Water Utility Journal 5: 3-13, 2013.

Salinity gradient energy: a new source of renewable energy in Australia

F. Helfer[1], O. Sahin[2], C. J. Lemckert[3] and Y. G. Anissimov[4]
[1] *School of Engineering, Griffith University, Australia, e-mail: f.helfer@griffith.edu.au*
[2] *School of Engineering, Griffith University, Australia, e-mail: o.sahin@griffith.edu.au*
[3] *School of Engineering, Griffith University, Australia, e-mail: c.lemckert@griffith.edu.au*
[4] *School of Biomolecular and Physical Sciences, Griffith University, Australia, e-mail: y.anissimov@griffith.edu.au*

Abstract: Energy production in Australia depends heavily on fossil fuel combustion, which has adverse effects on the environment, including climate change. To reduce its reliance on this perilous source of energy, the Australian government has been giving financial incentives to promote renewable energy. Today, renewable energy accounts for less than 5% of the total energy consumption in the country, but this share is estimated to reach 8% by 2030. Australia also expects 20% of the electricity generation to be provided by renewable sources by 2020, representing a significant increase compared to the current share of only 7%. This predicted growth in renewables is a response to the government targets to reduce carbon dioxide emissions, and to financial incentives for research and development on renewables. In this study, salinity gradient energy is presented as a new renewable energy source for Australia. Salinity gradient energy is released in nature, for example, where rivers meet the oceans. When appropriately harnessed, this energy can be turned into power. This article analyses Pressure Retarded Osmosis, a technology available to harness salinity gradient energy, and discusses possibilities for the exploitation of salinity energy in Australia. This research found that the country has significant potential for osmotic power production. Some favourable factors are: 1) The proximity of the major energy consumption centres to the ocean; 2) The high evaporation rates that could be used to generate more concentrated solutions with higher power production potential; 3) The existence of vast areas of salt beds that could be used to generate brine; 4) The projected desalination plants that could be coupled with osmotic power plants and 5) Government incentives for research on renewable energy.

Keywords: osmotic power, renewable energy, membranes, salinity

1. INTRODUCTION

The global energy supply for human activities is dominated by fossil fuel combustion. In Australia, 95% of the energy is supplied by this source, contributing significantly to global climate change. To exacerbate this issue, growing economy and population are projected to lead to increasing demands for energy in Australia. Total primary energy consumption is projected to grow by approximately 35% between 2008 and 2030 (Syed *et al*., 2010). Gross electricity generation is projected to grow by nearly 50% by 2030, from a current production of 247 TWh, to 366 TWh in 2030.

To reduce its reliance on fossil fuels, and minimise greenhouse gas emissions, the Australian Government has been supporting the development and use of technologies based on renewable sources of energy. It is estimated that 20% of the country's electricity generation will be provided by renewable sources by 2030 (Syed *et al*., 2010). This represents a significant growth compared to the current share of renewable resources, of only 7%. According to Syed *et al*. (2010), the Renewable Energy Target (RET), the Clean Energy Future Program and the introduction of a carbon emissions reduction target will be the main drivers of this growth in renewable energy in Australia. Through the RET, the Australian Government has established a target of 20% of Australia's electricity to be sourced by renewables by 2020. Additionally, the Victorian Renewable Energy Target (VRET) requires 10% of the total electricity generation in Victoria to be sourced by renewable energy sources by 2016. Through the Clean Energy Future Program, a carbon price has been introduced in Australia to accelerate the reduction of greenhouse gas emissions and to provide funding for the use of renewable energy sources.

The current share of renewable energy production in Australia is dominated by hydro (63.4%), followed by wind (22.9%), bio-energy (11.5%) and solar energy (2.1%) (Dopita and Williamson, 2010). The rest of the share is accounted for by wave, tidal and geothermal energies. Salinity gradient energy is another potential source of renewable energy for the country. From a global perspective, salinity gradient energy hasn't been applied in large scales due to the infant development stage of the technology required. Salinity gradient energy occurs in nature where there is mixing of waters with different salt concentrations, for instance, at locations where fresh water from rivers meet the ocean. When appropriately harnessed, this energy can be used to produce power. Pressure Retarded Osmosis (PRO) is the most popular technology available to harness salinity gradient energy for power generation. This technology employs basic principles of osmosis, and as such, the power generated is usually referred to as "osmotic power". The objective of this study is to discuss this new renewable energy source and to identify potential favourable conditions in Australia under which osmotic power could be generated in the near future. In the first part of this article, a brief review on PRO, including basic osmotic principles and technical aspects, is provided. The second part discusses potential conditions in Australia under which PRO could be implemented. It is hoped that this study will help disseminate the knowledge related to this new technology and encourage further projects based on salinity gradient energy.

2. OSMOTIC PROCESSES

Salinity gradient energy is the energy released when waters with different salt concentrations mix. Approximately 0.75 kWh is dissipated when 1 m^3 of fresh water flows into the sea (Yip and Elimelech, 2012). It can be estimated that the global salinity gradient energy potential is equivalent to each river ending at its mouth in a waterfall 225 m high (Norman, 1974). Using one tenth of the global river discharge, more than 1,300 TWh per year could be generated using the currently available technology for harnessing this type of energy.

The process of energy release through the mixing of fresh water and salt water can be demonstrated by considering basic osmotic principles. Figure 1 represents four processes, which occur due to the contact of fresh water and saline water via a semipermeable membrane, which is permeable to water but not to salt. The osmotic pressure of a solution represents the pressure which, if applied to the concentrated solution, would prevent transport of fresh water across the semipermeable membrane.

The first osmotic process shown in Figure 1(a) is Forward Osmosis (FO), or simply osmosis, and occurs when two solutions are separated by a semipermeable membrane and the only driving force for the transport of water through the membrane is the osmotic pressure differential ($\Delta\pi$). The flux through the membrane is proportional to the osmotic pressure difference between the two solutions and the permeability of the membrane:

$$J = A\left(\Delta\pi - \Delta P\right) \tag{1}$$

where J is the water flux (typically in L m^{-2} h^{-1}), A is the water permeability coefficient of the membrane (typically in L m^{-2} h^{-1} bar^{-1}), $\Delta\pi$ (bar) is the difference in osmotic pressure between the two solutions, ie $\Delta\pi = \pi_D - \pi_F$, where π_D is the osmotic pressure in the draw solution (saline water) and π_F is the osmotic pressure in the feed solution, assumed to be zero in case of fresh water. ΔP (bar) is the difference in hydrostatic pressure between the two solutions, i.e. $\Delta P = P_D - P_F$.

In FO the osmotic pressure difference between the two solutions, $\Delta\pi$, is non-zero and positive, and the solutions are not pressurized or pressurized at the same magnitude, making $\Delta P = 0$. It should be noted that the osmotic pressure difference depends on the salt concentration of each solution. If the feed solution is clean fresh water ($\pi \approx 0$) and the draw solution is sea water (ie, salt concentration ≈ 3.5%, and $\pi \approx 28$ bar), then the osmotic pressure differential will be around 28 bar. In FO, water will move through the membrane from the left (less concentrated) to the right (more concentrated) side, driven by the osmotic pressure difference, $\Delta\pi$. The flux through the membrane will be given by $J = A\,\Delta\pi$, as $\Delta P = 0$.

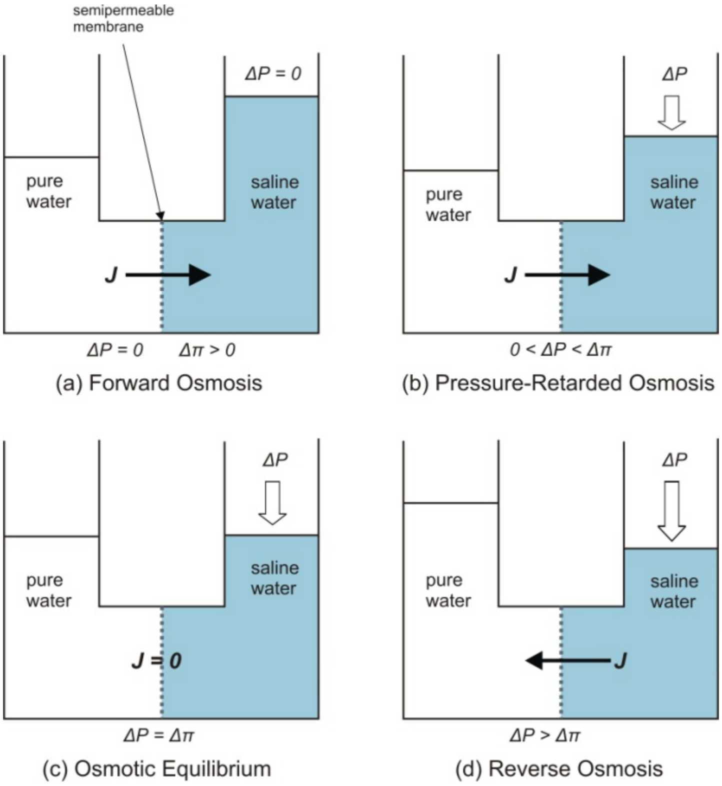

Figure 1. Schematic representation of osmotic processes. Reprinted from Journal of Membrane Science, 453, Helfer, F., Lemckert, C., Anissimov, Y.G., Osmotic power with pressure retarded osmosis: Theory, performance and trends - A review, p. 337-358, copyright (2014), with permission from Elsevier.

When water moves from the un-concentrated to the concentrated side, the hydrostatic pressure on the concentrated side increases and, eventually, the flow ceases. Mathematically, the flux will cease as ΔP approaches $\Delta\pi$ (ie, $\Delta\pi - \Delta P = 0$, and, therefore, $J = 0$). This condition determines the state of osmotic equilibrium and is illustrated in Figure 1(c).

At any stage when ΔP is between 0 and $\Delta\pi$, the water flux will be driven by the osmotic pressure difference, but the flow will be slowed 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 1(b) and is termed Pressure Retarded Osmosis (PRO). In PRO, the feed solution (less concentrated solution) flows towards the draw solution side due to the positive osmotic pressure difference, as long as this difference remains greater than the hydrostatic pressure difference (ΔP) during the process. It is on PRO that the production of power from salinity gradient energy is based. Since the power from salinity gradients is generated through an osmotic process, it is commonly referred to as “osmotic power”. For a constant base load power production, the salt water side has to be maintained at constant hydrostatic pressure, while the feed solution provides a constant flow through the membrane, increasing the volume on the salt water side for power production.

The fourth osmotic phenomenon occurs when $\Delta P > \Delta\pi$ and is illustrated in Figure 1(d). This condition is achieved when pressure is applied to the draw solution, with this pressure being greater than the osmotic pressure difference between the two sides. In this case, the water flux will occur from the salt water side to the freshwater side, resulting in a negative flux J. This process is called Reverse Osmosis (RO). The term “reverse” is because the water moves in the opposite direction to that of a natural osmotic process (i.e., forward osmosis).

3. PRESSURE RETARDED OSMOSIS

The PRO technology was discovered in 1973 in Israel (Loeb, 1975; 1976), but the high membrane prices and the immature membrane technology at that time restrained the implementation of PRO power plants in large scales. The continuing growth of the desalination industry, particularly in the late 2000s, brought about much improved membranes, encouraging further research on PRO. In 2009, the Norwegian state-owned company Statkraft opened the first prototype of an osmotic power plant working on the principles of PRO. This prototype has proved the feasibility of osmotic power generation using sea water and fresh water as draw and feed solutions, respectively, and has been used in the testing of different types of membranes and plant configurations. A general sketch of the Statkraft's power plant is shown in Figure 2. The river water enters the plant at low pressure, undergoes mechanical filtration and enters the permeator containing the semipermeable membrane modules. Concurrently, sea water is pumped into the plant, filtered and pressurized with the aid of a pressure exchanger before entering the permeator. Driven by the osmotic pressure difference, fresh water permeates the membranes, increasing the volume of water in the sea water pipe system. A part of this pressurized flow is diverted into a turbine to generate power, and another part is diverted to the pressure exchanger to help pressurize the incoming sea water. The power plant is equipped with 2000 m^2 of membranes and has a power output between 2 and 4 kW.

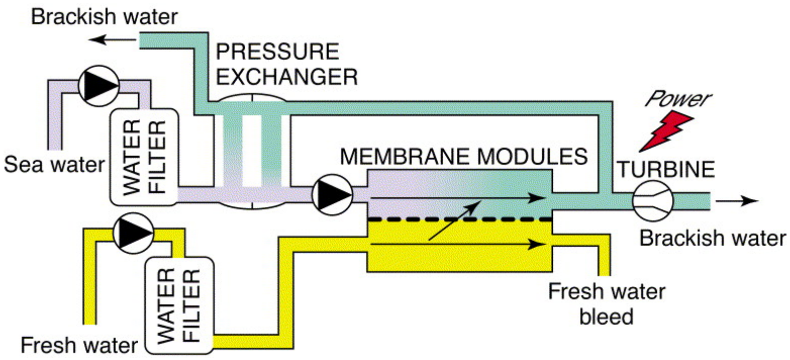

Figure 2. A typical simplified PRO process used in the Statkraft's osmotic power plant. Reprinted from Refocus, 4 (6), Aaberg, R.J., Osmotic power: A new and powerful renewable energy source? p. 1471, copyright (2003), with permission from Elsevier.

With the currently available membrane technology, the capital costs associated with an osmotic power plant is still very high, making salinity gradient energy not competitive with other sources of renewable energy such as wind and solar. The main components of the capital cost of an osmotic power plant are the hydroturbines, pumping and filtering systems, pressure exchangers and, most importantly, the membrane modules. Due to the lower power output of the current membranes (defined as the power generated per unit area of membrane, and varying between 0.5 and 2.5 W m^{-2} as reported by Helfer *et al.*, 2013), the area of installed membranes for a commercial power plant would have to be significantly large, reflecting directly on the capital costs of the plant. Since 2009, after the opening of the first prototype, the focus of PRO research has been primarily on improving or developing new membranes for specific PRO application, aiming to obtain higher power outputs. Adepts of PRO believe the technology will become available in about 5 to 10 years (Research and Markets, 2012). The target has been set to find or produce a membrane that is able to generate 5 W m^{-2}, making the installation of a commercial power plant financially viable (Skilhagen, 2010).

Another possibility for the exploitation of salinity energy via PRO is the use of solutions with concentrations higher than sea water (e.g., salt lakes or brines remaining from desalination plants). Research on membranes for this particular condition is also underway. The main issues to overcome in this case are the significantly higher osmotic pressure differences that the membranes will have to withstand, and the higher risks of salt built-up at the interface of the membranes. This salt built-up gradually decreases the effective osmotic pressure difference between the two solutions, and consequently decreases the flux through the membrane and the power density. Laboratory studies have discovered commercial membranes that could produce up to 11 W m^{-2} using fresh water as feed solution and brine from desalination plants (salt concentration ≈ 6%) as draw solution (Chou *et al*., 2012). Modelling results, however, have demonstrated that the potential power output is much higher, at 30 W m^{-2} (Efraty, 2012). Modelling studies have also shown that power densities above 500 W m^{-2} could be potentially achieved from the pairing of river water and hypersaline water, such as Lake Van (Turkey), Lake Eyre (Australia) and Lake Urmia (Iran), where salt concentration could be as high as 33% (Efraty, 2012).

In the next section, a discussion on possible conditions under which PRO could be implemented is provided. It should be noted that the examples given focus on Australia, but the conditions are likely to be encountered in other parts of the world as well.

4. POSSIBILITIES FOR IMPLEMENTATION OF PRO PLANTS

4.1 Sea water vs saline water from salt lakes or groundwater

Feed solution: sea water
Draw solution: concentrated brine from salt lakes or saline groundwater

This proposed scheme is based on sea water as feed solution and concentrated brine from salt lakes or saline groundwater as draw solution. Australian salt lakes have already been suggested in the literature (e.g., Kelada, 2010; 2011) for generation of osmotic power. The idea is based on pumping sea water into the salt lake and letting the volume of water in the lake decrease due to evaporation, consequently increasing the salt concentration in the water. This hyper-concentrated solution would then be paired with sea water (less concentrated) in a PRO plant.

According to Kelada (2010), Lake Torrens (South Australia) could be used as a source of hyper-concentrated salt water for osmotic power generation. The lake's area is 5,700 km^2 and it remains dry during almost the entire year. Mean annual rainfall is less than 250 mm, and annual potential evaporation is around 3,500 mm. Kelada (2010) suggests extending a seawater canal from the Spencer Gulf, located about 80 km south of the southern end of the lake, to Lake Torrens, to fill in the lake. The idea of permanently filling Lake Torrens and Lake Eyre (another dry lake located north of Lake Torrens) from the Spencer Gulf had already been considered by the Australian Government to improve the local climate, but the project was rejected in 1883. The idea is being reconsidered due to climate change predictions of a drier climate in southern Australia, which is likely to affect agricultural activities in that region. It is believed that filling the lakes will increase rainfall because of the increased evaporation rates from the lakes. Calculations show that Lake Torrens could provide brine at 32% salt concentration, which could act as the draw solution in an osmotic power plant when paired with the diverted sea water, with 3.5% salt concentration. The configuration proposed for Lake Torrens could generate up to 2.6 GW for a 225 $m^3 s^{-1}$ seawater flow rate.

In a follow-up publication, Kelada (2011) suggests the use of Lake Eyre in combination with Torrens Lake as a source of brine for osmotic power generation. Lake Eyre has a surface area of 9,500 km^2 and could be filled with sea water diverted from the Spencer Gulf, located 350 km south of the lake. The achievable brine salinity is estimated to be 35%. The sea water could be diverted into the lake from the Spencer Gulf through a canal that would first run through Lake Torrens. The power plant would be situated at the southern end of Lake Torrens. The configuration proposed is able to produce up to 10 GW, with about 1,000 $m^3 s^{-1}$ flow of sea water diverted into the plant.

These two projects are surely far-reaching and expensive. They involve the construction of extensive artificial canals, which would make their implementation costly. Neither the sizes of the power plants, nor the availability of membranes for this purpose, are mentioned in the above publications. Presumably, osmotic power plants of those magnitudes would require a large footprint area due to the large amount of membranes that the project would require. However, provided that membranes for high osmotic pressure differences become available one day at commercial scale and low cost, there is no doubt the projects would be highly justifiable, particularly for increasing Australia's electricity supply by over 20%.

Another source of saline water that could be paired with sea water to produce osmotic power in Australia is saline groundwater. Australia's mining industry utilises groundwater in broad scale across the country for being more readily available than surface waters and less affected by losses to evaporation. It is estimated that the mining sectors of Western Australia, Queensland and New South Wales are responsible together for the extraction of 1,130 hm^3 per year (36 m^3 s^{-1}) of groundwater (Queensland Department of Natural Resources, 1997; Economics Consulting Services, 2004), representing 22% of the total groundwater use of Australia. Most of the groundwater in Australia is saline or hypersaline.

The saline water is used in mine sites for general mining operations. In the extraction of coal seam gas, for example, the need to 'dewater' coal seams to depressurise the gas results in large volumes of produced water, which usually has large quantities of salts. The produced water gives rise to potential surface issues in the handling, disposal and use of the salt water (Rutovitz *et al.*, 2011). Coal seam gas production in Australia has been growing fast in recent years. Given the significant reserves predicted to exist in the Eastern states, this expansion is likely to continue as demands in the domestic and export market increase. The annual number of coal seam gas wells drilled in Queensland increased from 10 in the early 1990s to almost 600 in 2010-11 (Department of Employment, 2011). The salinity of the produced water varies from less than 0.2% to over 10% (Rutovitz *et al.,* 2011). The coal seam gas industry is estimated to extract 350 hm^3 of saline groundwater per year (11 m^3 s^{-1}) in Australia. The disposal of this water is one of the major challenges in the coal seam gas industry. Alternatives include the re-use of water for coal seam gas operations, injection into a non-coal aquifer or recreation. After the treatment to reduce the salt concentration, the produced water can be discharged directly onto surface waters to increase environmental flows, or used for wildlife and livestock watering and agriculture. Alternatively, the produced water could be transported to evaporation ponds, where concentrated brine would be produced after losses of water to evaporation. The brine could then be coupled with channelled sea water or less concentrated groundwater to produce osmotic power for the mines. This would reduce operation costs, as well as the environmental impacts due to the energy from fossil fuels. Potentially, around 140 MW of osmotic power could be produced using the current groundwater withdrawals from the coal seam gas mines in Australia.

Another alternative lies on the groundwater extracted by the gold mining industry. This industry heavily relies on the use of groundwater in Australia. Saline to hypersaline water is used in the gold ore processing. A pit is usually excavated and filled with groundwater (usually saline or hypersaline) and once in these ponds, the salt concentration of the water increases due to the high rates of evaporation. This concentrated brine could be used to run an osmotic power plant.

4.2 River water vs sea water

Feed solution: river water
Draw solution: sea water

The pairing of river water and sea water is perhaps the most realistic condition for Australia in the short or mid-term, due to the rapid advancements in membrane technology designed specifically for this purpose, and due to the existence of an installed river water *vs* sea water prototype plant (Norway), which is acquiring all the necessary know-how related to osmotic power production. A river *vs* seawater power plant would work more efficiently if located close to a river mouth, where access to both waters is facilitated. This location would also minimise the costs related to pumping sea water and river water into the plant, as well as the environmental impacts. Moreover, as the major consumption centres are usually located in the surroundings of river mouths, this strategic location would minimise the costs associated with power transmission.

Like Norway, Australia has various sites where the installation of osmotic power plants would be feasible. The difference lies in the seasonality of the power production, as Australian rivers have much higher temporal variability than European rivers. Moreover, as Australian rivers are significantly affected by tidal conditions, the point of extraction of river water would have to be further upstream, where tide has no or little influence on river salinity. This would incur additional costs related to the channelling and transport of the river water into the plant.

The Brisbane River (Queensland), for example, has a Q_{70} flow (flow that is equalled or exceeded 70% of the time) of 7 m^3 s^{-1} allowing the generation of 7 MW, making it competitive with other renewable energy plants located in Queensland, such as wind, solar and biomass (Department of the Environment Water Heritage and the Arts, 2012).

4.3 Energy production during non-functioning periods of desalination plants

Feed solution: river water
Draw solution: sea water

Current desalination technologies, such as reverse osmosis are expensive and energy intensive. On average, the production of 1 m^3s^{-1} of fresh water from sea water via RO requires 12,000 kW (Hoang *et al.,* 2009). On the other hand, 1 m^3 s^{-1} of fresh water can potentially generate 1,000 kW of power using a PRO system.

In Australia, desalination plants are secondary water supply sources, meaning that many desalination plants sit idle for long periods, increasing the costs of water production. Using membrane modules suitable for both desalination and osmotic power appears to be a convenient strategy for these plants. When the plants are not producing water, they would be producing energy, using the same membrane infrastructure. Apart from membranes designed specifically for this purpose, the existence of a nearby source of fresh water to feed the power plant would be another precondition for this scheme.

The Gold Coast Desalination Plant in Queensland, Australia, was designed and built in 2007 to produce 125,000 m^3 per day of potable water (Crisp, 2010) to attend the increasing water demands due to the growing population in the Brisbane region. However, as the availability of water from conventional sources (reservoirs) has been highly reliable over the years, the plant has been in stand-by mode for most of the time, operating only for short periods, such as during the flood events that occurred in January 2011 in Brisbane. Even during those events, the production of water by the plant was much less than 50,000 m^3 per day (Collins, 2012), meaning the plant was operating at less than 40% of its total installed capacity.

Assuming that the plant operates for three months per year, producing 50,000 m^3 of fresh water per day, the total energy required for the desalination process will be approximately 15 GWh per year. If the 630,000 m^2 of membrane modules were replaced by dual-purpose membrane modules, and assuming a membrane power output of 5 W m^{-2}, the power production capacity would be 3.2 MW. This translates into a generation of 20 GWh over 9 months, offsetting the energy consumed in the desalination process. To keep the power production at maximum however, a flow of around 3.2 m^3 s^{-1} would have to be diverted into the plant. Options include flows from nearby streams supplemented with flows from the local water supply reservoir located 30 km from the Gold Coast Desalination Plant.

The main hurdle to overcome before the implementation of this symbiotic relationship is the development of a membrane that could be efficiently used for both desalination and power generation. Advocates of osmotic power have already suggested that research and development of osmotic power membranes should start focusing on the possibility of employing the same membrane in both, power and desalination processes (Kachan & Co., 2010; Research and Markets, 2012).

4.4 PRO-assisted desalination plant (SWRO-PRO hybrid system)

Feed solution: river water
Draw solution: brine from the desalination process

Seawater Reverse Osmosis (SWRO) and Pressure Retarded Osmosis (PRO) hybrid systems (referred to as SWRO-PRO hybrid systems) constitute other interesting alternatives for Australian desalination plants. Under these schemes, fresh water is produced from sea water in RO modules as usually seen in ordinary desalination plants. Unlike normal desalination plants however, the power for the desalination process is produced in a separate PRO plant, located near the desalination plant. In this PRO plant, the feed solution consists of either fresh water or sea water, and the draw solution consists of concentrated brine (salt concentration ≈ 6%) remaining from the desalination process, which, under normal circumstances, would be disposed of in the natural environment. SWRO-PRO hybrid systems have been suggested and discussed by Achilli *et al.* (2012) and Kim *et al.* (2012).

Power generation under this scheme would depend on the concentration difference between the draw and the feed solutions. The power production could potentially reach 2.5 MW per $m^3 s^{-1}$ for fresh water as feed solution, or 1 MW per $m^3 s^{-1}$ for sea water as feed solution. The main advantage of this scheme is that sea water can be used as feed solution, which is plentiful and free. Additionally, the desalination plant could reduce its reliance on fossil fuels, contributing to reduced gas emissions to the atmosphere. The main disadvantage would be the high capital cost for the installation of the membrane modules designed uniquely for power production.

The Gold Coast Desalination Plant requires an input of 6.5 MW during the periods of freshwater production. Assuming 40% recovery, it can be estimated that the plant produces 75,000 m^3 per day of concentrated brine, which could be used as draw solution in the PRO plant. This amount of brine can draw 50,000 m^3 per day (or 0.6 $m^3 s^{-1}$) of sea water (considering 40% permeation ratio, as suggested by Saito *et al.*, 2012), which could generate about 0.6 MW. This is just a fraction of the energy required for the desalination process, but the capacity could be increased to 1.5 MW if fresh water was used instead of sea water.

4.5 Waste water vs brine from desalination plants

Feed solution: waste water
Draw solution: brine from the desalination process

Saito *et al.* (2012) propose another scheme that could work for Australia. It is an osmotic power plant based on concentrated brine from SWRO plants (draw solution) and treated waste water (feed solution). According to the authors, this scheme is a solution to the environmental problems caused by the disposal of both the desalination main by-product (brine) and the by-product of sewage treatment facilities. A small-scale prototype PRO plant has been built in Fukuoka (Japan), and the system has been producing power outputs beyond expectation. The prototype plant receives brine from a desalination plant located near the osmotic power plant. Fresh water is provided by the regional sewage treatment facility after treatment. Before entering the PRO plant, the treated waste water undergoes additional pre-treatment with ultra filtration (UF) followed by low pressure reverse osmosis, where potential foulants are removed.

In Australia, SEQ Healthy Waterways Partnership (2008) suggests the Fisherman’s Island (located at the Brisbane River mouth in Moreton Bay) as a potential location for a future desalination plant. On the opposite shore lies the largest wastewater treatment facility in Queensland, the Luggage Point Waste Water Treatment Plant. Discharges of brine of up to 3.2 $m^3 s^{-1}$ are projected for the future desalination plant. The Luggage Point Waste Water Treatment Plant in turn, is expected to release 2.0 $m^3 s^{-1}$ of treated waste water by 2051 (CH2M HILL, 2008). The combination of desalination brines and waste water could generate near 5 MW of osmotic power.

4.6 Waste water vs sea water

Feed solution: waste water
Draw solution: sea water

The Brisbane city in Queensland, Australia, has a population of 2,146,577 (2011) which is projected to increase 17% by 2026 and 47% by 2051 (MWH, 2007). Approximately 50% of the domestic and industrial effluents produced in Brisbane are treated in the Luggage Point Waste Water Treatment Plant. It is estimated that the salinity of fluid waste streams from waste water treatment plants are as low as the salinity of river water, ranging from 0.03 to 0.3% (Patterson, 1994). As described previously, it is estimated that the discharge from the Luggage Point WWTP will grow to 2.0 $m^3 s^{-1}$ by 2051, which could potentially produce 2 MW in a PRO plant paired with sea water. In this particular scheme, it is important to note that the Moreton Bay has a variable salinity as a result of the seasonal discharge of rivers, particularly the Brisbane River, and the tidal regime. Therefore, the nearest source of saline water (3.5% salt concentration) with non-oscillating salinity level would be located 30 km offshore from the Luggage Point WWTP, which would require additional energy consumption for the pumping of the sea water into the PRO plant.

5. FINAL CONSIDERATIONS

Australia and other countries should reduce their dependence on fossil fuel combustion by increasing the use of renewable energy. Continued reliance on fossil fuel to meet our growing energy demands is unsustainable due to its finite availability (Yip and Elimelech, 2011) and is accelerating changes in our climate towards long-term perilous effects. Pressure Retarded Osmosis (PRO) is an unexplored source of renewable energy, and more credibility has been given to it since the opening of the first osmotic power plant prototype in Norway in 2009. The method's major advantages are its ability to generate a constant and reliable supply of power as compared to other renewable sources, and low environmental risks.

Six different cases for exploring osmotic energy have been presented and discussed in this article. Although the examples are given for Australia, the six methods could also be applied in other countries with similar conditions.

Several favourable factors for the implementation of PRO plants in Australia in the mid-term have been identified in this study, and the most important have been listed below.

1. The country has been growing continuously, increasing demands for energy.
2. The Australian Government has been funding research on new sources of renewable energy as a result of targets to reduce carbon emissions and to increase the supply of energy by renewable sources.
3. The largest Australian urban centres are located near the ocean and close to river mouths, an ideal condition for the construction of osmotic power plants.
4. Growing demands for potable water have been driving the construction of new desalination plants. If same membrane modules could be used for both desalination and energy production purposes, desalination plants could be designed to generate energy when they are not operating for freshwater production.
5. Alternatively, desalination plants working all year round could be powered by osmotic energy using the rejected brine from the desalination process as the draw solution in the power plant. The feed solution could be sea water, river water or even treated effluent from nearby wastewater treatment plants.
6. Australia has vast areas of dry lakes which could be artificially filled with sea water. The water in these lakes will have its salt concentration increased after the loss of water to evaporation. The resulting brine could then be used as the draw solution in an osmotic power plant, combined with less concentrated sea water. Similarly, hypersaline groundwater could

be used in combination with sea water, particularly in areas close to mining sites, where the demand for energy is high.

Although the technology for osmotic power – particularly membranes designed for PRO – has been improving rapidly, osmotic power is still several years away from commercial viability. The main issue to overcome regarding membranes is their susceptibility to concentration polarization (i.e., the gradual salt built-up on the membrane interfaces which considerably reduces the effective osmotic pressure difference between the feed and the draw solutions). Currently, the closest commercially available membranes for osmotic power are those produced for FO desalination, but their power density has been demonstrated to be low. Membranes made specifically for osmotic power have not yet been produced on a commercial scale. However, Statkraft and Nitto Denko/Hydranautics have recently signed an agreement for the manufacturing of a specific membrane for PRO, which is expected to be available "off-the-shelf" within a few years (Halper, 2011).

There are other potential issues apart from membrane technology. From the technical point of view, there is the issue of parasitic process energy requirements associated with water conveyance and pre-filtration, which significantly reduce the net power output. Also, the high susceptibility of membranes to fouling could significantly reduce the efficiency of a commercial power plant over time – an issue that has not been investigated at laboratory and prototype scales.

Another issue will probably be the attraction of investors to this new business, given that PRO systems involve such a large capital cost and various technical uncertainties. Even with a satisfactorily-working prototype and with main technical issues gradually overcome, other factors are still hard to determine, such as the lifetime of the membranes and the ongoing maintenance costs. Therefore, investors will probably remain unattracted to osmotic power until these systems can demonstrate lower risks of failure.

Therefore, more research is required, together with increasing number of osmotic power plant prototypes that could be progressively scaled up to commercial units.

6. ACKNOWLEDGEMENTS

Funding for this project was provided by the Griffith Climate Change Response Program and by the Centre for Infrastructure Engineering and Management, Griffith University, Australia.

REFERENCES

Aaberg, R. J., 2003. Osmotic power: A new and powerful renewable energy source? Refocus, 4: 48-50.

Achilli, A., Prante, J. L. & Childress, A. E., 2012. The energetics of PRO-assisted desalination. In: 3rd Osmosis Summit Event, April 26-27, 2012, Barcelona.

CH2M Hill, 2008. Reuse of purified recycled water in South East Queensland. Report Rev 04, Reference 355570 prepared for the Queensland Water Comission. 71 p.

Chou, S., Wang, R., Shi, L., She, Q., Tang, C. & Fane, A. G., 2012. Thin-film composite hollow fiber membranes for pressure retarded osmosis (PRO) process with high power density. Journal of Membrane Science, 389: 25-33.

Collins, K. M., 2012. Desalination Plant Study to Examine Tugun Desalination Plant Operating Options. Queensland Government. Available: http://statements.qld.gov.au/Statement/Id/79447 [Accessed January 10, 2013].

Crisp, G. J., 2010. Reducing carbon footprint of a seawater desalination plant - an Australian case study. In: MSSC Annual Salinity Summit Water and Energy, February 18-19, 2010, Las Vegas.

Department Of Employment, Economic Development And Innovation, 2011. Queensland's coal seam gas overview. Department of Employment, Economic Development and Innovation. 6 p.

Department Of The Environment Water Heritage And The Arts, 2012. Map of operating renewable energy generators in Australia. Available: http://www.ga.gov.au/renewable/ [Accessed 13 November 2012].

Dopita, M. & Williamson, R., 2010. Australia's renewable energy future. Report for the Australian Academy of Science. 37 p.

Economics Consulting Services, 2004. Water and the Western Australian Minerals and Energy Industry: Certainty of Supply for Future Growth. Report prepared for The Chamber of Minerals and Energy of Western Australia. 57 p.

Efraty, A., 2012. Pressure retarded osmosis in closed circuit without need of energy recovery. In: 3rd Osmosis Summit Event, April 26-27, 2012, Barcelona.

Halper, M., 2011. Osmotic power pushes closer to reality. Smartplanet, June 20, 2011. Available: http://www.smartplanet.com/blog/intelligent-energy/osmotic-power-pushes-closer-to-reality/7184 [Accessed November 22, 2012].

Helfer, F., Lemckert, C. & Anissimov, Y. G., 2014. Osmotic Power with Pressure Retarded Osmosis: Theory, Performance and Trends – A Review. Journal of Membrane Science, 453: 337-358.

Hoang, M., Bolto, B., Haskard, C., Barron, O., Gray, S. & Leslie, G., 2009. Desalination in Australia. Report for the CSIRO Water for a Healthy Country National Research Flagship. 26 p.

Kachan & Co., 2010. Osmotic power: A primer. Technical Report. 18 p.

Kelada, M., 2010. Global potential of hypersalinity osmotic power (white paper). Houston, Texas: MIK Technology.

Kelada, M., 2011. South Australia development - considering the osmotic power generation option (white paper). Houston, Texas: MIK Technology.

Kim, J., Park, M. & Kim, J. H., 2012. Feasibility analysis of hybrid seawater reverse osmosis (SWRO) and pressure retarded osmosis (PRO) system. In: 3rd Osmosis Summit Event, April 26-27, 2012, Barcelona.

Loeb, S., 1975. Osmotic Power Plants. Science, 189: 654-655.

Loeb, S., 1976. Production of energy from concentrated brines by pressure-retarded osmosis : I. Preliminary technical and economic correlations. Journal of Membrane Science, 1: 49-63.

MWH, 2007. Report 4 - Regional Water Needs and Integrated Urban Water Management Opportunities. Report prepared for the Council of Mayors South East Queensland, the Queensland Government and the Queensland Water Commission.

Norman, R. S., 1974. Water salination: a source of energy. Science, 186: 350-352.

Patterson, R. A., 1994. On-site treatment and disposal of septic tank effluent. PhD thesis, University of New England. Armidale.

Queensland Department of Natural Resources, 1997. Water Allocation and Management Planning (booklet). Queensland. Dept. of Natural Resources, Brisbane. 16 p.

Research And Markets, 2012. Analysing Osmotic Power. 150 p.

Rutovitz, J., Harris, S., Kuruppu, N. & Dunstan, C., 2011. Drilling down - Coal Seam Gas: A background paper. Report prepared for the city of Sidney Council. 80 p.

Saito, K., Irie, M., Zaitsu, S., Sakai, H., Hayashi, H. & Tanioka, A., 2012. Power generation with salinity gradient by pressure retarded osmosis using concentrated brine from SWRO system and treated sewage as pure water. Desalination and Water Treatment, 41: 114-121.

Seq Healthy Waterways Partnership, 2008. SEQ Regional Desalination Plant Sitting Studies. Synthesis report prepared for the Queensland Water Commission. 18 p.

Skilhagen, S. E., 2010. Osmotic power - a new, renewable energy source. Desalination and Water Treatment, 15: 271-278.

Syed, A., Melanie, J., Thorpe, S. & Penney, K., 2010. Australian energy projections to 2029-30. ABARE research report 10.02, prepared for the Department of Resources, Energy and Tourism, Canberra.

Yip, N. Y. & Elimelech, M., 2011. Performance Limiting Effects in Power Generation from Salinity Gradients by Pressure Retarded Osmosis. Environmental Science and Technology, 45:10273-10282.

Yip, N. Y. & Elimelech, M., 2012. Thermodynamic and Energy Efficiency Analysis of Power Generation from Natural Salinity Gradients by Pressure Retarded Osmosis. Environmental Science and Technology, 46:5230–5239.