithm. The use of Baron was attempted, but even with initial values, it runs for 250 h before being stopped. This study includes the estimation of fixed capital, working capital, project total investment (TCC), and annual operating cost (AOC). Fixed capital costs are part of the annual operating costs, which refer to a new plant construction cost, and include the cost to purchase equipment, building cost, and the site development cost. Working capital cost characterizes operating liquidity and the organization of the processing facility.[1] The objective function to be minimized is the total annualized cost (TAC). The summarized model with the PRO equations (RO equations were already published[1] but are reproduced nonetheless for completeness), as well as the updated economic model, is presented in the Supporting Information.

4. SOLUTION STRATEGY

As stated above, we use a genetic algorithm based on surrogate models or metamodels to obtain initial values for the local optimizer. Our metamodels are simple quadratic polynomials as metamodels. This way, the mathematical complexity of the modeling of the transport phenomenon is reduced, allowing us to obtain a fast solution, which is used as initial values to solve the rigorous model. To obtain the metamodels, the equations for the transport phenomenon for each technology (RO and PRO) are solved numerically for different inlet conditions (values selected according to the bounds of the problem) to obtain a mesh of input−output data pairs.[1] To obtain the coefficients of the metamodels, we used a diploid genetic algorithm (DGA) programmed in MATLAB.[25] Details for the expressions, coefficients, and parameters used are presented in the Supporting Information. Details of the used genetic algorithm can be found in Fonteix et al.[26] Thus, the rigorous solution for each superstructure configuration and the corresponding above outlined rigorous model is solved using DICOPT[27] with CPLEX and CONOPT as MIP and NLP subsolvers, respectively, and the model was implemented in GAMS[28] version 23.7.3, using as initial values the results

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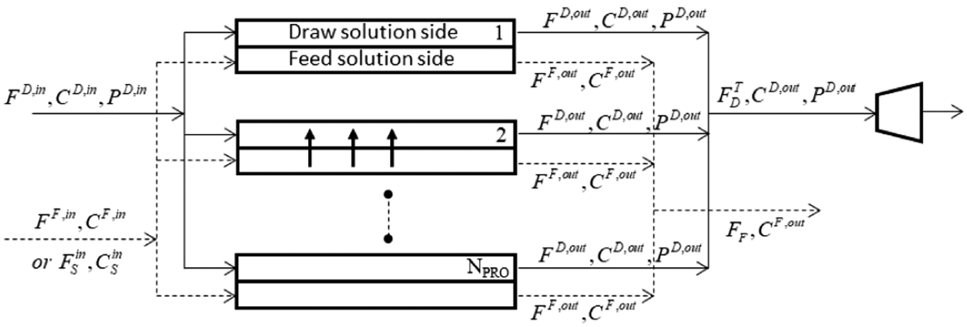

Figure 7. PRO unit arrangement.

Table 1. Relation between Scenarios and Networking Configurations

	scenario A	scenario B	scenario C	scenario D
configuration 1 (RO)	X			
configuration 2 (RO-PRO)	X			
configuration 3 (RO-PRO)	X			
configuration 4 (RO with low-salinity feed and/or reuse)		X	X	X
configuration 5 (RO-PRO with low-salinity feed and/or reuse)		X	X	X

obtained from a DGA using the corresponding metamodels for each technology (RO and PRO). The necessary parameters to describe the DGA[26] used were 1000 individuals, 10 generations, 100 survivors, 100 mutants, and a mutation rate equal to 0.01; more details can be found in our previous study.[1] To obtain the initial values for the rigorous model, the DGA solves the complete model, detailed in the Supporting Information, where equations A18, A19, A21, A23, A26, A27, and A30 are substituted by two polynomials A1 and A2 obtained performing a regression of the PRO rigorous model. We also use the polynomials developed earlier for RO.[1] The regression coefficients of these regressions are close to 0.99 and higher.

5. RESULTS

The data for RO and PRO modules and the economic parameters are presented in the Supporting Information. We targeted a permeate concentration of 500 ppm and an inlet water concentration of 35 000 ppm. We also set a maximum of 87 000 ppm for the RO second-stage brine concentration, a reasonable value before scaling onset.

The RO membrane parameters are the ones for a commercial membrane module (SW30HR-380). For the PRO membrane, the parameters were taken from the literature because of the lack of information about commercial modules. Tiraferri et al.[29] reported experimental data for different membranes including water and salt permeability, as well as structural parameters. According to Zhang et al.,[30] membranes with a high water permeability, low salt permeability, and small structural parameters are needed to enhance the water permeation volume, thus increasing energy production; therefore, we decided to use the PRO membrane parameters, selecting them from the experimental data available according to the mentioned recommendations, and the hydraulic parameters correspond to an 8 in. spiral wound module.

5.1. Scenario A: Configurations 1, 2, and 3.

Table 2 shows the optimization results for the RO system (config-

Table 2. Optimization Results[a]

	RO configuration 1		RO-PRO configuration 2		RO-PRO configuration 3	
TAC	$1 777 728		$1 882 039		$1 802 324	
cost per unit permeate ($/kg/s)	17 777.3		18 820.4		18 023.2	
total salted water flow (kg/s)	166.5		196.4		169.7	
RO Stage	S1	S2	S1	S1	S1	S2
inlet pressure (bar)	63.6	76.5	63.6	76.5	63.9	76.5
each pressure vessel inlet flow (kg/s)	2.6	2.2	2.6	2.2	2.6	2.1
number of modules	8	8	8	8	8	8
number of pressure vessels	64	44	64	44	65	45
flow recycle 1 (kg/s)	0		0		0	
flow recycle 2 (kg/s)	0		0		0	
total annualized operational cost	$1 018 000		$1 052 000		$1 29 900	
total capital costs	$8 632 800		$9 432 400		$8 777 600	
PRO Unit						
high-salinity solution inlet flow to each pressure vessel (kg/s)			4.0		4.0	
low-salinity solution inlet flow to each pressure vessel (kg/s)			1.8		2.3	
number of pressure vessels			16		17	
high-salinity solution inlet pressure (bar)			2.9		3.2	

[a]Permeate concentration, 500 ppm; permeate flow rate, 100 kg/s; and inlet water concentration, 35 000 ppm.

uration 1) and the two RO-PRO configurations (2 and 3) using the abovementioned seawater conditions and the targeted freshwater supply. The TAC value for RO-PRO configuration 2 is 5.9% larger than that of the single RO network (configuration 1); this is because of the pretreatment and pumping costs associated with the additional seawater used as feed solution for the PRO unit (196.4 kg/s of total seawater pretreated water instead of 165.5 kg/s for the single RON). These additional costs are necessary since the PRO is a membrane unit and therefore it needs low-salinity pretreated supply water. The TAC value for RO-PRO configuration 3 is slightly larger than that of single RO configuration 1 (1.38%), even though the total pretreated seawater consumption for both cases is similar (169.7 vs 166.5 kg/s, respectively). To determinate the effect of the capital charge factor (ccf) on the

TAC for configurations 2 and 3, the simulation was developed for different ccf values. Our ccf value was calculated for $i = 0.06$ and t of 20 years. Assuming lower ccf values, RO configuration 1 shows lower costs than the RO-PRO configuration because the annual operational costs will always be larger for configurations 2 and 3; this behavior is explained by the higher membrane cost for the PRO system and the low energy production that does not bring a significant reduction of the operational costs.

Results presented in Table 2 do not suggest a brine recycle flow, despite recycling helping in reducing concentration polarization (increasing the velocity through the membrane module). Optimal solutions avoid it because of the recycle pumps (HPPR) needed to compensate for the pressure drop of the membrane module, thus increasing the total capital cost and power consumption (they are high-pressure pumps). Incidentally, brine recycles also increase the system salt passage leading to unacceptable salt permeate concentrations in some cases,[31] and this was also observed in our previous results.[1]

5.2. Scenario A: Configurations 1 and 3. Different Inlet Concentrations and Feed Flows. Configuration 2 always produces a higher TAC value than a single RO configuration 1 and configuration 3 (Section 5.1). However, the difference between TAC for RO (configuration 1) and RO-PRO (configuration 3) is smaller than 1.4% (Table 2). Then, it is advisable to extend the comparison to different inlet concentrations and feed flows.

Figure 8 shows the comparison between the cost per unit permeate for RO (configuration 1) and the cost per unit permeate for the RO-PRO integrated system for different feed concentrations and feed flows (configuration 3). An increase in the cost per unit permeate with an increase in seawater concentration was observed, this behavior is explained by a higher energy requirement for higher inlet seawater concentrations. Therefore, a decrease in the inlet optimal pressure with an increase in the seawater salinity was observed; this is related to greater osmotic pressure for the low-salinity feed solution (seawater) reducing the osmotic exploitable gradient.

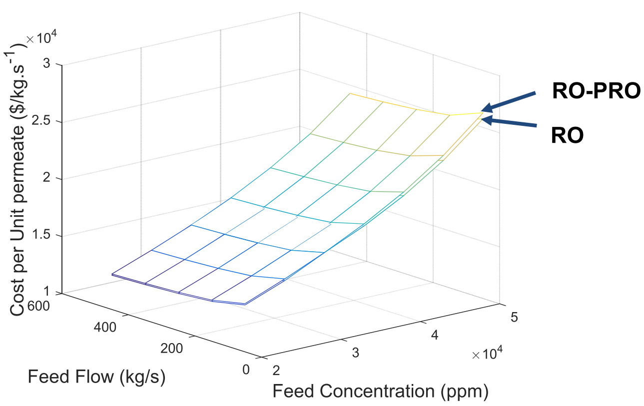

Figure 8. Comparison between the cost per unit permeate for RO and that for RO-PRO (configurations 1 and 3) for different feed concentrations and flows.

Figure 8 also shows that the cost per unit permeate of RO integrated with PRO reduces with the feed flow increase; this behavior agrees with the concept of economy of scale and is explained by the labor cost and other costs remaining constant even if the plant capacity increases.

RO integrated with PRO shows the highest cost per unit permeate for all of the evaluated coordinates. Nevertheless, the highest difference between both configurations was 2%. The use of PRO to aid RO does not produce enough energy to promote a TAC reduction. In conclusion, the PRO integration in RO configuration 3 did not reduce the cost per unit permeate for the studied conditions, since the PRO unit did not produce enough energy when using seawater as the feed solution. Although there is an osmotic potential between brine and the seawater, the produced energy is not significant given the electric energy consumption of the RO system; besides, mixing the seawater with the PRO output feed solution (which increases its salinity after passing by the PRO membrane) increases the RO salt inlet concentration, thus increasing the required pump potency.

We note that the conclusions made are not affected if the system is scaled to other total water flow rates because the equipment costs are linear (membrane cost is additive) unlike other equipment where the usual form is concave. Thus, economy of scale considerations are unlikely to alter the conclusions significantly.

5.3. Scenarios B, C, and D: Configurations 4 and 5. Table 3 shows the comparative results for RO (configuration 4) and configuration 5 using a low-salinity stream of 1000 ppm, seawater with 35 000 ppm (RO), and an equivalent inlet concentration of 21 000 ppm (resulting from the simple mixing of 35 000 and 1000 ppm). RO for the diluted feed solution (configuration 4) shows lower TAC than RO-PRO configuration 5. This behavior is because the total capital cost is higher for configuration 5 than configuration 4 due to the PRO equipment requirements. Besides, configuration 5 shows a

Table 3. Comparative Results for RO (Configuration 4) and RO-PRO (Configuration 5)[a]

	RO for final-salinity mix of 21 000 ppm (configuration 4)		RO-PRO for final-salinity mix of 21 000 ppm (configuration 5)	
TAC	$2 046 756		$2 169 090	
cost per unit permeate ($/kg/s)	13 645		14 460.6	
total salted water flow (kg/s)	233.2		138.2	
RO Stage	S1	S2	S1	S2
inlet pressure (bar)	51.7	77.9	54.4	77.7
each pressure vessel inlet flow (kg/s)	2.2	1.8	2.3	1.9
number of modules	8	8	8	8
number of pressure vessels	89	50	89	54
flow recycle 1 (kg/s)	0		0	
flow recycle 2 (kg/s)	0		0	
electrical power consumption (kWh)	1400.5		1473.9	
total annualized operational cost	$1 236 400		$1 282 600	
total capital costs	$9 208 700		$10 074 000	
PRO Unit				
high-salinity solution inlet flow to each pressure vessel (kg/s)			2.1	
low-salinity solution inlet flow to each pressure vessel (kg/s)			3.0	
number of pressure vessels			27	
high-salinity solution inlet pressure (bar)			10.8	
electrical power generation (kWh)			49.3	

[a]Permeate maximum conc., 500 ppm; permeate flow rate, 150 kg/s; and inlet water conc., 35 000 ppm.

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higher total annualized operational cost than configuration 4 because of higher requirements of pumping cost and pretreatment cost.

5.4. Energy Cost Effect on the RO-PRO System. Figure 9 shows the energy cost effect on the RO-PRO system

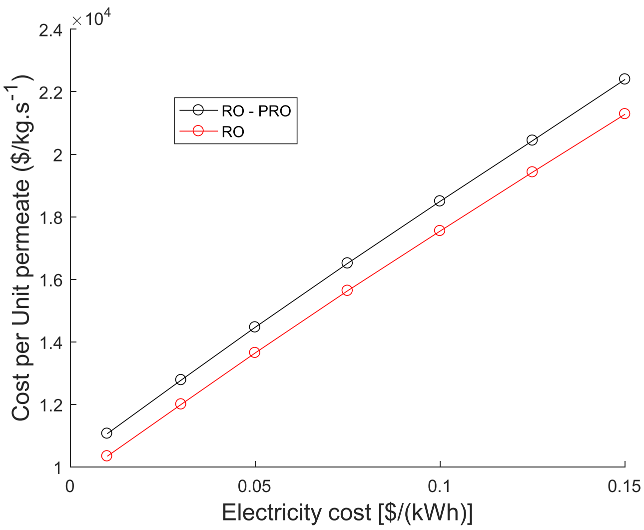

Figure 9. Electricity-cost effect on the RO-PRO system (configuration 5). RO for final-salinity mix of 21000 ppm (configuration 4). RO-PRO feed solution (1000 ppm). Permeate maximum conc., 500 ppm; permeate flow rate, 150 kg/s; and inlet water conc., 35 000 ppm.

(configuration 5) and its comparison with the RO system with equivalent diluted feed solution (configuration 4). The cost per unit permeate proportionally increases with the electricity cost in both configurations, and the RO system shows a lower cost per unit permeate for all of the studied electricity-cost values.

5.5. Water and Salt Permeability Effect on the RO-PRO System. Figure 10 shows the water and salt permeability (PRO membrane) effect on the RO-PRO system (configuration 5) and its comparison with the reference RO-PRO reported in Table 3. The cost per unit permeate linearly increases with the water permeability increase and linearly decreases with the salt permeability increase. These results indicate that the dilution effect in the feed stream promotes a greater cost per unit permeate reduction than the electrical generation from the PRO.

5.6. Final Considerations for the RO-PRO System Integration. In this work, we use a simplified PRO structure, constituted by two well-mixed chambers, and we omit complicating the modeling with co-current or countercurrent configurations. The reason for this is that our approach constitutes a lower bound of area for the same mass transfer task. Given that the structures obtained are not competitive, there is no reason to seek solutions that are even higher in cost. Yang et al.[32] report an ideal maximal power density of 30 w/m^2 for the countercurrent PRO system. Chung et al.[33] reported a net power density of 7.3 w/m^2 using a 10-Stage PRO countercurrent system, while Song et al.[34] reported a gross power density of 21.3 w/m^2. These power densities are lower than the theoretical generation of 48.5 w/m^2 obtained in this work for configuration 5 with a low-salinity feed for the PRO of 1000 ppm. Thus, even when using a high theoretical power density, the PRO did not help RO for all of the configurations and operational conditions studied in this work. As a side note, He et al.[35] developed the performance comparison between the co-current and the countercurrent flow schemes and they did not find significant differences between these configurations for high power density.

Changes in electricity cost and water and salt permeability (PRO membrane) show a lower cost per unit permeate for the RO system (configuration 4) than for the RO-PRO integrated system (configuration 5).

Configuration 5 showed a lower cost per unit permeate than the other RO-PRO configurations (comparative between Tables 2 and 3). However, the dilution effect in the feed stream renders a larger cost per unit permeate reduction than the electrical generation from the PRO.

For specific scenarios where the low-salinity stream in configuration 5 can be fed to the PRO system and cannot be fed to the RO system, the PRO may help the RO systems. However, Straub et al.[36] establish that hybrid systems RO-PRO that mix the concentrated seawater brine with low-salinity impaired water sources may also be infeasible. While the theoretical energy that can be recovered with the hybrid RO-PRO system is substantial if enough wastewater is

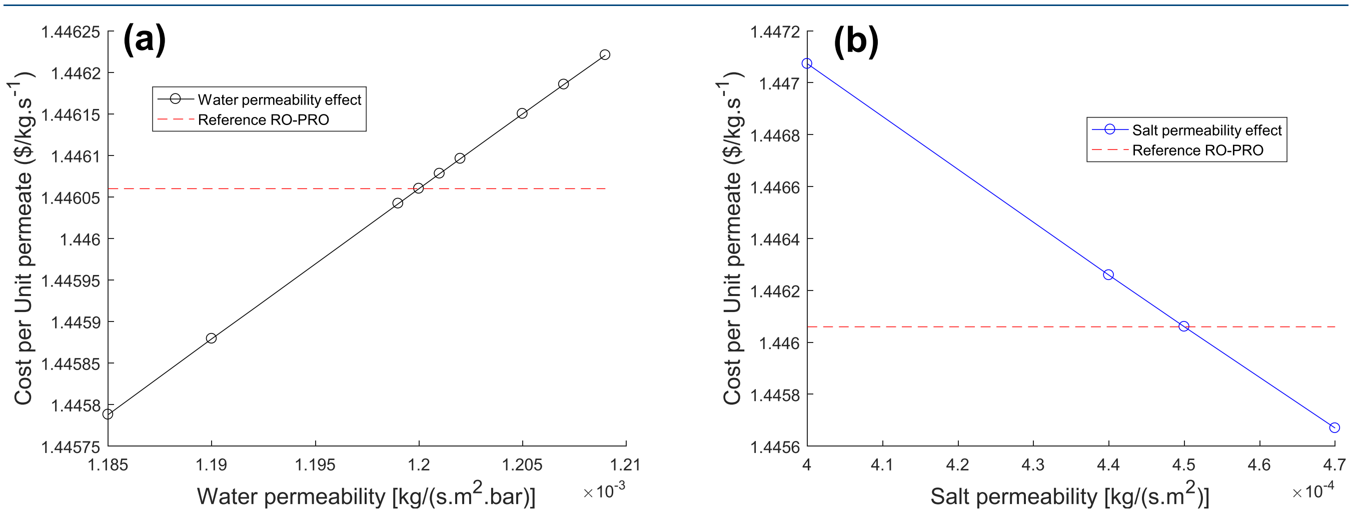

Figure 10. Water (a) and salt permeability (b) effect on the RO-PRO system (configuration 5). RO-PRO feed solution (1000 ppm). Permeate maximum conc., 500 ppm; permeate flow rate, 150 kg/s; and inlet water conc., 35 000 ppm.

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available, arid regions that require desalination find it more efficient and beneficial to use impaired water sources directly through wastewater reclamation. Additionally, fouling of membranes from the impaired water streams result in severe performance losses. Lin et al.[37] established that the PRO pretreatment energetic cost could be higher than the maximum specific energy obtained for the PRO process. These facts reinforce the conclusion that the PRO does not help RO.

6. CONCLUSIONS

A new methodology to solve a nonlinear mathematical model for the optimal design of RO integrated with PRO was implemented. Metamodels were used to reduce the mathematical complexity and obtain accurate solutions using a genetic algorithm. Then, the results were used as initial values to solve the full nonlinear model using GAMS/DICOPT. This allows for getting optimal solutions for a complex MINLP problem with less computational effort. One of the major advances of our approach is that initial values are not needed (always a problem for practitioners using MINLP codes).

Configuration 5 for the system RO-PRO showed a lower cost per unit permeate than the other RO-PRO configurations. Indeed, the lower feed solution concentration values promote a larger osmotic potential, generating higher values of electrical power and consequently reducing the cost per unit permeate. However, the RO standalone shows lower cost per unit permeate values for the equivalent diluted feed solution (configuration 4), indicating that RO-PRO configuration 5 improves the cost per unit permeate as a consequence of the feed dilution effect, and the PRO presence did not help the desalination cost per unit permeate for this configuration.

Further, changes in the electricity cost and changes in the water and salt permeability (PRO membrane) show a lower cost per unit permeate for the RO system (configuration 4) than for the RO-PRO integrated system (configuration 5).

Finally, for all of the configurations and operational conditions studied, the PRO did not help RO. As discussed, this conclusion does not change for other production rates. However, for specific scenarios where the low-salinity stream in configuration 5 can be fed to the PRO system and cannot be fed to the RO system, the PRO may help the RO systems. This is left for future studies.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.iecr.0c04382.

1. PRO metamodel fitting; 2. complete PRO mathematical model; 3. RO model; 4. general superstructure; 5. RO and PRO parameters; 6. optimal result complete information; and 7. optimal solutions for different seawater concentrations, configuration 3 (PDF)

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Notes

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