Integration and Optimization of Pressure Retarded Osmosis with Reverse Osmosis for Power Generation and High Efficiency Desalination

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Abstract:

Salinity gradient power is proposed as a source of renewable energy when two solutions of different salinity are mixed. In particular, Pressure Retarded Osmosis (PRO) coupled with a Reverse Osmosis process (RO) has been previously suggested for power generation, using RO brine as the draw solution. However, integration of PRO with RO may have further value for increasing the extent of water recovery in a desalination process. Consequently, this study was designed to model the impact of various system parameters to better understand how to design and operate practical PRO-RO units. The impact of feed salinity and recovery rate for the RO process on the concentration of draw solution, feed pressure, and membrane area of the PRO process was evaluated. The PRO system was designed to operate at maximum power density of $\Delta P = \frac{\Delta \pi}{2}$. Model results showed that the PRO power density generated intensified with increasing seawater salinity and RO recovery rate. For an RO process operating at 52% recovery rate and 35 g/L feed salinity, a maximum power density of 24 W/m^2 was achieved using 4.5 M NaCl draw solution. When seawater salinity increased to 45 g/L and the RO recovery rate was 46%, the PRO power density increased to 28 W/m^2 using 5 M NaCl draw solution. The PRO system was able to increase the recovery rate of the RO by up to 18%

depending on seawater salinity and RO recovery rate. This result suggested a potential advantage of coupling PRO process with RO system to increase the recovery rate of the desalination process and reduce brine discharge.

Keywords: Salinity Gradient Power; Pressure Retarded Osmosis; Reverse Osmosis; High recovery desalination; Brine Valorisation

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1. Introduction

Utilization of seawater has become common practice for fresh water supply to arid and semi-arid areas [1-4]. A range of processes have been described for seawater purification which can effectively reduce dissolved salt concentrations to levels appropriate for complying with drinking water quality specifications [5, 6]. Subramani and Jacangelo [7] recently reviewed a wide range of desalination technologies which encompassed thermal methods, membrane approaches and alternate systems such as microbial desalination units, capacitive deionization, ion concentration polarization and clathrate hydrates. Of these, membrane based systems such as Reverse Osmosis (RO) have become popular, particularly in areas of the world where energy prices are not heavily subsidized [8]. The capability of an RO process to treat a wide range of seawater salinities at an acceptable cost relative to other desalination strategies has been demonstrated [9-11]. Importantly, RO processes can exhibit relatively high water recovery rates compared to thermal desalination processes such as Multi Stage Flash (MSF) and Multi Effect Distillation (MED) [7, 12, 13]. High water recovery rates are desirable in desalination processes in order to reduce the cost of treatment and brine management [13, 14].

Brine management is a major issue in seawater desalination as brine discharge to the sea has the potential for undesirable consequences upon flora and fauna [15, 16]. The recovery rate of an RO process is indirectly proportional to the feed salinity, with a recovery rate less than 50% recommended for 35 g/L seawater salinity [17, 18]. Although higher recovery rates are desirable for RO systems, they are not feasible from a practical point of view due to various operating constraints. For example higher RO recovery rates may result in enhanced membrane fouling due to the precipitation of sparingly soluble salts and deposition of organics species on the membrane surface [17, 19]. Nevertheless, the recovery rate of RO can be indirectly increased through coupling with other membrane technologies such as Membrane Distillation (MD) or Forward Osmosis (FO) [20, 21]. In such cases, MD and FO processes recover some of the RO brine component before discharge to the sea [22]. Membrane distillation has an inherently low water recovery rate, hence brine is recycled into the membrane system until the desirable recovery rate is achieved [23]. In contrast, the recovery rate of an FO process is relatively high and can be controlled through manipulating the osmotic pressure difference across the membrane [20, 24]. However, the draw solution regeneration process demands high energy, hence the overall cost of a combined FO-RO system is scarcely advantageous compared to a standalone reverse osmosis unit [25].

Pressure Retarded Osmosis (PRO) is an alternate osmotically driven membrane filtration process which has received considerable attention in recent years due to the possibility of renewable power being generated when two solutions of different salinity are mixed [26-28]. The main difference between FO and PRO is that draw solution is pressurized before it enters the PRO membrane [29]. In the PRO process, chemical potential converts into hydraulic energy as water crosses the membrane from the feed to the draw solution; the pressurized draw solution goes to a turbine for power generation [30]. Thermolytic and inorganic metal salts, such as ammonia/ carbon dioxide and sodium chloride, respectively, are some candidates draw solutions for the PRO process [31, 32]. These solutions have high osmotic pressure, are easy to regenerate and inexpensive. Theoretically, coupling of an RO system with PRO creates the possibility of not only reducing the volume of brine discharge to sea but also generating power [33].

Preliminary studies by Kim *et al.* [34] discussed the impact of RO-PRO process configuration upon the water and energy return rate, and suggested that placing the RO unit before the PRO unit and using the RO brine to augment the draw solution was preferred. Almansoori and Saif [35] expanded the analysis of RO-PRO process configurations to include multiple RO and PRO stages. These authors noted that there was a need to reduce recycling of high total dissolved solids content streams to the RO unit and that research was required to prepare improved membranes for the PRO process. Achilli *et al.* [36] operated an RO-PRO pilot plant facility and confirmed that this latter approach may lead to significant reduction in energy consumption for desalination of high salinity solutions.

Our previous investigations have reported initial insights as to the performance [30] and process design of RO-PRO units [37]. It was apparent that a wide range of operational factors were important when trying to optimize process economics. Therefore there was a need for this study which was designed to determine the feasibility of an RO-PRO system for RO brine concentration and power generation by taking into account key environmental and operating parameters which impact the recovery rate and power generation of the RO-PRO system. For example, seawater salinity has considerable impact on the feed pressure and recovery rate of the RO process; this in turn affects the performance of the PRO process. The impact of operating parameters such as RO recovery rate, concentration of draw solution, membrane area, and PRO recovery rate on the system performance also needed to be understood in greater detail. A computer model was developed which could be used to predict the performance of the PRO process. Calculations were further extended to predict the optimized concentration of draw solution and PRO membrane area required. Overall, the aim was to improve the performance and power generation of the PRO process as well as reducing the operation cost through process optimization. Furthermore, the study optimizes the integration of RO process with the PRO process which reduces desalination environmental impact and avails of the RO brine before disposal.

2. Materials and Methods

A conceptual RO-PRO system as illustrated in Figure 1, was proposed to improve the recovery rate of desalinated water and potentially generate power via the PRO process. The system consisted of three major components: *i.e.* i) the RO membrane (1); ii) the PRO membrane (2); and, iii) the Regeneration unit (3). Pre-treated seawater entered the RO system (1) for desalination; RO brine was sent to a pressure exchanger to exchange pressure with the draw solution for the PRO process before entering the PRO membrane (2). Water crossed the membrane from the feed to the draw solution thus increasing the hydraulic potential of the draw solution; the flow rates of feed and draw solution to the PRO membrane (2) were equal; the diluted draw solution split into two flows after leaving the PRO membrane (2). The first flow which was equal to the volume of RO brine, returned back to a pressure exchanger to pressurize part of the seawater feed to the RO membrane; whereas the second flow proceeded to a turbine system for power generation. The first flow recombined with the second flow after it exited the turbine and this stream was processed in a regeneration unit (3) which extracted fresh water and created the concentrated draw solution that was recycled. It should be mentioned that thermal process is the preferable regeneration choice when a source heat waste is available besides its performance is not significantly affected by feed concentration. In the RO-PRO system, the PRO process was designed to recover water from the RO brine and convert the chemical energy into hydraulic power using the pressure of RO brine. This design should reduce the pumping cost and utilize the energy of pressurized RO brine in PRO process for power generation.

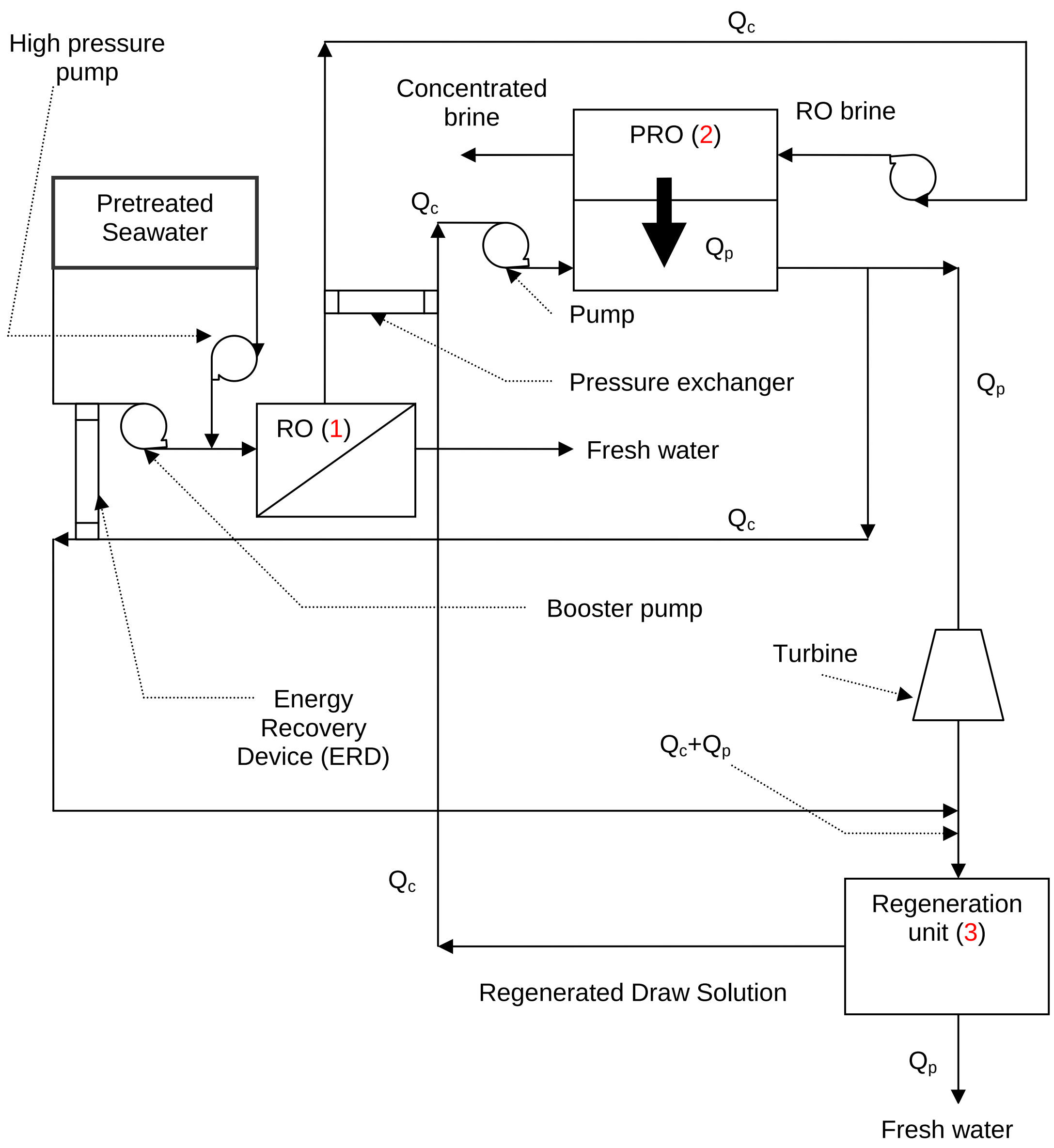


Figure 1: Schematic diagram of RO-PRO system

In the desalination unit, pre-treated seawater was pressurized and pumped into the RO membrane for fresh water production. Water flux, Jw (L/m^2h) in the RO membrane was calculated from Equation 1:

Equation 1: $$J_w = A_w(\Delta P - \Delta \pi)$$

Where, A_w is the water permeability coefficient (L/m^{2}h.bar), ΔP is hydraulic pressure difference across the RO membrane (bar), and $\Delta \pi$ is the osmotic pressure difference across the membrane (bar). The ratio of permeate flow to feed flow rate represented the recovery rate, *Re* (%), of the RO process as shown in Equation 2:

Equation 2: $$\mathrm{Re} = \frac{Q_p}{Q_f} 100\%$$

Where Q_p and Q_f are the permeate and feed solution flow rates (m^3/h). The RO recovery rate was an important parameter in determining the specific power consumption, Es (kWh/m^3), of desalination process and was calculated using Equation 3:

Equation 3: $$Es = \frac{P_f}{\eta * \mathrm{Re}}$$

In Equation 3, P_f is the feed pressure (bar) and η is the pump efficiency (assumed here to be 0.8). Practically, high RO recovery rates accelerate membrane fouling, hence most of the RO desalination plants operate at recovery rates less than 50% [17]. Different RO recovery rates were selected in order to evaluate the impact of the performance of the PRO process.

PRO was proposed for fresh water recovery from the RO brine and power generation. The RO-PRO design assumed that: i) the ratio of feed to draw solution, $Q_{F\text{-}in}/Q_{D\text{-}in}$, was equal to unity; ii) the concentration of feed solution to the PRO membrane was equal to that of the RO brine; and iii) the feed pressure of draw solution was equal to that of the RO brine. Several PRO recovery rates were investigated for feed salinities ranging from 32,000 to 45 mg/L. Permeate flow, Q_p (m^3/h), was calculated from the ratio of $Q_{f\text{-}in}$ to %Re, and the outlet concentration of feed solution, $C_{F\text{-}out}$ (mg/L), was estimated from the process mass balance [Figure 2a] as in Equation 4:

Equation 4: $$C_{F-out} = \frac{(Q_{F-in} * C_{F-in}) - (Q_p * C_p)}{Q_{F-out}}$$

Where, $Q_{F\text{-}in}$ is the inlet flow rate of feed solution (m^3/h) $C_{F\text{-}in}$ is the inlet concentration of feed solution (mg/L), C_p is the permeate concentration (mg/L), and $Q_{F\text{-}out}$ is the outlet flow rate of feed solution (m^3/h). The osmotic pressure of outlet feed concentration, π_{F-out} (bar), was estimated from the Van't Hoff equation [Equation 5]:

Equation 5: $$\pi_{F-out} = iCRT$$

Where, n is the Van't Hoff factor, C is the molar concentration of solution, R is the gas constant (0.082 L atm/ K mol) and T is the temperature in Kelvin (273+^{o}C). The inlet and outlet osmotic pressure of the PRO feed solution, π_{F-in} and π_{F-out}, respectively, were estimated from Equation 5 and the bulk osmotic pressure of the feed solution, π_{FB}, was calculated as the average of π_{F-in} and π_{F-out} [Figure 2a]. Power density in the PRO process, as demonstrated in previous studies [38], reached a maximum value at $\Delta P = \Delta\pi / 2$. In fact, $\Delta\pi$ was the difference between the osmotic pressure of bulk draw solution and bulk feed solution; *i.e.* $\Delta\pi = \pi_{DB} - \pi_{FB}$. As such, π_{DB} was estimated from the following expression [Equation 6] assuming that ΔP was equal to the pressure of the RO brine:

Equation 6: $$\pi_{DB} = 2 * \Delta P * \pi_{FB}$$

Equation 6 suggested that RO-PRO operated on the maximum power density using RO brine as the hydraulic pressure difference across the PRO membrane. The bulk concentration of draw solution, C_{DB}, can be predicted from rearranging Van't Hoff equation as shown in Equation 7:

Equation 7: $$C_{DB} = \frac{\pi_{DB}}{iRT}$$

In Equation 8, C_{DB} is the average of inlet and outlet concentrations of feed solution:

Equation 8: $$C_{DB} = \frac{C_{D-in} + C_{D-out}}{2}$$

Where, C_{D-in} and C_{D-out} are the inlet and outlet concentrations of draw solution (mg/L). Water permeation from feed to draw solution increased the volume of draw solution, hence the outlet flow rate draw solution, Q_{D-out}, was the sum of Q_p and Q_{D-in}; *i.e.* $Q_{D-out} = Q_{D-in} + Q_p$ [Figure 2]. Rearranging Equation 8 in terms of C_{D-out} to calculate the outlet concentration of draw solution from the mass balance equation [Figure 2] around the draw solution side of PRO membrane gave Equation 9:

Equation 9: $$C_{D-out} = \frac{(2 * C_{DB} * Q_{D-in}) + (C_p + Q_p)}{(Q_{D-out} + Q_{D-in})}$$

Where, Q_{D-in} and Q_{D-out} are the inlet and outlet flow rate of draw solution (m^3/h), Q_p is the permeate flow rate (m^3/h) and C_p is the permeate concentration (mg/L). C_{D-in}, then, can be estimated from the Equation 10:

Equation 10: $$C_{D-in} = 2 * C_{DB} - C_{D-out}$$

Equation 10 was used to estimate the concentration of draw solution for the PRO process to operate on a maximum power density. To estimate the required membrane area, PRO membrane flux, J_w (L/m^2h), was calculated from Equation 11 [38]:

Equation 11: $$J_w = A_w\left(\frac{\pi_{Db} e^{(\frac{-J_w}{k})} - \pi_{Fb} e^{(J_w K)}}{1 + \frac{B}{J_w}\left(e^{(J_w K)} - e^{(\frac{-J_w}{k})}\right)} - \Delta P\right)$$

Where, π_{Db} and π_{Fb} (bar) are the osmotic pressures of the bulk draw and feed solution, respectively, A_w is the water permeability coefficient (assumed to be 0.79*10^{-3} m/h bar), ΔP is the hydraulic pressure across the PRO membrane (bar), k is the mass transfer coefficient (assumed 0.31 m/s), B is the solute permeability coefficient (assumed to be 0.12*10^{-3} m/h), and K is the solute resistivity for diffusion within the porous support layer (assumed to be 23 s/m). Finally, the required membrane area, A (m^2), was deduced from Equation 12:

Equation 12: $$A = \frac{Q_p}{J_w}$$

Equations 11 and 12 were used to predict the membrane flux and the membrane area for the PRO process. The concentration of draw solution was estimated using Equation 10. Power density, W (W/m^2), is the power generated per membrane unit area as shown in Equation 13:

Equation 13: $$W = J_w * \Delta P$$

Where, ΔP is the hydraulic pressure (bar). Figure 2b illustrates the computer model to estimate the performance of PRO process. A pre-developed computer model was used to predict the performance of the PRO membrane. For simplicity, sodium chloride (NaCl) was suggested as the draw solution for the PRO process. Reverse Osmosis System Analysis (ROSA) software was used to simulate the performance of the RO process. Eight elements (RO membrane type Dow Filmtec SW30HRLE-400i) were packed in the pressure vessel for seawater simulation; more information about the RO membrane can be found in literature [39, 40].

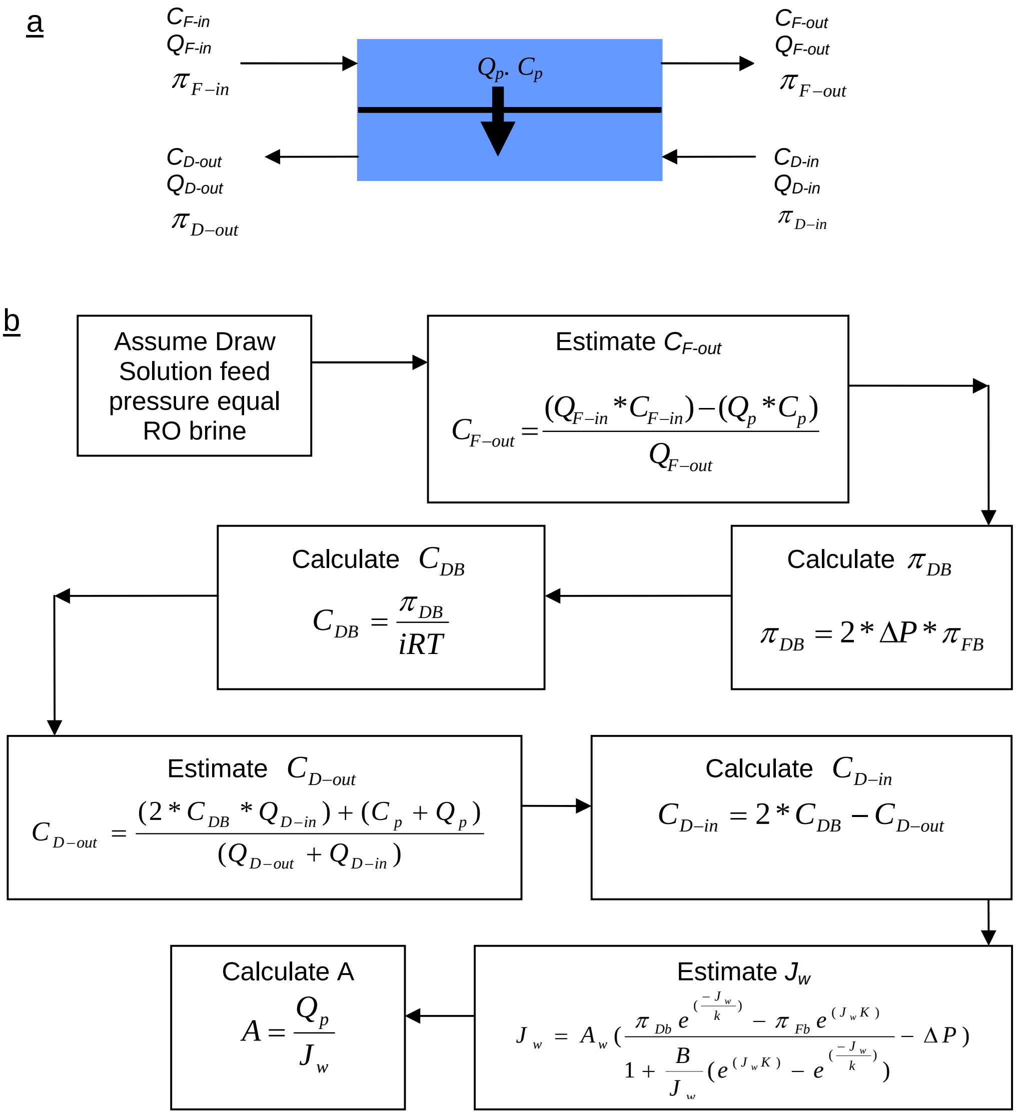


Figure 2: a) Feed and draw solutions flows in the PRO process b) model description to predict the performance of the PRO process

3. Results and Discussion

3.1 Model Validation

A pre-developed FO model was tested against the experimental data generated from a laboratory scale study [38]. Table 1 shows the PRO process testing parameters used for the model validation. Membrane flux, J_w, and power density, W, were calculated from equations 11 and 13 respectively. The model results were compared against those from the experimental work [38]. Membrane flux and power density are the key performance parameter in the PRO process.

Table 1: Testing parameters for model calibration

Parameter	k (m/h)	S (m)	K (h/m)	A (m/h.bar)	B (m/h)	D (m^2/h)
Value	0.306	$8*10^{-4}$	115-125	$6.7*10^{-4}$	$4*10^{-4}$	$6.1\text{-}6.4*10^{-6}$

The results presented in Table 2 show the experimental and model flux, $J_{w\text{-}exp}$, and $J_{w\text{-}mod}$ respectively, for 35 and 60 g/L draw solution concentrations, and feed solution concentrations ranging from 0 to 5 g/L. The difference between the experimental and model water flux values was calculated as the percentage value and shown in column 6, %Diff J_w [Table 2]. In general, the difference between the experimental and model values was approximately between 2.5 and 8.9% for 35 g/L draw solution and approximately between 3.5 and 8.2% for 60 g/L draw solution. In terms of power densities, W, the difference between experimental and model results was approximately between 3.5 and 8.8% for 35 g/L draw solution and approximately between 3.6% and 7.5 % for 60 g/L draw solution. It should be mentioned that all solutions osmotic pressure were calculated from OLI Systems Inc. (Morris Plains, NJ) in the experimental work whereas Van't Hoff equation was used for calculating the osmotic pressures of feed solutions in the Model; this may increased the difference between experimental and model results. Therefore, it was concluded that there was a good agreement between the experimental and model data.

Table 2 Comparison between experimental and model water flux

Draw TDS	Feed TDS	Pressure	$J_{w\text{-}exp}$	$J_{w\text{-}mod}$	% Diff. J_w	W_{exp+}	W_{mod}	% Diff. W

(g/L)	(g/L)	(bar)	(L/m²h)	(L/m²h)		(W/m²)	(W/m²)	
35	0	13	7.9	7.7	2.5%	2.9	2.8	3.5%
	2.5	12	6.8	6.2	8.8%	2.3	2.1	8.7%
	5	11	5.6	5.1	8.9%	1.7	1.55	8.8%
60	0	24	12.4	12	3.5%	8.3	8.0	3.6%
	2.5	23	10.1	9.5	5.9%	6.5	6.1	6.1%
	5	22.5	8.5	7.8	8.2%	5.3	4.9	7.5%

3.2 Performance of RO system

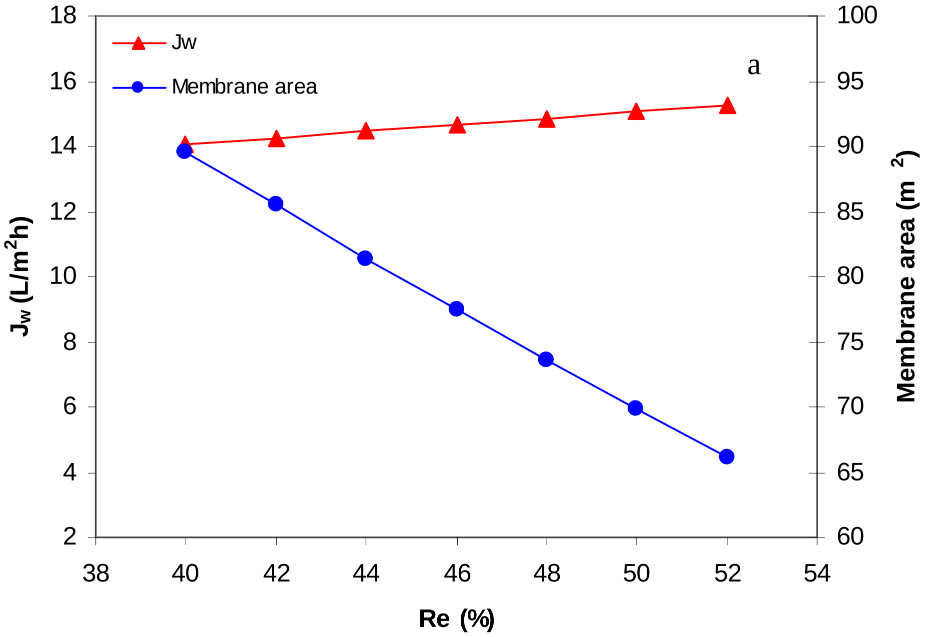
ROSA software was used to estimate the water flux, concentrate flow rate and pressure in the RO process [Table 3]. The results showed that membrane flux, J_w, increased as the recovery rate of the RO system was elevated; this was achieved by increasing the applied feed pressure across the RO membrane system. However, most seawater RO desalination plants operate at a recovery rate less than or equal to 50% and the generated RO brine is normally discharged to sea. As such, only 50% of the RO feed was converted to fresh water. By coupling the PRO process with an RO system, seawater recovery rates could be increased to in excess of 50% [Figure 1]; RO brine exchanged pressure with the PRO draw solution, before entering the PRO membrane as the feed solution. Recovery rates in Table 3 were only due to the RO process and further water recovery from the RO brine was achieved in the subsequent PRO process.

Table 3: Performance of RO membrane (feed salinity 35 g/L, feed flow rate 7 m^3/h)

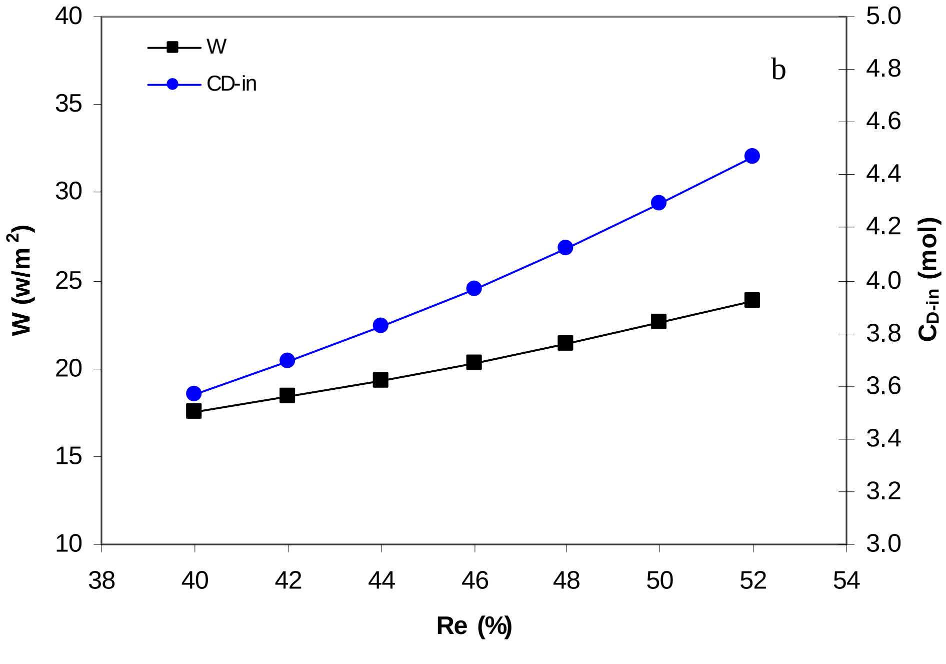
Re (%)	J_w L/m²h	P_f (bar)	Q_c m³/h	P_c (bar)
40	9.42	46.24	4.2	44.75
42	9.89	47.85	4.06	46.37
44	10.36	49.52	3.92	48.09
46	10.83	51.27	3.78	49.88
48	11.3	53.21	3.64	51.85
50	11.77	55.3	3.5	53.98
52	12.24	57.53	3.36	56.23

3.3 Performance of PRO system

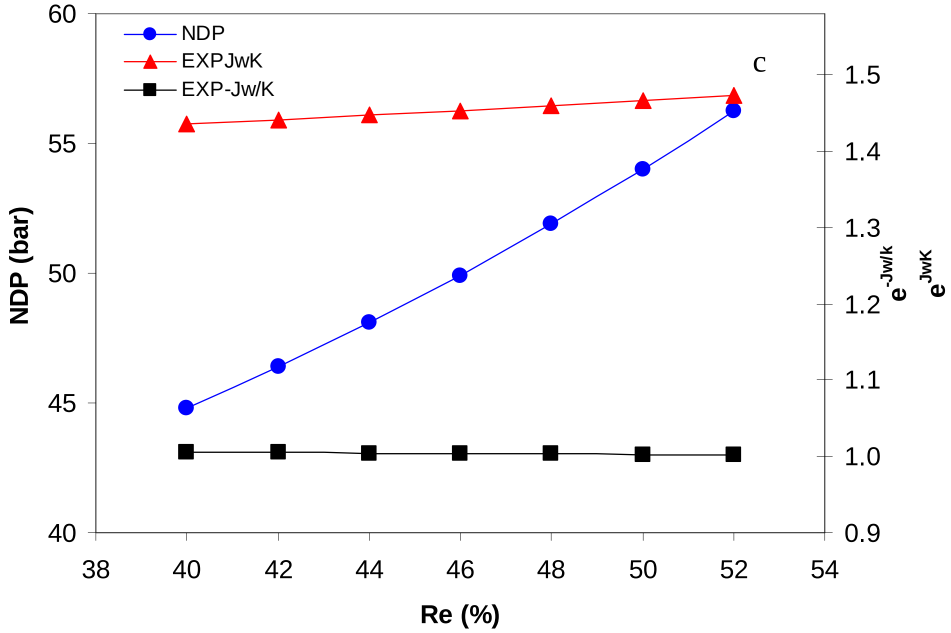
PRO aims to increase fresh water recovery from the RO brine before discharge and power generation. The process performance was estimated using a pre-developed computer model to optimize the PRO membrane area and the concentration of draw solution, in order to reduce capital and operating costs. Table 3 shows the flow rate and pressure of RO brine to the PRO process. It was assumed that the RO brine pressure was equal to that of the draw solution in the PRO process and that the PRO process operated with a maximum power density; *i.e.* $\Delta P = \Delta\pi / 2$. The recovery rate of the PRO process was fixed at 30% to evaluate the impact of RO recovery rate on the PRO performance. Figure 3a shows that the membrane flux increased with increasing recovery rate of RO process; this was attributed to the higher osmotic pressure gradient across the PRO membrane. The concentration of the draw solution increased from 3.6 to 4.5 M with increasing recovery rate of the RO process from 40 to 52%, respectively [Figure 3b]; the corresponding Net Driving Pressure's (NDP) were 45 and 56 bar, respectively [Figure 3c]. However, the NDP increased non-linearly with increasing recovery rate of the RO process because of the severe Concentration Polarization (CP) effect which adversely affected PRO membrane flux. Moduli of dilutive and concentrative concentration polarization, $e^{J_w K}$ and $e^{\frac{-J_w}{k}}$ respectively, were calculated [Figure 3c] and results indicated that $e^{J_w K}$ and to a lesser extent $e^{\frac{-J_w}{k}}$ slightly increased with the recovery rate of RO process. Previous studies showed dilutive and concentrative CP increases with increasing concentrations of the feed and draw solutions [41]. Therefore, higher draw solution concentration was required to maintain the recovery rate of PRO at higher RO recovery rate.



Jw
Membrane area
a
J_w (L/m^{2}h)
Membrane area (m ^{2})
Re (%)



W
CD-in
b
W (w/m ^{2})
C_{D-in} (mol)
Re (%)



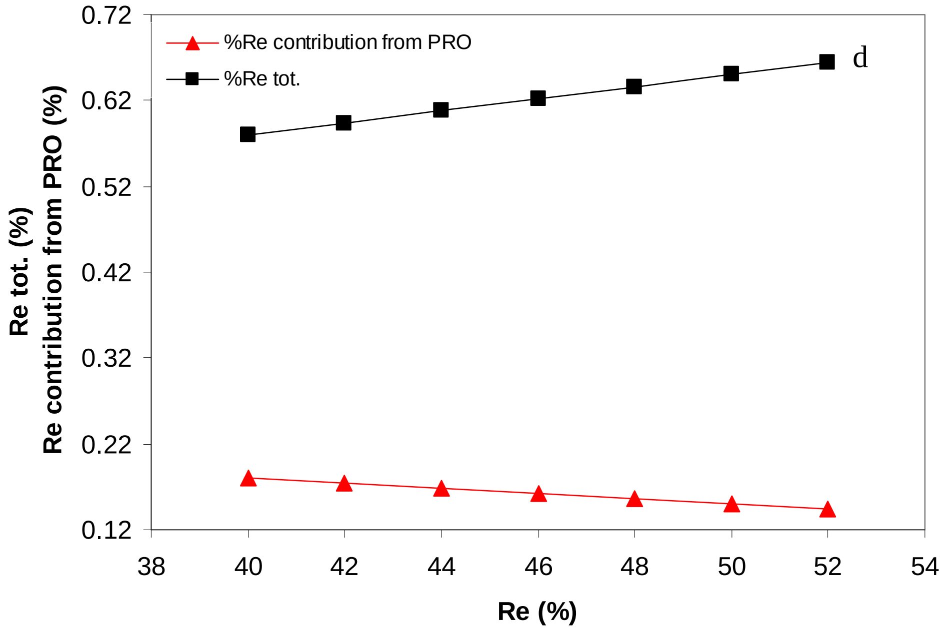


Figure 3: PRO process performance at different RO recovery rates a) membrane flux and membrane area b) power density and draw solution concentration c) NDP and moduli of concentration polarization d) recovery rate (PRO recovery rate 30% and RO feed salinity 35 g/L)

Membrane area was estimated as the ratio of permeate flow rate to membrane flux according to Equation 12 [Figure 3a]. Due to the higher membrane flux achieved at high RO recovery rates, PRO membrane area decreased at higher RO recovery rates. Membrane area decreased from 90 to 53 m^2 as RO recovery rate increased from 40 to 50%, respectively. Increasing the recovery rate of the RO process reduced the required PRO membrane area due to the higher membrane flux. In fact, high RO recovery rates also had the advantage of increasing the power density generated by the PRO process. However, it should be mentioned that 52% recovery rate was relatively high compared to the recovery rates of commercial RO seawater desalination plants. Furthermore, power density, W, was a function of the membrane flux and hydraulic pressure of the draw solution, which were increasing with the recovery rate of the RO process [Table 3 and Figure 3a]. Figure 3b shows that W increased with increasing recovery rate of the RO membrane. W increased from 17.5 to 28 kW/m^2 when RO recovery rate increased from 40 to 52%, respectively; this latter result corresponded to about 60% increase in the power density.

The total recovery rate of the RO-PRO system was estimated at different RO recovery rates [Figure 3d]. At a fixed PRO recovery rate of 30%, the simulation results showed that the total recovery rate of the RO-PRO system increased with increasing RO recovery rate. %Re total was 58% at 40% RO recovery rate and increased to 66.5% at 52% RO recovery rate [Figure 3d]. The contribution of the PRO recovery rate to the total RO-PRO recovery rate was estimated as the ratio of $\frac{Q_{p-PRO}}{Q_F}$; where Q_{p-PRO} is the permeate flow rate in the PRO process and Q_F is the feed flow rate (m^3/h). Results indicated that Q_{p-PRO} decreased with increasing recovery rate of the RO system; at 40% RO recovery rate Q_{p-PRO} was 18% but decreased to 14.5% at 52% RO recovery rate. For 50% RO recovery rate, which was the maximum RO recovery rate at 35 g/L feed salinity, the total recovery rate of the RO-PRO system was 65%. Table 4 shows the performance of the PRO system; interestingly membrane area and PRO recovery rate decreased with increasing power density of the process.

The results suggested that the performance of the PRO process was directly affected by the performance of the RO process. Therefore, RO recovery rate should be optimized to maximize the benefit of the PRO process for freshwater recovery from RO brine. Furthermore, there was a net power generation produced by the PRO system which could be invested in draw solution regeneration.

Table 4: Performance of PRO system at 35 g/L feed salinity and 30% PRO recovery rate

%Re (RO)	**A (m^2)**	**$C_{D\text{-}in}$ mol**	**P (bar)**	**Re (PRO)**	**%Re (tot.)**	**W w/m^2**
40%	90	3.6	44.8	18.0%	58.0%	17.5
42%	85	3.7	46.4	17.4%	59.4%	18.4
44%	81	3.8	48.1	16.8%	60.8%	19.3
46%	77	4.0	49.9	16.2%	62.2%	20.3
48%	74	4.1	51.9	15.6%	63.6%	21.4
50%	70	4.3	54.0	15.0%	65.0%	22.6
52%	66	4.5	56.2	14.4%	66.5%	23.8

Power generation by the PRO process, $P_{w\text{-}PRO}$, could be used to reduce the overall power consumption of the RO-PRO system, such as the RO system and the draw solution regeneration unit. The current study evaluated the impact of $P_{w\text{-}PRO}$ on power consumption of the RO system. Power generation, was in general a function of feed flow and pressure and calculated as shown in Equation 14:

Equation 14: $$P_w = \frac{Q_F * P_F}{\eta}$$

Where, Q_F is the feed flow rate (m^3/h), η is the motor efficiency (0.8), and P_F is the feed pressure (bar). Power consumption in the RO process, $P_{w\text{-}RO}$, can be reduced through compensation by the power generation by the PRO process, $P_{w\text{-}PRO}$. The power compensation value $P_{w\text{-}comp}$, represented the ratio of $P_{w\text{-}PRO}$ to $P_{w\text{-}RO}$. $P_{w\text{-}comp}$, was estimated assuming that $P_{w\text{-}}$

$_{PRO}$ was invested in the RO system [Figure 4]. $P_{w\text{-}comp}$ ratio decreased with increasing the recovery rate of RO system. Initially, this was due to increasing power demands of the RO system at high recovery rates. For RO without Energy Recovery Device (ERD), 14% reduction in RO power consumption, $P_{w\text{-}RO}$, occurred at 52% recovery rate but increased to about 17.5% at 40% RO recovery rate. With ERD, $P_{w\text{-}RO}$ was 22 and 32% at 52 and 40% recovery rates, respectively. The results showed that $P_{w\text{-}RO}$ was almost doubled when ERD was incorporated in the RO process.

In general, power harvested from the PRO can be invested in any process in the RO-PRO system although it is suggested here to be utilized in the RO unit. As such, power consumption can be reduced by integrating the PRO process with the RO process. Furthermore, the recovery rate of the desalination plant can be increased by applying the PRO process as a post-treatment for the RO brine.

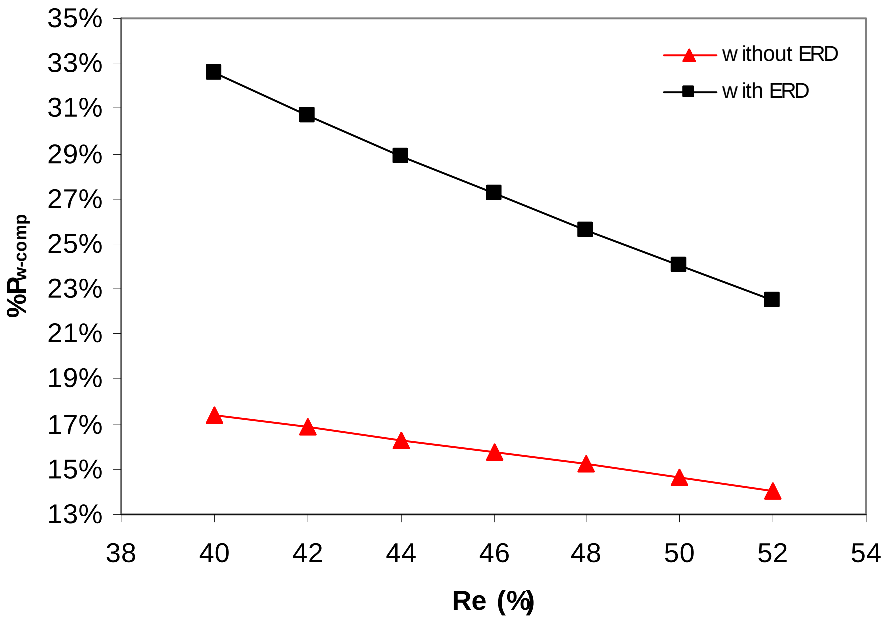


Figure 4: Percentage of power compensation value in the RO system by the PRO process (ERD efficiency is 80%)

3.4 Impact of Feed Salinity

The impact of feed salinity upon the performance of the RO process was evaluated using a range of feed salinities between 32 and 45 g/L. The recovery rate of the RO and PRO system was 45% and 30%, respectively and the total recovery rate of RO-PRO system was 62%. Figure 5a shows the membrane flux and area at different feed salinities. Membrane flux increased with increasing feed salinity due to the higher NDP across the PRO membrane at high feed salinities. The higher membrane flux resulted in a decrease in the membrane area required for the PRO process [Figure 5a]. Membrane flux increased from 14 to 16 L/m^{2}h as a result of feed salinity increase from 32 to 45 g/L. Flux increase resulted in a decrease in the membrane area from 82 to 73 m^2 at 32 and 45 g/L feed salinities, respectively. High membrane flux is always desirable in the PRO process to enhance power generation by the PRO process. Simulation results showed that the power density, W, increased with increasing seawater salinity from 32 to 45 g/L [Table 5]. Power density increased from 17.6 W/m^2 at 32 g/L to 28 W/m^2 at 45 g/L feed salinity [Figure 5b]; this was due to the higher membrane flux and hydraulic pressure at 45 g/L seawater salinity. However, the concentration of the draw solution, $C_{D\text{-}in}$, should be increased at higher seawater salinity to generate sufficient osmotic driving force across the PRO membrane [Figure 5b]. The required $C_{D\text{-}in}$ was 3.6 mol/L at 32 g/L but increased to 5 mol/L at 45 g/L due to the higher osmotic pressure of RO brine at 45 g/L. The results showed that higher seawater salinity had the potential for RO-PRO treatment but required higher concentrations of draw solution. This latter fact would increase the chemical cost. Thermal processes were more suitable for the regeneration of concentrated solution since power consumption was not affected by the feed salinity. Thermolytic draw solutions are suggested for the RO-PRO process due to their relatively low regeneration cost.

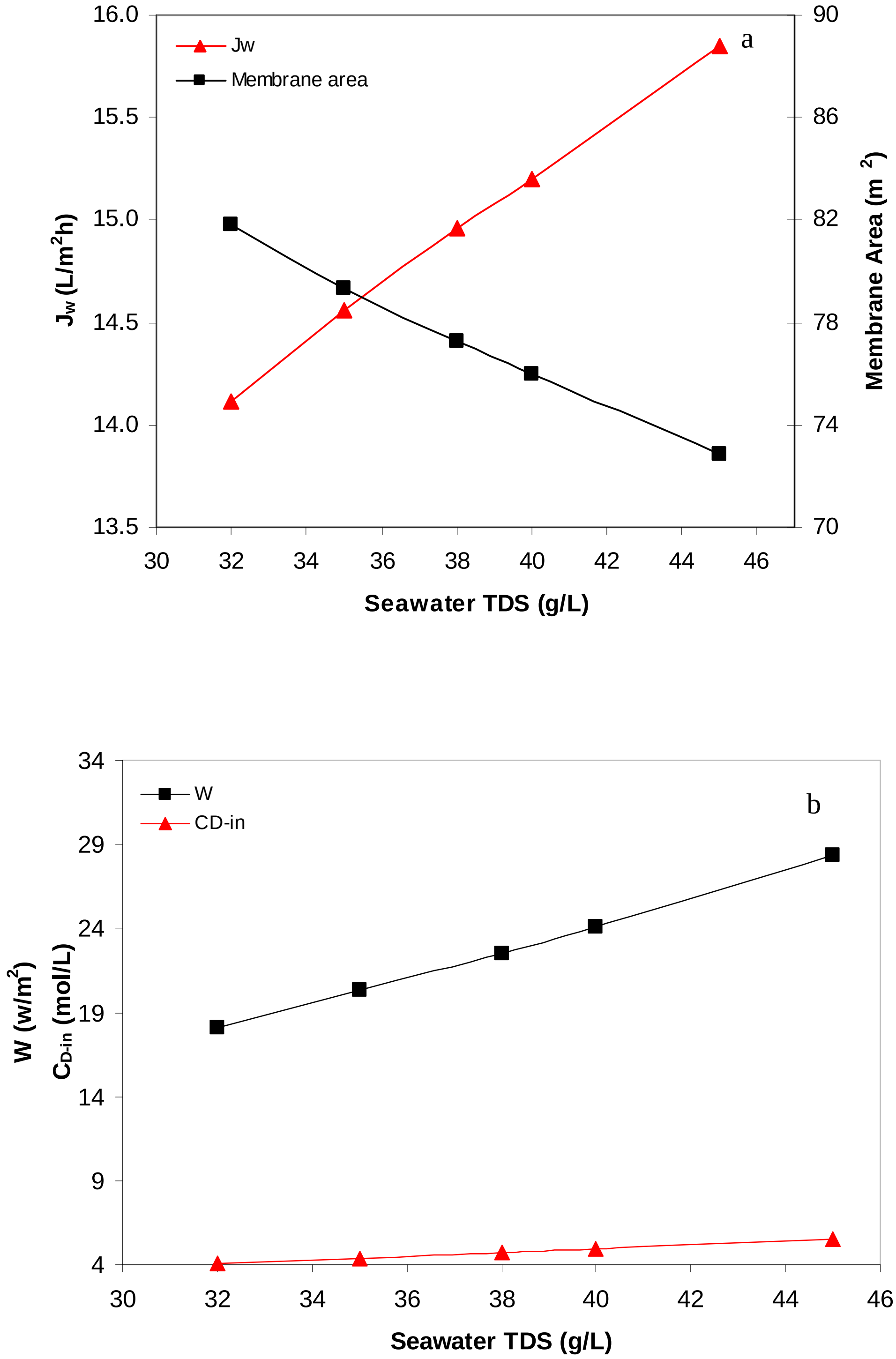


Figure 5: Performance of PRO process under different feed salinities a) membrane flux and area b) power density and draw solution concentration (PRO recovery rate 30%)

Table 5: performance of PRO at different seawater salinities and 30% PRO recovery rate

SW (g/L)	A (m^2)	C_{D-in} (M)	P (bar)	%Re (tot.)	W (W/m^2)
32	82	3.6	44.9	61.5	17.6
35	79	3.9	49.0	61.5	19.8
38	77	4.2	53.0	61.5	22.0
40	76	4.4	55.8	61.5	23.6
45	73	5.0	63.3	61.5	27.9

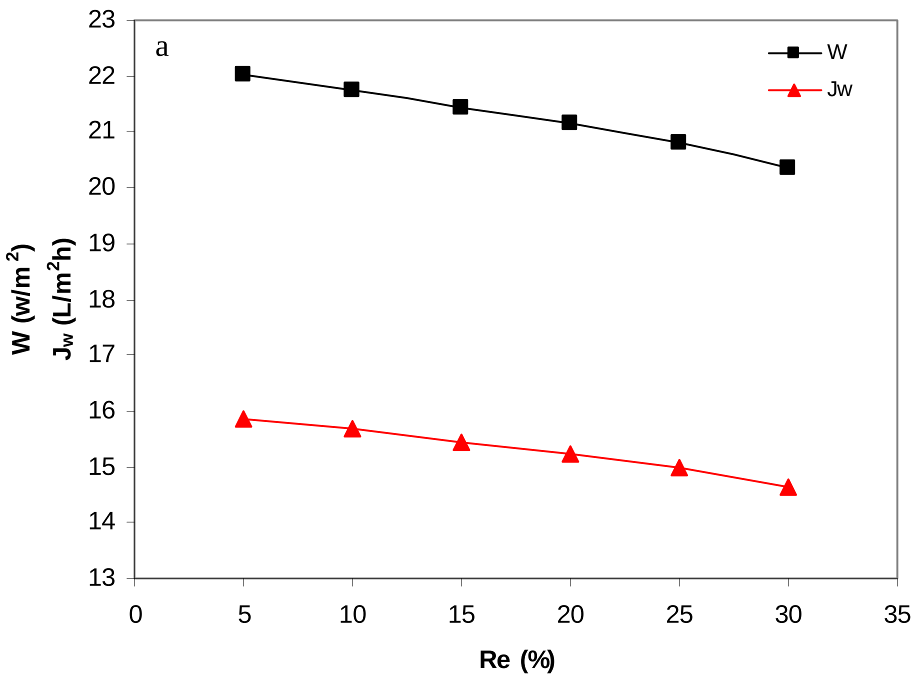
3.5 Impact of PRO recovery rate

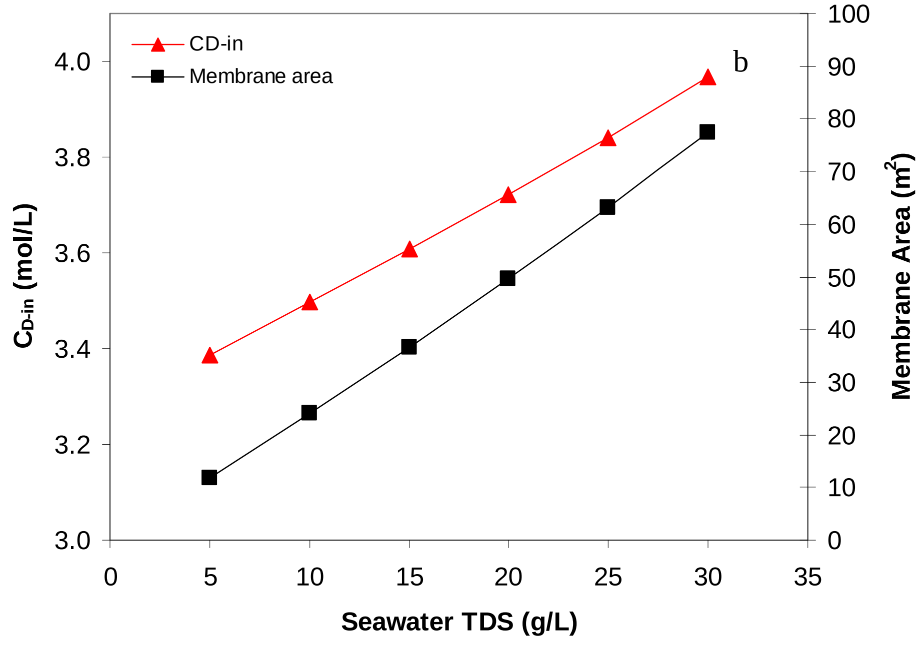
The impact of PRO recovery rate on the PRO performance was evaluated at 35 g/L and 46% RO feed salinity and recovery rate, respectively. Intuitively, PRO power density increases at higher PRO recovery rate and also increases the overall recovery rate of RO-PRO system. However, low PRO recovery rates were relatively important in sizing the PRO system for small pilot plants and experimental purposes. Simulation results suggested that membrane flux decreased with increasing recovery rate because of the higher osmotic driving force across the membrane [Figure 6a]. This resulted in a decrease in the power density of the PRO process with increasing recovery rate of PRO process. Power density decreased from 22 to 20.4 W/m^2 when the recovery rate of the PRO process increased from 5 to 30% [Figure 6a]. The concentration of draw solution, C_{D-in}, increased from 3.4 mol/L at 5% PRO recovery rate to 4 mol/L at 30% PRO recovery rate, to create sufficient osmotic pressure driving force for the PRO process [Figure 6b]. Membrane area also increased with increasing recovery rate of the PRO system [Figure 6b]. In general, the concentration of the draw solution and PRO membrane area increased in line with the PRO recovery rate. Fresh water recovery from the RO brine by the PRO process increased the total recovery rate of RO-PRO system, $\%Re_{tot}$, [Figure 6c]. The PRO process contributed a 3 to 16% increase of in the RO system recovery rate. The maximum $\%Re_{tot}$ reached 62% at 30% PRO recovery rate as shown in Figure 6c.

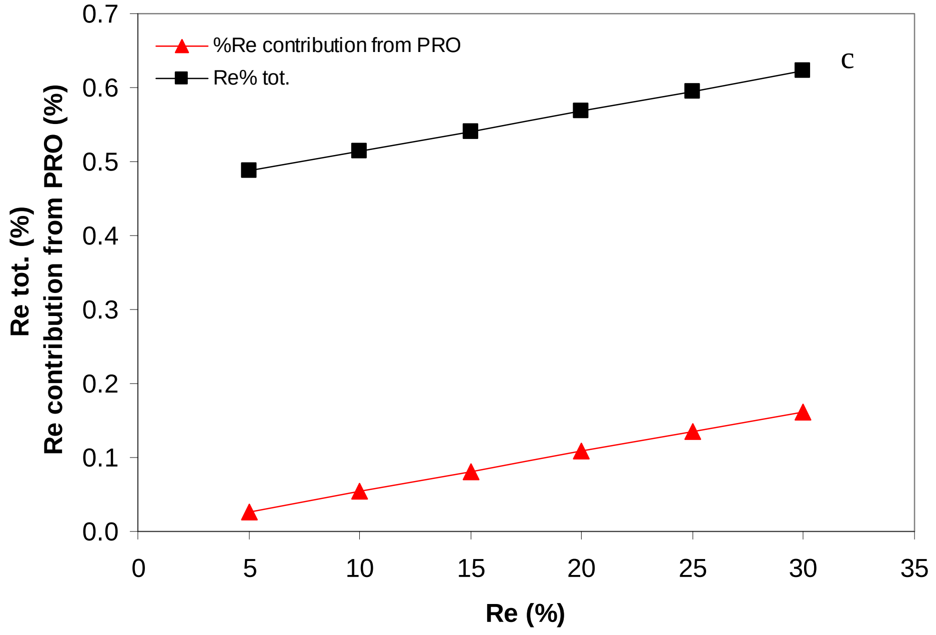
The percentage of power compensation, $P_{w\text{-}comp}$, was estimated for a range of PRO recovery rates between 5 and 30% [Figure 6d]. $P_{w\text{-}comp}$ increased with increasing recovery rate of the PRO process; the $P_{w\text{-}comp}$ was 3% at 5% PRO recovery rate but increased to about 16% at 30%

PRO recovery rate. The results also indicated that $P_{w\text{-}comp}$ was higher in the case of an RO plant using an ERD system. Interestingly, the difference in $P_{w\text{-}comp}$ between the RO plant without and with ERD increased with increasing recovery rate of the PRO process; $P_{w\text{-}comp}$ was almost doubled at 30% PRO recovery rate when ERD was used.

These results were contrary to those in Figure 4 which indicted that $P_{w\text{-}comp}$ decreased with increasing recovery rate of the RO system. The higher $P_{w\text{-}comp}$ the more energy efficient the desalination process was. Therefore, it is suggested that the recovery rate of RO and PRO processes should be increased in parallel for a more energy efficient desalination system.




CD-in
Membrane area
b
C_{D-in} (mol/L)
Membrane Area (m^2)
Seawater TDS (g/L)


%Re contribution from PRO
Re% tot.
c
Re tot. (%)
Re contribution from PRO (%)
Re (%)

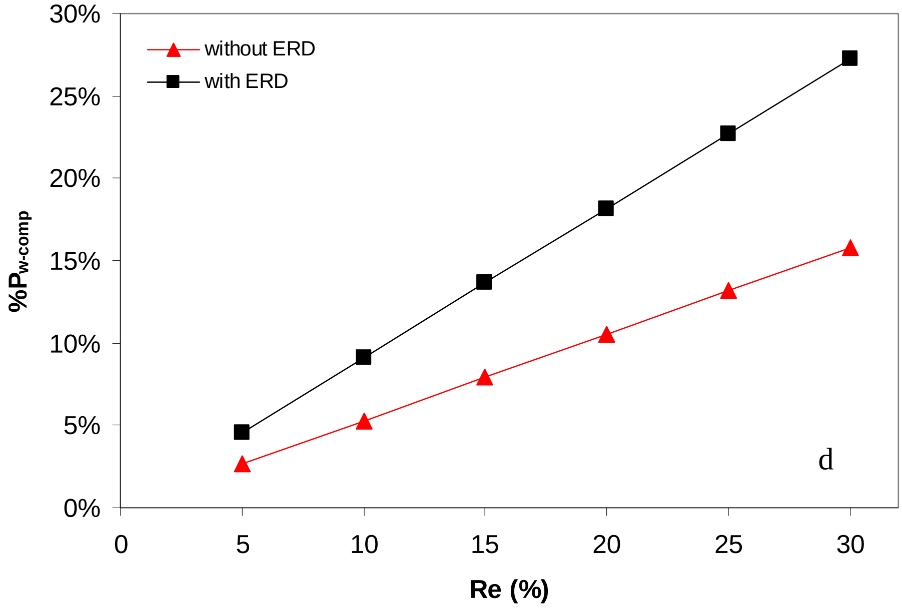


Figure 6: Performance of PRO at different recovery rates a) power density and membrane flux b) draw solution concentration and membrane area c) recovery rate d) %power compensation (RO feed salinity and recovery rate are 35 g/L and 46% respectively, ERD efficiency is 80%)

4. Conclusions

Modelling studies have shown that the integration of Pressure Retarded Osmosis with a Reverse Osmosis system may indeed reduce brine discharge volumes and also generate useful power which can be utilized for reduction of power consumption in a desalination process. A computer model was developed which facilitated optimization of the operating parameters of the PRO process, thus reducing the process operating and capital costs (assuming the process operated at a maximum power density; i.e. $\Delta P = \frac{\Delta\pi}{2}$. It was identified that the membrane area and concentration of the draw solution were key parameters in terms of PRO process optimization. Results indicated that the PRO process had potential for additional recovery of fresh water from the RO brine, but the performance was largely dependent on the RO feed salinity and recovery rate. It was found that PRO membrane flux and power density increased with increasing concentration of the RO brine, indicating that the PRO process efficiency may be particularly enhanced when coupled with an RO process treating high salinity seawaters. Furthermore, the energy efficiency of the RO-PRO system was evaluated based on the power compensation ratio, which was the ratio of $P_{w\text{-}PRO}$ to $P_{w\text{-}RO}$. It was discovered that the energy efficiency of the RO desalination process increased with increasing power compensation value from the PRO process and the impact was always higher at higher PRO recovery rates for RO plant with ERD system.

Theoretically, this study has confirmed that the PRO process has the potential of increasing the feed recovery rate of the RO desalination process. This conclusion is especially important at high seawater salinities due to the inherently low recovery rate of the RO process. Practically, thermolytic draw solutions such as ammonium carbon dioxide can be applied in the draw solution to reduce the regeneration cost. However, more work is required to demonstrate the system potential in practical terms.

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