Osmotic Power with Pressure Retarded Osmosis: Theory, Performance and Trends – a Review

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Abstract: A great quantity of renewable energy can be potentially generated when waters of different salinities are mixed together. The harnessing of this energy for conversion into power can be accomplished by means of Pressure Retarded Osmosis (PRO). This technique uses a semipermeable membrane to separate a less concentrated solution, or solvent, (for example, fresh water) from a more concentrated and pressurized solution (for example sea water), allowing the solvent to pass to the concentrated solution side. The additional volume increases the pressure on this side, which can be depressurized by a hydroturbine to produce power – thus the term 'osmotic power'. This paper reviews technical, economical, environmental and other aspects of osmotic power. The latest available research findings are compiled with the objective of demonstrating the rapid advancement in PRO in the last few years – particularly concerning membrane development – and encouraging continued research in this field. Also, the hurdles involved in the effectuation of PRO plants and the research gaps that need to be filled are analyzed in this article. Additionally, osmotic power production using configurations other than the traditional pairing of river water and sea water are discussed. It is hoped that this review will promote further research and development in this new and promising source of renewable energy.

Keywords: osmosis, salinity, pressure retarded osmosis, renewable energy, ocean energy

1. Introduction

Global energy supply for human activities is dominated by fossil fuel combustion [1], which due to high emissions of greenhouse gases, is accelerating changes in our climate towards dangerous long-term effects [2, 3]. It is estimated that only 13% of our energy is sourced by renewable resources, mainly shared between biomass and waste (75%), hydro (17%) and solar and wind (6%) [1]. Geothermal, wave and tidal energies account for the rest of the share

(2%). To reduce the reliance on fossil fuels while also satisfying growing energy requirements, new alternative sources have to be explored and embraced, particularly renewable sources due to the smaller impact on our environment.

A type of renewable and gas emission-free energy that has just recently been given credibility is salinity-gradient energy, which is based on the release of free energy upon mixing of waters with different salt concentrations, as between rivers and oceans. When appropriately harnessed, this energy can be used to produce power [4].

In the context of this review, the process of harnessing salinity-gradient energy is best explained in terms of osmotic pressure. Osmosis occurs when two solutions of different concentrations (for example, different salinities) are separated by a membrane which will selectively allow some substances through it but not others. If these two solutions are fresh water and sea water, for example, and they are kept separated by a semipermeable membrane that is only permeable to water, then water from the less concentrated solution side (fresh water) will flow to the more concentrated solution side (sea water). This flow will continue until the concentrations on both sides of the membrane are equalized or the pressure on the concentrated solution side is high enough to stop further flow. Under no flow conditions, this pressure will be equal to the osmotic pressure of the solution. Osmotic pressure of a given solution is therefore not a pressure that the solution itself exerts, but a pressure that must be applied to the solution (but not the solvent) from outside in order to just prevent osmotic flow.

Pressure Retarded Osmosis (PRO) is the process through which osmotic energy can be harnessed and power generated [5]. Putting it simply, in PRO, a water flow is diverted at low pressure into a module wherein a semipermeable membrane keeps it separated from a pressurized and saltier water flow. The saltier water flow draws the less concentrated water through the semipermeable membrane due to its higher osmotic pressure, increasing the volume of the flow. A turbine is coupled to the pipe containing the increased pressure flow to generate power. Power generated via PRO is referred to as ‘osmotic power’.

The most known and studied application of PRO technology for power generation is the pairing of river water (less concentrated solution or feed solution) and sea water (more concentrated solution or draw solution), as schematized in Figure 1. Under this arrangement, incoming river water and seawater are both diverted into adjacent chambers of a membrane module. The two flows are separated by a semipermeable membrane with the active layer facing the seawater side, allowing only river water to flow through it. This process increases the volume of water on the seawater side. The resultant high-pressure, brackish water is then split into two paths: part of the flow is used to drive a turbine, and generate power, and the other part returns to the pressure exchanger. The pressure exchanger is designed to transfer pressure energy from the pressurized brackish water to the incoming sea water. Similarly, sea water could also be used as feed solution, paired with a more concentrated solution, such as brine from seawater desalination plants [6, 7, 8], or hypersaline water from salt lakes or salt domes [9, 10].

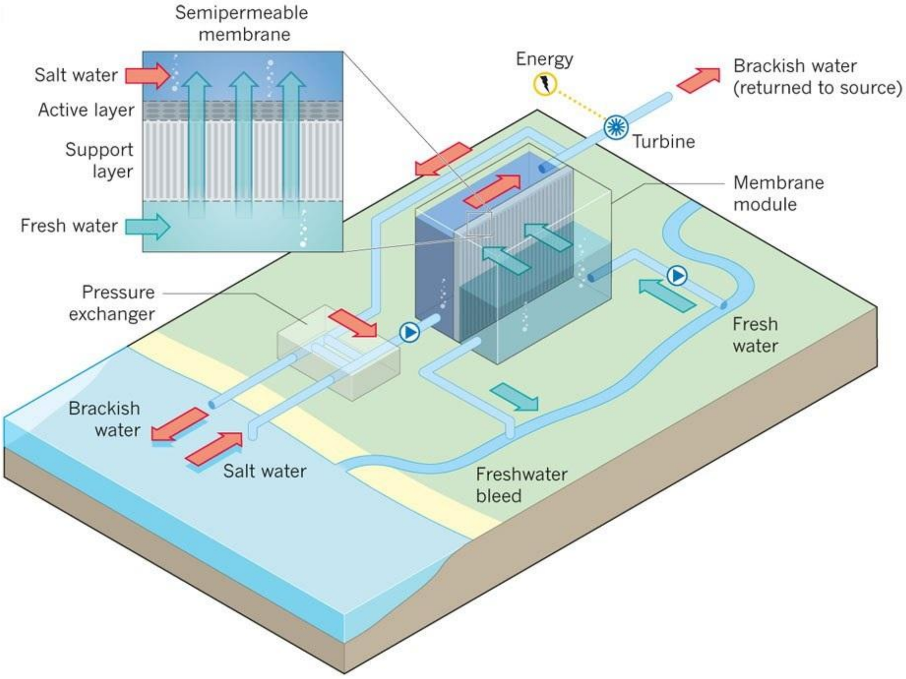


Figure 1. Schematic diagram of a PRO plant run on river water *vs* sea water. Figure retrieved from Ref. [11].

PRO was invented by Prof. Sidney Loeb in 1973 at the Ben-Gurion University of the Negev, Beersheba, Israel, with his first publication released in 1975 [5]. The method has been improving over the years, particularly after the opening of the first osmotic power plant prototype by the Norwegian state-owned power company, Statkraft, in 2009 [12]. This prototype has been designed to develop and test new PRO technologies, particularly novel semipermeable membranes, and is projected to become the first large-scale osmotic power production facility in the world by 2015 [13]. The plant operates using river water and sea water, as shown in Figure 1.

This article analyses technical, economical, environmental and other aspects of PRO. It combines the findings of the latest research, outlining the advancements achieved in the last few years and the hurdles that need to be overcome for the effectuation of osmotic power production on a commercial scale. This article also discusses some combinations of water solutions under which osmotic power could be produced, beyond the traditional pairing of river water and sea water. It is also an objective of this paper to provide an informative document that encourages governments, research institutions and private investors to combine efforts to accelerate the development of PRO technology and its availability as a renewable energy source.

2. World's potential for osmotic power

Salinity-gradient energy is the energy released when waters with different salt concentrations are mixed together. Presumably, this energy can be easily encountered at the interface between waters of differing salt concentrations, for instance where rivers meet the ocean. Approximately 0.70 - 0.75 kWh (2.5 - 2.7 MJ) is dissipated when 1 m^3 of fresh water flows into the sea [14, 15], meaning that 1 m^3 s^{-1} of fresh water can potentially generate 2.5 - 2.7 MW). Table 1 summarizes the maximum energy that could be theoretically extracted from the mixing of fresh water with saline water from five different sources.

Table 1. Maximum extractable energy from the mixing of fresh water with saline water from different sources

	Osmotic Pressure (bar)	Theoretical Energy[1] (kWh m^{-3})	Theoretical Power[1] MW $(m^3/s)^{-1}$	Osmotic Pressure (source)
Sea water	27	0.75	2.7	Calculated using Eq. 1, assuming 0.55 M NaCl concentration
SWRO brine	54	1.5	5.4	Calculated using Eq. 1, assuming 1.1 M NaCl concentration
Salt-dome solution	316	8.8	31.6	Logan and Elimelech [11]
Great Salt Lake	375	10.4	37.5	Wick and Isaacs [16]
Dead Sea	507	14.1	50.7	Wick and Isaacs [16]; Loeb [5]

[1] The theoretical energy and power are calculated from the osmotic pressure of the solution (converted to Pa) and the unit volumetric flow (m^3 s^{-1})

Considering the average discharge of all the world's rivers into the ocean, it can be estimated that the energy released when this mixing occurs is equivalent to each river ending in a 225 meters high waterfall [17]. The global potential for osmotic power is reported to be 1,650 TWh y^{-1} [15, 18]. This is equivalent to about half the current annual hydropower generation, reported to be 3,551 TWh y^{-1} [19]. In the United States, as another example, the total surface runoff of water from streams and rivers into the ocean is about 1,700 km^3 y^{-1} [17], which could generate about 55 GW, assuming an energy conversion efficiency of 40% (i.e., an output of 1.0 MW per m^3 s^{-1} of river water [15]). This is enough power for a PRO system to supply electricity to around 40 million people in the US, assuming an average electricity consumption of 1,400 W per person [20]. The Mississippi River alone accounts for about one-third of the total US runoff [17], and if 10% of the Mississippi flow was used, this volume would be enough to deliver around 1,800 MW of power assuming 40% energy conversion efficiency. Wick [21] reports that the osmotic power that could be generated from the Columbia River (USA and Canada) discharge into the Pacific Ocean is around 2,300 MW when considering an energy conversion efficiency of 30% and half of the river flow.

Table 2 summarizes the power due to salinity gradients that could be generated from the major sources of fresh water in the world in a hypothetical mixing with sea water (NaCl concentration ≈ 3%), in a PRO system with energy conversion efficiency of 40% and using 10% of the river flow. The sites were suggested by Wick [21].

Table 2. Osmotic power production capacity from some major rivers across the world

Source of fresh water	Average flow rate (m^3 s^{-1})	Power (MW)[2]	Electricity supply (thousands of households)[1]
World	1.2×10^6	124,800	N/A
Amazon River, Brazil	2×10^5	20,800	77,600
La Plata – Parana River, Argentina	8×10^4	8,320	29,100
Congo River, Congo Angola	5.7×10^4	5,930	282,300
USA	5.4×10^4	5,620	4,000
Yangtze River, China	2.2×10^4	2,290	5,800
Ganges River, Bangladesh	2×10^4	2,080	74,300
Mississippi River, USA	1.8×10^4	1,870	1,300
Columbia River, USA	7.5×10^3	780	550

[1] Based on household's average consumption per country reported in Central Intelligence Agency [20]
[2] Power was estimated by using 10% of the river discharge and assuming a power output of 1 MW per m^3 s^{-1} of river water (i.e., 40% energy conversion efficiency).

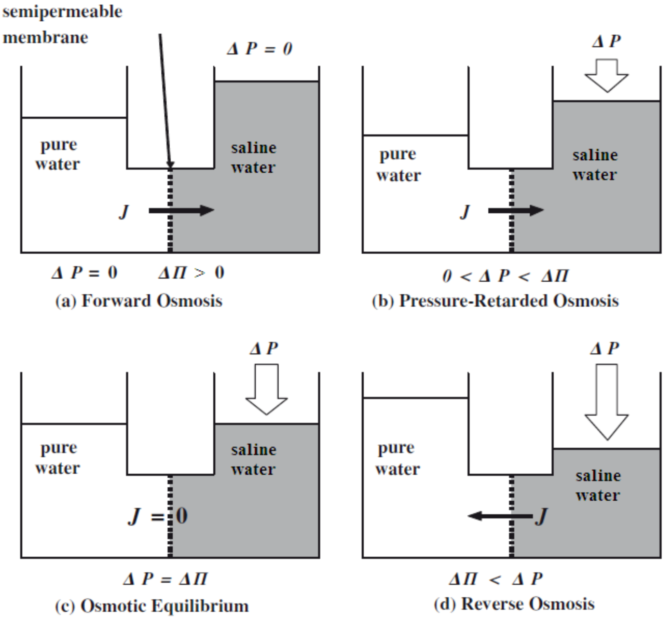
3. Osmotic processes

The energy released through the mixing of fresh water and salt water can be more easily explained using the osmosis effect, hence the name 'osmotic energy'. Osmosis is the transport of water across a semipermeable membrane from a solution of higher chemical potential (i.e., lower osmotic pressure or lower salt concentration) – typically referred to as the 'feed solution' – to a solution of lower chemical potential (i.e., higher osmotic pressure or higher salt concentration) – referred to as the 'draw solution'. This semipermeable membrane allows passage of feed solution, rejecting solute molecules or ions. Osmotic pressure is the pressure that would cease the passage of feed solution across the semipermeable membrane if applied to the draw solution. The osmotic pressure (π) of any solution can be calculated using the *van't Hoff* equation, as shown below:

$$\pi = i\, c\, R\, T \qquad (1)$$

where c is the molar concentration (mol L^{-1}), R is the universal gas constant (8.31441 N m mol^{-1} K^{-1}), T is the absolute temperature (K) and i is the number of osmotically active particles in the solution, given as $i = 1 + \alpha\,(v - 1)$, with α being the degree of dissociation and v, the stoichiometric coefficient of dissociation reaction (for NaCl, $\alpha = 1$ and $v = 2$, thus $i = 2$). The resulting unit for π in Eq. 1 is the kPa. For sea water, for example, where the NaCl concentration ranges from 3.0% to 4.0% (or approximately 30 – 40 g L^{-1}, or 0.51 to 0.68 mol L^{-1}), the osmotic pressure is between 25 and 33 bar, for a temperature of 25^{o}C. Other solutions with higher osmotic pressures would be, for instance, concentrated brine remaining from reverse osmosis (RO) desalination plants and hypersaline waters from salt lakes, such as the Great Salt Lake (USA), the Aral Sea (Kazakhstan and Uzbekistan), the Dead Sea (Israel) and Lake Eyre (Australia). Concentrated brines from RO desalination plants have typical salt concentrations ranging from 6% to 7%, meaning osmotic pressures between 50 and 59 bar. The salinity of salt lakes ranges from 24% (Great Salt Lake) to 34% (Dead Sea), meaning an osmotic pressure variation from 200 to 290 bar. For fresh water, the osmotic pressure is close to zero.

Figure 2 represents four possible osmotic processes that occur from the contact of pure water and saline water via a semipermeable membrane. Forward osmosis (FO), or simply osmosis, occurs when the only driving force for the flux of water through the membrane (J) is the osmotic pressure differential ($\Delta\pi$) between the feed and the draw solutions (Figure 2(a)). In FO, $\Delta\pi$, is non-zero and positive, that is, $\Delta\pi > 0$, and the solutions are either not pressurized or pressurized at the same magnitude, making $\Delta P = 0$. It should be noted that the osmotic pressure differential depends on the concentration of each solution, as described by Eq. 1. For example, if the feed solution is clean fresh water ($\pi \approx 0$) and the draw solution is sea water (i.e., salt concentration ≈ 3.0%, and $\pi \approx 26$ bar), the osmotic pressure differential is 26 bar, which is equivalent to a hydrostatic pressure from a 265-m high water column. This said, water moves through the membrane from the left (less concentrated) to the right (more concentrated) side, driven solely by the osmotic pressure differential between the two solutions.



(a) Forward Osmosis
(b) Pressure-Retarded Osmosis
(c) Osmotic Equilibrium
(d) Reverse Osmosis

Figure 2. Schematic representations of four osmotic processes. Figure adapted from Ref. [6].

Once the water starts moving from the less concentrated to the more concentrated side, the hydrostatic pressure on the more concentrated side gradually increases and, eventually, the osmotic flow J will cease. More precisely, when a pressure equivalent to a 265-m high water column has built up on the salty side of the membrane, the osmotic flow will stop. Mathematically, the flux will cease when ΔP equals $\Delta\pi$ (i.e., $\Delta\pi - \Delta P = 0$, and therefore $J = 0$). This condition determines the state of osmotic equilibrium and is illustrated in Figure 2(c).

At any stage when the hydrostatic pressure differential ΔP is between 0 and $\Delta\pi$, the water flux is still driven by the osmotic pressure differential, $\Delta\pi$, but the flux slows down due to the increasing ΔP as a result of the increase in water level on the draw solution side. This effect is illustrated in Figure 2(b) and is termed Pressure Retarded Osmosis (PRO). In PRO, the feed (less concentrated) solution flows towards the draw solution side because of the positive osmotic pressure differential, for as long as this difference remains greater than the hydrostatic pressure difference (ΔP). It is on this principle that the production of osmotic power is based. For steady power production, the salty water side has to be maintained at constant pressure and concentration while the feed solution provides a constant flow through the membrane, increasing the volume flow on the salty water side. This additional flow can then be used to generate power.

The fourth osmotic phenomenon occurs when $\Delta P > \Delta\pi$, and is illustrated in Figure 2(d). This condition is achieved when pressure is applied to the draw solution side, with this pressure being greater than the osmotic pressure difference between the two sides. In this case, the water flux occurs from the salty water to the freshwater side, resulting in a negative flux. This process is called reverse osmosis (RO) because the water moves in the opposite direction to that of a natural osmotic process. It is on this principle that most modern seawater desalination plants operate. Sea water is pressurized to a magnitude that is greater than its osmotic pressure, forcing it to flow through the semipermeable membrane. The membrane stops the flux of salts and only fresh water permeates, which can later be safely consumed by end-users. The relationship between the four cases described above in terms of water fluxes and pressures is illustrated in Figure 3.

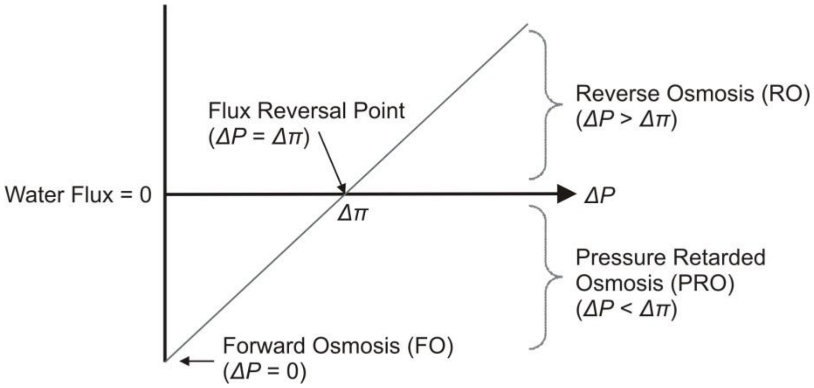


Figure 3. Direction of water flux as a function of applied pressure in FO, PRO and RO. FO takes place when the hydrostatic pressure differential, ΔP, is zero and the flux is driven by the osmotic pressure differential, $\Delta\pi$. PRO occurs when the hydrostatic pressure differential is non-zero and less than the osmotic pressure differential. RO takes place when the applied hydrostatic pressure differential is greater than the osmotic pressure differential. Figure adapted from Ref. [22].

The potential flux through the membrane is calculated as a function of the difference in osmotic pressure between the two solutions ($\Delta\pi$, in bar), the difference in hydrostatic pressure (ΔP, in bar) and the intrinsic water permeability coefficient of the membrane (A, typically in L m^{-2} h^{-1} bar^{-1}):

$$J = A(\Delta\pi - \Delta P) \tag{2}$$

where J is the water flux (typically in L m^{-2} h^{-1}), $\Delta\pi = \pi_D - \pi_F$, where π_D is the osmotic pressure in the draw solution and π_F is the osmotic pressure in the feed solution, and $\Delta P = P_D - P_{F.}$.

4. Osmotic power with PRO

The concept of harvesting the energy generated from mixing waters of different salinities was first reported by Pattle [4], and then re-investigated in the mid 1970s, when the world's energy crisis prompted further research into energy supply alternatives. The discussions on PRO expanded rapidly after 1970 particularly due to the theoretical and experimental publications of Sidney Loeb [5, 9], showing the feasibility of PRO. Loeb [9] was the first to report that osmotic energy could indeed be harnessed using the principles of this technology. However, research slowed down again in the 80s and 90s due to the expensive prices of the available membranes, which would make osmotic power generation financially unviable.

With recent advances in membrane technology, resulting from increasing demands for desalination and water treatment, there has also been advancement in membrane production technology and a subsequent reduction in membrane prices. Consequently, experimental investigations on PRO were resumed in the late 2000s by Skilhagen et al. [23], Gerstandt et al. [24] and Thorsen and Holt [15]. Encouraged by new research findings, Statkraft opened the world's first PRO power plant prototype in November 2009 in Norway. This prototype has proved that the PRO concept can be used to generate electricity. The plant is being used to test different types of membranes and plant configurations and has been key for the advance of osmotic power.

Figure 4 shows an idealized arrangement for a PRO power plant with continuous, steady state flow. First, a concentrated solution of volume V and with osmotic pressure π_D, such as sea water, is pumped into the plant at a hydraulic pressure P_D. The power input is given by the product of the volume flow (V) and the input hydraulic pressure P_D. At the same time, less concentrated water, for example, river water, enters the permeator on the other side of the membrane module at osmotic and hydraulic pressures that are low in comparison to these quantities on the concentrated side. Water permeates the membrane from the less concentrated side to the more concentrated side at a rate ΔV (note $\Delta V = J\, A_m$, where A_m is the membrane area and J is the water flux from Eq. 2) and acquires a pressure of P_D. The mixture of the feed and draw solutions creates a new solution of brackish water, with much lower osmotic pressure. The brackish water (volume $V + \Delta V$) enters a hydroturbine in which the hydraulic pressure P_D is reduced to zero, as it delivers power of magnitude $P_D\,(V + \Delta V)$.

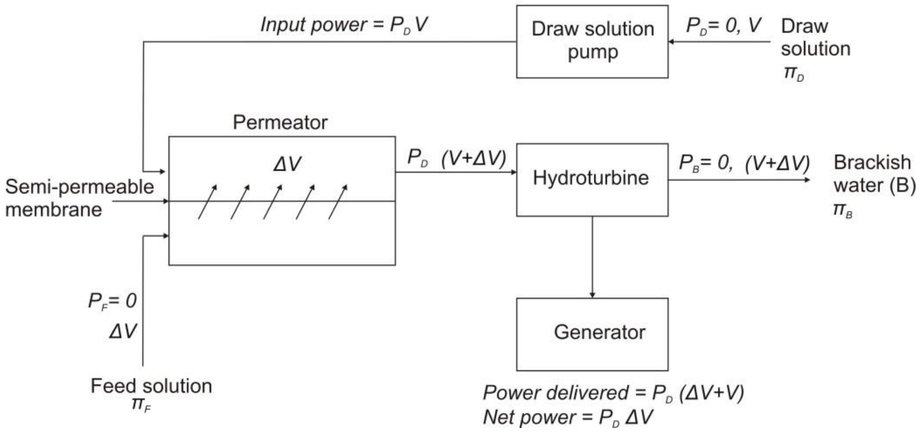


Figure 4. Continuous PRO system – idealized by assuming: 1. 100% efficiency for rotating components. 2. No friction losses in plant streams. 3. Membranes perfectly semipermeable. Figure modified from Ref. [9].

The maximum net power (PW_{NET}^{MAX}) that could be produced under this ideal PRO scheme is the difference between the quantity delivered by the hydroturbine, $P_D\,(V + \Delta V)$, and the power input into the system, $P_D\,V$:

$$PW_{NET}^{MAX} = P_D(V + \Delta V) - P_D V = P_D \Delta V \qquad (3)$$

where $P_D \Delta V$ is the net power. It should be noted that this net power is achieved for 100% mechanical efficiency for all components and no energy losses. This scheme also assumes that the feed solution enters the system by gravity.

The ideal operating pressure for maximum power output is half the osmotic pressure differential, as will be demonstrated later in this article. Therefore, for a river water *vs* sea water PRO scheme, where the osmotic pressure differential is about 26 bar, the ideal operating pressure would be 13 bar, and the maximum net power output, 1.3 MW per m^3 s^{-1} of permeate.

For mechanical efficiencies less than 100% for PRO system components, which is what would be expected in reality, the net power would be:

$$PW_{NET}^{REAL} = P_D \Delta V \eta \qquad (4)$$

where η is the mechanical efficiency of the system, which is dependent upon the efficiencies of the rotating components such as pumps, motors, turbines and generators, the friction losses in the flow passages of the permeator, and the configuration of the equipment in the plant [25]. For example, assuming that approximately 20% of the maximum theoretical net power achievable from a fresh water *vs* sea water PRO system (i.e., 20% of 1.3 MW per m^3 s^{-1} of permeate) is lost from inefficiencies in the PRO system components [14], a river water *vs* sea water scheme could generate around 1.0 MW of net power per m^3 s^{-1} of river water (assuming that the only parasitic power consumption is the pressurization of the incoming sea water). This means an overall efficiency of 40% when compared to the maximum extractable energy from mixing of sea water and fresh water (i.e., 2.7 MW per m^3 s^{-1} of river water). Furthermore, an efficiency of 81% has been reported for a below sea-level plant that relies on gravity, rather than pumps, to pressurize the incoming sea water [26].

It follows, therefore, that the actual power output of a PRO plant will be dependent upon [10, 25]:

- The frictional pressure drop across the salt water side of the PRO permeator;
- The frictional pressure drop across the freshwater side of the PRO permeator;
- the configuration of the equipment in the plant;

- The inefficiencies of all pumping and rotating components (hydroturbine-generator, freshwater pump-motor, seawater pump-motor, and the flushing solution pump-motor);
- All power inputs into the system, including those for pressurizing the incoming fresh water and sea water and for pre-treatment;
- The fact that current membranes are not perfectly semipermeable.

As seen in Eq. 3, the net maximum theoretical power ($P_D \Delta V$) does not depend on the volume of the draw solution (V). It only depends on the operating pressure (P_D) and on the flux of water through the permeator, J (note $\Delta V = J\ A_m$), which is essentially a function of the membrane type (parameter A - permeability) and the osmotic pressure differential, as shown by Eq. 2. Therefore, one could infer that in order to generate high net powers, great pressures (P_D) should be applied to the draw solution. However, in a real PRO system, it should be noted that the volume flow rate of the incoming draw solution (V), to which P_D is applied, will be relevant to the inefficiencies of the system. A low draw solution flow (low applied pressure) will increase the contribution of membrane costs (capital cost) to power costs because of the decrease in hydraulic pressure, and consequently, power output, which is undesirable. A high draw solution flow will be similarly undesirable due to the higher input power into the system, which will cause damage to the membranes [25]. Loeb et al. [9, 10] found that for a system to be energy efficient, the volume of the draw solution (V) has to be equal to but not higher than twice the volume of the permeate (ΔV).

It should be noted that the efficiency of a PRO power plant nowadays can be significantly improved by using energy recovery devices (pressure exchangers) to pressurize the incoming draw solution [15, 23-28]. Loeb [27] was the first to acknowledge and demonstrate the importance of pressure exchangers in enabling cost-effective PRO systems, due to the substantial reduction of parasitic power consumption. Without energy recovery devices, the value of the energy generated would barely outweigh the costs with the pressurization of the incoming solutions (particularly the draw solution) [15]. According to Skilhagen and Aaberg [26], with improved membranes, optimized flows and minimized energy losses, an efficiency of 70% for a terrestrial sea-level plant with pressure exchangers can be achieved. A schematic diagram showing the configuration of a PRO plant with pressure exchangers is shown in Figure 5.

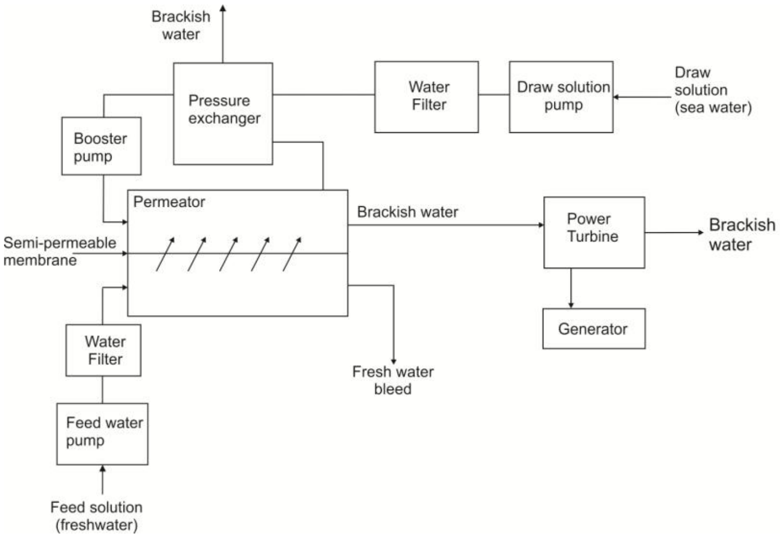


Figure 5. Power production from a PRO scheme powered by pressure exchangers. Diagram based on Ref. [5, 11, 28].

5. Membrane performance

Membrane performance in PRO is usually measured in terms of power output per unit area of membrane – referred to as membrane power density. The power density of the membranes is particularly important as it will directly affect the costs of osmotic power. The higher the power output per unit area of membrane, the cheaper the costs with installation, maintenance and plant operation. It should be noted, however, that the power generation capacity of an osmotic power plant is not limited by the power density of the membranes, but rather by the availability of feed solution in the environment, making it important that the plant operates at high efficiency (i.e., high power output per m^3 s^{-1} of feed solution). Nevertheless, the power density may limit the activity by increasing the costs of the power production to a level that makes it unprofitable. Since the late 2000s, PRO research has been focusing on finding an existent or developing a new membrane that would generate at least 5 W m^{-2} of power. This power density has been demonstrated to be the break-even point for osmotic power to be profitable after an n^{th}-of-a-kind plant has been built [23, 29, 30]. The main problem with the development of such membrane is concentration polarization, referred to the reduced concentration gradient created by salt molecules which cannot pass through the membrane. This issue greatly reduces membrane water fluxes and power densities in PRO, as discussed in the next sections.

5.1. Concentration polarization

Initial studies on osmotic power were based on RO membranes installed in laboratory scale PRO modules [31-35]. This continued until the discovery of the concentration polarization phenomenon, an important issue that occurs in osmotically driven membrane processes [36-38, 39]. This phenomenon was found to drastically decrease the theoretical water flux J through RO membranes (refer to Eq 2). The reduction in water flux further decreases the power outputs of the membranes.

This concentration polarization issue was discovered by Mehta and Loeb [32, 33] and Lee et al. [35] after their PRO experiments revealed power outputs that were far below the outputs estimated based on theoretical osmotic pressure differentials. Mehta and Loeb [32, 33] observed a sharp decline in the water permeation rate after about two hours of testing with RO membranes. They attributed this issue to concentration polarization. External concentration polarization (ECP) was referred to as the concentration of salt that occurs over time on the external side of the membrane (represented by C_1 and C_2 in Figure 6), while internal concentration polarization (ICP) was defined as the accumulation of salt within the active layer of the membrane (C_3 in Figure 6). It was found that salt concentration build-up significantly reduces the effective osmotic pressure differential that drives the flux of water through the membrane, decreasing its power efficiency [32, 33, 39]. This means that, instead of being driven by the bulk osmotic pressure differential between C_D and C_F, the water flux is actually driven by the osmotic pressure differential due to C_1 and C_3.

In Figure 6, J represents the flux of water from the less to the more concentrated side. As water permeates the dense active layer of the RO-membrane (facing the draw solution), the draw solution is diluted, and the concentration on the membrane-draw solution interface is reduced to C_1. Concurrently, as membranes are not perfectly semipermeable, there is a counter flux of sea water (J_s in Figure 6) to the feed solution side. During this process, salt accumulates at the interface of the membrane layers, reducing the effective osmotic pressure differential – that is, the driving force of the water flux – and consequently, the membrane power output.

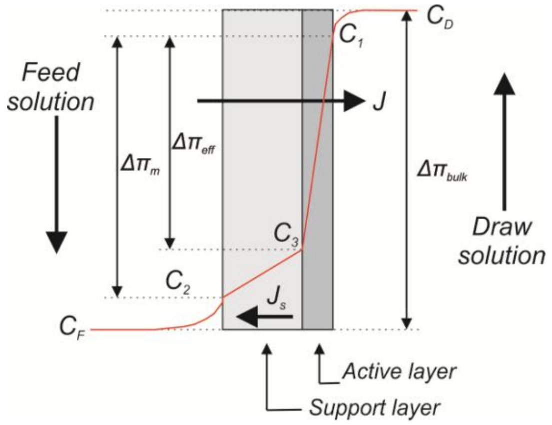


Figure 6. External and internal membrane concentration polarizations that occur during PRO. C_D and C_F are the salt concentrations of the bulk feed and draw solutions, respectively. C_1 and C_2 are the salt concentrations due to external concentration polarization, resulting in a reduced osmotic difference $\Delta\pi_m$. C_3 is the salt concentration due to internal concentration polarization, resulting in an effective osmotic pressure differential of $\Delta\pi_{eff}$. Figure adapted from Ref. [22].

Recent studies have confirmed that ICP is the main cause of the substantial flux decline through membranes that are applied in PRO [18, 40] and consequently, of the reduced power outputs of the membranes. ECP, in turn, has demonstrated a relatively small effect on reducing the osmotic pressure driving force under low flux conditions [41]. The phenomenon, however, becomes more important under high flux conditions (i.e., high membrane power densities), as demonstrated by Yip and Elimelech [40].

It should be noted that the requirements of membranes for PRO are quite different from the requirements of membranes for RO. In RO, the membranes have to withstand high applied pressures, since sea water is forced through the membrane, against the natural gradient of the osmotic pressure. For this reason, as shown in Figure 6, the porous support layer of the RO membrane has to be thick, dense and highly resistant [42]. It should also be noted that concentration polarization is not as important in RO as it is in PRO, as in RO both water and salt flows occur in the same direction, as opposed to PRO, where salt and water flows occur in opposite directions. Loeb et al. [43] and Cath et al. [22] were the first to report that commercial RO membranes would unlikely be suitable for PRO and that a membrane for this purpose would have to be made much thinner and deprived of a fabric support layer to allow for higher water flux. In this context, FO membranes, because of their thinner support layer, are significantly less susceptible to concentration polarization [36], and so are more often used in PRO studies [e.g., 38, 41, 44].

5.2. Membrane flux and power density

As discussed above, concentration polarization greatly reduces the flux of water through membranes used in PRO systems, and this reduction further decreases power output. As demonstrated by Eq. 2, the ideal (potential) volume flux through the membrane (J) is a function of the balance of hydrostatic and osmotic pressures between the feed and the draw solution sides of the membrane, and the intrinsic water permeability of the membrane (A). Therefore, if the effective osmotic pressure is reduced due to concentration polarization, the flux and power are also reduced. This can be understood by analyzing the equation for the ideal power output:

$$W = J\ \Delta P = A\left(\Delta\pi - \Delta P\right)\Delta P \tag{5}$$

where the power density of the membrane is given in W m^{-2}, the flux J is in m^3 m^{-2} s^{-1}, the hydrostatic pressure ΔP, in Pa, and the membrane permeability, A, in m^3 m^{-2} s^{-1} Pa^{-1}. Note that for a river water and sea water combination, where the osmotic and hydrostatic pressures of the incoming river water are approximately zero, Eq. 5 can be re-written as:

$$W = J\ P_D = A\left(\pi_D - P_D\right)P_D \tag{6}$$

By differentiating Eq. 5 and Eq. 6 with respect to ΔP and P_D, respectively, it can be shown that W reaches a maximum when $\Delta P = \Delta\pi/2$, or in the case of a fresh water *vs* sea water system, when $P_D = \pi_D/2$. For instance, the osmotic pressure potential of a river *vs* sea water PRO system corresponds to a pressure of 26 bar whereas the optimal working pressure is half of this, that is., 13 bar.

As for the intrinsic membrane permeability parameter A, typical values range from 0.40 L m^{-2} h^{-1} bar^{-1} to 7.7 L m^{-2} h^{-1} bar^{-1}, depending on the characteristics of the membranes and conditions under which the parameter was determined, as shown by different sources summarized in Figure 7. Cellulose acetate FO membranes have an average permeability of around 1.0 L m^{-2} h^{-1} bar^{-1}. Conventional thin-film composite RO membranes have an average permeability of about 1.50 L m^{-2} h^{-1} bar^{-1}. Modified or treated thin-film composite membranes (which alter the structure and morphology of the membrane [18, 45]) can reach 7.7 L m^{-2} h^{-1} bar^{-1}, leading to an increase in water flux J, and consequently in membrane performance for power generation.

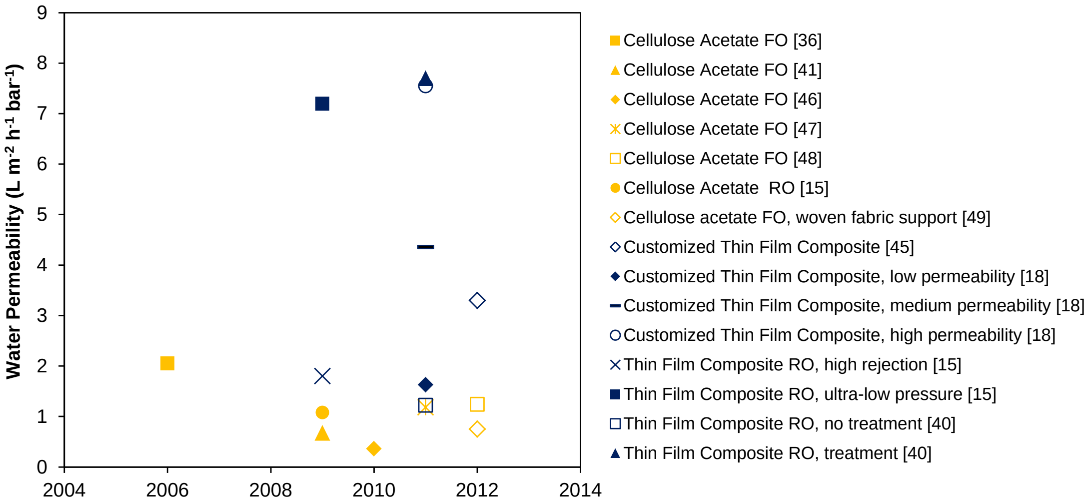


Figure 7. Water permeability values reported in the literature for different FO and RO membranes. The light (yellow) symbols represent cellulose acetate membranes and the dark (blue) symbols, thin-film composite membranes.

Using the published values of A, and assuming that sea water is pressurized at 13 bar, and that J is solely a function of the pressure differential and the membrane permeability (Eq. 2), membrane fluxes of fresh water would theoretically range from 5.0 L m^{-2} $h^{-1}$to 100 L m^{-2} h^{-1}, meaning that power outputs could be in the range of 1.8 to 36 W m^{-2}. However, as discussed before, the effective pressure differential $\Delta\pi$ is actually less than the theoretical osmotic pressure differential due to ICP, ECP and the reverse flux of salts. Lee et al. [35] were the first to modify Eq. 2 to develop a model to estimate the actual flux through the membrane (J_{act}), accounting for the effects of ICP. More recently, Yip et al. [18] modified the existing model to also incorporate the effect of ECP and the reverse permeation of salt:

$$J_{act} = A\left(\frac{\pi_D \, exp\left(-\frac{J}{k}\right) - \pi_F \, exp\left(\frac{JS}{D}\right)}{1+\frac{B}{J}\left[exp\left(\frac{JS}{D}\right) - exp\left(-\frac{J}{k}\right)\right]} - \Delta P \right) \qquad (7)$$

where A is in m^3 m^{-2} s^{-1} bar^{-1}, J is in m^3 m^{-2} s^{-1}, J_{act} is the actual water flux through the membrane (m^3 m^{-2} s^{-1}), π_F is the osmotic pressure (bar) of the bulk feed solution (e.g., fresh water), π_D is the osmotic pressure (bar) of the bulk draw solution (e.g., sea water), B is the salt permeability coefficient of the membrane active layer (in m^3 m^{-2} s^{-1}), k is the mass transfer coefficient (in m^3 m^{-2} s^{-1}) and D is the diffusion coefficient of salt in the membrane substrate (m^2 s^{-1}). The parameter S (in m) represents the resistance to salt transport in the porous substrate (support layer of the membrane) and is given by $\tau\, t/\epsilon$, where τ, t and ϵ are the tortuosity (dimensionless), thickness (m) and porosity (dimensionless) of the porous substrate respectively [15, 18]. Hence, the actual power density of the membrane will then be defined as:

$$W_{act} = J_{act} \Delta P \qquad (8)$$

with ΔP in Pa and W_{act} in W m^{-2}.

As with A, the other membrane parameters to feed the model (Eq. 7) are also customarily determined for RO and FO membranes and can be found in the literature. This model has been extensively used in the search for membranes that allow for higher flux and power densities. The main parameters that have been under study are the support layer structural parameter (S), the active layer salt permeability (B) and the active layer water permeability (A). The structural parameter determines the extent of ICP and has to be minimized to produce a higher water flux [40]. RO membranes have a large S value (which means they are thick and dense), because the membranes have to withstand high applied hydraulic pressures. In PRO, however, the support layer can be much thinner and with larger porous, which would increase the flux of water though the membrane. B is a measure of the reverse flux of draw solution. Ideally, this value should be as minimal as possible to avoid salt build-up in the membrane layers, because this would reduce the osmotic pressure differential. A, on the other hand, has to be increased as much as possible, to allow for more feed solution flux. However, as noted by Yip et al. [18], an increase in water permeability is always accompanied by an increase in salt permeability, which is undesirable. Increasing the value of A up to a certain point will benefit PRO because the water flux will increase; after this point, the reverse flux of the draw solution will increase, overwhelming the effect of the water permeability.

The ratio between the theoretical (Eq. 2) and the actual (Eq. 7) power outputs was referred to as the "Loss Factor" by Yip and Elimelech [40]. The same authors analyzed in detail the separate effects of each of the performance limiting phenomena – ICP, ECP and reverse flux of salt – on PRO performance as illustrated in Figure 8.

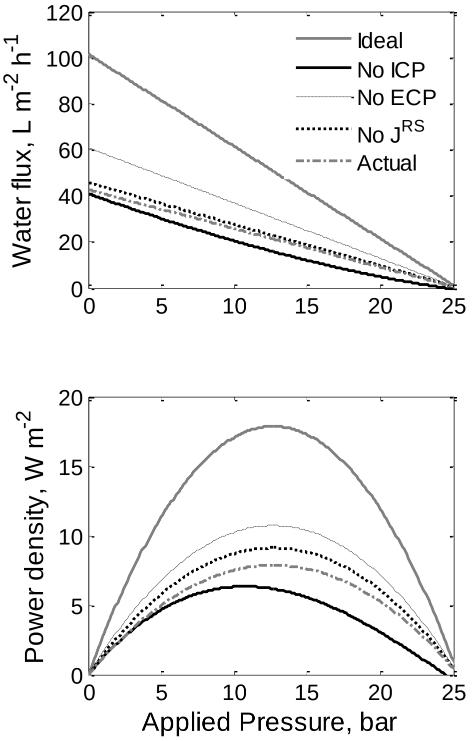


Figure 8. Water flux and power density as a function of applied hydraulic pressure. The ideal water flux and power density without any detrimental effect are indicated by the solid gray line and calculated using Eq. 2 (for the water flux) and Eq. 5 (for the power output), with A = 4.0 L m^{-2} h^{-1} bar^{-1}. The solid dark line represents the actual water flux and power density calculated using Eq. 7 and 8 with parameters derived for a thin-film composite membrane. The dashed lines indicate the water flux and power densities when each of the detrimental effects are absent (ICP = internal concentration polarization, ECP = external concentration polarization and J^{RS} = reverse flux of salt). The calculations were performed for a fresh water *vs* sea water system. Figure adapted from Ref. [40].

From Figure 8, it can be seen that ICP, ECP and the reverse flux of salt have a significant detrimental effect on PRO performance. The ideal water flux for this hypothetical membrane simulated on a fresh water *vs* sea water PRO system is around 50 L m^{-2} h^{-1}. The peak – and ideal – power output is about 18 W m^{-2}. However, actual water flux and actual power output are only about 20 L m^{-2} h^{-1} and 6 W m^{-2}, respectively, due to the reduced osmotic pressure differential caused by ICP, ECP and the reverse flux of salts. It should be noted that the modeled actual power output is significantly higher than the power outputs measured in laboratory conditions for thin-film composite membranes. This can be attributed to the parameters adopted in the calculations, particularly the structural parameter, S, in which the value chosen was 350 μm [40]. According to Yip and Elimelech [40], conventional thin-film composite membranes have a thick and dense support layer to withstand the pressure of RO with typical S values around 10,000 μm. Nevertheless, the model shows that high power outputs can be obtained with the improvement of membrane properties. The latest finding on membrane development is that of Chou et al. [45], who modified the structure of a thin-film composite hollow fiber membrane and achieved a water flux of 32 L m^{-2} h^{-1} bar^{-1} for a fresh water *vs* sea water system, which projects to a power density of 5.7 W m^{-2}.

Figure 9 shows the projected power densities calculated from water fluxes measured in different experimental conditions since 1976. Under an osmotic pressure differential similar to a fresh water *vs* sea water scheme, power densities up to 5.7 W m^{-2} have been achieved in laboratory conditions using thin-film composite membranes [45] and 2.7 W m^{-2} using cellulose triacetate membranes [41]. Under an osmotic pressure differential similar to fresh water *vs* brine at 6% NaCl concentration, Saito et al. [50] reported power densities of 7.7 W m^{-2} from a PRO module prototype made of cellulose triacetate hollow fiber membranes. Achilli et al. [41] projected a power density of 5.1 W m^{-2} for a flat-sheet cellulose triacetate membrane designed for FO. Chou et al. [45] achieved a power output of 10.6 W m^{-2} using a customized thin-film composite hollow fiber membrane. This is the highest power output ever found under laboratory conditions for a fresh water *vs* brine scheme. The latest reported results are from Kim and Elimelech [48], who achieved a power density of 3.2 W m^{-2} for a flat-sheet, cellulose-based FO membrane, using a draw solution of brine at 20% NaCl and sea water as the feed solution. It is also notable the increase in power densities achieved in the late 2000s in comparison to the initial results reported in the late 70s using RO membranes.

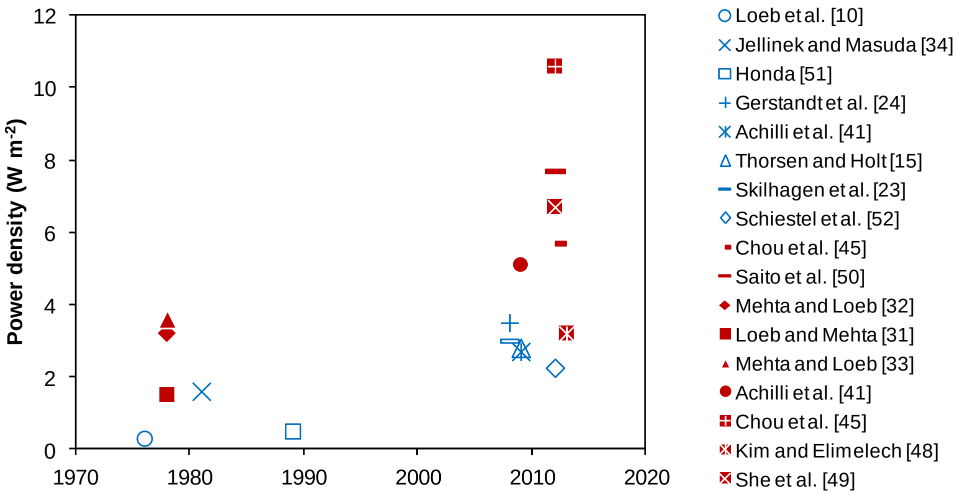


Figure 9. Comparison of existing experimental PRO power density results. The unfilled, blue symbols represent the maximum power densities achieved using draw solutions with concentrations similar to sea water, and the filled, red symbols represent the maximum power densities achieved using draw solutions with concentrations higher than sea water. Figure updated from Ref. [53].

Table 3 shows water fluxes and respective projected power densities obtained from recent laboratory experiments using different membranes and sea water as the draw solution. The bottom section of the table refers to modeled results, using parameters obtained for modified thin-film composite membranes presented by Yip et al. [18] and Eq. 7 and Eq. 8. It can be observed that under laboratory conditions, water fluxes up to 32 L m^{-2} h^{-1} have been reported, which translates to a power density of 5.7 W m^{-2}. This refers to a modified thin-film composite membrane with a thinner support layer and higher water permeability and salt rejection as compared to conventional thin-film RO membranes. As seen from the modeled results (last section of Table 3), power performances of up to 9.2 W m^{-2} could be achieved with a membrane with high water permeability of the active layer combined with a moderate salt permeability and high salt rejection of the support layer [18]. Table 4 shows water fluxes and respective power densities obtained under laboratory conditions for various membranes using draw solutions with salt concentration higher than sea water, and either fresh water, brackish water or sea water as the feed solution. The last section of the table refers to modelled results with parameters for an existing thin-film composite membrane.

Table 3. Summary of recent experimental results using combinations of solutions representing either fresh water *vs* sea water or brackish water *vs* sea water PRO schemes

	Feed solution	Operating pressure (bar)	Water flux ($Lm^{-2}h^{-1}$)	Power density (Wm^{-2})	Membrane type	Source
Experimental results	River water (< 0.06% NaCl)	11-15	4.8	1.0	Modified thin-film composite membrane for PRO	Gerstandt et al. [24], Skilhagen et al. [23], Skilhagen [29]
	River water (< 0.06% NaCl)	5.0	32.0	5.7	Customized TFC hollow fiber membrane for PRO	Wang et al. [54], Chou et al. [45]
	Waste water (≈ 0.2% NaCl)	8.9	22.7	5.6	Customized TFC hollow fiber membrane for PRO	Wang et al. [54], Chou et al. [45]
	Waste water (≈ 0.5% NaCl)	8.9	16.7	4.1	Customized TFC hollow fiber membrane for PRO	Wang et al. [54], Chou et al. [45]
	DI water (0.0% NaCl)	9.7	10	2.7	Commercial flat sheet cellulose triacetate FO membrane from HTI	Achilli et al. [41]
	Brackish water (≈ 0.25% NaCl)	9.7	9.0	2.4	Commercial flat sheet cellulose triacetate FO membrane from HTI	Achilli et al. [41]
	Brackish water (≈ 0.5% NaCl)	9.7	8.2	2.2	Commercial flat sheet cellulose triacetate FO membrane from HTI	Achilli et al. [41]
	Fresh water (< 0.06% NaCl)	12	1.03	0.35	RO Aromatic Polyamide hollow fiber membrane	Loeb et al. [10]
	Fresh water (< 0.06% NaCl)	8	10	2.25	Improved flat sheet cellulose triacetate membrane	Schiestel et al.[52]
	Fresh water (< 0.06% NaCl)	N/A	N/A	1.3	Modified cellulose acetate membrane	Gerstandt et al.[24]
	Fresh water (< 0.06% NaCl)	N/A	N/A	3.5	Modified thin-film composite membrane	Gerstandt et al.[24]
	Fresh water (< 0.06% NaCl)	7	8.2	1.6	Commercial cellulose acetate membrane from Osmonics	Thorsen and Holt [15]
	Fresh water (< 0.06% NaCl)	12	8.1	2.7	Thin-film composite membrane from GKSS, Germany	Thorsen and Holt [15]
	Fresh water (< 0.06% NaCl)	9	5	1.2	Commercial asymmetric cellulose acetate membrane	She et al. [49]
Modelled results	River water (< 0.06% NaCl)	9.6	74	7.4	Modified thin-film composite membranes, with $A = 7.7\ L\ m^{-2}\ h^{-1}\ bar^{-1}$, $B = 7.7\ L\ m^{-2}\ h^{-1}$ and $S = 350\ \mu m$	Efraty [55]
	River water (< 0.06% NaCl)	12.5	16.7	5.8[a]	Modified thin-film composite membranes, with $A = 1.6\ L\ m^{-2}\ h^{-1}\ bar^{-1}$, $B = 0.1\ L\ m^{-2}\ h^{-1}$ and $S = 349\ \mu m$	Yip et al. [18]
	River water (< 0.06% NaCl)	12.5	26.5	9.2[b]	Modified thin-film composite membranes, with $A = 4.4\ L\ m^{-2}\ h^{-1}\ bar^{-1}$, $B = 0.76\ L\ m^{-2}\ h^{-1}$ and $S = 340\ \mu m$	Yip et al. [18]
	River water (< 0.06% NaCl)	9.7	23	6.2[c]	Modified thin-film composite membranes, with $A = 7.6\ L\ m^{-2}\ h^{-1}\ bar^{-1}$, $B = 4.5\ L\ m^{-2}\ h^{-1}$ and $S = 360\ \mu m$	Yip et al. [18]
	Brackish water (≈ 0.25% NaCl)	12.5	14.4	5.0[a]	Modified thin-film composite membranes, with $A = 1.6\ L\ m^{-2}\ h^{-1}\ bar^{-1}$, $B = 0.1\ L\ m^{-2}\ h^{-1}$ and $S = 349\ \mu m$	Yip et al. [18]
	Brackish water (≈ 0.25% NaCl)	12.5	21	7.3[b]	Modified thin-film composite membranes, with $A = 4.4\ L\ m^{-2}\ h^{-1}\ bar^{-1}$, $B = 0.76\ L\ m^{-2}\ h^{-1}$ and $S = 340\ \mu m$	Yip et al. [18]
	Brackish water (≈ 0.25% NaCl)	9.7	19.3	5.2[c]	Modified thin-film composite membranes, with $A = 7.6\ L\ m^{-2}\ h^{-1}\ bar^{-1}$, $B = 4.5\ L\ m^{-2}\ h^{-1}$ and $S = 360\ \mu m$	Yip et al. [18]

[a] – average of three types of membranes with lower water and salt permeabilities subjected to no treatment

[b] - average of three types of membranes with medium water and salt permeabilities subjected to treatment

[c] - average of three types of membranes with high water and salt permeabilities subjected to treatment

Table 4. Summary of experimental results using NaCl concentrations > 6% as draw solution

	PRO scheme (feed solution *vs* draw solution)	Operating pressure (bar)	Water flux ($Lm^{-2}h^{-1}$)	Power density (Wm^{-2})	Membrane type	Source
Experimental results	River water (< 0.06% NaCl) *vs* seawater brine (≈ 6% NaCl)	8.4	47.2	11	Customized TFC hollow fiber membrane for PRO	Wang et al. [54], Chou et al. [45])
	Waste water brine (0.23% NaCl) *vs* seawater brine (≈ 6% NaCl)	9	42.5	10.6	Customized TFC hollow fiber membrane for PRO	Wang et al. [54], Chou et al. [45]
	Concentrated waste water brine (≈ 0.5% NaCl) *vs* seawater brine (≈ 6% NaCl)	9.1	33.3	8.4	Customized TFC hollow fiber membrane for PRO	Wang et al. [54], Chou et al. [45]
	DI water (0.0% NaCl) *vs* 6% NaCl solution	9.7	19.0	5.1	Commercial flat sheet cellulose triacetate FO membrane from HTI	Achilli et al. [41]
	Brackish water (≈ 0.25% NaCl) *vs* seawater brine (≈ 6% NaCl)	9.7	16.2	≈ 4.0	Commercial flat sheet cellulose triacetate FO membrane from HTI	Achilli et al. [41]
	Brackish water - concentrated (≈ 0.5% NaCl) *vs* seawater brine (≈ 6% NaCl)	9.7	16.2	≈ 4.0	Commercial flat sheet cellulose triacetate FO membrane from HTI	Achilli et al. [41]
	Waste water (≈ 0.06% NaCl) *vs* RO brine (6-7% NaCl)	25	N/A	7.7	Commercial hollow fiber modules from Toyobo Co. Ltd.	Saito et al. [50]
	Water (< 0.06% NaCl) *vs* 12% NaCl solution	19.2	2.92	1.6	FRL composite membrane	Loeb and Mehta [31]
	Water (< 0.06% NaCl) with 0.2% formaldehyde *vs* 10% NaCl solution	40.5	2.92	3.3	RO Aromatic polyamide hollow fiber membrane	Mehta and Loeb [33]
	Water (< 0.06% NaCl) *vs* 10% NaCl solution	40.5	2.92	3.10	RO Aromatic polyamide hollow fiber membrane	Mehta and Loeb [32]
	3% NaCl solution *vs* 6% NaCl solution	9.30	2.83	0.73	Commercial flat-sheet cellulose triacetate FO membrane from HTI	Kim and Elimelech [48]
	3% NaCl solution *vs* 10% NaCl solution	12.6	5.91	2.1	Commercial flat-sheet cellulose triacetate FO membrane from HTI	Kim and Elimelech [48]
	3% NaCl solution *vs* 12% NaCl solution	12.6	9.23	3.2	Commercial flat-sheet cellulose triacetate FO membrane from HTI	Kim and Elimelech [48]
	Water (< 0.06% NaCl) *vs* 6% NaCl solution	13	11	3.8	Commercial asymmetric cellulose acetate membrane from HTI	She et al. [49]
	Water (< 0.06% NaCl) *vs* 12% NaCl solution	13	19.0	6.7	Commercial asymmetric cellulose acetate membrane from HTI	She et al. [49]
Modelled results	River water (< 0.06% NaCl) *vs* brine from ocean RO (7% NaCl)	19.4	149	30.6	Thin-film composite membranes, with A = 7.7 L m^{-2} h^{-1} bar^{-1}, B = 7.7 L m^{-2} h^{-1} and S = 350 μm	Efraty [55]
	River water (< 0.06% NaCl) *vs* Mediterranean sea (4% NaCl)	11	84	9.8	Thin-film composite membranes, with A = 7.7 L m^{-2} h^{-1} bar^{-1}, B = 7.7 L m^{-2} h^{-1} and S = 350 μm	Efraty [55]
	River water (< 0.06% NaCl) *vs* Great Salt Lake (24% NaCl)	67.2	518	367	Thin film composite membranes, with A = 7.7 L m^{-2} h^{-1} bar^{-1}, B = 7.7 L m^{-2} h^{-1} and S = 350 μm	Efraty [55]
	River water (< 0.06% NaCl) *vs* hypersaline domains such as Lake Van (Turkey), Lake Eyre (Australia), Lake Urmia (Iran), 33% NaCl	92.5	712	696	Thin film composite membranes, with A = 7.7 L m^{-2} h^{-1} bar^{-1}, B = 7.7 L m^{-2} h^{-1} and S = 350 μm	Efraty [55]

As shown in Table 4, for a scheme based on fresh water and brine at 6% NaCl, the maximum recorded water flux using a modified thin-film composite membrane has been 47.2 L m^{-2} h^{-1}, corresponding to a power output of 11 W m^{-2} [45, 54]. It is interesting to note that in 1976-1978 (refer to references 31, 32 and 33 in Table 4), power outputs for similar osmotic pressure differentials were all below 3.1 W m^{-2}. This again demonstrates the advances of research and development towards improved membranes for osmotic power.

Within the context exposed, it is also important to mention the experiments with ammonium salt solutions carried out by McCutcheon et al. [36], and McGinnis et al. [38]. McCutcheon et al. [36] tested the flux of water through cellulose triacetate membranes under FO conditions subjected to high osmotic pressure differentials created by various solutions of ammonium salts. Driving forces up to 250 bar were tested. The water flux through the membrane was observed to increase with the increase of the osmotic pressure differential. However, while theoretical results showed that increases in osmotic pressure differential would lead to proportional increases in water flux, this proportionality was not observed in practice. For instance, when increasing the osmotic pressure differential by five times, the water flux was only increased by three times. Water fluxes through the membrane reached 36 L m^{-2} h^{-1} for an osmotic pressure differential of 250 bar, representing only 7% of the theoretical (potential) flux. It was concluded that draw solutions with high salinities severely increased concentration polarization – particularly internal concentration polarization - which is the reason why the flux was significantly affected. Similarly, McGinnis et al. [38] tested the flux of deionized water through a FO membrane under PRO conditions using a range of draw solution concentrations made of ammonium salts. A maximum water flux of 90 L m^{-2} h^{-1} was recorded for a driving force of 250 bar, representing only around 18% of the maximum theoretical flux. As internal concentration polarization was minimized due to the use of deionized water, the low performance was attributed to external concentration polarization caused by dilution of the draw solution at the membrane surface on the permeate side of the membrane. Nevertheless, the power output projected from the recorded water flux could be in excess of 250 W m^{-2}, which is quite high compared to the power densities expected for river *vs* seawater salinity PRO power plants.

5.3. Research and development trends in PRO membranes

As discussed above, in order to increase water flux and consequently power density, membranes with the combination of higher permeability, low salt permeability in the skin layer and a high rate of salt diffusion in the porous substrate have to be developed. Also, PRO membranes should be hardy enough to withstand the constant pressure of water flowing through them. When compared to RO membranes, PRO membranes should have a much thinner porous support layer to minimize internal salt build-up [22].

Finding an appropriate membrane for PRO means finding an optimum combination of the membrane properties: *A*, *B* and *S*. According to Yip and Elimelech [40], a membrane designed for maximum power output would have to preferably possess a balance between parameters *A* and *B* (active layer properties) as shown in Figure 10. The magnitude of this combination, however, is constrained by the support layer parameter *S* [40]. The lower the *S* value, the maximum the power output for a given combination of *A* and *B*. For thin-film polyamide composite membranes commercially available for RO, typical values of *S* are about 10,000 μm (which means a very dense support layer), but values down to 100 μm have been reported in the literature [40], which is encouraging information for PRO membrane developers. For the desired power output of 5 W m^{-2}, a membrane with an *S* value lower than 1,000 μm would be preferred.

At this point in time, research has proven that existing membranes can be improved in terms of the parameters *A*, *B* and *S*, allowing for higher water fluxes and consequently, for higher osmotic power outputs. Modeling studies have found that peak power densities of around 9 W m^{-2} could be achieved in a fresh water *vs* sea water PRO scheme if membranes of medium water and salt permeabilities, and with a thin, porous, resistant support layer, could be fabricated [18, 40]. As discussed earlier, a minimum power density of 5 W m^{-2} has been demonstrated to be ideal for a fresh water *vs* sea water PRO system to be profitable after a n^{th}-of-a-kind large-scale plant has been established [23, 29, 30]. Below this power output, the cost of membrane installation would not justify the construction of a power plant. If a scheme combining river water and concentrated brine from RO desalination (NaCl concentration ≈ 6-7%) was considered, modeling results have estimated that power outputs of around 30 W m^{-2} could be reached with an improved membrane [41, 55]. What is more, according to the modeling results presented by Efraty [55], a thin-film composite membrane, with *A* = 7.7 L

m^{-2} h^{-1} bar^{-1}, $B = 7.7$ L m^{-2} h^{-1} and $S = 350$ μm, would yield a power output of 697 W m^{-2} for a scheme combining sea water (feed) and hyper concentrated water from salty lakes.

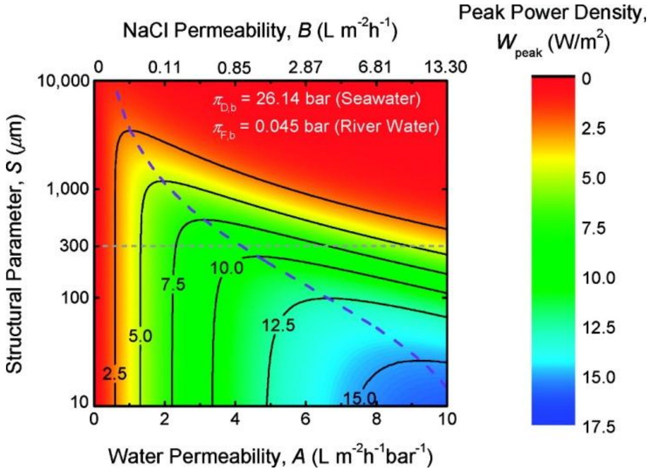


Figure 10. Maximum power density (W_{peak}) as a function of the membrane parameters A, B and S. The dotted horizontal line represents a structural parameter S of 300 μm. The diagonal violet line represents the optimal active layer properties to achieve peak power density for the specific structural parameter. The mass transfer coefficient in the draw solution side boundary layer was set as $k = 38.5$ μm s^{-1}. Simulations were for a fresh water *vs* sea water scheme. Figure retrieved from Ref. [40].

It follows, therefore, that the main reason for the low inefficiency of the currently available membranes is simply the fact that they have not been designed for the purpose of osmotic power production. Also, as the initial results on PRO were based on RO or FO membrane experiments, the real potential of osmotic power production via PRO has yet to be demonstrated.

It is also important to point out that, in addition to the development of better membranes, there is also significant progress to be made regarding the design and development of membrane modules. As described in the literature [29, 56, 57], standard spiral wound module designs have severe limitations in relation to the internal flow pattern and pressure losses, and are not adequate for scaling up to larger units due to their low membrane area. Since an osmotic power plant will require several million square meters of membrane, the membrane modules should contain several hundreds or even thousands of square meters [29]. In this respect, the authors have set several design criteria for new membrane elements. These include that the elements should have the ability to convey flow on both sides of the membrane, should possess a much larger membrane area and should be much less susceptible to membrane fouling compared with the current membrane modules.

With the opening of the first osmotic power prototype plant in 2009, which proved that the concept of PRO can indeed be used for power generation, research institutions such as Yale University (Connecticut, USA), the Singapore Membrane Technology Centre at the Nanyang Technological University and the University of Nevada (USA) have come forward to help find a suitable membrane for use in a real osmotic power plant and have been making major contributions in the field, from PRO modeling to PRO membrane development. Private initiative has also been a driving force in PRO development. Hydration Technology Innovations (HTI), Arizona USA, for example, is planning to supply membranes for PRO in the near future [58]. HTI FO membranes have been tested widely for power generation [e.g., 22, 36, 38], although a desired power density has not yet been achieved. Recently, Statkraft signed an agreement with the Japanese company Nitto Denko/Hydranautics for the development and supply of membranes for PRO [56, 59, 60]. According to Nitto Denko/Hydranautics, the development of more efficient membranes will contribute to making PRO competitive with other new, renewable energy sources and will bring osmotic power further towards future commercialization [56]. Even more recently, Statkraft and Hydro-Québec (Canadian government-owned public utility for generation, transmission and distribution of electricity) entered a collaboration agreement to study mechanisms of pre-treatment of fresh water in an osmotic power plant [61]. The Canadian company has identified 12 GW of osmotic power potential along the Hudson Bay, James Bay and St Lawrence estuary that could add 25% to its current power generation capacity [59]. Other companies involved in the development of membranes for RO, such as General Electric, the Dow Chemical Co., Toray Industries and Koch Membrane Systems, are also likely to be involved in the development of membranes for PRO in the near future [58].

Membranes for use in sea water *vs* hypersaline water schemes will probably come after the development of membranes for fresh water *vs* sea water systems, as the former will have much more severe concentration polarization problems, as well as requiring more resistance to withstand the higher operating pressures. According to Achilli et al. [41], a sea water *vs* hypersaline water scheme would require a membrane with a tenth of the thickness of the current membranes, water permeability of a nanofiltration membrane and extremely low salt permeability to overcome the issues with concentration polarization and reverse flux of salt.

Moreover, according to She et al. [49], and Kim and Elimelech [48], maximum water fluxes and projected optimum power densities for sea water *vs* hypersaline water schemes are difficult to obtain in laboratory conditions with commercially available membranes due to their inability to withstand high pressures. For instance, a pressure of approximately 13 bar was reported to be the maximum supported by a cellulose triacetate membrane [49]. Beyond this value, the applied pressure would cause deformation of the membrane, with consequent blockage of the feed channels. In this sense, one may be tempted to consider RO membranes for this purpose, but these membranes, albeit resistant to high pressures, would perform poorly in PRO conditions due to their high susceptibility to concentration polarization.

Noticeably, all these problems are more easily overcome in fresh water *vs* sea water schemes. Nevertheless, if appropriate membranes were available for PRO systems using draw solutions with concentrations higher than sea water, it would be clear that the production of osmotic power would become more attractive than the production of osmotic power from the traditional pairing of fresh water and sea water, as the power output per unit membrane would be fourfold. This is supported by the fact that using high concentration solutions, for example sea water *vs* hypersaline water from salt lakes, would not affect our fresh water resources, as opposed to a river water *vs* sea water scheme. Also, the power production would not be limited by the availability of feed solution because sea water is plentiful and practically unlimited. This is in contrast to a fresh water *vs* sea water system which would require large volumes of fresh water which cannot always be relied upon, particularly in areas with high water demands, where the resource has to be shared with other water users, some of them with higher priority than power production. Nonetheless, should the fresh water be in ready and regular supply and in sufficient quantity, the situation would presumably be different. It is important to note that in general, availability of fresh water is more limited by average river discharge than by competition for drinking water or irrigation.

MIK Technology, from Texas, USA, has identified numerous hypersaline domains that could be used in combination with sea water to produce power under PRO conditions [62-67]. Loeb [5] had already suggested that hypersaline lakes, such as the Dead Sea and the Great Salt Lake, could be used as sources of draw solution for osmotic power generation if membranes for this purpose could be manufactured. Based on the osmotic pressure differential of the proposed domains (summarized in Table 5), it is unquestionable that these are potential sources of this new type of renewable energy. Several white papers have been written by

MIK Technology detailing the pumping and pipe systems, the potential for osmotic power production at different sites, the environmental and other aspects, in the search for investors for the business [62-67]. However, the mechanism for harnessing the potential energy (and this includes, of course, the membranes) has not been revealed by the author and one could argue about the technical viability of these projects, at least within the next few years. Nevertheless, it is important that these sites have been already identified and once the technology becomes available, that some of those projects can be implemented.

Table 5. Potential hypersaline domains for osmotic power production

Salt water source[1]	Salt (%)[1]	Conjugate low salinity water[1]	Salt (%)[1]	Approximate osmotic pressure difference – $\Delta\pi$ (bar)[1]	Power (MW)[1,2]	Electricity supply (thousands of households)[3]
Great Salt Lake, USA	24	Bear, Weber or Jordan Rivers	< 0.1	200	400	300
Lake Torrens, Australia, Phase I	32	Indian Ocean	3.5	240	2,000	1,770
Lake Torrens, Australia, Phase II	32	Indian Ocean	3.5	240	4,000	3,500
Lake Eyre, Australia	33	Indian Ocean	3.5	245	3,300	2,900
Lake Gairdner, Australia	Salt bed	Indian Ocean	3.5	N/A	1,500	1,300
Sebjet Tah, Western Sahara	Lowland	Atlantic Ocean	3.5	N/A	400	4,000
Lake Assal, Djibouti	35	Ghoubbet al-Kharab Hot Springs	3.5	270	200	6,250
The Aral Sea, Kazakhstan	30	The Caspian Sea	0.1-0.12	250	16,000	26,000
Zaliv Kara-Bogaz-Gol, Turkmenistan	33	The Caspian Sea	1.0-1.5	270	4,500	15,000
Lake Baskunchak, Russia	30	The Volga River / Caspian Sea	0.1-0.12	250	40	60
Chott el Jerid, Tunisia	32	The Mediterranean	3.5	240	3,000	2,000
Chott Melrhir, Algeria	Salt bed	The Mediterranean	3.5	N/A	3,000	3,000
Qattara Depression, Egypt	Lowland	The Mediterranean	3.5	N/A	3,000	3,000
Lake Urmia, Iran	33	Zarrineh & Simineh / Caspian Sea	< 0.1	280	800-1,400	2,500-4,400
Lake Tuz, Turkey	33	Kizil Irmak River	< 0.1	280	400	1,600
Arabian Peninsula	Lowland	Red Sea, Persian Gulf	0.45	N/A	Varies	Varies
The Dead Sea, Israel/Jordan	33	The Mediterranean / The Red Sea	3.5/4.5	240	60-200	200-650
Gran Bajo de San Julian	33	Atlantic Ocean – Argentina shore	3.5	245	Pending	-
Laguna Salgada, Mexico	Salt bed	Gulf of California	3.5/4.5	N/A	500	2,600

[1] Information compiled from Ref. [62, 64, 65]
[2] Calculation method described in Ref. [66]
[3] The number of supplied households was calculated using the average electricity consumption per capita in each country [20]

6. The existing PRO pilot power plant

Until 2009, PRO studies had only been conducted in laboratory scale and no one had tested the feasibility of the technology in real scale. In 2009, the first osmotic power plant prototype based on the PRO technology was finally opened in Tofte, Norway. The plant prototype belongs to Statkraft and was built driven by the encouraging results demonstrated by ‘The Osmotic Power Project’ (2001-2004), funded by the European Union and conducted by a joint effort of Statkraft, ICTPOL of Portugal, SINTEF of Norway, GKSS-Forschungszentrum of Germany, and the Helsinki University of Technology of Finland [68]. As mentioned previously, membrane developer Nitto Denko/Hydranautics has recently signed an agreement with Statkraft to develop and supply membranes designed specifically for PRO [56, 59, 60]. One of the main objectives of this collaboration is to develop membranes that have a production capacity equivalent to the break-even point of 5 W m^{-2} [23, 24, 29, 56, 69, 70]. Statkraft will also construct a pilot facility in Sunndalsøra, Norway, in the coming years with an installed power capacity of 2 MW [71, 72]. In 2012, Japan also started to carry out research on osmotic power production using a plant prototype built in Fukuoka City [50], but limited results have been published so far. The prototype and related research is a partnership between Kyowakiden Industry Co. (a Japanese industrial infrastructure, maintenance and operation provider), Tokyo Institute of Technology and the Nagasaki University [59].

The prototype built in Norway is equipped with 2,000 m^2 of membranes, and is reported by Statkraft to have a membrane output of 1 W m^{-2} [73], meaning an overall output capacity of 2 kW. With the development of improved membranes (i.e., power output of at least 5 W m^{-2}) the same prototype will be able to generate 10 kW. A general sketch of the power plant is shown in Figure 1. The plant works essentially similar to a saltwater RO desalination plant running backwards. The river water enters the plant at low pressure, passes through a mechanical filtration system to remove impurities and enters the permeator. Concurrently, sea water is pumped into the plant, filtered and pressurized with the aid of a pressure exchanger before entering the permeator. Due to the osmotic pressure differential between the fresh water and the sea water in the permeator, the fresh water permeates the membranes, increasing the volume of water in the pressurized pipe system. Part of this pressurized flow is diverted into a turbine to generate power and part is diverted to the pressure exchanger to add pressure to the incoming sea water. The prototype is described to utilize 20 L s^{-1} of sea water and 13 L s^{-1} of freshwater [57, 74].

The first generation of PRO membranes (2009-2010) in the prototype, as described by Statkraft [29, 73], was based on conventional flat sheet cellulose acetate membranes in spiral wound elements, but their performances were reported to be only about 0.5 W m^{-2} [56, 73]. The second and current generation of membranes is based on RO spiral wound thin-film composite membrane elements [73]. The power performance of these membranes has been demonstrated in laboratory conditions to be around 2.7-3.0 W m^{-2} under modified conditions of the porous structure (support layer) [15, 29]. The most recent reference is that Statkraft's plant has been able to actually produce 1 W m^{-2} with this type of membrane [73]. As seen previously, the main problem with RO membranes is the high susceptibility to membrane concentration polarization as a result of their dense support layer structure. While this structure is necessary in RO to withstand the high operating pressures, it is undesirable in PRO as the salt concentration in the layer substantially reduces the osmotic pressure gradient, reducing the flux of fresh water through the membrane.

Crucial for the power performance and reduction of membrane fouling in the prototype is the pre-treatment of the incoming fresh water, which according to Statkraft [75] is based on mechanical filtration. Rivers usually contain significant amounts of organic matter and silt with contents that may vary considerably during the seasons. In Statkraft's power plant, the pre-treatment system for the river water is comprised of a 50-μm pore size filter and a cellulose acetate UF plant, similar to what is used for river water treatment [75]. The sea water, in turn, is supplied through water pipes from approximately 35 meters below sea level [74], with a pre-treatment based solely on a 50-μm pore size filter [75]. As the volume of incoming sea water significantly exceeds the volume of fresh water, it has been very important to demonstrate that it is possible to operate the plant with minimal pre-treatment of the sea water [75]. Also, the plant has been showing that mechanical filtration in combination with a standard cleaning and maintenance cycle of the membranes is enough to sustain the membrane performance for 7 – 10 years [76]. Also important for the efficiency of the system is the use of pressure exchangers [26-28, 76]. Pressure exchangers or energy recovery devices have been extensively used in desalination plants to reuse the pressure that would be wasted under normal conditions. These devices have been proved to save around 60% of the energy input in these systems [58].

The current membrane power output of the Statkraft prototype is still very far from the target of 5 W m^{-2}. With an output of only 1 W m^{-2}, a commercial power plant would have to rely on a large area of membranes, increasing capital, maintenance and operating costs, and making the business financially unviable. For instance, the total membrane area for a 2 MW and a 20 MW power plants would have to be 2 km^2 and 20 km^2, respectively. With 2,000 m^2 of membranes, the Statkraft power plant prototype has been able to produce a minor output power of 2 kW, which is just enough to operate an electric kettle [77]. However, the project has been vital as it is proving that the PRO technology works and osmosis can indeed produce electricity. Moreover, the plant has been establishing the necessary theoretical and practical know-how at a pre-engineering level for the future commercialization of the technology [76].

7. Environmental impacts of osmotic power

Overall, osmotic power with PRO is claimed to have very limited to non-existent environmental impacts in comparison to current power production methods [e.g., 26, 29, 56, 69]. This is mainly attributable to emission-free energy production and to the fact that the brackish water discharged from the plant would mimic the natural discharge of a river into the ocean [78]. The water from the river diverted into the plant would not be consumed, but only cycled through the plant [58]. However, as PRO is still an immature technology, it should be recognized that a large research gap persists regarding its actual environmental impacts, and that any application of PRO on a large scale would require thorough study to quantify the actual impacts on the local receiving environment.

Following the example of the Statkraft plant, the river water for an ordinary osmotic power plant would be deviated before the point of its natural discharge into the ocean. At the same time, sea water would be diverted from a deep and distant location offshore. The two fluids (river and sea waters) would be mixed during the power production process, generating brackish water which, after running through the plant, would be discharged near the river mouth, as shown in Figure 11. As a result of these deviations and discharge, some environmental impacts may arise.

Walday et al. [79], and Staalstrom and Gitmark [74] have warned about three main potential impacts of the discharge of brackish water from osmotic power plants using river and sea water as incoming solutions. The first impact is related to the release of brackish water in superficial layers of the ocean. At the Statkraft plant, sea water is pumped up from 35 meters, run through the plant, and released at the surface of the ocean. As is well known, nutrient concentration is usually greater in deep waters compared with shallow waters. As such, this discharge would release nutrients at the surface layer, and subsequently lead to local eutrophication. Kleverud [57] has reported that eutrophication effects, particularly due to the addition of phosphates, will be the main concern in up-scaled osmotic power plants. After three years of monitoring and investigation, water samples from the saltwater intake of the prototype indicate that the phosphorous concentration is often higher at 35 m depth than in the euphotic layer, which suggests that there will be a net supply of phosphorous to this layer under a large scale PRO process, an issue that requires further investigation.

The second issue proposed by Walday et al. [79], and Staalstrom and Gitmark [74] is temperature changes in the surface water due to the brackish water discharge. The temperature of deep waters is usually more stable than shallow waters. As a consequence, the brackish water discharge would be warmer than the ambient water in winter and relatively colder in summer. This may lead to changes in the local aquatic ecosystems, which warrants further research.

The third potential issue is from the chemical cleaning of the membranes. The cleaning agents used in PRO are usually similar to those utilized in the desalination and water treatment industries [23, 76]. While these chemicals do not usually accumulate in the environment, there is a potential danger of local toxic effects if concentrations exceed acceptable limits [74, 80]. On the positive side however, at the Statkraft plant, biological investigations have shown no impacts of the discharge water on the local benthic communities in the last three years [57, 79].

In addition to nutrients, temperature and chemicals, regular discharges of brackish water may also alter the local aquatic environment due to salinity changes [74, 81]. Recent monitoring of salinity near the discharge point of the Norwegian power plant prototype has shown that the discharge of brackish water is usually responsible for an increase in surface salinity as a result of the high salinity levels of the deep sea water that is diverted into the plant [74]. While an important finding, this cannot be fully generalized to other plants and locations, as the salinities of deep sea waters could be greatly affected by local winds and currents. As such, salinity reductions, rather than increases, may sometimes occur in deep sea water, resulting in an opposite effect. While some variation in salinity is normal, high fluctuations may result in severe changes in the communities of animals and plants if some species cannot tolerate the salinity change. This could further result in imbalances in the local ecosystem. Fernandez-Torquemada et al. [82], for example, have shown that the discharge of brine from RO desalination plants is diluted at much lower rates than usually accepted levels, affecting marine communities in surrounding areas. It was found that this discharge has severe impacts on important Mediterranean seagrass species and associated organisms [83]. On the other hand, however, other studies on the impacts of the discharge of brine from desalination plants have found no significant variations attributable to brine discharges [e.g., 84, 85]. For PRO plants, one could expect low changes in local salinity as compared with RO desalination plants, owing to the discharge of brackish water rather than brine. Nevertheless, given the level of uncertainty in the field, the impacts of the salinity change should always be quantified for new PRO establishments, as each location will have its own influencing factors on salinity, as well as species with different responses to salinity changes. Overall, salinity, temperature and nutrient changes and, to some extent, chemical effects may be avoided by positioning the outlet plume below the euphotic zone [57, 79].

The deviation of fresh water from a river to feed an osmotic power plant is also of great concern to the natural environment surrounding a PRO plant. At large scale, an osmotic power plant would rely on great quantities of fresh water. A full scale plant will possibly have a fresh water volume flux greater than 10 m^3 s^{-1} [74]. Assuming a power production of 0.75 MW per m^3 s^{-1} of incoming fresh water, and osmotic power facilities of 2 MW and 20 MW capacities – which are typical outputs of power plants based on renewable sources – these facilities would have to pump in freshwater at rates of 2.7 m^3 s^{-1} and 26.7 m^3 s^{-1} respectively, which are considerably high amounts of fresh water. For comparison, the River Thames in London, England, and the Rio Grande River, in the US, each have an average discharge of approximately 65 m^3 s^{-1}, and the Yarra River in Melbourne, Australia, has an average discharge of 37 m^3 s^{-1}. Under such large freshwater intakes, osmotic power plant developers must ensure that the rivers retain the minimum flow required downstream of the deviation point. In some cases, it may be even necessary to change the hydraulic system and water management rules, because of the substantial amount of water needed [86]. In addition, other interests of the water bodies used in the PRO system, such as navigation and recreation, as well as infrastructural works should be taken into account [86].

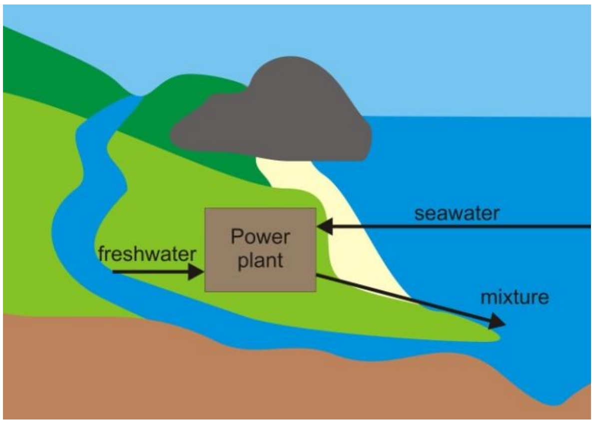


Figure 11. Inlet and outlet locations of a typical osmotic power plant that uses river water and sea water. The project should comply with the ecological flow (minimum flow) requirement between the inlet of fresh water and the outlet of the mixture.

Intuitively, if an osmotic power plant was paired with a desalination plant as suggested in the literature [7, 8], this could help reduce the potential environmental impacts of the disposal of brine from the desalination process. In a conventional desalination plant, brine is generated and disposed of into the sea. For some locations, this disposal has been shown to have adverse effects on the local aquatic environment [e.g., 82, 83]. If the brine could be used as a draw solution for an osmotic power plant rather than being immediately disposed of, it would be diluted by the permeated fresh water prior to its disposal, and the impacts of the discharge would be significantly reduced. Moreover, osmotic power, for its zero carbon-dioxide footprint, would indirectly reduce the environmental impact of the desalination process by reducing its reliance on fossil fuel consumption [8] and consequently, diminish the discharge of greenhouse gases into the atmosphere.

Other impacts from osmotic power plants could be associated with the building of the facilities, access roads, channels and connections to the electricity grid [29]. It should be noted, however, that osmotic power plants are usually described as requiring a relatively small footprint area. For instance, a facility with a power production capacity of 25 MW would have the size of a football field [87]. Some experts in osmotic power have suggested underground, partially-underground or below sea-level plants to minimize the visual and physical impacts on the local environment [3, 23, 25, 26, 29, 69]. Below sea-level facilities would also increase the efficiency of the power production as the incoming sea water could be pressurized by gravity [25, 26]. Additionally, many authors have suggested that as most of the river mouths have already been occupied by adjacent urban or industrial developments, the majority of the osmotic power plants could be established without damaging unspoiled areas, such as river deltas or protected areas [26, 69]. These authors further argue that in developed areas the estuaries have already been affected by the anthropic occupation. As such, under a controlled and careful design and building of an osmotic power plant, the present environmental conditions of the river, the estuary and the sea could even be enhanced [69].

Some more ambitious and far-reaching osmotic power projects which are based on sea water and concentrated saline water from salt lakes [e.g., 63, 65, 88, 89] would probably involve many more risks to the environment. Most of these projects would require the construction of long seawater canals, to transport the sea water into the salt lakes and into the plants since salt lakes are not always located close to the ocean. In Australia, for example, if Lake Eyre or Lake Torrens were to be used as sites for osmotic power production, a 350-km canal would have to be built for seawater transport [65].

An alternative method of producing osmotic power with minimum environmental impact would be the use of subterranean brine near a source of fresh water or sea water. As an example, Wick [21] suggests several salt domes in the northern Gulf of Mexico, from which osmotic power could be produced at a rate of 1,000 MW for approximately 10 years.

8. The economics of PRO

As with some other ocean energy technologies, it is difficult to estimate the cost of osmotic power due to the absence of large-scale plants to validate cost assumptions. The main advantage of PRO in relation to other renewable energy sources lies in its reliable baseload power, which can make the annual energy costs comparable and competitive with other renewables. Under a constant supply of feed and draw solutions, it is anticipated that an osmotic power plant can be designed to operate continuously for more than 8,000 hours annually, yielding a very high power generation capacity for each MW installed [68, 69] and reducing PRO energy costs to an attractive level [15].

Provided a membrane with at least 5 W m^{-2} of power output can be fabricated cheaply, the cost of fresh water *vs* sea water osmotic power will fall between \$0.065 - \$0.13 kWh^{-1} by 2030, making it competitive with other renewables [58]. Moreover, as a renewable energy source with high environmental performance, it is expected that PRO will qualify for subsidy programs and other government incentives similar to those already seen today for wind and solar power. With subsidies included, the osmotic power cost could drop to \$0.05 – \$0.06 kWh^{-1} in 2015 [26].

The most recent publication on osmotic power cost is perhaps that of Skilhagen [56], which gives a levelized cost of energy between \$0.09 kWh^{-1} and \$0.11 kWh^{-1} projected for a nth-of-a-kind large osmotic power plant (i.e., including cost reductions due to technology improvements, economy of scale and learning rates). Of this levelized cost, membranes are projected to account for more than 35%.

It has been demonstrated by Kleiterp [90] that intake and outfall systems, pre-treatment facilities, and membranes all combined would account for 76% of the total installation cost. As pointed out by Loeb [27], capital amortization would amount to more than 60% of the total energy cost. In conventional power-generating plants, as would be expected in PRO power plants, operation and maintenance would be only a small fraction of the total power costs. The main components of the operation and maintenance costs are those related to the pressurization of incoming solutions as well as the filtration required for pre-treatment of the water before it reaches the membrane.

The following sections of this article discuss the two economic metrics of most interest for power generation, namely the cost per installed kW and the cost per kWh of electricity produced, with focus on PRO systems.

10.1. Capital costs

Undoubtedly, commercial osmotic power plants today would incur an extremely high capital cost as they would require a large membrane area to overcome the low power densities produced by the current membranes. For example, assuming a cost per unit area of installed membrane of \$30 [91], the difference between the membrane costs for a 1 W m^{-2}-membrane plant and for a 5 W m^{-2}-membrane plant would be approximately \$500 million for a 20-MW capacity power plant. In addition to membranes, the large capital costs would also be attributable to the pre-treatment facilities, hydroturbines, pumps, pressure exchangers and other devices.

A unit capital cost can be estimated through the following relationship:

$$C_c = \frac{C_m}{W} \tag{9}$$

where C_c is the unit capital cost (\$ kW^{-1}), C_m is the installed membrane cost which includes all equipment costs (\$ m^{-2} of membrane), and W is the power density of the installed membranes (kW m^{-2}).

The unit capital costs as a function of the membrane power outputs for various installed membrane costs are presented in Figure 12. The installed membrane costs were derived from the desalination industry, which use similar technology to osmotic power plants [35].

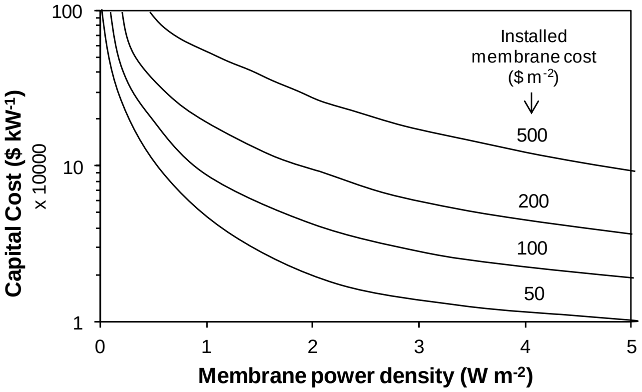


Figure 12. PRO capital costs *vs* membrane power outputs for various installed membrane costs. Figure adapted from Ref. [35].

As seen in Figure 12, the capital cost for a 1 W m^{-2} membrane could vary from \$50,000 kW^{-1}, for an installed membrane cost of \$50 m^{-2}, to \$400,000 kW^{-1}, for an installed membrane cost of \$500 m^{-2}. If a 5 W m^{-2} membrane were available, the capital cost would be reduced to \$10,000 kW^{-1} and \$100,000 kW^{-1} for capital investments of \$50 m^{-2} and \$500 m^{-2}, respectively. A more recent study reported in Harrysson et al. [92] utilized an installed membrane cost of \$60 m^{-2} for a power plant containing at least 2 km^{2} of membrane. For a power density of 5 W m^{-2} this plant would have an installed capacity of 10 MW and a unit capital cost of \$12,000 kW^{-1}, which is significantly lower than the installed membrane costs of \$100 m^{-2} reported in 1981 [35]. An even more recent study reported installed membrane costs for desalination plants ranging from \$20 to \$40 m^{-2} [91]. The lowest value of the range would incur a capital cost of \$4,000 kW^{-1} for a membrane power density of 5 W m^{-2}. For the current achievable power density (1 W m^{-2}, based on the most recent outputs reported by Statkraft), the resulting capital cost is around \$20,000 kW^{-1}. These capital costs are all above those associated with wind power, but some are competitive with solar. The International Renewable Energy Agency reports installation costs of onshore wind farms varying from \$1,700 to \$2,450 kW^{-1}[93], whereas Hinkley et al. [94] reports installation costs for solar power in the order of \$6,800 to \$7,700 kW^{-1}. Therefore, to make osmotic power generation competitive with solar power, a combination of power density of 5 W m^{-2} and a maximum installed membrane cost of \$35 m^{-2} would be required. If power density is lower, for instance 3 W m^{-2}, the installed cost would have to decrease to \$20 m^{-2}.

When compared with other forms of ocean energy, osmotic power costs seem similar to (or even less than) those for other ocean energy sources, such as tidal energy. According to the International Energy Agency, the capital costs of tidal technologies vary between \$7,000 $kW^{-1}$and \$10,000 kW^{-1} [95]. Moreover, Statkraft's current cost estimates also demonstrate that osmotic power generation can be developed to become cost-competitive with bio-power sources [26].

More optimistically, the capital cost for a power plant based on a hypersaline draw solution could be up to 40 times less than that of a seawater draw solution [5]. Therefore, provided technical barriers are overcome (i.e., the development of a membrane able to withstand high pressure differentials), it seems there is more potential for the development of osmotic power based on salinity gradients greater than that of a fresh water *vs* sea water scheme. Loeb [88] studied investment costs for a PRO plant that would use brine from an RO plant as the feed solution, and brine from the Dead Sea as the draw solution. Due to the considerably larger area of membranes required within an osmotic power plant, compared to a typical desalination plant, the author used a scale-up factor that reduced the capital cost per membrane area from \$42 m^{-2} to \$18.6 m^{-2}. With a power output of 4.7 W m^{-2}, which is a reasonable output for this particular salinity differential, the resulting unit capital cost was estimated as \$3,980 kW^{-1}. In the pairing of river water and brine from the Great Salt Lake, Loeb [89] estimated a unit capital cost of \$9,000 kW^{-1}, assuming an installed membrane cost of \$160 m^{-2} and a membrane power density of 17 W m^{-2}.

As pointed out by Loeb [27], capital amortization can amount to more than 60% of total electricity costs. While it is clear that a reduction in capital expenditure would greatly impact on the cost of this technology, it is important to acknowledge there are significant differences between RO (on which PRO cost studies are based) and PRO. A dedicated cost analysis to PRO has been made by Kleiterp [90], who broke down all the costs involved in the PRO process for three hypothetical fresh water *vs* sea water osmotic power plants designed for three locations in the Netherlands. The power plants' capacities were 1 MW, 25 MW and 200 MW, and the assumed membrane power output was 2.4 W m^{-2}. The main new inclusions in this cost analysis study were the costs related to the intake and outfall systems and the pre-treatment of incoming solutions. The objective was to verify whether a levelized cost of energy of \$0.08 kWh^{-1} would ever be possible. The capital costs of a 25 MW and a 200 MW PRO plants were predicted to be around \$32,000 kW^{-1} and \$29,200 kW^{-1}, respectively. These high capital costs were attributed to the inclusion of intake and outfall systems costs, pre-treatment facility costs, land acquisition, power plant building and electrical installations and grid connection costs – which had not been included in the cost analyses from prior studies. The main components of the capital costs were found to be the membranes, intake and outfall systems and the pre-treatment facilities, collectively accounting for 76% of the total installation cost.

10.2. Total energy cost

When studying the costs of producing power from brine generated from desalination plants as feed solution, and brine from the Dead Sea as draw solution, Loeb [88] concluded that power could be generated at a cost of \$0.07 kWh^{-1}. In the pairing of river water and brine from the Great Salt Lake, Loeb [89] estimated a unit energy cost of \$0.09 kWh^{-1}. These unit costs are comparable with the reported costs of \$0.06 - \$0.14 kWh^{-1} for wind power [93] and much below the reported values for solar power (\$0.23 kWh^{-1} [94]).

However, pre-treatment costs were not included in the studies by Loeb [88, 89], and according to Ramon et al. [96] and Kleiterp [90] these would be major contributors to the final production cost. Pre-treatment is necessary for both the feed and draw solutions to avoid membrane fouling and shortening of the membrane lifetime [14, 40, 97, 98].

Achilli and Childress [53] estimated the revenue per unit area of installed membrane and compared it with actual installed membrane costs reported in the literature. At an energy price of \$0.10 kWh^{-1}, a power density of 5 W m^{-2}, and an expected membrane lifetime of five years, the authors estimated a resulting membrane revenue of \$22 m^{-2}. This is at the lowest range of estimated costs of membranes per square meter, \$20 - \$40 m^{-2} [91], demonstrating that the technology is not economically feasible at the current membrane costs and power densities. However, when considering a membrane lifetime of 10 years, membrane revenue could increase to \$40 m^{-2}.

In the study by Kleiterp [90], who analyzed capital and unit energy costs for both 25 and 200 MW osmotic power plants in the Netherlands using a membrane output of 2.4 W m^{-2}, a unit energy cost of \$1.21 kWh^{-1} resulted from the 25 MW osmotic power plant analysis, and \$1.0 kWh^{-1} from the 200 MW plant. These values demonstrate that osmotic power is financially unviable compared to the levelized cost for alternative renewable energy sources.

Kleiterp [90] also analyzed the feasibility of a 1 MW PRO plant integrated with a sewage treatment plant, resulting in a unit energy cost of \$0.25 kWh^{-1}. This was shown to be the most cost-effective configuration for a PRO plant under current technological conditions. The sewage treatment plant would provide the feed solution to the power plant, and the integration of the two plants would allow for a considerable reduction in the costs of pre-filtration, intake and outfall systems.

According to Kleiterp [90], when considering developments in membrane technology – such as an increase in membrane power density to 5 W m^{-2} and a reduction in membrane prices – plus reductions in the capital costs related to the intake and outfall systems (by, for instance, reducing the distance between the fresh and salt water sources), and reductions in costs related to land acquisition, plant building and pre-filtration, the energy production costs for the power plants could be significantly reduced. The unit energy costs could potentially be as low as \$0.12 kWh^{-1} and \$0.07 kWh^{-1} for the 25 and the 200 MW PRO plants, respectively. The unit energy cost of the 1 MW plant integrated into the sewage treatment plant could be reduced to \$0.08 kWh^{-1}. These are all marketable values of the energy unit rate. It should be noted that all modifications to the original design are feasible, provided membrane and pre-treatment technologies are improved [90]. Using a similar approach, Skilhagen [56] predicts that the levelized cost of energy for a demonstration osmotic power plant (25 MW) will settle at \$0.16 kWh^{-1} when factoring in cost reductions due to technology improvements and economy of scale. More encouragingly, the cost could reach \$0.09 kWh^{-1} in 2030 based on a n^{th}-of-a-kind plant, with the accountability of cost reductions as technology manufacturers accumulate experience [56]. The cost predicted by Skilhagen [56] for a demonstration plant ($0.16 kWh^{-1}) is higher than the reported energy costs for wind power by the International Renewable Energy Agency ($0.06 - $0.14 kWh^{-1}) [93], but comparable to wind energy costs reported by other sources such as Tanioka et al. [6] ($0.16 - $0.28 kWh^{-1}) and Syed et al. [99] ($0.11 - $0.22 kWh^{-1}). As for solar power, osmotic power is comparable to the costs reported by Hinkley et al. [94] ($0.23 kWh^{-1}), and more economical than the costs presented by Tanioka et al. [6] ($0.86 kWh^{-1}) and Syed et al. [99] ($0.30 - $0.74 kWh^{-1}). Table 6 summarizes all osmotic power costs found in the literature in terms of the two most important economic metrics – cost per installed kW and total energy cost per KWh.

10.3. Cost trends

Membrane modules are the main component of the capital costs of an osmotic power plant, and if these are to be reduced, a high power density membrane (able to be supplied at a reasonable cost) would be required in the market. Moreover, the improved membrane will have to present a low susceptibility to fouling to increase its lifetime and, consequently, reduce operation and maintenance costs. Unfortunately, at this stage of development, PRO application is still limited by the absence of such an ideal membrane. Therefore, although it must be acknowledged that PRO technology has been significantly improving since the 2000s, osmotic power remains economically unviable with the current membranes.

Encouragingly, however, advancing research for improved membranes indicates that osmotic power will soon become as or more competitive than the current common sources of renewable energy such as wind and solar. Figure 13 shows evidence of the reducing prices of desalination membranes over the years, with the prices including pressure vessels and connections. According to Kleiterp [90], the current average membrane price is $6.6 m^{-2}; but experts have indicated that within a few years it will be possible to produce membranes at a cost price of $2.6 m^{-2} [69]. Installed membrane costs have been reported to vary between $20 to $40 m^{-2} [91].

Table 6. Summary of the capital and total costs of osmotic power reported in the literature

Feed *vs* draw solutions	Assumed membrane power density (W m^{-2})	Assumed installed membrane cost ($ m^{-2})	Capital cost ($ kW^{-1})	Energy cost ($ kWh^{-1})	Source
Fresh water *vs* sea water	1	20	20,000	N/A	Estimated in this study based on relations shown in[35]
Fresh water *vs* sea water	1	40	40,000	N/A	Estimated in this study based on relations shown in[35]
Fresh water *vs* sea water	1	50	50,000	N/A	Lee et al. [35]
Fresh water *vs* sea water	1	500	400,000	N/A	Lee et al. [35]
Fresh water *vs* sea water with development	5	N/A	N/A	0.09-0.16	Skilhagen [56]
Treated sewage *vs* sea water	2.4	15	6,000	0.25	Kleiterp [90]
Fresh water *vs* sea water	2.4	70-77	30,000-32,000	1.00 – 1.21	Kleiterp [90]
Fresh water *vs* sea water	3	20	7,000	N/A	Estimated in this study based on relations shown in[35]
Fresh water *vs* sea water	3	40	13,000	0.18	Dinger et al. [100]
Brine from RO *vs* brine from the Dead Sea	4.7	18.6	4,000	0.07	Loeb [88]
Fresh water *vs* sea water – with development	5	N/A	N/A	0.12 – 0.07	Kleiterp [90]
Treated sewage *vs* sea water – with development	5	N/A	N/A	0.08	Kleiterp [90]
Fresh water *vs* sea water	5	20	4,000	N/A	Estimated in this study based on relations shown in[35]
Fresh water *vs* sea water	5	35	7,000	N/A	Estimated in this study based on relations shown in[35]
Fresh water *vs* sea water	5	40	8,000	N/A	Estimated in this study based on relations shown in[35]
Fresh water *vs* sea water	5	50	10,000	0.15	Lee et al. [35]
Fresh water *vs* sea water	5	60	12,000	N/A	Harrysson et al. [92]
Fresh water *vs* sea water	5	500	100,000	0.30	Lee et al. [35]
Fresh water *vs* sea water	6	40	7,000	N/A	Estimated in this study based on relations shown in[35]
Fresh water *vs* sea water	7.7	92	12,000	0.06	Ramon et al. [96]
Fresh water *vs* brine from the Great Salt Lake	17	160	9,000	0.09	Loeb [89]
Fresh water *vs* sea water	N/A	N/A	N/A	0.21	Tanioka et al. [6]
Fresh water *vs* brine from desalination plants	N/A	N/A	N/A	0.16	Tanioka et al. [6]

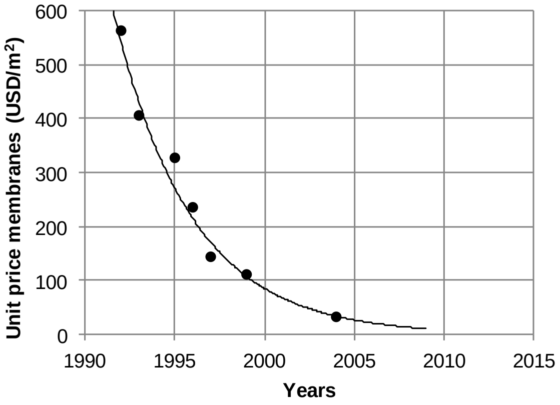


Figure 13. The trend in membrane prices over the years. Figure adapted from Ref. [90].

It can be speculated that the costs involved with osmotic power production will be driven down by many factors, and the desalination industry will be a key player in this process. The prices of membranes (as shown in Figure 13) have reduced abruptly over the last decade, and the same trend could be expected for membranes employed in PRO. The desalination industry is also the driver of technological advances and cost reductions of other equipment (such as pressure exchangers, pressure vessels, filters, pumps and pipes) that can be transferred to the osmotic power industry with only minor modifications [68].

Similarly, the water treatment industry is also believed to be driving down the costs of the processes and equipment used in the industry, which will have a direct impact upon the costs of the pre-treatment of the incoming solutions of an osmotic power plant. According to Greenlee et al. [101], membrane pre-treatment systems, which would be more effective in removing solids from the water, are in general decreasing in capital cost and are now becoming cost-competitive with conventional systems.

Osmotic power can also be seen as a new business potential for suppliers of the desalination and water treatment industries. For a 1 MW installed capacity, an osmotic power plant will require about 200,000 m^2 of membrane (assuming a power density of 5 W m^{-2}), which appears to be a very attractive number for membrane manufacturers. According to The Salinity Project Group [68], the replacement market for the same power plant would be up to four times this amount over the lifetime of the power plant. The same source states the European continent alone could have 700 million m^2 of membrane in operation at any time, if only 10% of the continent's fresh water *vs* seawater salinity-gradient potential was exploited. Expectedly, the exploitation of the global salinity gradient potential would drive a major increase in demand for membranes and other related equipment and consequently, in the market of equipment suppliers. The increased competition among suppliers will then put downward pressure on equipment prices.

As reported by Bræin et al. [70], Statkraft has established a detailed economic model based on a hypothetical large-scale osmotic power plant to estimate the cost forecast for the production of osmotic power. The model uses the costs of existing 'off-the-shelf' equipment and installations, such as membranes, from the desalination industry. This estimate also uses the existing prices for engineering, construction, known components, and also considers the scales and improvements expected for all components related to osmotic power. The model also takes into account the cost decrease of new components as a function of the building of additional plants. The estimate is based on the assumption that 30 plants will be built by 2030. This economic analysis has yielded a unit energy cost in the range of \$0.065 – \$0.13 kWh^{-1} by 2030, a range also reported by Kho [58]. Such energy cost will make osmotic power comparable and competitive with the other renewable energy sources. Moreover, being a renewable energy source with a high environmental performance, PRO is expected to be subject to subsidy programs and other government incentives similar to those already seen for wind and solar power today. If subsidies are included in the analyses, the power cost could drop to \$0.05 – \$0.06 kWh^{-1} [26].

10.4. Keeping costs at minimum

Apart from higher power density and cheaper membranes, there are other important factors that would decrease osmotic power costs even further. Transmission costs, for example, could be reduced by choosing a strategic location for the installation of the plant, preferably near the energy consumption centers [87]. In this sense, a fresh water *vs* sea water scheme would be advantageous as compared to a sea water *vs* hypersaline lake scheme. This is due to the fact that most settlements occur near the shore, at locations where rivers flow into oceans. Similarly, most desalination plants are also located near the shore and settlements, making an integrated desalination/osmotic power plant favorable and less cost-intensive [8].

The design of the osmotic power plant is also of great importance. A couple of different designs have been proposed by Skilhagen and Aaberg [26], Loeb et al. [25] and Honda and Barclay [39]. A traditional design would be placing a power plant at sea level, with fresh water taken from a nearby river and sea water fed into the plant by underground pipes. An alternative design to the traditional one, which would allow for a substantial reduction in costs, would be locating the plant below sea-level, where sea water would be pressurized by gravity, avoiding the use of feed pumps in the plant.

Another factor in cost reduction is to avoid locations requiring long intake and outfall tunnels. Ideally, the distance between the feed and the draw solution sources should be the shortest possible. Kleiterp [90] studied the impacts of reducing the piping and tunneling systems on the energy production costs of an osmotic power plant. Downsizing the plant’s pipe system from 10 km to 100 m would result in a reduction of costs ranging from 27 to 39%, depending on the plant size.

Fouling is a key issue affecting productivity, and thus costs, in any membrane processes [14, 97, 102]. As such, fouling is also expected to be a problem in PRO. Fouling could be reduced, to some extent, with pre-treatment of the incoming solutions. This could be accomplished with the use of physical separation processes such as filtration. Pre-treatment would be particularly important for the feed solution as this solution would face the porous layer of the membrane, making fouling more prevalent on this side than on the draw solution side [103, 104]. The energy applied in the pre-treatment process however, would incur reduction in net power, increasing the energy costs of the PRO plant. In this context, Yip and Elimelech [14] suggest that groundwater could have an important advantage over river water, as the former would be naturally filtered through the subsurface, reducing energy consumption in the pre-treatment process, and consequently the chance of membrane fouling. Yip and Elimelech [103] also suggest that intermittent osmotic backwashing of fouled membranes could be another effective way of performance recovery, requiring only nominal pumping energy and posing negligible operational disruption. Nevertheless, fouling caused by natural organic matter seems to be an issue that should be addressed in membrane development (by developing fouling-resistant membranes, for instance) rather than in pre-treatment or cleaning technology development. As such, fouling still remains an important challenge in PRO.

As discussed in this study, a combination of a desalination and an osmotic power plant seems another option for a financially viable PRO application [7, 8, 58]. In this combination scheme, each plant would supply resources that the other needs. This symbiotic relationship would be more feasible than two separate plants, as desalination plants can provide clean brine to the osmotic power plant, reducing the costs of the pre-treatment of the incoming solution. At the same time, the power plant provides part of the energy required for the desalination process, thus reducing the cost of water production. Sim et al. [7] estimated a reduction of up to 23% in energy consumption via a hybrid process based on desalination and PRO. Moreover, as similar technology is employed in both processes, it could be expected that maintenance and operation costs would be also minimized.

9. Final considerations

The world should reduce its dependence on fossil fuel combustion by increasing the production of renewable energy. Continued reliance on fossil fuel to meet our growing energy demands is unsustainable due to its finite availability [40] and the fact that it is accelerating climate change towards long-term, dangerous effects [2, 3]. The harnessing of the salinity-gradient energy originated at the interface between waters of different salt concentrations through the PRO technology could make an important contribution to energy supply and to the mitigation of climate change in the coming decades, provided the technical challenges identified in this study can be overcome, and costs reduced.

This study identified that the most important advantages of the PRO technology are its ability to generate a constant and reliable supply of power compared to other renewable sources like wind and solar, and its low environmental impacts. As long as a PRO power plant is located in the proximity of sources of constant fresh water (such as a river) and salt water, the system will be able to provide steady baseload power. Alternatively, a power plant could also operate on salinity gradients existing between sea water and concentrated brine from desalination plants, or even between sea water and hypersaline waters or groundwater.

This article has demonstrated that the PRO technology has been improving rapidly, particularly in recent years. However, although membrane prices have been declining over time, at the current stage of development, osmotic power outputs remain below expectation and a technical barrier to an economical energy production. Osmotic power will become financially viable when membranes that output a minimum power of 5 W m^{-2} are available ‘off-the-shelf’. Once this is achieved, the activity will be as or even more cost-effective than the currently-available renewable energy sources, such as wind and solar power. Custom-made membranes have already been produced on a small scale, and proved to generate the minimum required power. This is certainly encouraging towards further research and development. The agreement set between Statkraft and Nitto Denko/Hydranautics to produce a specialized membrane for osmotic power appears to be the first step towards upgrading PRO from laboratory and prototype scales to a commercial large-scale plant.

Since no full-scale plants exist at this stage, it is difficult to determine the costs incurred in osmotic power production. From the analysis presented in this article, it can be concluded that the unit energy cost of an osmotic power plant would be dependent upon numerous factors, such as:

i) The salinity gradient between the feed and draw solutions (e.g., river water *vs* sea water or river water *vs* brine from desalination plants). A scheme based on river water *vs* concentrated brine seems to involve lower costs, as more flux will occur through the membranes, generating more power per unit membrane area. However, it needs to be noted that higher flux may exacerbate membrane fouling;

ii) The water quality of the feed and draw solutions (e.g., muddy water *vs* clean water), as well as the pre-treatment system utilized in the plant. Feed solutions derived from clean rivers or from groundwater will incur lower pre-treatment costs and allow for increased membrane lifetimes;

iii) The power density of the membranes. High power outputs per membrane area will result in less installed membrane area, and thus lower capital costs;

iv) The production rate (economy of scale). High capacity plants will have a lower capital cost per unit of installed power as compared to low capacity plants;

v) The distance between the sources of the feed and draw solutions. Long piping systems will result in high capital costs as well as high energy losses, increasing costs as well as efficiency. Ideally, a plant should be placed in a strategic location where the costs for the construction of tunnels and pipes used to convey the two solutions into the plant are minimized;

vi) Government subsidies. The inclusion of osmotic power in subsidy programs will reduce energy costs.

At the current membrane efficiency and cost, it seems PRO is still unable to produce energy at a competitive rate. To increase its competitiveness, a substantial increase in power density, decrease in membrane cost, or increase in membrane life (or some combination thereof) must be achieved [53]. Furthermore, government subsidies for alternative energy sources (including PRO) may be needed in order to sustain continuing development of this technology until technical issues can be overcome.

As already demonstrated, when cheap and power-effective membranes become commercially available, desalination plants will most likely be the primary markets for osmotic power, as these systems employ similar technology and require vast amounts of energy to create fresh water [58]. Reducing energy costs is one of the main challenges in the desalination industry, and as such, there has been a growing trend toward employing renewable energy in the desalination process [105]. While traditional renewable energy sources tend to have a variable power output, PRO provides a constant baseload power, and therefore could be highly beneficial for the desalination industry. In this combined scheme, part of the energy required for the desalination process would be provided by the PRO plant, while this plant would utilize the remaining concentrated brine from the desalination process as draw solution for power generation.

According to Kleverud et al. [57], there are a few technical areas of improvement towards reducing the costs of osmotic power, and targets have been set such that a levelized unit cost, that is competitive to conventional renewable energy sources, can be achieved. These areas are:

i) Membrane power output: this must be increased from the current power output in production of 1 W m^{-2} to at least 5 W m^{-2};

ii) Membrane elements: these must be able to accommodate about 5,000 m^2 of membrane area, as compared to the current element size average of 30 m^2, which incurs higher capital and maintenance costs;

iii) System efficiency: this must be incremented from the current efficiency of 40% to an improved efficiency of 80% - which could be done with the development of less energy-intensive systems for water conveyance and treatment, and the reduction in energy losses in the piping system;

iv) Scale-up: the system, as well as the components, must be scaled up as a whole from laboratory to pilot, then into commercial production.

Apart from the above issues, the high susceptibility of membranes to fouling is also a problem that should be overcome for the success of PRO. This problem could reduce the efficiency of a commercial power plant significantly over the years – an issue that laboratory and prototype scales have been unable to demonstrate as yet.

Further barriers to the success of PRO include, for instance, the difficulty companies will face in obtaining permits to build an osmotic power plant, particularly given that osmotic power is a new and immature type of technology. Also, the process of connecting the plants to existing grids will probably be lengthy, complex and expensive. Therefore, more research is needed in this area, together with an increase in the number of prototypes that could be progressively scaled up to commercial units.

Another potential problem will be how to attract investors to this new business [58] given these systems will have a large capital cost, and the uncertainties involved. Even with a satisfactorily-working prototype, and the main technical issues being progressively overcome, other factors, such as the lifetime of the membranes and the maintenance costs, will still be difficult to determine. Therefore, investors will probably remain unattracted to osmotic power as long as these systems show potential risks of failure.

Additional shortcomings are the entrenched competition from conventional renewable energy sources and other general impediments for new renewable energy types. These include governmental policies favoring fossil-fuel technologies, and market prices not reflecting public benefit of renewable energy [106].

Nonetheless, the world has great potential for osmotic power generation due to the abundance of fresh water that could be mixed with sea water or sea water that could be paired with more concentrated solutions. The major problem is still how to harness this energy with great efficiency and at low cost. Provided technical issues are overcome, it seems reasonable to think the other issues related to osmotic power will be naturally resolved. In this respect, the existing prototype has been a major player by contributing to technological improvements in order to reach cost-effectiveness, as well as by building knowledge towards the further scaling-up of its components.

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