Progress, Challenges, and Prospects of Forward Osmosis (FO) and Pressure Retarded Osmosis (PRO) as An Alternative solution for Water and Energy Crisis

Graecia Lugito*, Danu Ariono, Mochamad Rizqy Trihutama Putra, and Zoealya Nabilla Zafra

Department of Chemical Engineering, Institut Teknologi Bandung, Bandung 40132 Indonesia.

*graecia@che.itb.ac.id

Abstract. Blue energy is found fascinating to be implemented in Indonesia, the largest archipelago country of which 70% territory is covered with water. The utilization of osmotic-driven membranes in addressing water and energy scarcity has received much attention. Forward osmosis (FO) and pressure-retarded osmosis (PRO) are two osmotic driven membrane processes that utilize draw solution with higher osmotic pressure than the feed solution to drive the water flux. These processes are less energy-intensive compared to other pressure-driven membranes. However, the applications of each of these processes are still limited due to three main challenges, which are the production of high-performance membrane materials for high water flux and selectivity, the selection of draw solutions, and the need for post-treatment to recover the draw solution. In this study, recent developments in FO and PRO membrane processes are reviewed, then the potentials of the utilization of osmotic-driven membrane in addressing the water and energy crisis are discussed and evaluated. The review is based on asymmetric polyamide (PA) membranes with strong porous support performing in FO and PRO processes. Draw solution plays a significant role in attaining good performance in osmotic-driven membrane processes. Integrated FO/PRO/RO hybrid processes have been proposed and evaluated in terms of their energy consumption and carbon footprint. The results indicate positive prospects of these hybrid processes pushing forward the research on continuous and self-sustaining osmotic-driven water and energy productions.

1. Introduction
Indonesia, of which 70% territory is covered by water, is apparently vulnerable to clean water and energy scarcity. The constant decline of the amount of available groundwater drives the government to promote seawater reverse osmosis (SWRO) desalination projects; yet these projects require large amounts of energy, investment costs, and operating costs [1]. The current status of energy use for water desalination plant is approximately 2.5 – 4 kWh/m³ [2] and produce anthropogenic waste of concentrated brine [3]. As an alternative, forward osmosis membranes (FO) based on osmotic pressure have been developed to lower the energy requirements. Furthermore, FO membranes also have a lower fouling propensity due to hydraulic pressure than RO membranes [4]. However, to reclaim the drawn water molecules and regenerate the draw solution, the FO has to be integrated with another separation post-treatment [5]. Integrated FO with nanofiltration (NF) in a hybrid closed-loop system has proven to be the best in terms of economic and environmental aspects for water reclamation from wastewater. However, for seawater
desalination, the FO-RO hybrid system is superior in both economic and environmental aspects. The diluted draw solution from FO can be directly processed in less energy-intensive compared to SWRO desalination [6].

Energy requirements from desalination of seawater and reclamation of wastewater are also important to note, considering that excessive energy consumption has also contributed to the climate crisis. Therefore, we need a sustainable integrated process that can supply renewable energy to produce clean water. One potential untapped renewable energy is water salination or blue energy, which comes from mixing river water and seawater [7]. There are two emerging membrane technologies in harvesting the blue energy, known under the names of pressure-retarded osmosis (PRO) and reverse electrodialysis (RED). Yip and Elimelech [3] have encompassed a comparative study between PRO and RED regarding their power densities and feasibilities for salinity energy extraction. They imply that PRO is more suitable for blue energy harvesting. Furthermore, integrating PRO on RO site as brine effluent treatment as well as power generation can partially offset the desalination energy cost [3].

Although there is a growing interest in the FO and PRO processes, there are still some challenges that hamper their commercial applications. Those challenges include the need for a membrane material that could mitigate concentration polarization and fouling providing high membrane performance and efficiency, the selection of suitable draw solution, and the need for post-treatment to regenerate the draw solution for the recycling process. In this study, the recent developments and technological advances of FO and PRO membranes for water and energy reclamation are reviewed and evaluated to propose their prospects in integration with SWRO membranes to overcome the water and energy crisis.

2. Osmotic-driven Membrane

In osmotic-driven processes, water molecules move from a feed solution with a lower salt concentration to a draw solution with a higher salt concentration. As such, this prolonged separation process will end up with a diluted draw solution. The osmotic-driven membrane has to have as minimum water transport resistance and as high solute rejection as possible yet strong enough to retain its form under the operating pressure. Both FO and PRO processes use selective FO membranes promoting the water flux from FS to DS while blocking the reverse solute flux from DS. The main challenges in FO membranes include a trade-off between permeability (water flux) and selectivity (reverse solute flux), concentration polarization, and fouling. Asymmetric membrane with an ultra-thin dense active layer (AL) and a porous support layer (SL) has been introduced to achieve a high-performance and selective separation with low hydrodynamic resistance and potentially high water flux [8]. Figure 1 displays the typical solute concentration profiles in FO and PRO processes.

![Figure 1](image_url)

**Figure 1.** Typical solute concentration profiles in (A) AL-FS FO and (B) AL-DS PRO processes. Adapted from ref. [Bogler, 2017].

2.1. Membrane configurations

In FO processes, the feed solution typically flows in contact with the active layer (AL-FS mode) [4]. Ideally, the available osmotic pressure difference is shown as $\Delta\pi_{\text{total}}$ that drives the movement of water molecules from feed solution to draw solution in a determined rate ($J_w$). Under certain hydrodynamic conditions, a boundary layer (BL) can be formed on top of the dense active layer which causes additional
resistance to mass transport. As such, accumulation of solutes in this layer is prone to happen, resulting in a higher solute concentration on the membrane surface \( (C_{m,f}) \) compared to solute concentration on the bulk phase of the feed solution \( (C_{b,f}) \) \[9\]. In contrast on the other side of the membrane, the accumulation of water molecules on the surface of the support layer results in the reduction of solute concentration from the initial concentration of draw solution on bulk phase \( (C_{b,d}) \). This phenomenon, called concentrative and dilutive external concentration polarization (ECP) respectively for AL and SL, creates a decline in osmotic pressure difference. On the other hand, internal concentration polarization (ICP) happens when water flux through the relatively thick support causes a lower concentration of solute on the interface between AL and SL \( (C_{m,d}) \) compared to \( C_{b,d} \). As a result of both ICP and ECP, the initially available driving force reduces tremendously from \( \Delta \pi_{\text{total}} \) to \( \Delta \pi_{\text{eff}} \) \[10\].

While ECP has been proven to be easily overcome by manipulating hydrodynamic parameters, ICP still proves as the major drawback in FO applications. ICP in FO processes is highly related to the membrane’s structural parameter \( (S) \) which is defined as a product of membrane thickness \( (t) \) and ratio of tortuosity \( (\tau) \) to porosity \( (\varepsilon) \):

\[
S = \frac{t}{\varepsilon} \tag{1}
\]

The higher the structural parameter of a support layer, the more severe the ICP is \[4\]. As such, to achieve a membrane with higher performance a thin, highly porous, and not tortuous support layer is required \[11\]. Besides low structural parameters, a support layer of FO membranes has to have high hydrophilicity, stability, and mechanical strength to accommodate water flux \[12\].

As a result of the asymmetrical configuration, the FO membrane is still prone to fouling even without additional hydraulic pressure \[4\]. The foulants deposit on the active layer surface foulants in the form of a loose matrix which is easy to wash by physical cleaning \[13\]. Even so, fouling still contributes to a decline of water flux which requires periodical cleaning hence increasing maintenance cost. One way to suppress fouling is to incorporate inorganic nanomaterials in the membrane matrix, forming a nanocomposite with enhanced properties \[14\]. Ultrasonication can also be done to improve the active layer’s performance and provide anti-fouling properties on the active layer.

An apparent difference between the PRO and FO process is the presence of external hydraulic pressure applied to the draw solution of the PRO process to offer higher conversion of mechanical energy to electricity \[10\]. This additional external pressure is maintained not to be higher than osmotic pressure difference as the main driving force \[15\], causing water molecules to permeate from feed to draw solution. This permeate will be pressurized upon mixing with the draw solution and provide net potential energy in the draw solution flow \[10,15\]. Theoretically, the maximum energy density of the RO process can be achieved at hydraulic pressure equals to half of the available osmotic pressure difference \[16\].

In contrast to FO, PRO processes commonly operate in AL-DS configuration in which the active layer directly in contact with the draw solution, to reduce the impact of ICP and increase the specific power generation of the process \[10\]. Similar to that of FO processes, ICP, along with ECP, also poses a major threat in PRO processes by causing a significant drop in water flux and power density. While the ECP phenomenon is exactly the same as what happens in FO processes, instead of dilutive, concentrative ICP takes place at the interface of AL and SL of the membrane. Accumulation of solutes in the matrix of the support layer increases \( C_{m,f} \) compared to \( C_{b,f} \) which reduces the initial osmotic pressure difference.

Overall, membrane characteristics to attain good-performance PRO processes are similar to FO membrane characteristics. It is required for the support layer to have high hydrophilicity, stability, chemical and thermal durability, resistance to oxidizing agents, and low structural parameter \[11,12\]. In addition to the appliance of external pressure in the PRO process, the support layer must offer adequate mechanical strength while still exhibiting good transport properties \[16\].

AL-DS configuration used in the PRO process, while offering lower ICP \[17\] causes more severe fouling problems compared to fouling in FO processes, resulting in unstable water flux. Pores of the support layer which directly in contact with feed solution are really prone to plugging by foulants \[18\].
The foulants can deposit even inside the matrix of the support [19]. As such, a more complicated and difficult fouling cleaning system is required compared to FO processes [20]. To overcome this fouling problem, research has been conducted such as grafting, support pre-treatment, and feed solution pH adjustment. As for now, hydraulic backwash and flushing with alkaline cleaning agents have been used to wash off the foulants from the support matrix [21].

2.2. Membrane materials
The active layer of an FO membrane has to be thin, dense, and hydrophilic. Cellulose acetate (CA), cellulose triacetate (TCA), polyamide (PA), and even the biomimetic aquaporin have been considered as the candidate. However, in this review, the evaluation is made based on the polyamide active layer due to its ability to form an ultrathin layer. Depending on its monomer, PA can be either aliphatic, aromatic, or even the combination of the two. In general, aromatic PA has shown to exhibit superior properties compared to aliphatic PA ranging from a stronger polymeric chain and higher chemical stability [22].

The support layer of an asymmetric membrane mainly functions as a base to offer sufficient mechanical strength so the membrane will not deform under certain operating conditions [4]. The intrinsic properties of a membrane are closely related to the material and fabrication method used. In this regard, several studies have been conducted to fabricate supports that can provide good mechanical strength by keeping polarization concentrations low, as shown in Figure 2.

![Figure 2. Permeability-mechanical strength diagram of various supports.](image)

From Figure 2, it can be seen that recent studies have focused on using PES and PSf as support due to their ease of fabrication. From the few studies that have been carried out for PI and PEI, it can be seen that PI and PEI can provide support with higher mechanical strength accompanied by fairly good flux. The hydrophilic nature of PI and PEI also supports the development of these two materials for the use of PRO and FO for desalination. On the other hand, PP appears as an alternative material for the support layer due to the availability and stability of the material. The use of PP as a support material can expand the use of FO towards separation that involves organic compounds such as obtaining clean water from produced water. In the future, the authors suggest further studies on PI, PEI, or other hydrophilic materials, as well as PP as support for FO and PRO. Especially for PROs, studies on highly hydrophilic supports should also be developed to solve the fouling problem in the support layer.

2.3. Membrane fabrication methods
There have been various methods introduced to coat support layer with a polymer, such as dip-coating, spray-coating, spin-coating, interfacial polymerization (IP), in-situ polymerization, plasma polymerization, and grafting [23]. Among them, IP emerges as the most common route to fabricate an active layer of a membrane due to its capability of forming an ultrathin layer and simple reaction mechanism [24]. In general, IP is conducted in five steps: pre-treatment of support, the immersion of support in aqueous monomer, removal of excess solution, the immersion of support in organic monomer,
and post-treatment [10]. The precursor solutions, both aquatic and organic, contain two different reactive monomers and are immiscible [25]. In some cases, only one of the precursors is required to contain monomers while the other only keep the reaction to only occurs on the interface of the two precursors [26].

Properties of the active layer are significantly affected by monomer concentration and composition used in the IP process [24]. Petersen, on the other hand, has reported that diffusivity and solubility of the polymer in solvent precursors are among the most important factors that control membrane properties [23]. In the most recent study, ultrasonic power could enhance the PA coverage on the support surface leading to a more hydrophilic membrane surface and higher water flux while simultaneously forming a thick layer with excellent rejection as well as lower fouling propensity [27].

3. Draw solutions

The need for a draw solution with high osmotic pressure and low salt return flux is still very much needed to realize good FO and PRO performance. Previous studies have mostly explored inorganic and organic draw solutions based on their water flux and their salt return flux. A graph comparing several types of inorganic and organic draw solutions is presented in Figure 3 as follows.

![Graph showing comparison of draw solutions](image)

**Figure 3.** (A) Reverse solute-water flux diagram of various draw solution for FO processes (B) Peak power density-water flux diagram of various draw solution for PRO processes.

Based on Figure 3, most of the inorganic draw solutions are still superior to organic draw solutions because of their high-water flux and low salt return flux. Therefore, studies regarding the use of inorganic draw solutions for the FO process are considered feasible to be developed. The use of seawater as a draw solution is also a good option, considering that seawater is a widely available source of inorganic draw solutions.

For the PRO process, the draw solution with organic salts has a high-water flux which is also accompanied by a large energy density. Based on this study, several types of organic draw solutions turned out to have high osmotic pressures accompanied by lower salt fluxes than some types of inorganic draw solutions that are often studied. This shows that some organic salts are also interesting for further research as an alternative to lab-scale PRO process draw solutions.

However, apart from having high osmotic pressure and low salt return flux, draw solutions for a PRO process should also be widely available, particularly if they are used to produce large amounts of energy. Therefore, the PRO membrane currently being developed generally uses seawater as a draw solution and river water as a feed solution. However, this method has not been proven to be economically sound because the difference in salinity between seawater and river water is not too large so that the energy generated is not comparable to the operational costs of the PRO. In addition, the use of seawater as a draw solution requires a pre-treatment step to maintain the sustainability of the PRO membrane.

Several studies were conducted to find an alternative to seawater as a PRO membrane draw solution. One of them is the use of RO retentate as a draw solution. Retentate RO which has high salinity, high pressure, and has gone through a pre-treatment process. RO brine has an osmotic pressure of 1.6 to 2
times higher than seawater so that the energy density generated from the PRO process can increase up to 4 times as high as the use of seawater. In addition, the use of RO brine as a draw solution for the PRO process can mitigate desalination waste that can damage marine ecosystems. The development of a suitable PRO membrane support layer material also allows the use of wastewater from various oil and gas processing processes as a feed solution for the PRO process. The large salinity difference between RO brine and wastewater can be exploited to produce large amounts of energy. Therefore, future PRO studies can focus on the use of RO desalination retentate as a draw solution and river water as a feed solution.

4. Post-treatment and case study

Regeneration of draw solutes and reclamation of the drawn water molecules from diluted draw solutions to produce clean water is still the main challenge in the FO process. The concentration of draw solutes for the FO process is important because replenishment costs for draw solutes are a significant component of operational costs. The draw solutes reconcentration method is chosen based on the application of the FO process itself. Some of the post-treatments carried out to concentrate draw solutes include heating, distillation, the NF process, the RO process, and so on. As explained in the background, several ways to overcome the water crisis through the FO process are wastewater reclamation and seawater desalination. For FO applications as wastewater reclamation, the FO-NF hybrid closed-loop system has proven to be the best in terms of economic and environmental aspects compared to other hybrid closed-loop systems. However, for the application of FO in the seawater desalination process, the FO-RO hybrid system is superior in both economic and environmental aspects, because the energy consumption of RO desalination is drastically reduced with FO as the pre-treatment of the RO process. That way, the product diluted draw solution from FO can be further processed in the form of a feed solution from the RO process.

In the PRO process, post-treatment that needs to be done is the conversion of hydrostatic energy into electrical energy. This can be achieved by flowing the diluted draw solution to turn the turbine. Furthermore, the PRO process can also be combined with the RO process to supply the RO process energy into a PRO-RO hybrid system. Therefore, the RO process acts as a post-treatment of the PRO process by utilizing the salinity energy of the PRO process as a power source for the high-pressure pump used to pump the RO process feed. For PRO processes that use lab-scale inorganic or organic salts, the draw solutes reconcentration process still needs to be done to obtain draw solutes so that they can be reused. However, for PRO membranes that use seawater or RO brine as a draw solution, the reconcentration process is no longer a problem, but a new problem arises, namely fouling. Therefore, the next development of PRO membrane post-treatment lies in innovative and effective membrane cleaning techniques.

Based on a comprehensive review of this study, the water and energy crisis still needs resolution. One source of water and energy that can be utilized simultaneously is seawater, through a process of desalination of seawater using various membrane processes. Indonesia is a coastal country with a wide sea line so that it has the potential to develop desalination of seawater as a source of water and new renewable energy. For further research, the FO-RO-PRO hybrid closed-loop system is a good system to develop because of its potential to be able to answer the three main challenges of FO and PRO membranes, such as the research conducted by Cheng et al. in 2018 [28]. A schematic of this combined process is shown in Figure 4.

Reconcentration and recovery of draw solution in osmotic-driven membranes is done to significantly reduce the cost of draw solution replenishment by allowing reuse of the draw solution. In the case of FO, this additional process is a crucial part; without a post-treatment, clean water is not obtainable and still in form of a diluted draw solution. Hybrid systems in certain applications have been previously proposed to negate the need for complicated post-treatment processes. In impaired water reclamation using FO, a hybrid system of FO-NF has been proposed and proven to have a sustainable and economically viable continuous closed-loop of osmotic-driven process. In seawater desalination, however, integration of FO as RO feed pretreatment can result in energy reduction. Another example is
the hybrid system of RO-PRO, in which the diluted draw solution of the PRO process can be directly flowed to move water turbines and safely discharged while continuously supplied from RO as concentrated brine.

The use of the hybrid RO-PRO system has been previously mentioned as a way to simultaneously desalinate seawater and reclaim wastewater instead of using river water, addressing the water crisis. This system, unfortunately, faces a major problem in which PRO membranes are very susceptible to foulants in the feed solution. As such, Cheng et al. in 2018 proposed a hybrid system of FO-PRO-RO for simultaneous seawater desalination and wastewater reclamation as shown in Figure 4. In this system, FO acts as a bridge to prevent direct contact of wastewater feed to PRO support, removing potential severe fouling in the PRO system using an interloop cycle of additional draw solution. The diluted draw solution from the FO system is then flowed to the PRO system where it is reconcentrated and used to produce energy by direct mixing with RO brine from the RO system. Theoretically, this proposed hybrid system potentially constructs self-sustaining and continuous osmotic energy and water production.

![Figure 4. Simulation case study of FO-PRO-RO hybrid system. Adapted from ref. [29].](image)

In this system, the interloop concentration of the draw solution acts as an important parameter to be determined as it affects both FO and PRO performance contrarily. A high interloop concentration will increase the driving force in the FO system but simultaneously decrease the power density generated by PRO as a result of water flux decline. To determine an optimum interloop concentration, a simplistic simulation is conducted to see the effect of interloop concentration variation, ranging from 0 to 0.6 M, to process parameters of another system. In this simulation, RO is operated under 50% recovery and 60 bar pressure referring to the commercial application of seawater desalination RO. Dilution ratio, defined as the ratio of diluted solution TDS to that of concentrated solution, of 0.5 is applied at the PRO and FO system to produce diluted draw solution with the same salinity as seawater, avoiding environmental damage of discharge [28]. Applied retarded pressure in the PRO system is assumed to be half of the available osmotic pressure [29] Lastly, membrane intrinsic properties, water permeability coefficient (A), salt permeability coefficient (B), and structural parameter (S) are listed in Table 6.1 from previous studies. Water-salt diffusivity (D) of $1.48 \times 10^{-9} \text{ m/s}^2$ is obtained from ref. [28].
Table 1. Intrinsic properties of the membrane used in the simulation.

| System | Parameters          | Ref. |
|--------|---------------------|------|
|        | A (μm/s Pa) | B (μm/s) | S (mm) |      |
| FO     | 6.20      | 0.056    | 0.59   | [30] |
| PRO    | 4.22      | 0.067    | 0.61   | [31] |
| RO     | 3.33      | 0.069    | 0.14   | [32] |

Four system parameters are evaluated in this simulation: FO and PRO water flux, PRO power density, net specific energy consumption (Net SEC) of the overall hybrid system, and required membrane area of FO and PRO system as shown in Figures 5. Net SEC is estimated by subtracting total energy produced by PRO system from RO high-pressure pump energy requirement.

Figure 5A confirmed that an increase in interloop concentration will result in higher water flux in the FO process while a decline in PRO water flux, which in turn decreases the power density of the PRO system as shown in Figure 5C. In Figure 5D, it can be seen that the use of lower interloop concentration will result in a lower net SEC which is desirable towards self-sustaining osmotic energy and water production. While energy-wise it looks better to operate with lower interloop concentration, the very low water flux in FO operation results in an infinite required membrane is to keep the amount of draw solution in the interloop constant as shown in Figure 5B.

Figure 5. Effect of interloop concentration to: (A) FO and PRO water flux and (B) required membrane area as well as to (C) PRO power density and (D) net SEC of the overall hybrid system.

In this simulation, a trade-off point of 0.163 M interloop concentration is chosen as a base of further analysis to operate this hybrid FO/PRO/RO system with equal FO and RO membrane area. At 0.163 M interloop concentration, the system is simulated to be capable of producing 7.15 W/m² while requiring a net SEC of 0.76 kW electricity for every 1 m³/hour clean water produced. Compared to the stand-alone RO process with the same parameters which costs 2.15 kW, simulation-wise this hybrid system can reduce energy consumption by up to 64% (1.39 kW). This electrical energy reduction, according to
the United States Environmental Protection Agency, is equal to a carbon emission reduction of 0.98 kg/hour. Results of this simulation are summarized in Table 2.

Table 2. Simulation result of hybrid FO/PRO/RO system.

| Parameter                      | Value | Unit  |
|--------------------------------|-------|-------|
| Concentration                  |       |       |
| RO feed (seawater)             | 0.600 | M     |
| RO brine                       | 1.200 | M     |
| PRO discharge                  | 0.600 | M     |
| Interloop (PRO feed)           | 0.163 | M     |
| Interloop (FO draw)            | 0.325 | M     |
| RO Recovery                    | 50    | %     |
| PRO Dilution Ratio             | 0.5   |       |
| FO Dilution Ratio              | 0.5   |       |
| Applied Pressure               |       |       |
| RO system                      | 60.0  | bar   |
| PRO system                     | 25.9  | bar   |
| Membrane area                  |       |       |
| FO                             | 96.6  | m²    |
| PRO                            | 96.6  | m²    |
| RO                             | 28.8  | m²    |
| Water flux                     |       |       |
| FO                             | 10.35 | LMH   |
| PRO                            | 10.35 | LMH   |
| RO                             | 34.73 | LMH   |
| Efficiency                     |       |       |
| Pump                           | 80    | %     |
| Pressure Exchanger             | 95    | %     |
| Water Turbine                  | 90    | %     |
| PRO power density              | 7.15  | W/m²  |
| Net SEC                        | 0.76  | kWh   |
| Global warming impact          |       |       |
| Electricity reduction          | 1.39  | kWh   |
| CO₂ emission reduction         | 0.98  | kg CO₂/jam |

Although simulation-wise this hybrid system has shown a lot of potentials both by performance and environmental impacts, as this simulation is still based on an ideal operating condition, FO and PRO with susceptible mechanical strength and low reverse solute flux are still necessary to carry out operating under high pressure with high water flux. Economic analysis and thorough life cycle assessment are still required to be conducted to further study the feasibility of this system as a solution towards self-sustaining and continuous osmotic energy and water production.

5. Conclusion
Osmotic-driven membranes have been garnering a lot of interest in membrane processes due to their low energy consumption. Although showing excellent potentials theoretically, these membranes still face concentration polarization and other major problems that prohibit their commercial use due to their poor performance. To achieve better performances, materials play an important role to tune membrane properties which in turn affect separation performance. An idea of using RO brine as PRO draw solution has also been proposed to obtain a high-osmotic pressure draw solution while simultaneously reducing the environmental effect of brine discharge. As for post-treatment necessity, application of hybrid
systems such as FO/RO, PRO/RO, or even FO/PRO/RO have been previously suggested to remove the need for a post-treatment system. The latest invention of FO/PRO/RO hybrid system simulation-wise is capable of saving 0.42 kWh of electricity per hour for each 1 m3/hour water produced. This reduction of electricity is equivalent to 0.99 kg CO2 emission reduction per hour. However, as this SI is still based on ideal operating conditions, further studies in the economical and life-cycle aspects of this system are required.

References
[1] Le N L, Nunes S P 2016 Materials and membrane technologies for water and energy sustainability Sustainable Materials and Technologies 7 1–28.
[2] Voutchkov N 2018 Energy use for membrane seawater desalination – current status and trends Desalination 431 2-14.
[3] Yip N Y, Elimelech M 2014 Comparison of Energy Efficiency and Power Density in Pressure Retarded Osmosis and Reverse Electrodialysis Environmental Science and Technology 48 11002–12
[4] Eyvaz M, Arslan S, Imer D, Yüksel E, Koyuncu I 2018 Forward Osmosis Membranes – A Review: Part I Osmotically Driven Membrane Processes - Approach, Development and Current Status 11–40.
[5] Nagy E 2019 Forward Osmosis Basic Equations of Mass Transport Through a Membrane Layer 447–56.
[6] Cheklei L, Phuntsho S, Vigneswaran S, Shon H K, Kandasamy J, Chanan A 2012 A review of draw solutes in forward osmosis process and their use in modern applications Desalination and Water Treatment 43 167–84.
[7] Aaberg R J 2003 Osmotic power: A new and powerful renewable energy source? Refocus 4 48–50
[8] Scott K 1998 Introduction to membrane separation Handbook of Industrial Membranes 3–185.
[9] Bogler A, Lin S, Bar-Zeev E 2015 Biofouling of membrane distillation, forward osmosis and pressure retarded osmosis: Principles, impacts and future directions Journal of Membrane Science 542 378-98.
[10] Alsvik I L, Hägg M B 2013 Pressure retarded osmosis and forward osmosis membranes: Materials and methods Polymers 5 303–27
[11] Tiraferri A, Yip N Y, Phillip W A, Schiffrin J D, Elimelech M 2011 Relating performance of thin-film composite forward osmosis membranes to support layer formation and structure Journal of Membrane Science 367 340–52
[12] Han G, Chung T S, Toriida M, Tamai S 2012 Thin-film composite forward osmosis membranes with novel hydrophilic supports for desalination Journal of Membrane Science 423–24:543–55
[13] Lee S, Boo C, Elimelech M, Hong S 2010 Comparison of fouling behavior in forward osmosis (FO) and reverse osmosis (RO) Journal of Membrane Science 365 34–9
[14] Qin D, Liu Z, Sun D D, Song X, Bai H 2015 A new nanocomposite forward osmosis membrane custom-designed for treating shale gas wastewater Scientific Reports 5 14530
[15] Achilli A, Cath T Y, and Childress A E 2010 Selection of inorganic-based draw solutions for forward osmosis applications Journal of Membrane Science 364 233–41
[16] Han G, Zhang S, Li X, Chung T S 2015 Progress in pressure retarded osmosis (PRO) membranes for osmotic power generation Progress in Polymer Science 51 1–27
[17] Klaysom C, Cath T Y, Depuydt T, Vankelecom I F J 2013 Forward and pressure retarded osmosis: potential solutions for global challenges in energy and water supply Chemical Society Reviews 42 6959–89
[18] Tang N, Jia Q, Zhang H, Li J, Cao S 2010 Preparation and morphological characterization of narrow pore size distributed polypropylene hydrophobic membranes for vacuum membrane distillation via thermally induced phase separation Desalination 256 27–36
[19] Mi B, Elimelech M 2008 Chemical and physical aspects of organic fouling of forward osmosis membranes Journal of Membrane Science 320 292–302
[20] Yip N Y, Elimelech M 2013 Influence of natural organic matter fouling and osmotic backwash on pressure retarded osmosis energy production from Natural Salinity Gradients Environmental Science and Technology 47 12607–16
[21] Han G, Zhou J, Wan C, Yang T, Chung T S 2016 Investigations of inorganic and organic fouling behaviors, antifouling and cleaning strategies for pressure retarded osmosis (PRO) membrane using seawater desalination brine and wastewater Water Research 103 264–75
[22] Raaijmakers M J T, Benes N E 2016 Current trends in interfacial polymerization chemistry Progress in Polymer Science 63 86–142
[23] Petersen R J 1993 Composite reverse osmosis and nanofiltration membranes Journal of Membrane Science 83 81–150
[24] Gohil J M, Ray P 2017 A Review on Semi-Aromatic Polyamide TFC Membranes Prepared by Interfacial Polymerization : Potential for Water Laboratory for Advanced Research in Polymeric Materials ( LARPM ), Central Institute of Plastics Engineering & Technology Reverse Osmosis Membrane Separation and Purification Technology 181 159–82
[25] Morgan P W 2011 Interfacial Polymerization Encyclopedia of Polymer Science and Technology
[26] Bean K, Black C F, Govan N, Reynolds P, Sambrook M R 2012 Preparation of aqueous core/silica shell microcapsules Journal of Colloid and Interface Science 366 16–22
[27] Shen L, Hung W S, Zuo J, Tian L, Yi M, Ding C, Wang Y 2020 Effect of ultrasonication parameters on forward osmosis performance of thin film composite polyamide membranes prepared with ultrasound-assisted interfacial polymerization Journal of Membrane Science 599 117834.
[28] Cheng Z L, Li X, Chung T S 2018 The forward osmosis-pressure retarded osmosis (FO-PRO) hybrid system: A new process to mitigate membrane fouling for sustainable osmotic power generation Journal of Membrane Science 559 63–74
[29] Luo L, Wang P, Zhang S, Han G, Chung T S 2014 Novel thin-film composite tri-bore hollow fiber membrane fabrication for forward osmosis Journal of Membrane Science 461 28–38
[30] Wang R, Shi L, Tang C Y, Chou S, Qiu C, Fane A G 2010 Characterization of novel forward osmosis hollow fiber membranes Journal of Membrane Science 355 158–67
[31] Chou S, Wang R, Fane A G 2013 Robust and High performance hollow fiber membranes for energy harvesting from salinity gradients by pressure retarded osmosis Journal of Membrane Science 448 44–54
[32] Xiaoxiao S, Prince J A, Sun D D 2016 Relating Water/Solute Permeability Coefficients to the Performance of Thin-Film Nanofiber Composite Forward Osmosis Membrane Journal of Membrane Science and Technology 6 4

Acknowledgement
This research has been financially supported by Research Programs, Community Services, and Innovation, Institut Teknologi Bandung (P3MI ITB).