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## Evaluation of the potential of osmotic energy as renewable energy source in realistic conditions

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### Abstract

The possibility of using osmotic energy as renewable energy source is discussed here, and some experimental results at realistic operating conditions are presented. It is shown how a membrane-based PRO system could transform osmotic energy of seawater into electricity aided by river or wastewater. This process mainly requires novel membranes, currently in development: some of these membranes are tested in realistic conditions of temperature, salinity and different flows values which makes possible to predict expected power productions

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## 1. INTRODUCTION

The salinity gradient (SG) power generation approach is a renewable energy technique based on exploiting the chemical differences between liquids with different concentrations of salts [1-2]. Several approaches are being developed, with a few pilot plants already in operation: we can emphasize the one based on reverse electro-dialysis, in development by REDStack in the Netherlands, and especially those installed by Statkraft in Norway and by Kyowakiden in Japan, that have shown the feasibility of one of the proposed SG technologies: the pressure retarded osmosis (PRO) technique [3-13].

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This paper concentrates on the use of PRO techniques to recover energy from seawater. In fact, the high salinity of seawater stores a significant amount of energy that can be recovered by being mixed with low-salinity water sources in salinity gradient power plant. As sources of this low salinity water, rivers and pre-treated effluent from wastewater treatment plants have been proposed [4-5-12].

Loeb and Mehta [6] used hydrophobic polymeric membranes and hollow-fiber membrane modules not particularly suited for PRO applications. From the point of view of implementation, the proposal requires mainly novel PRO membranes, as the performance of standard RO membranes in these PRO applications are limited and useless, due to the different pressures and flow directions: for a discussion of the characteristics of the required membranes, see, for example, [7-8]; for some recent advances see [9-10].

An evaluation of the potential of the proposal is presented here, based on a specific proposal for a PRO plant, together some experimental results based on measuring in a laboratory the characteristics of some PRO membranes. It is shown that if the performance of current laboratory-size membranes is maintained when scaling to an industrial-size membranes, the salinity gradient approach would provide a reliable renewable energy source, especially when warm water sources are available. In parallel works the possible implementation of PRO energy recovery systems is being studied for reverse osmosis [14-15].

## 2. PRO PLANT PROPOSAL

Figure 1 presents the basic idea behind any PRO process: water from a low salinity feed solution permeates through a membrane into a pressurized, high salinity draw solution; power is obtained by depressurizing a portion of the diluted through a hydro turbine to produce electricity.

As draw solution we propose to use brine water, whereas for feed solution there are a variety of possible sources (river water, municipal wastewater, industrial wastewater, etc). In practice, the low salinity flow always contains some impurities and its salinity increases due to a small diffusion of salts from the high salinity flow, so it has to be continuously purged. Moreover, pressure exchangers (ERIs) are the best option to produce the pressure needed at the high-salinity flow, as these pressure exchangers ensure a highly efficient transfer of pressure to the high-salinity flow inlet, from the draw solution outlet (which is a medium salinity flow thanks to the mixing with the feed solution that passed through the membranes), and with very little mixing.

Regarding the operating pressure  $P$ , as it is discussed later the optimal value can be estimated from the osmotic concentrations of the draw and feed solutions and the pressure at the feed side  $P_F$  (which must be maintained at a low value to improve the efficiency of the process).

Finally, as the pressure at the draw side outlet is slightly lower than at the inlet (due to losses), it has to be increased before the pressure exchangers using an impulse pump.

Summing up the above discussions gives our practical proposal for a PRO plant, which is presented in Figure 2.

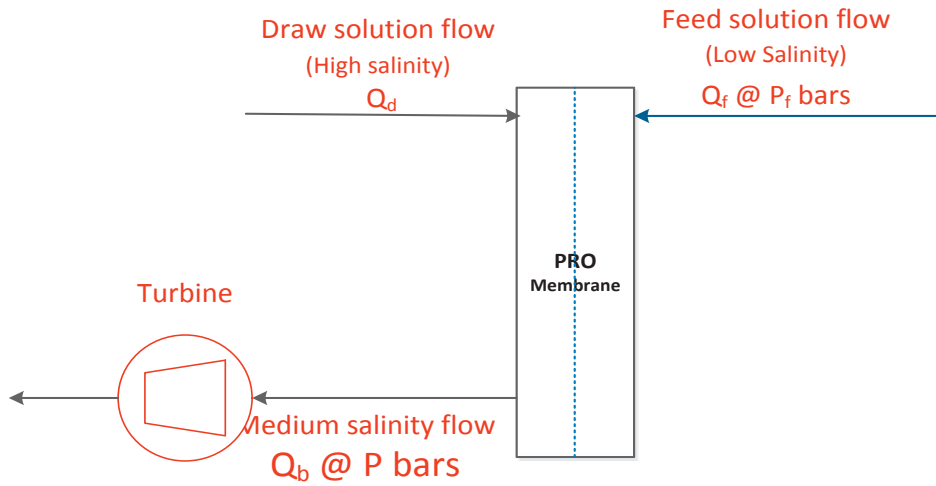


Figure 1: Basic Concept of the Pressure-Retarded Osmosis process

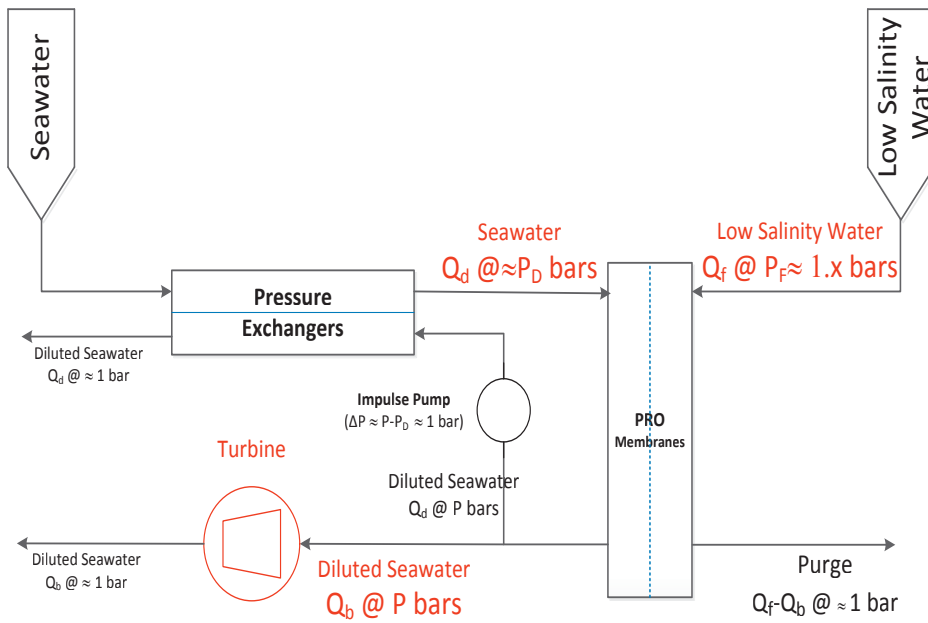


Figure 2: Schematic Diagram of seawater Salinity Gradient Plant using PRO membranes

## 2.1. PRESENTATION

As it can be seen in figure 1, two streams are pumped to the PRO membranes:

- 1) The draw flow ( $Q_D$ ), that has high salt concentration (around  $36 \text{ kg/m}^3$  for seawater), and would be regulated to have the pressure optimal for the PRO process (around half the difference of osmotic pressures, as it is discussed in next section).
- 2) A feed flow ( $Q_F$ ), of low-salinity water (in practice less than  $5 \text{ kg/m}^3$ ), from surface water or wastewater treatment plants. This stream would be regulated to have low pressure (slightly over 1 bar).

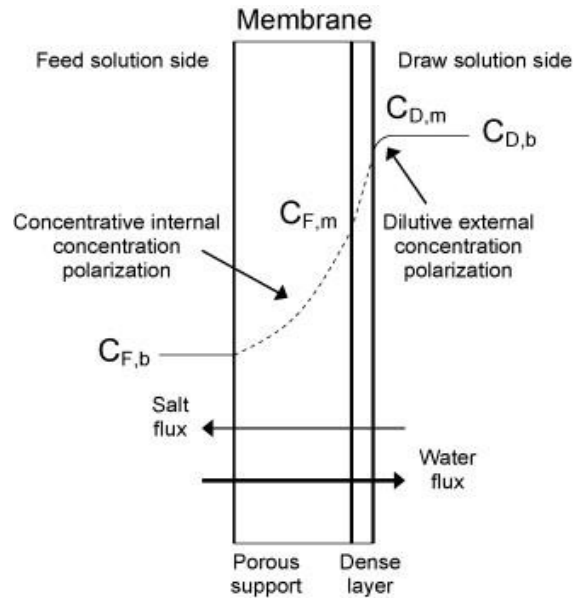


Figure3: Representation of Flows at the membrane surface, generated by salinity gradients. Internal and external concentration polarization are also shown

## 2.2 ESTIMATION OF PRODUCED ENERGY

The energy recovered at the turbine can be estimated from:

$$W \text{ (watt)} = Q_b \cdot P \cdot \eta \quad (1)$$

With  $Q_b$  the flow of water that crosses the PRO membrane,  $P$  operating pressure and  $\eta$  the efficiency of the turbine producing the electricity (As it is expected for the process to operate at varying flows, this turbine is assumed to be a Pelton or crossflow turbines, that give good efficiencies at a wide range of water flows: around 90% of for Pelton and 80% for a crossflow turbine. The efficiency of the turbines available in the industry is in the 20% to 100% range).

The main control parameter is the operating pressure  $P$ . In optimum conditions, it has been shown that the maximum energy for the PRO process is obtained when the difference of pressures between both sides of the PRO membrane is half of the osmotic pressure at the membrane (created by the difference of salinity between the draw and feed solutions); that is, the optimal value of the operating pressure is

$$P = P_f + \frac{\Delta\pi}{2} \quad (2)$$

Thus, a central aspect of the recovery of osmotic energy using PRO systems is to regulate this pressure at its optimal value; for this, the effective osmotic pressure is needed. This osmotic pressure is slightly smaller than the difference of osmotic pressures of draw and feed solutions (due to polarization and mixing effects). Taking into consideration the effect of the internal and external polarization concentrations on the water flux in PRO, the following model has been proposed [11]:

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

where the coefficients, described in the Nomenclature section, are experimentally determined, and the main parameter is  $J_w$ , the water flow that crosses the membrane per surface unit, that can be estimated solving the implicit equation

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

Where  $A$  is an empirical constant that depends on the membrane characteristics, the operating conditions (the temperature  $T$  in particular) and the degree of fouling and aging of the membrane.

Once the operating parameters are fixed, a certain  $Q_b$  would be obtained. If necessary, it is possible to estimate  $Q_b$ , by multiplication of the water flux  $J_w$  with the effective PRO membrane surface ( $S$ ):

$$Q_b = S \cdot J_w \quad (5)$$

### 2.3. EXPERIMENTAL VALIDATION

To validate the proposed energy recovery technique, experiments have been carried out at the Fraunhofer Institute for Interfacial Engineering and Biotechnology. Self-developed cellulose acetate membranes with an optimized internal structure [9] have been measured under realistic operating conditions, in order to estimate the expected energy production for the 1000 m<sup>3</sup>/h SW plant presented in Figure 4, using the models presented in section 2.2. More precisely, variation in process parameters (salt concentrations, pressures and flow rates) were used to get information on the obtained water flux through the membrane, which made possible to estimate the flow  $Q_b$ , and then predict the produced power using eq. (1), when the pressure applied to brine water is regulated at  $P = 13$  bars.

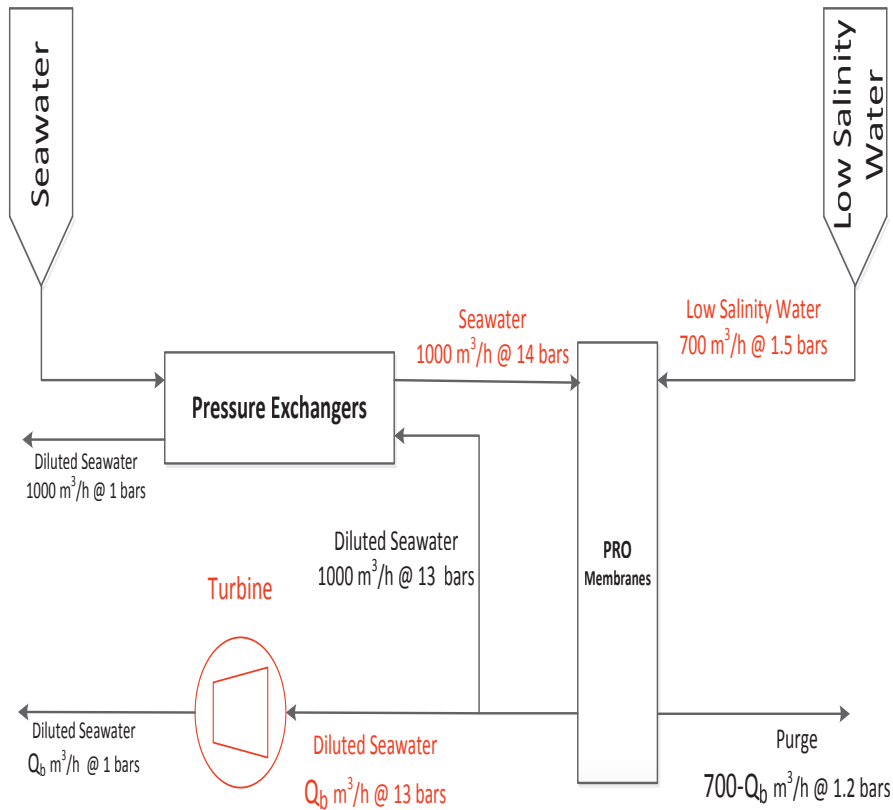


Figure 4: Schematic Diagram of a Seawater Salinity Gradient Plant using PRO membranes

Figures 5, 6 and 7 present some of these extrapolations from the experimental results, obtained at different values of salinities, crossflows and temperatures. The figure 5 shows that by increasing the velocity, the energy increases. That seems logical because the energy is directly proportional to the flow. It is also worth noting that at low values of velocity, increasing the power density is quite remarkable (see values for low flows), whereas for high values of the effect of velocity becomes smaller. It can be shown that we are near a change in the modification is to change the nature of flow through the membrane flux. Indeed, the Reynolds number characterizing the nature of the flow is directly related to the viscosity. Then, the concentration of fresh water side was increased significantly and the concentration of salt water side was kept constant. Also the temperature of both feed solutions was increased and kept equal for both sides of feed solutions. It can be seen that with the current first generation of PRO membranes, powers up to 150 kW could be obtained when both water feed temperatures are around 30°C. This value decreases with lower temperatures (about 40kW at 15°C) and higher feed salinities (around 40kW when using 10g/l draw solutions). Similarly, this power is expected to significantly increase with temperature. Thus, PRO seems already a promising renewable energy source in hot regions, and when there is adequate access to water at high temperatures (industrial wastewaters, cooling towers, etc).

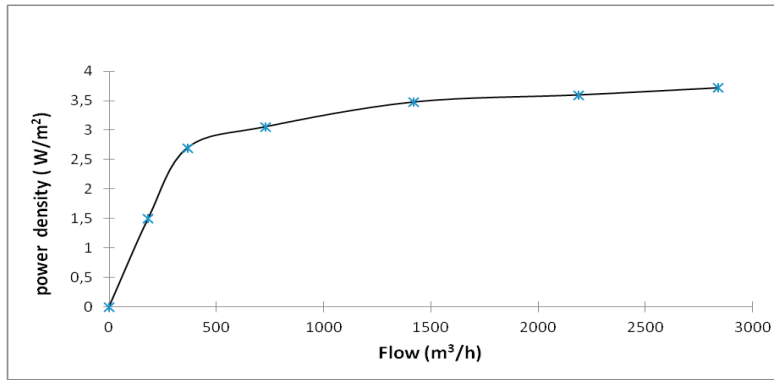


Figure 5: Power produced vs. flow [feed salinity fixed to be 0gr/l; Draw Feed Salinity: 36gr/l; temperature fixed to be 25°C].

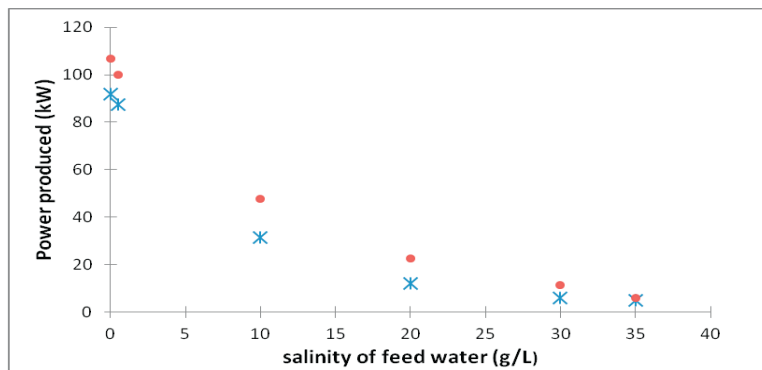


Figure 6: Power produced vs. feed water salinity at different flows [(•): 1430 m³/h, (\*):730 m³/h; temperature fixed to be 25°C]

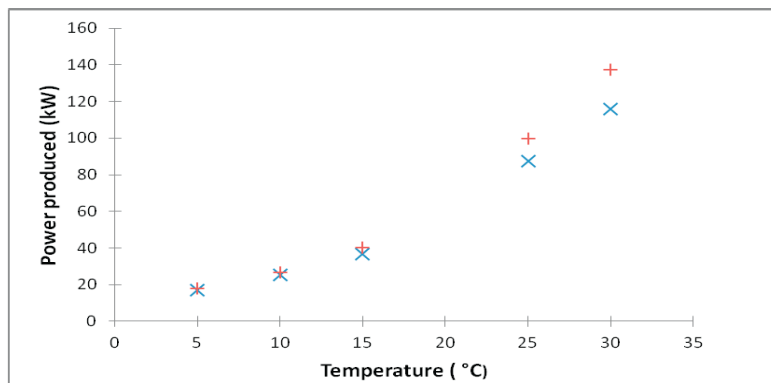


Figure 7: Power produced vs. temperature at different flows [(+): 1430 m³/h, (x):730 m³/h; fresh feed salinity fixed to be 0gr/l; Draw Feed Salinity: 36gr/l]

### 3. CONCLUSIONS

Preliminary results of the capability of recovering osmotic energy are discussed in this paper. Using certain Pressure Retarded Osmosis membranes it is shown that it is possible to recover as hydraulic pressure a significant part of the osmotic energy of the seawater, using different low-salinity water sources. Some experimental results using the current first generation of membranes make possible to predict the produced power, showing that PRO is a promising renewable energy source when using warm water sources.

Further work is being done to study in detail the effect of water sources at different temperatures and operating points, and propose control systems adequate for variable energy production.

### 4. ACKNOWLEDGEMENTS

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### Nomenclature

|             |  |
|-------------|--|
| $C_{F,b}$   | Salt concentration of the feed stream ( $\text{m}^3/\text{h}$ ).                       |
| $C_{F,m}$   | Salt concentration on the membrane surface at the feed side ( $\text{m}^3/\text{h}$ ). |
| $C_{D,b}$   | Salt concentration of the feed stream ( $\text{m}^3/\text{h}$ ).                       |
| $C_{D,m}$   | Salt concentration on the membrane surface at the draw side ( $\text{m}^3/\text{h}$ ). |
| $J_W$       | Water flux that crosses the membrane ( $\text{m}/\text{h}$ ).                          |
| $K$         | Salt resistivity ( $\text{h}/\text{m}$ ).  |
| $k$         | Mass transfer coefficient of the draw solution ( $\text{m}/\text{h}$ ).                |
| $P$         | Pressure at the draw side outlet of the PRO membranes (bar).                           |
| $P_T$       | Pressure at the turbine inlet of the PRO membranes (bar).                              |
| $P_F$       | Pressure at the feed solution side of the PRO membranes (bar).                         |
| $P_D$       | Pressure at the draw solution side of the PRO membranes (bar).                         |
| $Q_b$       | Volumetric flow of the water at the turbine ( $\text{m}^3/\text{h}$ ).                 |
| $Q_d$       | Volumetric flow of the draw solution: (high salinity, $\text{m}^3/\text{h}$ ).         |
| $Q_f$       | Volumetric flow of the feed solution: (low salinity, $\text{m}^3/\text{h}$ ).          |
| $S$         | Effective area of the PRO membranes ( $\text{m}^2$ ).                                  |
| $T$         | Temperature (K).   |
| $W$         | Electrical power produced (Watts).   |
| $w$         | power density ( $\text{W}/\text{m}^3$ ).   |
| $\eta$      | Pressure recovery efficiency (-).  |
| $\Delta\pi$ | Osmotic pressure (bar).  |
| $\pi_{D,b}$ | Osmotic pressure (bulk) of the draw solution (bar).                                    |
| $\pi_{F,b}$ | Osmotic pressure (bulk) of the feed solution (bar).                                    |



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