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# Economic evaluation of the reverse osmosis and pressure retarded osmosis hybrid desalination process

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ABSTRACT

This paper presents a performance evaluation and economic analysis of a reverse osmosis (RO) and pressure retarded osmosis (PRO) hybrid process to propose guidelines for its economic competitiveness use in the field. A model to predict the performance of a hybrid process using RO and PRO was developed based on a solution-diffusion model modified with film theory. The effects of external and internal concentration polarization (ICP) on PRO efficiency were considered in the model. Moreover, a simple cost model was applied to analyze the effects of seawater TDS and feedwater for the PRO process, water and salt permeability of PRO membrane, and membrane and energy cost on the RO-PRO hybrid process. The results show that the water transport coefficient, ICP, and seawater and feedwater TDS are important factors affecting the performance of the PRO process. On the other hand, the effect of the salt transport coefficient is not substantial. 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.

*Keywords:* Reverse osmosis; Pressure retarded osmosis; Hybrid desalination; Economics; Model

## 1. Introduction

Water and energy are basic components of life, economic growth, and human progress. The two resources are now more interconnected because significant amounts of water are required in almost all energy generation processes. Conversely, water production requires energy, mainly in the form of electricity, to extract, treat, and transport water [1,2]. However, water and energy resources are under unprecedented pressure, and there is growing competition for their use from people, industries, ecosystems, and growing economies. As the world's population reaches nine billion, meeting demand will require a 50% increase in agricultural production and a 15% increase in already strained water withdrawals. By 2035, the world's energy consumption will increase by

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35%, which, in turn, will increase water use by 15% and consumption by 85%, according to the International Energy Agency [1,2]. Growing concern for the lack of water and energy has encouraged scientists to find new resources for water and energy supply [3]. Membrane technology can reduce energy demands as well as alleviate water demands [4]. Membrane technologies, such as reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD) are widely recognized as promising potable water production processes because of their ability to desalinate saline water, which is the most abundant global water source [5]. Among the membrane processes, RO is one of the most dominant technologies in the seawater desalination and water treatment market because it has the least geographical restrictions and is a proven, reliable, and established process [6–8]. In recent years, energy consumption of RO plants has dropped to around 3 $kWh/m^3$ with the development of more efficient energy recovery devices (ERDs) and improved membrane materials. Despite these improvements, the RO process requires relatively high amounts of energy to treat the brine for disposal and remains a limiting factor [9]. If pressure retarded osmosis (PRO) and RO processes are successfully integrated, seawater desalination will be less energy dependent, more sustainable, and could significantly alleviate the problem of disposing of waste RO brine and the environmental effects. Moreover, because the RO brine has been thoroughly pretreated in its previous processes, the use of RO brine may significantly reduce membrane fouling in a high-pressure compartment [10]. PRO is a variant of forward osmosis in which a pressurized concentrated draw stream and a more diluted feed stream are separated by a semi-permeable membrane. The permeate from the feed can enter the draw stream in a pressurized state, and useful power can be extracted [11]. After the early works of the 1970s, there was slow progress on the study of salinity gradient energy generation. Currently, PRO technology is still in the early stages of commercial applications. Therefore, further work is required to bring PRO technology into practice, including the development of new PRO membranes and new process designs. This paper provides a performance and economic evaluation of an RO-PRO hybrid process to propose guidelines to achieve price competitiveness in the process in the field. We develop a model to predict the performance of the hybrid process incorporating RO and PRO based on the solution-diffusion model modified with film theory. We consider the effects of external and internal concentration polarization (ICP) on PRO efficiency in the model. A simple cost model is applied to analyze the effects of seawater TDS and feedwater from the PRO process, water and salt permeability of the PRO membrane, and membrane and energy cost on the RO-PRO hybrid process.

## 2. Materials and methods

### 2.1. RO-PRO hybrid process

Fig. 1 shows the proposed hybrid configurations in this study. The brine from the RO process is used as a draw solution for the PRO process without additional pretreatment, and pretreated effluent from a wastewater treatment plant is used as the feed solution for the PRO process to produce higher osmotic power and alleviate the disposal and environmental problems of waste RO brine. Typically, the produced hydraulic energy from the PRO process is converted to electricity by hydraulic turbine. However, the efficiency of a hydraulic turbine is lower than that of a PX-type ERD. In this study, we focus on pressure recovery rather than energy production, where the produced hydraulic energy from PRO is used to lower the pressure demand of desalination instead of electricity.

### 2.2. Models

We applied the solution-diffusion model modified using the film theory model to analyze PRO process performance. To analyze the effects of major parameters, such as seawater TDS and feedwater from the PRO process, water and salt permeability of the PRO membrane, membrane and energy cost on RO, and the RO-PRO hybrid process, simple cost functions were formulated. Many reports on the cost analysis of the RO process have been published, and various cost functions exist [12–17]. Here, the selected cost functions are widely available.

#### 2.2.1. RO model

For an RO process, the water flux ($J_w$) and solute flux ($J_s$) equations can be defined as follows [18]:

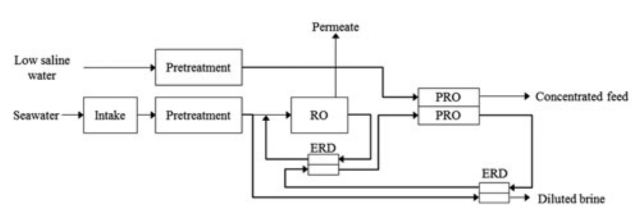


Fig. 1. Schematic of RO-PRO hybrid configuration.

$$J_w = A(P - \Delta\pi_{C_{F,m}} - P_{loss}) \quad (1)$$

$$J_s = B(C_{F,m} - C_p) \quad (2)$$

where $A$ is the water transport coefficient, $B$ is the salt transport coefficient, $C_{F,m}$ is the salt concentration on the membrane surface, $C_p$ is the salt concentration at the permeate side, $\Delta\pi_{C_{F,m}}$ is the osmotic pressure, $P$ is the feed pressure, and $P_{loss}$ is the pressure drop in the module.

$$P_{loss} = \frac{k_f 12\mu u\, L}{H^2} \quad (3)$$

where $k_f$ is the friction coefficient for the channel wall and spacers, $\mu$ is the dynamic viscosity of feedwater, $H$ is the feed channel height, $L$ is the feed channel length, and $u$ is the cross-flow velocity of the feedwater.

The osmotic pressure is directly related to the concentration of each solution with the modified van't Hoff formula.

$$\pi = \frac{NRT}{M_w} C \quad (4)$$

where $N$ is the ionization number in the water, $R$ is the ideal gas constant, $T$ is the temperature, $M_w$ is the molecular weight, and $C$ is the salt concentration.

$C_{F,m}$ is calculated according to film theory to interpret the concentration polarization, and the solvent concentration profile on the surface can be calculated according to equation [18]:

$$\frac{C_{F,m} - C_p}{C_{F,b} - C_p} = e^{\frac{J_w}{k}} \quad (5)$$

where $C_{F,b}$ is the salt concentration in the feed bulk solution, and $k$ is the mass transfer coefficient for the back diffusion of the solute from the membrane to the bulk solution on the high-pressure side of the membrane [19] as follows:

$$k = \frac{ShD}{d_h} \quad (6)$$

$$Sh = 1.85\left(Re\, Sc \frac{d_h}{L}\right)^{0.33} \quad (Re \le 2100) \quad (7)$$

$$Sh = 0.04\, Re^{0.75}\, Sc^{0.33} \quad (Re > 2100) \quad (8)$$

where $D$ is the diffusion coefficient, $d_h$ is the hydraulic diameter, $Sh$ is the Sherwood number, $Re$ is the Reynolds number, and $Sc$ is the Schmidt number.

The RO process for economic evaluation is composed of six major parts: The seawater intake, pretreatment, high-pressure pump, booster pump, RO membrane, and ERD. The capital and operating costs of the intake, pretreatment, high-pressure pump, booster pump, RO membrane module, and ERD are expressed as follows [12–17]:

$$CC_{IT\_RO}\,[\$] = 598 \times (Q_f[m^3/d]/0.9)^{0.78} \quad (9)$$

$$OC_{IT\_RO}[\$/d] = 0.028\, P_{IT}[bar]\, Q_f[m^3/d]\, D_{Ele}[\$/kWh]/\eta_{P\_IT} \times PLF \quad (10)$$

$$CC_{Pre\_RO}\,[\$] = 400 \times 0.7 \times (Q_f\,[m^3/d]/0.9)^{0.78} \quad (11)$$

$$OC_{Pre\_RO}\,[\$/d] = 0.028\, P_{Pre}\,[bar]\, Q_f\,[m^3/d]\, D_{Ele}\,[\$/kWh]/\eta_{P\_Pre} \times PLF \quad (12)$$

$$CC_{HP\_RO}\,[\$] = Q_f[m^3/d]\,(393{,}000 + 10{,}710\, P_{f,in}[bar]) \quad (13)$$

$$OC_{HP\_RO}\,[\$/d] = 0.028\, P_{f,in}\,[bar]\, Q_f\,[m^3/d]\, D_{Ele}\,[\$/kWh]/\eta_{P\_HP} \times PLF \quad (14)$$

$$CC_{BP\_RO}\,[\$] = (Q_f\,[m^3/d] - Q_p\,[m^3/d])\,(393{,}000 + 10{,}710\,(P_{f,in}\,[bar] - P_{f,out}\,[bar]\eta_{ERD}) \quad (15)$$

$$OC_{BP\_RO}[\$/d] = \frac{(0.028\,(P_{f,in} - P_{f,out})\,[bar]\,\eta_{ERD}\,(Q_f - Q_p)[m^3/d]\,D_{Ele}\,[\$/kWh])}{\eta_{P\_BP}} \times PLF \quad (16)$$

$$CC_{\mathrm{ERD\_RO}}\,[\$] = (Q_{\mathrm{f}}\,[\mathrm{m^3/d}] - Q_{\mathrm{p}}\,[\mathrm{m^3/d}])\,(393{,}000 + 1.07\,P_{\mathrm{f,in}}\,[\mathrm{bar}])/2 \tag{17}$$

where $CC$ and $OC$ denote the capital cost and operating cost. $P$ and $\eta$ represent pressure and efficiency. The subscripts, IT, Pre, HP, BP, and ERD denote the intake, pretreatment, high-pressure pump, booster pump, and ERD. $Q_{\mathrm{f}}$ and $Q_{\mathrm{p}}$ are the feed and permeate flow rate, respectively. $D_{\mathrm{energy}}$ is the unit electricity price, and $PLF$ is the plant load factor. Assuming that the capital cost of the membrane is linear to the membrane area, the annualized capital cost of the membrane is calculated by the following [20]:

$$CC_{\mathrm{Mem\_RO}}\,[\$] = \mathrm{Area_{Mem}}\,C_{\mathrm{Mem}}\,[\$/\mathrm{m^2}] \tag{18}$$

where the subscripts Mem denote the membrane, $\mathrm{Area_{mem}}$ is the total membrane area, and $C_{\mathrm{Mem}}$ is the unit membrane cost.

The total capital cost is composed of the direct capital cost and the indirect capital cost. The direct capital cost is the sum of the cost for plant equipment and the cost for site development, which is set at 20% of equipment cost [17]. The indirect capital cost is set at 30% of the direct capital cost [17]. The total and annual capital costs of the RO process are expressed as follows [14–17]:

$$CC_{\mathrm{Equipment\_RO}}\,[\$] = CC_{\mathrm{IT\_RO}} + CC_{\mathrm{Pre\_RO}} + CC_{\mathrm{HP\_RO}} + CC_{\mathrm{BP\_RO}} + CC_{\mathrm{Mem\_RO}} \tag{19}$$

$$CC_{\mathrm{Site\_RO}}\,[\$] = CC_{\mathrm{Equipment\_RO}} \times 0.2 \tag{20}$$

$$DCC_{\mathrm{RO}}\,[\$] = CC_{\mathrm{Equipment\_RO}} + CC_{\mathrm{Site\_RO}} \tag{21}$$

$$CC_{\mathrm{RO}}\,[\$] = DCC_{\mathrm{RO}} \times 0.3 \tag{22}$$

$$TCC_{\mathrm{RO}}\,[\$] = DCC_{\mathrm{RO}} + ICC_{\mathrm{RO}} \tag{23}$$

$$ACC_{\mathrm{RO}}\,[\$/\mathrm{y}] = TCC_{\mathrm{RO}}\frac{i(1+i)^n}{(1+i)^n - 1} \tag{24}$$

where $DCC_{\mathrm{RO}}$ is the direct capital cost, $ICC_{\mathrm{RO}}$ is the indirect capital cost, $TCC_{\mathrm{RO}}$ is the total capital cost, $ACC_{\mathrm{RO}}$ is the annual capital cost, $i$ is the interest rate, and $n$ is the plant lifetime.

The annual operating cost is composed of the annual power cost, annual membrane replacement cost, and other costs (labor, chemicals, maintenance). The annual operating costs of the RO process are expressed as follows [14–17]:

$$OC_{\mathrm{Power\_RO}}\,[\$/\mathrm{y}] = (OC_{\mathrm{IT\_RO}} + OC_{\mathrm{Pre\_RO}} + OC_{\mathrm{HP\_RO}} + OC_{\mathrm{BP\_RO}}) \times 365 \tag{25}$$

$$OC_{\mathrm{MR\_RO}}\,[\$/\mathrm{y}] = CC_{\mathrm{Mem\_RO}} \times 0.2 \tag{26}$$

$$OC_{\mathrm{etc\_RO}}\,[\$/\mathrm{y}] = AOC_{\mathrm{RO}} \times 0.3 \tag{27}$$

$$AOC_{\mathrm{RO}}\,[\$/\mathrm{y}] = OC_{\mathrm{power\_RO}} + OC_{\mathrm{MR\_RO}} + OC_{\mathrm{etc\_RO}} \tag{28}$$

where $OC_{\mathrm{Power\_RO}}$ is the annual power cost, $OC_{\mathrm{MR\_RO}}$ is the annual membrane replacement cost, and $OC_{\mathrm{etc\_RO}}$ is the other cost. Finally, the water cost of RO process is as follows:

$$WC_{\mathrm{RO}}\,[\$/\mathrm{m^3}] = (ACC_{\mathrm{RO}} + AOC_{\mathrm{RO}})/(365 \times Q_{\mathrm{p}} \times PLF) \tag{29}$$

### 2.2.2. PRO model

In the PRO process, the water and salt flux are limited by external concentration polarization (ECP) from stagnant layers caused by reduced mixing on the membrane surface and ICP from resistance against salt transport in the porous support layer [9,10]. Therefore, the water flux ($J_{\mathrm{w}}$) and salt flux ($J_{\mathrm{s}}$) equations for PRO can be defined as follows [9,10]:

$$J_{\mathrm{w}} = A\left(\pi_{\mathrm{D,m}} - \pi_{\mathrm{F,m}} - P\right) \tag{30}$$

$$J_{\mathrm{s}} = B\left(C_{\mathrm{D,m}} - C_{\mathrm{F,m}}\right) \tag{31}$$

where $\pi_{\mathrm{D,m}}$ and $C_{\mathrm{D,m}}$ are the osmotic pressure and salt concentration of draw water on the membrane surface, and $\pi_{\mathrm{F,m}}$ and $C_{\mathrm{F,m}}$ are the osmotic pressure and salt concentration of feedwater in the membrane support layer. $C_{\mathrm{D,m}}$ and $C_{\mathrm{F,m}}$ are expressed as the following [10,21]:

$$C_{\mathrm{D,m}} = \left[C_{\mathrm{D,b}}\exp\left(-\frac{J_{\mathrm{w}}}{k}\right)\right] \tag{32}$$

$$C_{\mathrm{F,m}} = \left[C_{\mathrm{D,m}} - \frac{C_{\mathrm{D,m}} - C_{\mathrm{F,b}}\exp(KJ_{\mathrm{w}})}{1 + \frac{B}{J_{\mathrm{w}}}[\exp(KJ_{\mathrm{w}}) - 1]}\right] \tag{33}$$

where $K$ and $k$ are the mass transfer coefficient for ICP and ECP, respectively.

Using $C_{\mathrm{D,m}}$ and $C_{\mathrm{F,m}}$ in place of $C_{\mathrm{D,b}}$ and $C_{\mathrm{F,b}}$, the water flux ($J_{\mathrm{w}}$) and salt flux ($J_{\mathrm{s}}$) equations can be modified as follows:

$$J_w = A\left(\frac{N_D R T_D}{M_{w,D}} C_{D,b} \exp\left(-\frac{J_w}{k}\right) - \frac{N_F R T_F}{M_{w,F}}\left(C_{D,m} - \frac{C_{D,m} - C_{F,b}\exp(KJ_w)}{1 + \frac{B}{J_w}[\exp(KJ_w) - 1]}\right) - P_S\right) \quad (34)$$

$$J_s = B\left(C_{D,b}\exp\left(-\frac{J_w}{k}\right) - C_{D,m} - \frac{C_{D,m} - C_{F,b}\exp(KJ_w)}{1 + \frac{B}{J_w}[\exp(KJ_w) - 1]}\right) \quad (35)$$

where $P_S$ is the pressure of the draw water for the PRO process.

The power density $W$ of the PRO membrane module is calculated using the product of $J_w$ and $P_S$ [21]:

$$PD = J_w P_S \quad (36)$$

The PRO cost model is almost the same as the RO cost model. The PRO cost is developed to evaluate the RO-PRO hybrid processes. The PRO process is composed of four major parts: pretreatment for treated wastewater, the RO brine and treated wastewater pump, the PRO membrane, and ERD. The capital and operating costs of the intake, pretreatment, seawater and wastewater pump, and PRO membrane cost are expressed as follows:

$$CC_{Pre\_W\_PRO}\,[\$] = 400 \times (Q_W\,[m^3/d]/0.9)^{0.78} \quad (37)$$

$$OC_{Pre\_W\_PRO}\,[\$/d] = 0.028\,P_{Pre\_W}\,[bar]\,Q_W\,[m^3/d]\,D_{Ele}\,[\$/kWh]/\eta_{Pre\_W} \times PLF \quad (38)$$

$$CC_{P\_W\_PRO}\,[\$] = (Q_W\,[m^3/d])\,(393{,}000 + 10{,}710\,(P_W\,[bar]) \quad (39)$$

$$OC_{P\_W\_PRO}\,[\$/d] = 0.028\,P_W\,[bar]\,Q_W\,[m^3/d]\,D_{Ele}\,[\$/kWh]/\eta_{P\_W} \times PLF \quad (40)$$

$$CC_{P\_S\_PRO}\,[\$] = (Q_S\,[m^3/d])\,(393{,}000 + 10{,}710\,(P_{S,in}\,[bar] - P_{S,out}\,[bar]\,\eta_{ERD}^2)) \quad (41)$$

$$OC_{P\_S\_PRO}\,[\$/d] = \frac{(0.028\,(P_{S,in}\,[bar] - P_{S,out}\,[bar]\,\eta_{ERD}^2)\,Q_S)\,[m^3/d]\,D_{Ele}[\$/kWh])}{\eta_{P\_S}} \times PLF \quad (42)$$

$$CC_{Mem\_PRO}\,[\$] = \text{Area}_{Mem\_PRO}\,C_{mem\_PRO}\,[\$/m^2] \quad (43)$$

$$OC_{MR\_PRO}\,[\$/y] = CC_{Mem\_PRO} \times 0.2 \quad (44)$$

$$CC_{ERD\_PRO}\,[\$] = (Q_f\,[m^3/d])\,(393{,}000 + 10{,}710\,P_{S,out}\,[bar])/2 \quad (45)$$

where the subscripts S and W denote the seawater brine and treated wastewater.

The annualized capital cost of the RO-PRO hybrid process is calculated using the same methodology as the RO process. The total capital cost is composed of the direct capital cost and the indirect capital cost. The direct capital cost is the sum of the cost for plant equipment and the cost for site development, which is set at 20% of the equipment cost [17]. The indirect capital cost is set at 30% of the direct capital cost. The total and annual capital costs of the RO-PRO process are expressed as follows [14–17]:

$$CC_{Equipment\_RO\text{-}PRO}\,[\$] = CC_{Equipment\_RO} + CC_{Equipment\_PRO} \quad (46)$$

$$CC_{Site\_RO-PRO}\,[\$] = CC_{Equipment\_RO-PRO} \times 0.2 \quad (47)$$

$$DCC_{RO-PRO}\,[\$] = CC_{Equipment\_RO-PRO} + CC_{Site\_RO-PRO} \quad (48)$$

$$ICC_{RO-PRO}\,[\$] = DCC_{RO-PRO} \times 0.3 \quad (49)$$

$$TCC_{RO-PRO}\,[\$] = DCC_{RO-PRO} + ICC_{RO-PRO} \quad (50)$$

$$CC_{RO-PRO}\,[\$/y] = TCC_{RO-PRO}\frac{i(1+i)^n}{(1+i)^n-1} \quad (51)$$

The annual operating cost is composed of the annual power cost, annual membrane replacement cost, and other costs (labor, chemicals, maintenance). The annual operating costs of the PRO and RO-PRO process are expressed as follows [14–17]:

$$OC_{Power\_FO-RO}\,[\$/y] = (OC_{Power\_RO} + OC_{Power\_FO}) \times 365 \quad (52)$$

$$OC_{MR\_RO-PRO}\,[\$/y] = CC_{Mem\_RO} \times 0.2 + CC_{Mem\_PRO} \times 0.2 \quad (53)$$

$$OC_{etc\_RO-PRO}\,[\$/y] = AOC_{RO-PRO} \times 0.3 \quad (54)$$

$$AOC_{RO-PRO}\,[\$/y] = OC_{power\_RO-PRO} + OC_{MR\_RO-PRO} + OC_{etc\_RO-PRO} \quad (55)$$

Finally, the water cost of the FO process is as follows:

$$WC_{RO-PRO}\,[\$/m^3] = (ACC_{RO-PRO} + AOC_{RO-PRO})/(365 \times Q_p \times PLF) \quad (56)$$

### 2.3. Simulation conditions

To investigate the hybridization effect of RO and PRO, economic evaluations were performed for 100,000 $m^3/d$ RO and a RO-PRO hybrid desalination plant. Table 1 lists the values for the model parameters and operating conditions in this study. The seawater and feedwater from the PRO process (treated wastewater) TDS are changed to predict the performance and cost of the RO and RO-PRO process. Additionally, the $A$, $B$, and $K$ values of the PRO membrane are changed to predict the performance and cost of the RO and RO-PRO hybrid process. The value of the model parameters and operating conditions is set to ensure that the RO-PRO hybrid process has greater price competitiveness than the RO process.

Table 1
Parameters and operating conditions

| | Parameter | Value |
|---|---|---|
| RO membrane | $A$ | $2.0 \times 10^{-12}$ m/sec-Pa |
| | $B$ | $1.8 \times 10^{-8}$ m/sec |
| | Flux | 12 LMH |
| | Recovery | 40% |
| | Membrane area | 40 $m^2$/module |
| | Module configuration | 7 modules per a vessel |
| PRO membrane | $A$ | 1.0–5.0 × $10^{-12}$ m/sec-Pa (3 × $10^{-12}$ m/sec-Pa) |
| | $B$ | 1–5 × $10^{-8}$ m/sec (3 × $10^{-8}$ m/sec) |
| | $K$ | 0.5–7 × $10^5$ sec/m (0.5 × $10^5$ sec/m) |
| | Recovery ($Q_{d,out}/Q_{d,in}$) | 166.7 |
| | Membrane area | 20 $m^2$/module |
| | Module configuration | 7 modules per a vessel |
| TDS | Seawater | 35,000–43,000 mg/L (43,000 mg/L) |
| | Treated wastewater | 1,000–9,000 mg/L (2,000 mg/L) |
| Efficiency | Pump | 75% |
| | ERD | 95% |
| Cost | Electricity cost | 0.05–0.4 $/kWh (0.25 $/kWh) |
| | Membrane cost (RO/PRO) | 30/30–60 $/$m^2$ (30 $/$m^2$) |
| | Plant load factor | 0.91 |
| | Interest rate | 0.03 |
| | Plant life | 20 years |

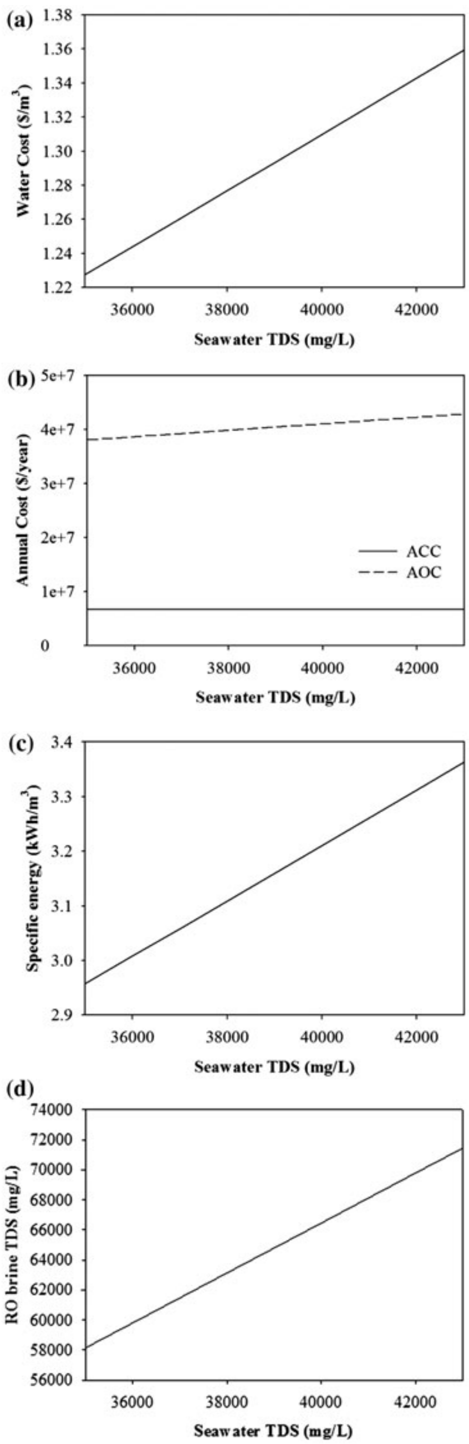


Fig. 2. The simulation results for a 100,000 $m^3$/d RO process according to a variation of seawater TDS from 32,000 to 43,000 mg/L: (a) water production cost, (b) AOC and ACC, (c) total specific energy consumption, and (d) RO brine TDS.

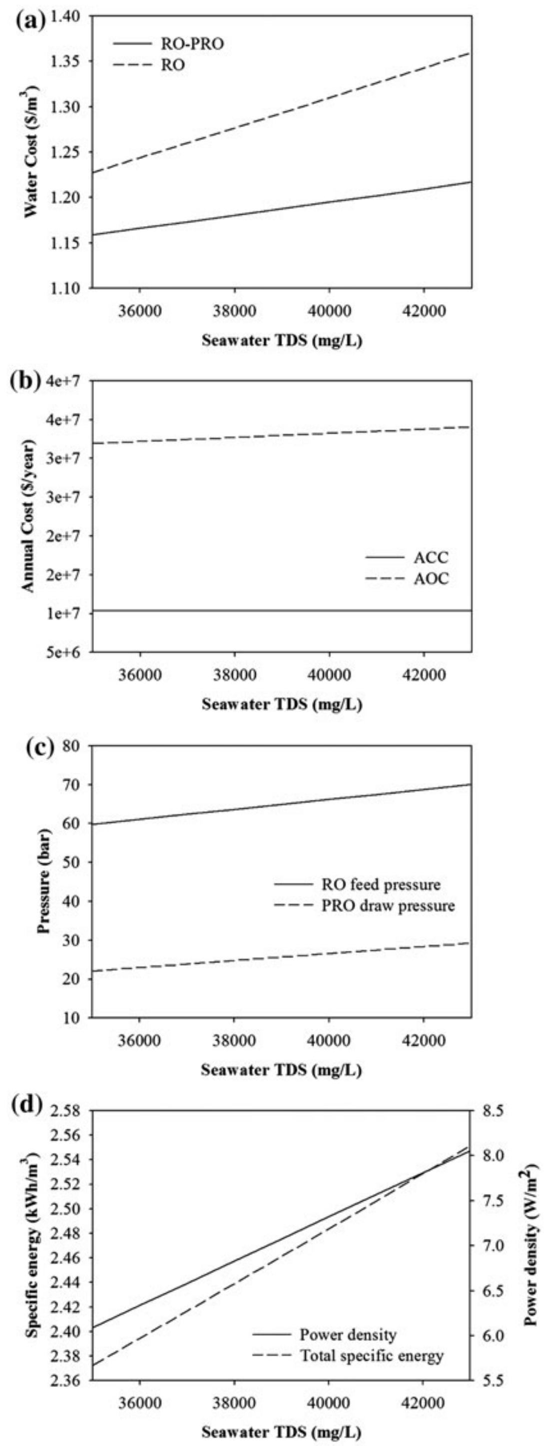


Fig. 3. The simulation results for a 100,000 $m^3$/d RO-PRO process depending on a variation of seawater TDS from 32,000 to 50,000 mg/L: (a) water production cost, (b) AOC and ACC, (c) PRO draw solution pressure and RO feed pressure, and (d) power density and total specific energy consumption.

## 3. Results and discussion

Fig. 2 shows the simulation results for a 100,000 $m^3/d$ RO process according to a change in seawater TDS from 32,000 to 43,000 mg/L. In this calculation, the parameters and operating condition are the same as those shown in Table 1. The water production cost increases with increasing seawater TDS because of increased energy consumption by the high-pressure pump to produce the same water flux. The annual capital cost does not change, but the annual operating cost increases because the specific energy increases. In this calculation, the seawater brine TDS changes from 58,000 to 71,000 mg/L, and energy consumption changes from 2.96 to 3.36 $kWh/m^3$.

Fig. 3 shows the simulation results for a 100,000 $m^3/d$ RO-PRO hybrid process according to a change in seawater TDS from 32,000 to 43,000 mg/L. The treated wastewater TDS, *A*, *B* value, and *K* value of the PRO membrane are set to 2,000 mg/L, $3.0 \times 10^{-12}$ m/sec-Pa, $3.0 \times 10^{-8}$ m/sec, and $0.5 \times 10^5$ sec/m, respectively. Additionally, the electricity cost and PRO membrane cost are set to 0.25 \$/kWh and 30 $\$/m^2$. The water cost of the RO-PRO hybrid plant is calculated as between 1.16 and 1.22 $\$/m^3$ depending on the change in the seawater TDS. The annual capital cost is constant at 10,381,000 \$/year, whereas the annual operating cost increases from 32,918,000 to 34,038,000 \$/year. The pressure of the draw solution of the PRO process to produce energy is calculated as between 21.1 and 29.3 bars. The power density and total specific energy consumption are calculated as between 6.1 to 8.1 $W/m^2$ and 2.37 to 2.55 $kWh/m^3$.

The water production cost of the RO-PRO hybrid process increases with increasing seawater TDS. As the seawater TDS increases, the power density of the PRO process also increases because the RO brine becomes more concentrated. However, the water production cost increases. This implies that the energy production from the PRO process is less than the energy consumption from the RO process in the RO-PRO hybrid process shown in Fig 3(a). The water cost differential between the RO and RO-PRO hybrid increases as seawater TDS increases. Therefore, as seawater TDS increases, the RO-PRO hybrid process becomes more advantageous than the RO process.

Fig. 4 shows the simulation results for a 100,000 $m^3/d$ RO-PRO hybrid process according to a change in treated wastewater TDS (PRO feedwater) from 1,000 to 9,000 mg/L. The seawater TDS is set to 43,000 mg/L. The *A*, *B*, and *K* value of PRO membrane, electricity cost, and PRO membrane cost are set to the same values as the prior simulations.

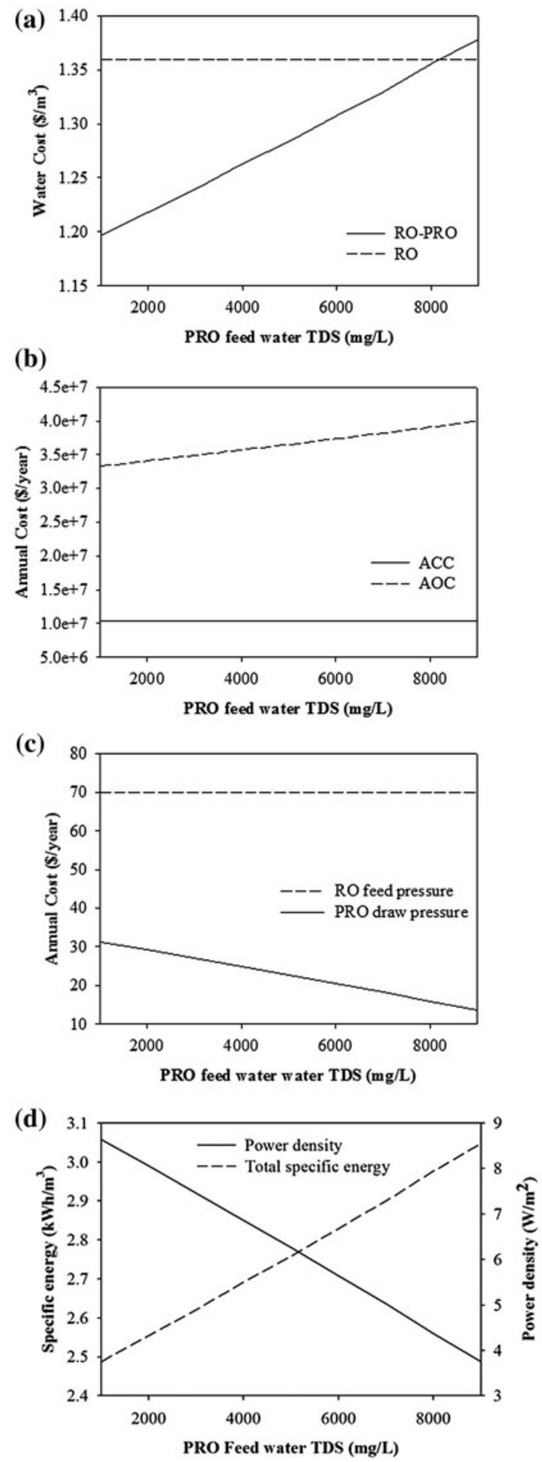


Fig. 4. The simulation results for a 100,000 $m^3/d$ RO-PRO process according to a variation in treated wastewater TDS from 1,000 to 9,000 mg/L: (a) water production cost, (b) AOC and ACC, (c) PRO draw solution pressure and RO feed pressure, and (d) power density and total specific energy consumption.

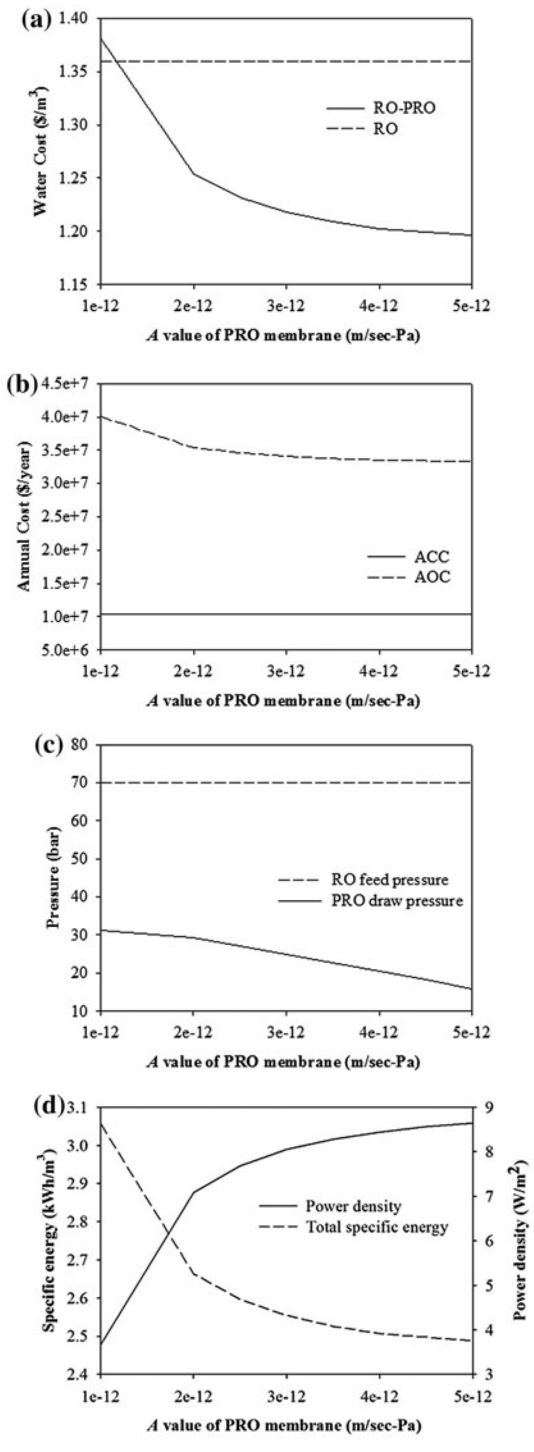


Fig. 5. The simulation results for a 100,000 $m^3$/d RO-PRO process according to a variation in the *A* value of the PRO membrane from $1 \times 10^{-12}$ to $5 \times 10^{-12}$ m/sec-Pa: (a) water production cost, (b) AOC and ACC, (c) PRO draw solution pressure and RO feed pressure, and (d) power density and total specific energy consumption.

The water cost of the RO-PRO hybrid plant is calculated as between 1.20 and 1.38 \$/$m^3$ depending on the change in treated wastewater TDS. The annual capital cost is constant at 10,381,000 \$/year, whereas the annual operating cost increases from 33,288,000 to 39,925,000 \$/year. The pressure of the PRO process draw solution to produce energy is calculated as between 31.3 and 13.6 bars. The power density and total specific energy consumption are calculated as between 3.7 to 8.1 W/$m^2$ and 2.49 to 3.05 kWh/$m^3$. The water production cost of the RO-PRO hybrid process increases with increasing treated wastewater TDS. As the treated wastewater TDS increases, the power density of the PRO process decreases. Because of the driving force, the osmotic pressure difference of draw and feedwater of the PRO process decreases. Fig. 1(a) shows that for the RO-PRO hybrid process to have greater price competitiveness than the RO process, the treated wastewater TDS cannot exceed 8.000 mg/L.

Fig. 5 shows the simulation results for a RO-PRO hybrid process according to a change in the *A* value of the PRO membrane from $1 \times 10^{-12}$ to $5 \times 10^{-12}$ m/sec-Pa. In this calculation, seawater and treated wastewater TDS, the *B* value, and *K* value of the PRO membrane are set to 43,000, 2,000 mg/L, $3.0 \times 10^{-8}$ m/sec, and $0.5 \times 10^5$ sec/m, respectively. The water cost of the RO-PRO hybrid plant is calculated as between 1.20 and 1.38 \$/$m^3$ depending on the change in the *A* value of the PRO membrane. The annual capital cost is constant at 10,381,000 \$/year, whereas the annual operating cost decreases from 40,037,000 to 33,288,000 \$/year. The pressure of the draw solution of the PRO process to produce energy is calculated as between 13.3 and 31.3 bars. The power density and total specific energy consumption are calculated as between 3.70 to 8.65 W/$m^2$ and 2.49 to 3.06 kWh/$m^3$. The water cost of the RO-PRO hybrid plant decreases with an increasing *A* value of the PRO membrane because of an increase in energy production from the PRO process. Because the energy production from the PRO process increases, the annual operating cost decreases. The power density of the PRO process increases logarithmically as the *A* value of PRO membrane decreases. For the RO-PRO hybrid process to have greater price competitiveness than the RO process in this condition, the *A* value must be greater than $1.2 \times 10^{-12}$ m/sec-Pa.

Fig. 6 shows the simulation results for a 100,000 $m^3$/d RO-PRO hybrid process according to a change in the *B* value of the PRO membrane from $1 \times 10^{-8}$ to $5 \times 10^{-8}$ m/sec-Pa. In this case, the

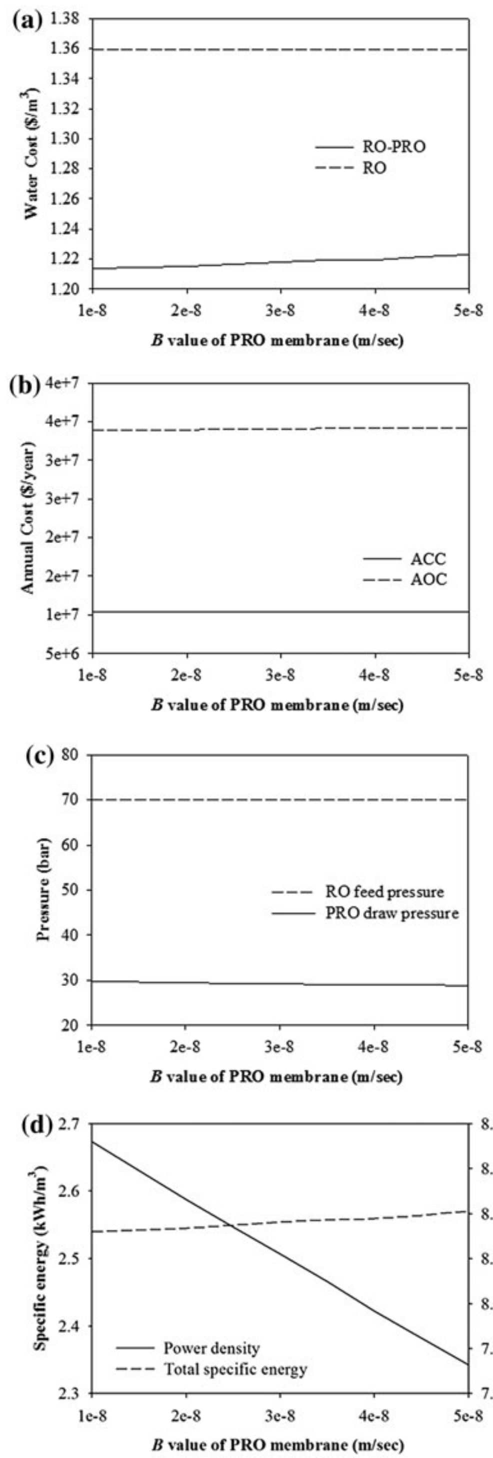


Fig. 6. The simulation results for a 100,000 $m^3/d$ RO-PRO process according to a variation in the *B* value of the PRO membrane from $1 \times 10^{-8}$ to $5 \times 10^{-8}$ m/sec-Pa: (a) water production cost, (b) AOC and ACC, (c) PRO draw solution pressure and RO feed pressure and, (d) power density and total specific energy consumption.

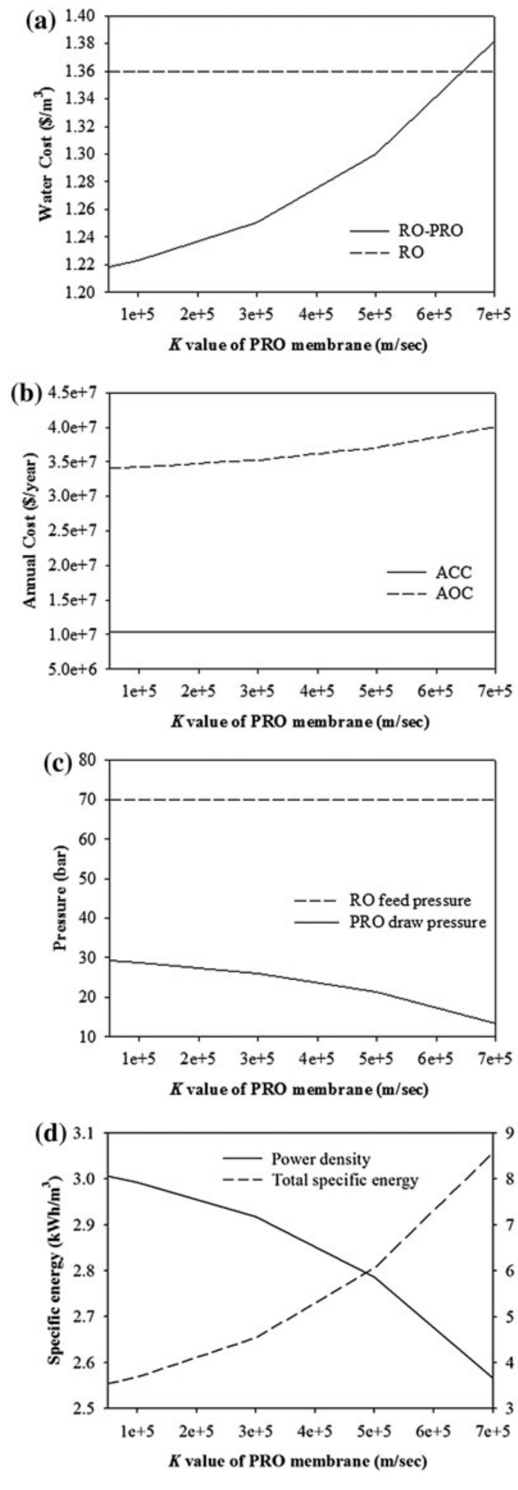


Fig. 7. The simulation results for a 100,000 $m^3/d$ RO-PRO process according to a variation in the *K* value of the PRO membrane from $0.5 \times 10^5$ to $7 \times 10^5$ m/sec-Pa: (a) water production cost, (b) AOC and ACC, (c) PRO draw solution pressure and RO feed pressure, and (d) power density and total specific energy consumption.

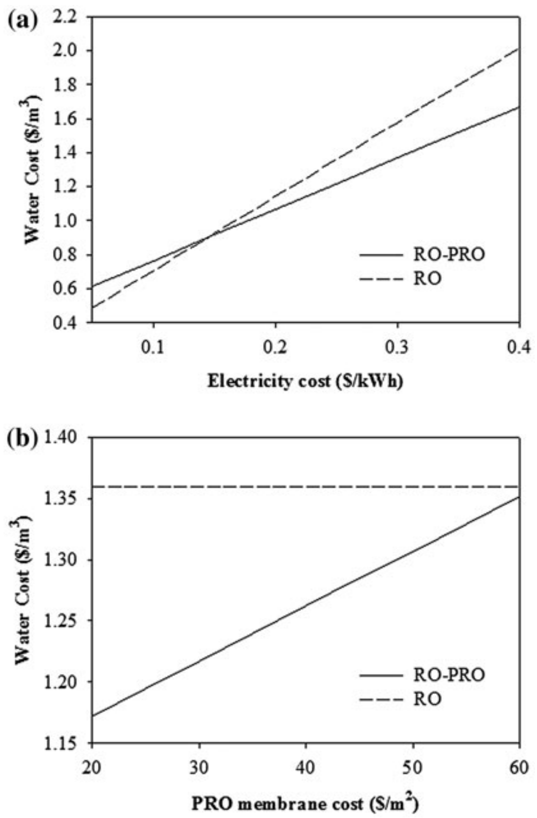


Fig. 8. The water cost of a 100,000 $m^3$/d RO-PRO process according to a variation in electricity cost and membrane cost from 0.05 to 0.4 \$/kWh and from 20 to 60 \$/$m^2$, respectively: (a) water cost according to electricity cost and (b) water cost according to PRO membrane cost.

seawater and treated wastewater TDS, *A* value, and the *K* value of the PRO membrane are set to 43,000, 2,000 mg/L, $3.0 \times 10^{-12}$ m/sec-Pa, and $0.5 \times 10^5$ sec/m, respectively. The water cost of the RO-PRO hybrid plant is calculated as between 1.21 and 1.22 \$/$m^3$ depending on the change in the *B* value of the PRO membrane. The annual operating cost increases from 33,907,000 to 34,244,000 \$/year. The pressure of the draw solution of the PRO process to produce energy is calculated as between 29.7 and 28.8 bars, and the power density and total specific energy consumption are calculated as between 8.18 to 7.93 W/$m^2$ and 2.54 to 2.57 kWh/$m^3$, respectively. In this calculation, although the *B* value of the PRO membrane shows a fivefold increase, the variation in power density and specific energy consumption is small. Thus, the water cost is mostly unaffected by the range of the new *B* value of the PRO membrane that was set in this calculation.

Fig. 7 shows the simulation results for a RO-PRO hybrid process according to a change in the *K* value of the PRO membrane from $0.5 \times 10^5$ to $7 \times 10^5$ sec/m. In this calculation, the seawater and treated wastewater TDS, *A* value, and the *B* value of the PRO membrane are set to 43,000, 2,000 mg/L, $3.0 \times 10^{-8}$ m/sec, and $3.0 \times 10^8$ m/sec, respectively. The water cost of the RO-PRO hybrid plant is calculated as between 1.22 and 1.38 \$/$m^3$ depending on the change in the *K* value of the PRO membrane. The annual capital cost is constant at 10,381,000 \$/year, whereas the annual operating cost increases from 34,076,000 to 40,037,000 \$/year. The pressure of the draw solution of the PRO process to produce energy is calculated as between 13.3 and 29.2 bars. The power density and total specific energy consumption are calculated as between 3.66 to 8.06 W/$m^2$ and 2.55 to 3.06 kWh/$m^3$. As expected, the water cost of the RO-PRO hybrid process is sensitive to the *K* value. As the *K* value increases, the ICP increases. This implies that the pressure of PRO draw water decreases to meet the set PRO recovery because of an increase in the ICP.

Fig. 8 shows the cost estimation results of a 100,000 $m^3$/d RO-PRO hybrid plant at different electricity costs and PRO membrane costs. The seawater and treated wastewater TDS, *A* value, and *B* value of the PRO membrane are set to the same values as the previous simulations. The PRO membrane cost is set to 30 \$/$m^2$ to estimate the water cost according to electricity cost variation, and the electricity cost is set to 0.25 \$/kWh to estimate the water cost according to the PRO membrane cost variation. The water cost of the hybrid process is calculated as between 0.62 and 1.67 \$/$m^3$ depending on the change in the electricity cost. Table 2 also compares the relationships between water cost and electricity cost for RO and RO-PRO. On the other hand, the water cost of the hybrid process is calculated as between 1.17 and 1.35 \$/$m^3$ depending on the change in the PRO membrane cost.

Table 2
Relationship between water cost and electricity cost in RO and RO-PRO

| | RO | RO-PRO |
|---|---|---|
| Water cost (*Y*) (\$/$m^3$) | *Y* = 4.32 EC + 0.28 | *Y* = 3.02 EC + 0.46 |

Note: EC: Electricity cost (\$/kWh).

These results indicate that the water cost is highly sensitive to variations in the electricity cost. For the RO-PRO hybrid process to have greater price competitiveness than the RO process in this calculation, the electricity cost must be greater than 0.15 $/kWh.

## 4. Conclusions

In this study, we evaluated the performance and economics of the RO and RO-PRO hybrid processes using a theoretical model. The following conclusions can be drawn from this work. If the PRO membrane has good performance (high water permeation, high salt rejection, low CP resistance), the seawater and feedwater TDS of the PRO process are important factors affecting the water cost of the RO-PRO hybrid process. The performance and economics of the RO-PRO hybrid process are influenced by the water transport coefficient ($A$), ICP resistance, and $K$. On the other hand, the effect of the salt transport coefficient ($B$) is not significant. The electricity cost and PRO membrane cost are also crucial factors in determining economic feasibility. 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 recovery of the PRO process are high.


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