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Overview of pressure-retarded osmosis (PRO) process and hybrid application to sea water reverse osmosis process

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ABSTRACT

The development and exploitation of sustainable and environment-friendly energy resources are required in order to resolve global energy shortages. Recently, salinity gradient power (SGP) has been considered a feasible candidate, with high potential to become a substitute for the current use of fossil fuels due to benefits such as less periodicity, abundance and no emission of carbon dioxide. In this paper, one SGP, pressure-retarded osmosis (PRO) system, was reviewed in terms of its mechanism, limitations and available applications. In the PRO system, water permeates through a semipermeable membrane from the feed solution to the draw solution, and energy is generated by depressurizing the permeated flow through a hydro turbine. Models for understanding its mechanism and for improving of its performance were reviewed. In addition, applications of sea water reverse osmosis (SWRO), wastewater treatment (WWT) and PRO hybrid process were introduced in order to develop new water-energy nexus processes. In particular, it is thought that the SWRO–PRO hybrid process and SWRO–PRO–WWT hybrid process can contribute to reducing the total energy consumption in SWRO plants as well as to applying the SGP energy to other engineering fields.

Keywords: Pressure-retarded osmosis; Renewable energy; Salinity gradient power; Power density; SWRO–PRO hybrid system; SWRO–PRO–WWT system

1. Introduction

The global economic system has a strong dependence on fossil fuels, which are one of the major forms of energy resources. In attempts to meet the increasing demand of energy, oil consumption has currently reached almost 1,000 barrels a second [1], in other words, approximately 2 L a day per person. As fossil fuels are rapidly being depleted, the golden age of oil has almost passed and this generation is now encountering perhaps the biggest challenge of the twenty-first century [2]. Furthermore, climate change is accelerating because of the increased consumption of fossil fuels. Thus, as Ciamician stated as far back as 1912 [3], it is now time to transition from fossil fuels to renewable energy resources.

In order to overcome the drawbacks of fossil fuels, sustainable and environment-friendly energy resources need to be explored. To date, several candidates of renewable energy have been investigated, such as biomass, geothermal and hydro energies, due to their sustainability [4]. Such renewable energy resources

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amount to almost 8% of the total energy consumption; hydro energy is the biggest portion among them. Salinity gradient power (SGP), one type of hydro energy, also has a high potential to substitute fossil fuels. First, SGP is less periodic than resources such as wind and solar power. For example, solar energy production that is highly dependent on weather conditions making it difficult to use as a constant energy supply. Second, the SGP process does not emit any greenhouse gases such as carbon dioxide [5], which meets the demands of the Kyoto Protocol. Moreover, use of sea water makes the SGP process more favourable, because sea water is the most abundant water resource in the world.

Among membrane-based processes, pressure-retarded osmosis (PRO) and reverse electrodialysis (RED) have been highly recommended as a means to generate power from the salinity gradient. In general, both technologies are referred to as the opposite versions of two existing membrane-based desalination processes: sea water reverse osmosis (SWRO) and electrodialysis, respectively [6]. Although both membrane-based processes utilize chemical potential difference between feed and draw solutions to produce power, the driving force of PRO is mechanical potential and that of RED is electrical potential. In the RED process, a cathode and an anode are located at both ends, while cation exchange membranes and anion exchange membranes are alternately arranged between them [7].

In the PRO process, water permeates through a semipermeable membrane from a low concentration feed solution to a high concentration draw solution, and energy is generated by depressurizing the volumetric increase of the draw side via permeated flow through a hydro turbine (Fig. 1). Since the concept of extracting energy from mixing of freshwater and saltwater has been first introduced in 1954 [8], several historical developments in PRO were observed (Table 1).

As sea water and freshwater are generally used as the draw and feed solutions, respectively, it is expected that PRO can play an essential role in generating clean energy. In spite of this benefit, however, utilizing the PRO process has faced difficulties such as the absence of specialized PRO membranes, the need for pretreatment and the amount of energy consumed in the energy recovery device, referred to as a pressure exchanger [16]. An adequate membrane for the PRO process has yet to be developed even though the researches on PRO were started in 1950s; the need for a pretreatment process and pressure exchanger is also problematic due to the energy consumption. However, the rapid progress of forward osmosis (FO) membranes recently has seemed to accelerate the improvement of PRO membranes to a practical stage, due to their intimate connection. In addition, optimization of the PRO process and development of a novel PRO plant design would decrease the total energy consumption—as well as increase the feasibility.

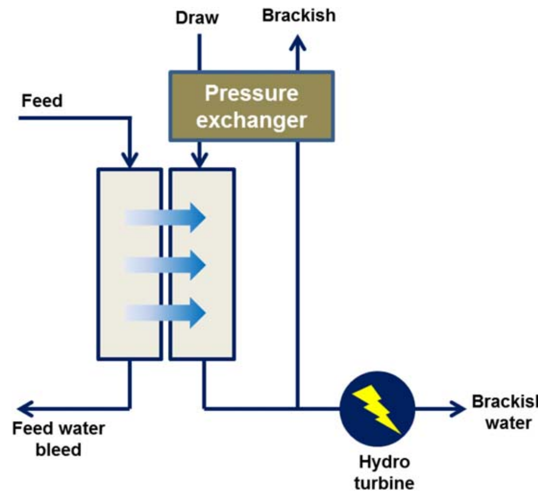

Fig. 1. Schematic of PRO process.

Based on the above considerations, the objectives of this paper are to introduce the PRO mechanism in terms of model equations, to compare PRO performance and to suggest potential applications for this new water-energy nexus process.

2. Model development

2.1. Water transport

Water flux and transport in the PRO process can be described as in Eq. (1). The osmotic pressure difference is the natural driving force that draws water from the feed side to the draw side. Unlike other membrane-based desalination processes such as RO and FO, a hydraulic pressure lower than the osmotic pressure difference is applied to the draw side.

$$J_w = A(\Delta\pi - \Delta P) \tag{1}$$

where J_w is the water flux, A is the water permeability coefficient, $\Delta\pi$ is the osmotic pressure differential and ΔP is the hydraulic pressure. Note that this flux equation does not include concentration polarization (CP) phenomena, as will be discussed later.

2.2. CP and reverse draw solute

In the PRO process, the active layer faces the draw solution, while the porous support layer faces the feed solution (Fig. 2). When water permeates through the membrane, CP occurs on both sides of the membrane, which concentrates or dilutes the solute near the

Table 1
Historical development of PRO

References	Developments
Pattle [8]	Suggestion of generating energy from mixing freshwater and saltwater
Loeb et al. (1976) [9]	Publication of the first PRO model and experimental results
Lee et al. [10]	Improvement of PRO model considering internal CP
Loeb et al. (1990) [11]	Suggestion of several PRO plant configurations
Loeb (2002) [12]	Enhancement of PRO plant schematic using pressure exchanger
Statkraft[a] (2009) [13]	Installation of first PRO prototype pilot plant in Norway
Achilli et al. [14]	Taking external CP into Lee et al.'s model
Yip et al. [15]	Development of advanced PRO model considering internal CP, external polarization and reverse draw solute flux

[a]Statkraft is a Norwegian energy company.

membrane surface [14]. CP occurs in two different ways: inside the porous layer, referred to as internal CP; and on the outer surface of membrane, which is called as external CP. Both forms of CP decrease the osmotic pressure difference and finally reduce the PRO performance, being inevitable phenomena.

2.2.1. Internal CP

Internal CP denotes the accumulation of solutes inside the porous support layer of the membrane. In the case of PRO, concentrative internal CP occurs because the solute easily flows into the porous support layer since it has difficulty to penetrate the active layer [17,18]. In 1981, Lee et al. [10] developed a PRO model that considers internal CP.

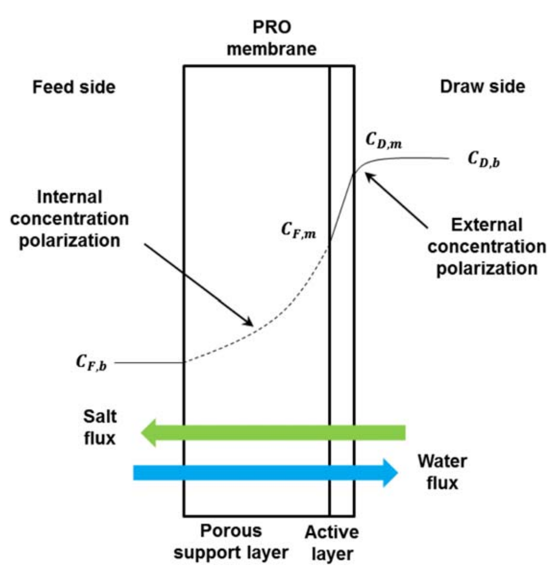

Fig. 2. Illustration of CPs on a PRO membrane [14]. Internal CP occurs inside the porous support layer, whereas external CP occurs at the membrane surface of the active layer.

$$J_w = A\left[\pi_{D,m}\frac{1-\frac{c_{F,b}}{c_{D,m}}\exp(J_wK)}{1+\frac{B}{J_w}(\exp(J_wK)-1)} - \Delta P\right] \quad (2)$$

where $\pi_{D,m}$ is the osmotic pressure of the draw solution at the membrane surface, $c_{F,b}$ is the salt concentration of the bulk feed solution, $c_{D,m}$ is the salt concentration of the draw solution at the membrane surface, K is the solute resistivity and B is the solute permeability coefficient.

2.2.2. External CP

External CP is the depletion of solutes near the draw side on the membrane surface of the active layer. Achilli et al. [14] designed a PRO performance model to include the effects of both external and internal CPs.

$$J_w = A\left[\pi_{D,b}\exp\left(-\frac{J_w}{k}\right)\frac{1-\frac{\pi_{F,b}}{\pi_{D,b}}\exp(J_wK)\exp\left(\frac{J_w}{k}\right)}{1+\frac{B}{J_w}(\exp(J_wK)-1)} - \Delta P\right] \quad (3)$$

where $\pi_{D,b}$ is the osmotic pressure of the bulk draw solution, k is the external CP mass transfer coefficient and $\pi_{F,b}$ is the osmotic pressure of the bulk feed solution.

2.2.3. Reverse draw solute flux

Reverse salt flux is the draw solute permeation from the draw solution side into the feed solution side [19] through the active layer, and it accelerates the harmful effects of internal CP. Yip et al. [15] developed a PRO model for estimating the PRO performance, which included the effects of internal CP, external CP and reverse draw solute flux. The accuracy of the flux prediction is enhanced by considering the factor of flux deterioration.

$$J_w = A\left[\frac{\pi_{D,b}\exp\left(-\frac{J_w}{k}\right) - \pi_{F,b}\exp\left(\frac{J_w S}{D}\right)}{1+\frac{B}{J_w}\left(\exp\left(\frac{J_w S}{D}\right) - \exp\left(-\frac{J_w}{k}\right)\right)} - \Delta P\right] \quad (4)$$

where S is the membrane structure parameter, which is used as a deterministic ICP factor in the membranes [20].

3. Improvement of PRO performance

In the PRO process, performance can be expressed in terms of power density (W), the power per unit membrane area. The power density is calculated as in Eq. (5), by multiplying the water flux (J_w) and applied hydraulic pressure (ΔP).

$$W = J_w \Delta P = A(\Delta\pi - \Delta P)\Delta P \quad (5)$$

Gerstandt et al. [21] reported that the power density of the PRO process should be in the range of 4–6 W/m^2 in order to attain economic feasibility. However, even though the PRO process has been experimentally studied since the 1970s, when the concept of PRO was first introduced [14,21–25], its commercialization has not yet been deemed completely feasible. Table 2 shows several experimentally achieved power density results. In all cases, the feed solution was freshwater, whereas the draw solution varied. Note that two experiments were conducted using synthesized membranes [24,25], and the power density results were estimated from FO experiments. As shown in the Table 2, power densities of over 5 W/m^2 were reported, which indicates that the PRO process can indeed be a practical alternative for power generation. However, this performance should be further confirmed with commercialized membrane prior to practical use. Furthermore, additional theoretical and experimental research is required in order to successfully scale-up the PRO process [26].

4. Applications

The PRO process can be applied to various sources of feed and draw solutions, including a combination of freshwater and sea water, pretreated sea water and concentrated brine (SWRO–PRO hybrid process), and effluent and concentrated brine (SWRO–PRO–WWT hybrid process).

4.1. PRO pilot power plant prototype

Post [27] reported that 1.4 MJ of energy could be obtained from the osmotic pressure difference between river water (0.01 M) and sea water (0.5 M). In 2009, the first prototype of a PRO power plant was opened by Statkraft in Norway [13], and an improved version of the pilot PRO plant was reopened in 2011. Fig. 3 presents a schematic of the pilot PRO plant installed in Norway, which is a stand-alone PRO system. In brief, sea water flows into the draw side while river water goes into the feed side; both sources usually require pretreatment processes. A hydraulic pressure pump is located between the pretreatment processes and membrane modules in order to pressurize the draw solution. After sea water and river water pass through membrane modules, sea water is diluted, which is followed by a volumetric increase. Diluted sea water is later divided into two flows: the increased volumetric flow is used to operate a hydro turbine to generate electricity, and the other is reused by the pressure exchanger.

There are three drawbacks to this application; as mentioned above, no adequate membrane has yet been developed. As a result, the performance and

Table 2
Comparisons of PRO power density

Cases	Draw solution	Power density (W/m^2)
Loeb and Mehta [22]	Concentrated water	1.4
Skilhagen et al. [23]	Sea water	3
Gerstandt et al. [21]	Sea water	3.5
Achilli et al. [14]	Sea water	2.7
	Concentrated water	5.1
Tiraferri et al.[a] [24]	Sea water	6.1
	Concentrated water	15.3
Wang et al.[a] [25]	Sea water	5.5
	Concentrated water	8.7

[a]Estimated potential power density from FO operation. In each case, freshwater is used as the feed solution.

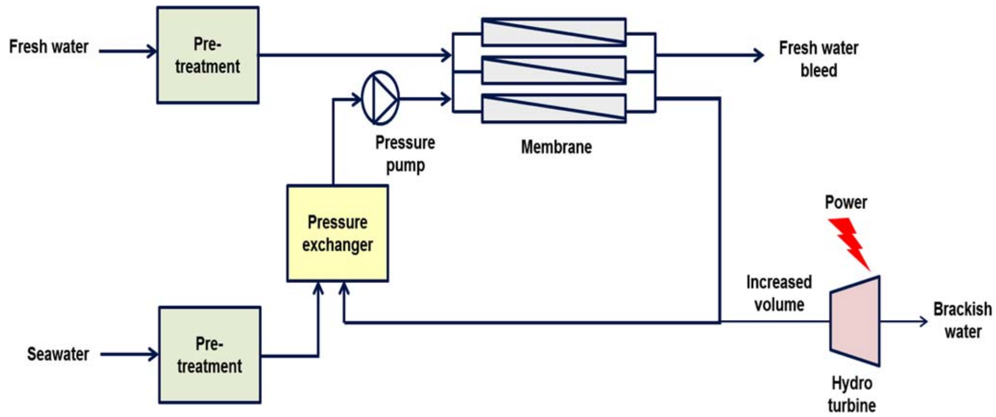

Fig. 3. Schematic of pilot PRO plant in Norway, constructed by Statkraft [23].

efficiency of the PRO process is reduced due to internal CP, external CP and reverse draw solute flux, which occur inside and at the surface of the membrane. Second, pretreatments are problematic as the quality of river water as a feed solution seasonally varies, such that the pretreatment also has a seasonal variation, resulting in increased costs for the total process. Finally, the PRO process is considered a site-specific process, because it is generally recommended to construct a PRO plant at the river outlet due to the need for a large amount of freshwater.

4.2. Hybrid SWRO and PRO power plant

The PRO process can be hybridized with other membrane processes to produce water. The hybrid process can complement the deficiencies of each process to more effective water and energy generation, as a water-energy nexus process. Membrane-based water treatment systems have become popular, especially SWRO. However, the SWRO process has the two biggest drawbacks: large energy consumption and concentrated brine discharge [18]; in particular, the discharge of concentrated SWRO

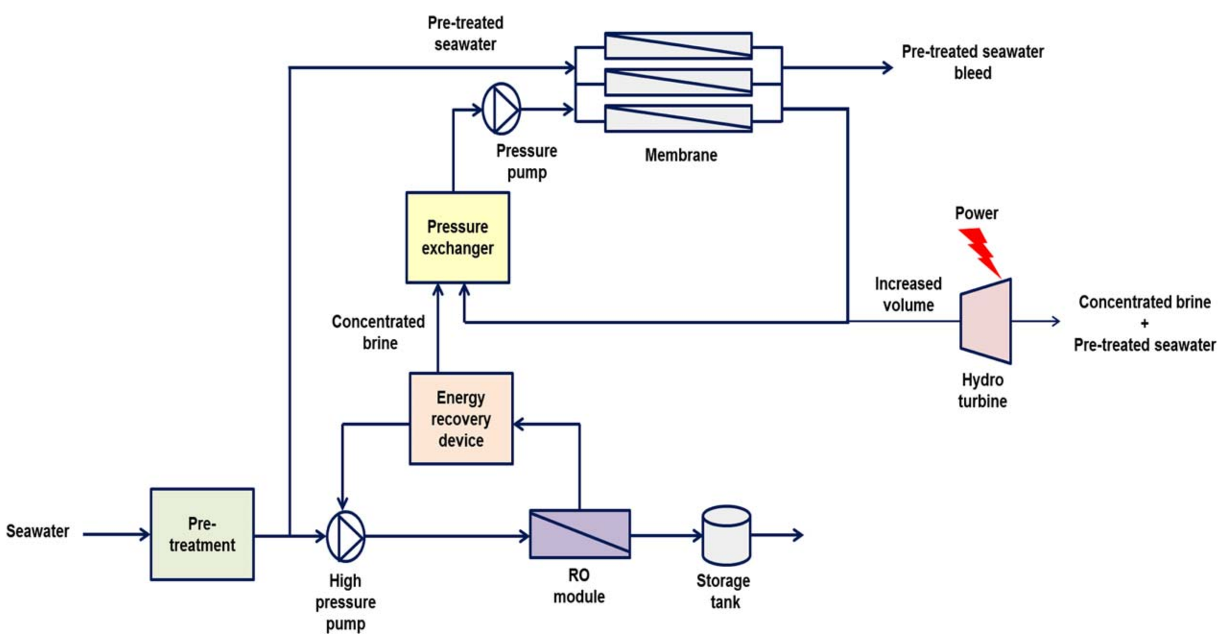

Fig. 4. Schematic of SWRO–PRO hybrid process. In the PRO process, the draw and feed solutions are concentrated brine and pretreated sea water, respectively. Both are obtained from the SWRO process.

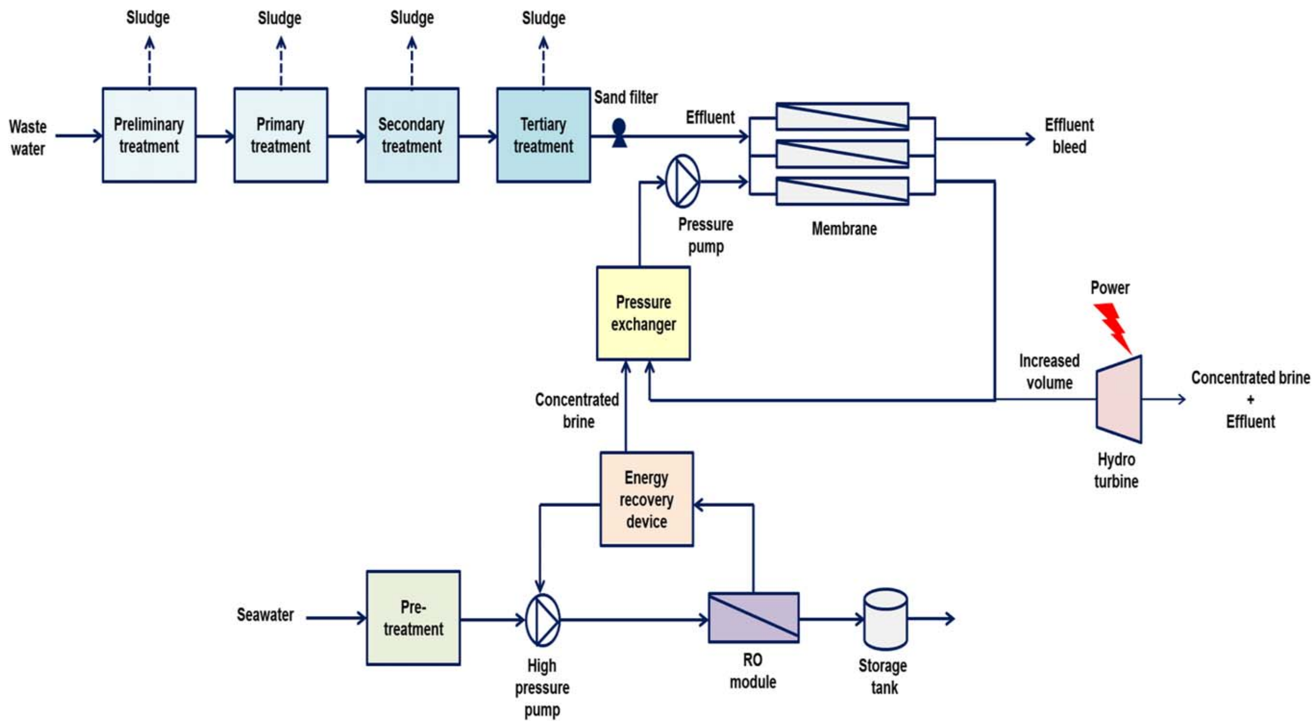

Fig. 5. Schematic of SWRO–PRO–WWT hybrid process. In the PRO process, the draw and feed solutions are concentrated brine from the SWRO plant and effluent from WWT, respectively.

brine has strong adverse effects on the marine environment [28]. On the other hand, an SWRO–PRO hybrid process can concurrently resolve some of these issues. As shown in Fig. 4, a combination of pretreated sea water and concentrated brine [29,30] can be a possible PRO application, and its mixing energy through the osmotic pressure difference is estimated to be up to 10 MJ [27]. In this case, concentrated brine from the SWRO plant can be used as draw solution while sea water as the feed solution flows into the PRO plant after being pretreated in the SWRO plant. Here, no additional pretreatment is required; therefore, energy consumption for the pretreatment process can be exempted. Furthermore, PRO can function as an assistant source of energy for SWRO plant during water production.

4.3. Hybrid SWRO plant, PRO power plant and wastewater treatment (WWT) plant

A hybrid SWRO, PRO and conventional WWT plant is also suggested. When effluent is released into a river, the effluent should be of a quality comparable to that of the receiving waterbody. In this case, as the effluent quality is the same as river water, it can be used as a feed solution, while concentrated brine from the SWRO plant can be used as draw solution to generate energy (Fig. 5); based on the osmotic pressure difference, it is expected that 15 MJ of mixing energy can be extracted from this combination [27]. Three benefits are obtained by the SWRO–PRO–WWT hybrid process. First, since the effluent quality does not seasonally vary, use of a sand filter alone is sufficient to pretreat the feed solution, significantly reducing the pretreatment cost. Moreover, as concentrated brine from the SWRO plant is reused for energy production, this hybrid process would be a promising solution for managing the disposal of concentrated brine. Last, energy generated from the PRO process can be re-utilized in the SWRO process, thereby reducing the unit cost of water production.

5. Conclusions

PRO is a promising membrane technology that has the potential to generate renewable energy from SGP. Since initial research on PRO began in 1950s, experiments have since been conducted to prove the feasibility of PRO process and model equations have been developed.

Conventional desalination processes such as SWRO and FO are attempting to attain sustainable water production, while PRO works for sustainable energy production. Although the purposes of these processes are different, the development of an effective membrane is the key factor that must be overcome prior to their practical application. Performance of SWRO membranes is already at the commercial stage, and that of FO membranes is improving due to the growing attention of FO processes in recent years [31,32]. With the rapid development of membrane technology, many studies on the performance of PRO membrane have also been carried out; according to these trends, adequate membrane and membrane modules are expected to be available in the near future. However, not only progress in membrane development, but also that of plant design is required in order to improve the feasibility of the PRO process. In general, PRO plants are operated using both sea water and river water, as the respective draw and feed solutions. Under these conditions, it becomes difficult (even impossible) to operate this process in countries with severe water shortages or not enough clean water (i.e. site-specific concerns). Thus, it is more likely that SWRO–PRO hybrid plant or SWRO–PRO–WWT hybrid plant can be made capable of overcoming these limitations, as new water-energy nexus processes. It thereby seems possible to achieve the primary goals of energy consumption as well as cost saving, although the specific benefits have to be fully defined through energy or cost analysis.

Nevertheless, the PRO system has been markedly improved compared to its early stages; however, development of an effective PRO membrane and optimization of the entire PRO process remain as a further study in order to make the PRO process feasible. In response to the rapid growth of interest in renewable energy and desalination processes, construction of a commercialized plant will be likely in the near future.

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Nomenclature

ΔP	—	hydraulic pressure differential, kPa
$\Delta\pi$	—	osmotic pressure differential, kPa
$\pi_{D,b}$	—	osmotic pressure of the bulk draw solution, kPa
$\pi_{D,m}$	—	osmotic pressure of the draw solution at the membrane surface, kPa
$\pi_{F,b}$	—	osmotic pressure of the bulk feed solution, kPa
A	—	water permeability coefficient, $m^3/m^2\,s\,Pa$
B	—	solute permeability coefficient, m/s
$c_{D,b}$	—	salt concentration of the bulk draw solution, g/L
$c_{D,m}$	—	salt concentration of the draw solution at the membrane surface, g/L
$c_{F,b}$	—	salt concentration of the bulk feed solution, g/L
$c_{F,m}$	—	salt concentration of the feed solution at the membrane surface, g/L
J_w	—	water flux, $m^3/m^2\,s$
k	—	external CP mass transfer coefficient, m/s
K	—	solute resistivity, s/m

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