Osmotic Power Prototype for Generating Electricity and Reducing Greenhouse Gas Emissions in Remote Regions of Quebec

CCTC 2015 Paper Number XXXXXXXXXX

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Abstract

In many remote regions of Quebec, communities rely on expensive and polluting diesel-generators for electricity. Salinity gradients have been identified as an alternative source of energy for such applications. The free energy of mixing that is released when rivers meet the sea can be harnessed via pressure retarded osmosis (PRO) to generate sustainable and emission-free electricity. The process of PRO is explained here and a description is given of an osmotic power prototype that is being developed for Quebec. The system's performance and environmental impact are illustrated with a case study of its application to the remote community of Kuujjuarapik.

Keywords: osmotic power, pressure retarded osmosis, renewable energy, salinity gradient power

Résumé

Si l'article est en français, le résumé français sera le premier.

Mots clés : conférence, article, modèle, dix mots maximum

1. Introduction

One of the great challenges of our time is for society to adapt such that its activities become sustainable. Climate change and other environmental impacts have created the incentive for renewable energy as an alternative to traditional fossil fuels [1]. The earth's hydrological cycle is a huge store of renewable energy, among which a significant portion is available in the form of salinity gradients. Solar energy is absorbed by water as it is separated from solutes and evaporates into the atmosphere. When freshwater precipitation returns to the sea that potential energy is dissipated as heat. This source of power was first recognized by Pattle in 1954 [2], who observed that the energy available from a river meeting the ocean is equivalent to that of a waterfall over 200 m high [3, 4].

Although the total life cycle of osmotic power technologies has not yet been analyzed, the osmotic energy conversion process itself releases no greenhouse gases and it is hoped therefore that such technology can contribute to the goal of reducing carbon-emissions. In remote regions of Quebec where there are significant water resources, osmotic energy could conceivably replace diesel-powered generating stations and their associated greenhouse gas emissions. Electricity generation for a typical remote micro-grid in Quebec produces 10 000 tonnes of equivalent CO_2 emissions every year [5]. There is also a strong economic incentive for alternatives because the cost of generating electricity in such regions is on average 0.46 $/kWh [6].

Several processes have been proposed for converting salinity gradient energy to electricity however among the most promising is pressure retarded osmosis (PRO) [7]. In 2009 the Norwegian power company *Statkraft* placed the first PRO power plant prototype into operation [8]. The plant is located in Tofte, Norway and has a 10 kW design capacity based on its targeted membrane performance of 5 W/m^2 of membrane surface area. Until now it has been operated between 2 and 4 kW [9]. Other research institutes and companies also pursue the technology's development and potential commercialization, for example the *Mega-Ton Water System* project sponsored by the Japanese government. In this case the PRO process is integrated with a desalination plant, making use of the concentrated waste brine to produce electricity and thereby reduce the net power consumption of the desalination plant [10].

It is within this context that the OSMOP project was launched by a partnership including *Hydro-Québec*, *H_2O Innovation* and *Concordia University*, the goal of which is the development of a PRO power prototype in Quebec, Canada. This article reports on the progress of this project. The preliminary design of the prototype has been completed and is described here. The simulated performance of the prototype is also shown. Its potential for application to remote regions of Quebec is illustrated with a case study of its application to the in the community of Kuujjuarapik, in the northern region of Nunavik.

2. Theory

2.1. Energy and power from salinity gradients

The osmotic pressure difference $\Delta\Gamma$ between two solutions can be approximated by:

$$\Delta\Gamma \approx i_v \times R_g \times T \times \Delta c / M \qquad (1)$$

Where i_v is the number of ions in the solute, R_g is the ideal gas constant, T is the absolute temperature, Δc is the difference between the draw concentration c_D and the feed concentration c_F, and M is the molar mass of the solute.

In the case of the Great Whale River (c_F=0.1 g/l) (near Kuujjuarapik) flowing into the Hudson Bay (c_D=30 g/l), where T=0°C, and assuming that the solute is NaCl, in which case i_v=2 and M=0.05844 mol/kg, the osmotic pressure difference $\Delta\Gamma$= 23.2 bar.

The salinity gradient energy E_{SG} available from mixing a volume of feed solution V_F with an infinite volume of draw solution is given by,

$$E_{SG} = \Delta\Gamma \times V_F \qquad (2)$$

Similarly, the salinity gradient power W_{SG} available from a feed solution with flow rate Q_F is given by,

$$W_{SG} = \Delta\Gamma \times Q_F \qquad (3)$$

Referring again to the previous example, the energy and power available from the Great Whale River as it flows into the Hudson Bay is equivalent to the osmotic pressure difference between the solutions:

$\Delta\Gamma = E_{SG} / V_F = W_{SG} / Q_F$ = 23.2 bar = 0.65 kWh/m^3 = 2.32 MW/m^3/s

Because osmotic pressure is approximately proportional to concentration, super-saline sources offer greater energy potential. For example, the salinity gradient energy potentials of the Great Salt Lake and the Dead Sea are approximately 10.5 kWh/m^3 and 14.5 kWh/m^3 respectively [11, 12].

2.2. Pressure retarded osmosis

The process of pressure retarded osmosis (PRO) is illustrated in Fig. 1. In PRO a diluted feed solution (e.g. river water) with flow rate Q_F and a concentrated draw solution (e.g. sea water) with a flow rate Q_D are brought in to contact across a semipermeable membrane. The osmotic pressure difference between the solutions causes solvent to permeate (with flow rate Q_p) from the feed side to the draw side. When a hydraulic pressure ΔP (less than the osmotic pressure difference) is applied to the draw side, the rate of permeation is reduced (i.e. *retarded*) but the result is an expanding volume of pressurized draw solution. Electricity can be extracted from this volume via a hydro-turbine connected to a generator [13]-[16].

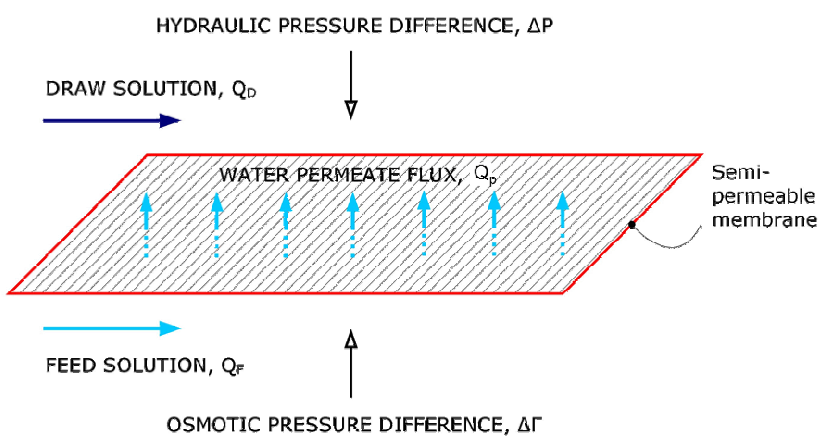

Figure 1. The process of pressure retarded osmosis (PRO).

The flow rate of water permeate across the membrane is given by,

$$Q_p = A \times A_m \times (\Delta\Gamma - \Delta P) \quad (4)$$

Where A is the membrane water permeability and A_m is the membrane surface area. From this relationship Q_p can be plotted as a function of ΔP, as shown in Fig. 2. As ΔP increases Q_p is reduced, until finally when $\Delta P = \Delta\Gamma$, $Q_p = 0$.

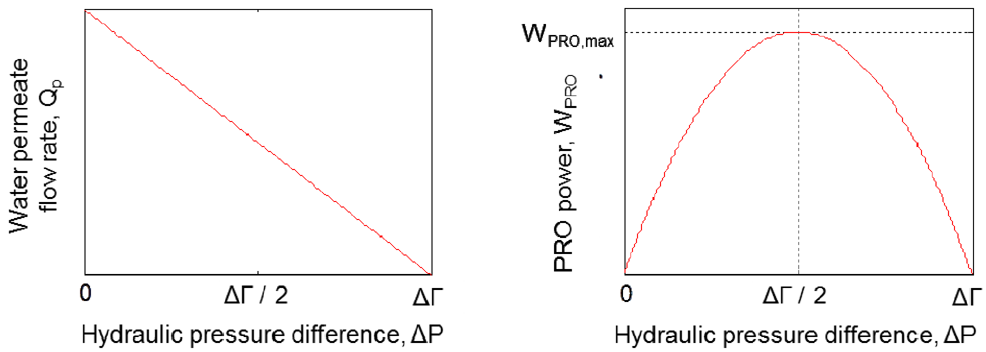

Figure 2. Water permeate Q_p and PRO power W_{PRO} as functions of the hydraulic pressure difference ΔP. The maximum power point $W_{PRO.max}$ is obtained when ΔP = ΔΓ / 2.

The power available from pressure retarded osmosis W_{PRO} is given by,

$$W_{PRO} = Q_p \times \Delta P \quad (5)$$

If equation (4) and (5) are combined, then W_{PRO} can be written as a function of ΔP,

$$W_{PRO} = [A \times A_m \times (\Delta\Gamma - \Delta P)] \times \Delta P = A \times A_m \times (\Delta\Gamma \times \Delta P - \Delta P^2) \quad (6)$$

By solving for $dW_{PRO} / d\Delta P = 0$, the theoretical maximum power point $W_{PRO,max}$ can be identified, as illustrated in Fig. 2.

$$dW_{PRO} / d\Delta P = d[A \times A_m \times (\Delta\Gamma \times \Delta P - \Delta P^2)] / d\Delta P = 0$$

$$\Delta P = \Delta\Gamma / 2$$

$$W_{PRO,max} = A \times A_m \times (\Delta\Gamma / 2)^2$$

In other words, in order to extract maximum power from the pressure retarded osmosis process only half of the osmotic pressure gradient can be exploited. If we desire to extract all of the energy available in the osmotic pressure gradient by setting ΔP = ΔΓ, the water permeate will approach zero and as a result so will power. This dynamic is analogous to the current-voltage relationship in a photovoltaic device, to the force-speed relationship in a wind turbine, and to the Carnot efficiency in a heat engine. In each case, in the interest of generating maximum power, not all of the potential energy is extracted from the source.

2.3. Osmotic power system

The configuration of the osmotic power plant is provided in Fig. 3. This is the same layout used in the *Statkraft* prototype [17-19]. Feed solution is supplied by an electric pump and is filtered before being introduced to one side of the membrane unit. Similarly, draw solution is supplied by an electric pump and is filtered. Before being introduced to the membrane unit, it is pressurized through a pressure exchanger and electric boost pump. This establishes the desired hydraulic pressure difference across the membrane. At the membrane outlet, draw solution is recirculated through the pressure exchanger while permeate flow is depressurized across a turbine and generator.

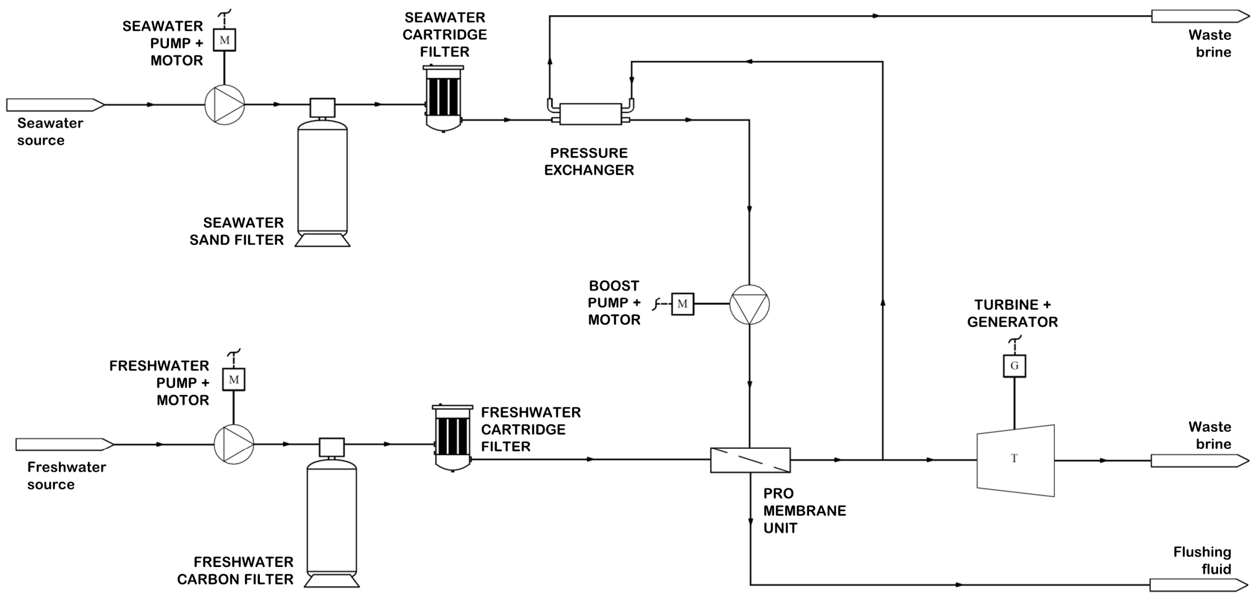

Figure 3. Diagram of PRO power plant prototype.

As previously described in equations (5) and (6), the hydraulic power developed by PRO is the product of the permeate flow rate and its hydraulic pressure above ambient. This hydraulic power must then be converted to electric power and the efficiency of the turbine $\eta_{turbine}$ and efficiency of the generator $\eta_{generator}$ will determine the gross electric power W_{gross},

$$W_{gross} = W_{PRO} \times \eta_{turbine} \times \eta_{generator} \quad (7)$$

Net electric power W_{net} available for the grid will then be gross electric power minus the power consumed by each of the electric pumps W_{pumps},

$$W_{net} = W_{gross} - W_{pumps} \quad (8)$$

Parasitic loads supplied by the electric pumps include pressure losses across the filters and across the membrane, and mechanical losses in the pressure exchanger.

The power flow in an osmotic power system is summarized in Fig. 4. The difference between the maximum theoretical PRO power and the effective PRO power is due to non-ideal membrane effects, as described in the next section.

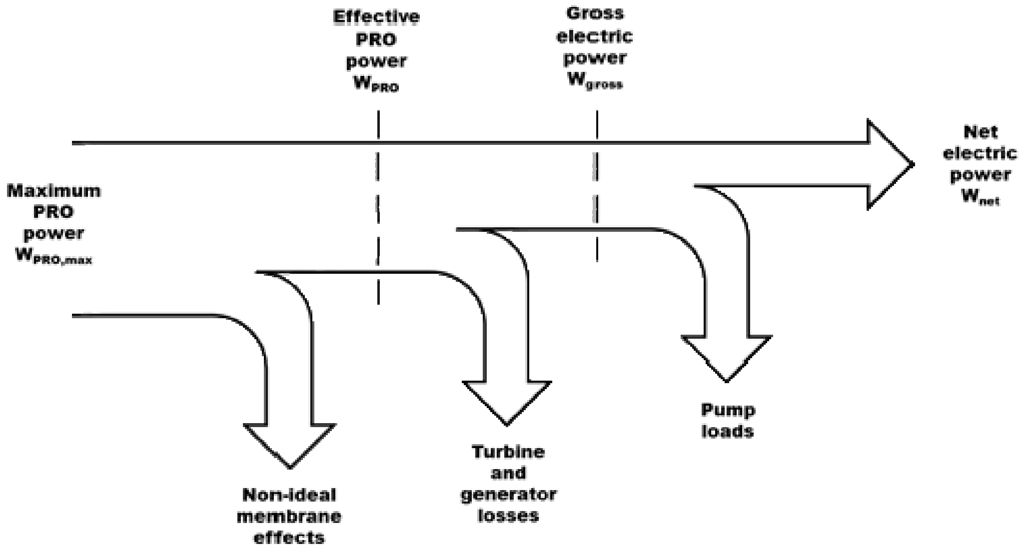

Figure 4. Power flow in a PRO power conversion system.

2.4. Non-ideal membrane effects

Values of PRO power are generally normalized over the membrane surface area and expressed in W/m^2. This provides a measure of the systems efficiency because system cost is expected to be proportional to the surface area of the membrane. It also provides a measure of membrane performance. This is useful because membrane technology has been the focus of most PRO power research and development. A power density of 5 W/m^2 has been proposed as a target for commercial viability [17].

From equation (4) it is clear that an upper bound to water permeate is imposed by the membrane, namely its water permeability. An ideal PRO membrane will have high water permeability. Achieving this however is complicated by the fact that water permeability is proportional to salt permeability, which is undesirable. Efforts have been made to optimize this trade-off in membrane parameters [20] and recent advances in membrane technology show laboratory results that surpass the 5 W/m^2 target [21, 22].

Salt leakage leads to concentration of the feed solution as it moves along the length of the membrane [23, 24]. This spatial variation in the feed concentration is illustrated in Fig. 5. The resulting outlet feed concentration $c_{F\ (out)}$ will be specific to the conditions under which the PRO process occurs. Fig. 5 also shows the spatial variation of the draw concentration, which is caused by water permeate. The result is that as flow advances along the length of the membrane the concentration gradient (and hence osmotic pressure gradient) is reduced.

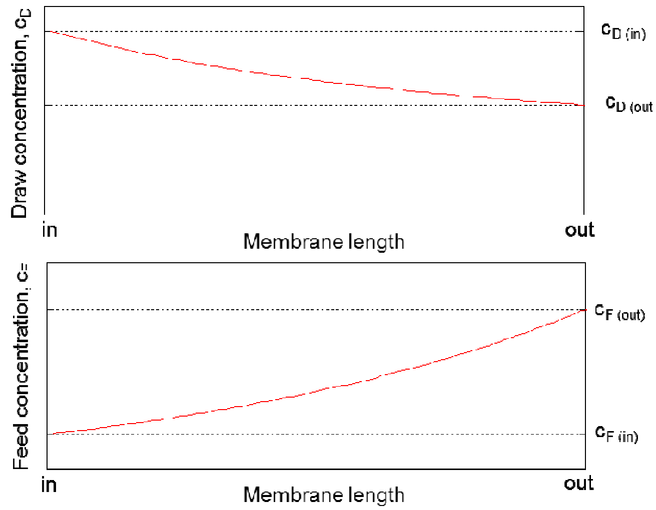

Figure 5. Variation in feed and draw concentrations along the length of the membrane.

Salt leakage also exacerbates another non-ideal membrane effect know as concentration polarization [23, 24]. As salt permeates to the feed side, it accumulates on the surface of the membrane and in the support layer which provides strength to the active membrane skin. Likewise, as water permeates to the draw side, it accumulates on the surface of the membrane. The result is that the effective concentration difference Δc_m across the active membrane skin is only a fraction of the bulk concentration difference Δc_b. The phenomenon is illustrated in Fig. 6, where the non-linear concentration profile is shown across the membrane skin and support layer.

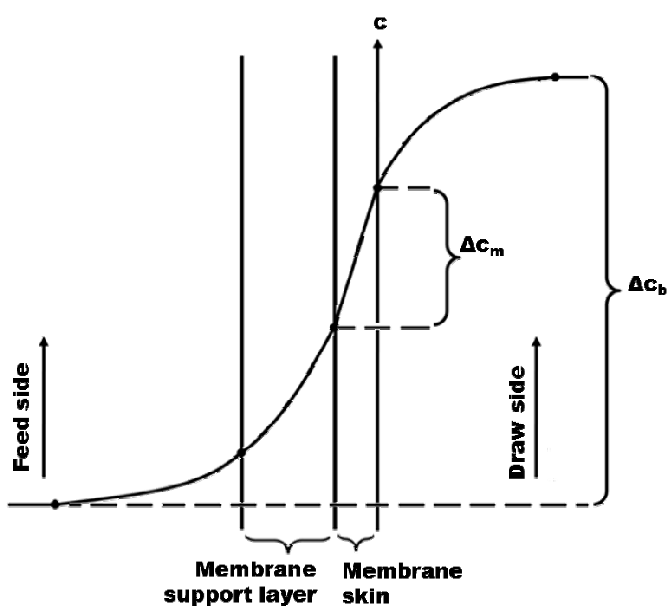

Figure 6. Concentration polarization causes the effective concentration difference Δc_m to be only a fraction of the bulk concentration difference Δc_b.

3. Osmotic power plant prototype

3.1. Prototype description

The PRO membrane is at the heart of the PRO power system. A commercially available membrane was selected for the prototype based on promising results achieved at the bench-scale. The key membrane parameters are summarized in Table 1 along with the suggested research and development targets for PRO membranes [19]. The selected membrane has high water permeability (above the target) which is desirable, but as discussed previously, this is accompanied by a high salt permeability (also above the target). The selected membrane has a very minimal structure parameter. This is a measure of the thickness, porosity and tortuosity of the membrane support layer. It is important to minimize this in order to reduce concentration polarization across its width.

Table 1. Membrane parameters

	Selected membrane	Target membrane [19]
Water permeability ($m^3/Pa{\cdot}s{\cdot}m^2$)	11.7×10^{-12}	10.0×10^{-12}
Salt permeability ($m^3/s{\cdot}m^2$)	0.40×10^{-6}	0.03×10^{-6}
Structure parameter (m)	267×10^{-6}	400×10^{-6}

The main mechanical and electrical components of the system include the pumps, motors, pressure exchanger, turbine, generator and filters. Efficiencies and pressure losses will vary as a function of the operating flow rates and hydraulic pressures however their specifications under average conditions are provided in Table 2.

Table 2. Equipment specifications

Component	Value
Pump and motor combined efficiency (%)	77
Pressure exchanger efficiency (%)	95
Turbine and generator combined efficiency (%)	85
Pressure drop on feed side filter (bar)	0.35
Pressure drop on draw side filter (bar)	0.35

3.2. Prototype operation and performance

The performance of an osmotic power plant is strongly influenced by the conditions under which it is operated [25, 26]. Previous studies have found that by adjusting operating flow rates and hydraulic pressures, non-ideal effects and pump loads can be minimized [23]. Using the methodology proposed by [23] the best operating conditions for the prototype were determined and the results are summarized in Fig. 7. These results assume that the prototype is installed in an environment similar to Kuujjuarapik, where c_F = 0.1 g/l, c_D = 30 g/l, and T = 0°C. As shown in Fig. 7, the maximum net electric power output of the system is achieved when the system is supplied with Q_F = 0.0042 m^3/s and Q_D = 0.0042 m^3/s, and when ΔP = 7.9 bar. The resulting net electric power output is 0.85 W/m^2.

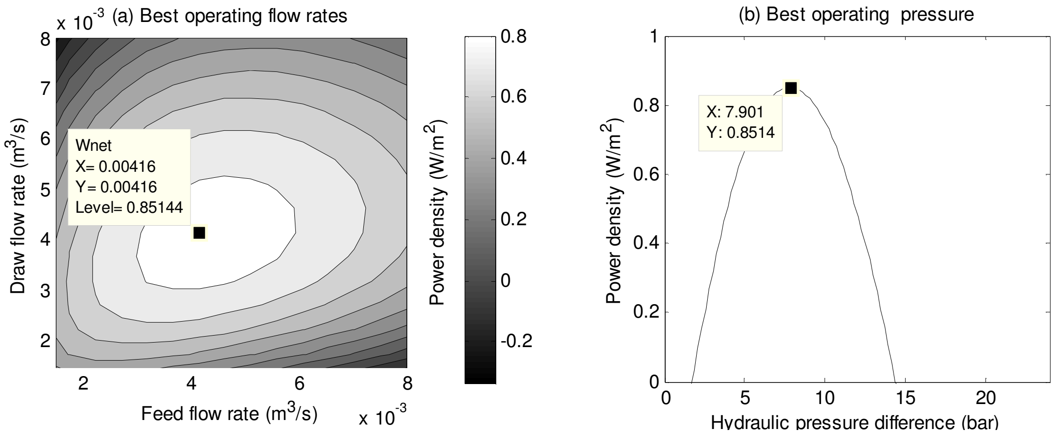

Figure 7. Operating conditions for achieving maximum net electric power output, showing the best feed and draw supply flow rates, and the best hydraulic pressure difference across the membrane.

Table 3 provides a summary of the power flow throughout the system and shows where the majority of the losses occur. An impressive 15.74 W/m^2 is available as the theoretical maximum of the PRO process under such conditions. Non-ideal membrane effects reduce the effective power of the PRO process to 1.84 W/m^2. Finally, mechanical and electrical inefficiencies and pump loads leave 0.85 W/m^2 of net electric power available for the grid. In other words, the efficiency of the power conversion process is 5.4%. In terms of energy, 7.7% of the energy available in the salinity gradient is harvested.

Table 3. Prototype performance

	Power W (W)	Power density W / A_m (W/m^2)	Energy density W / Q_F (kWh/m^3)
Maximum PRO	14 000	15.74	0.65
Effective PRO	1 630	1.84	0.11
Gross electric	1 400	1.56	0.09
Net electric	760	0.85	0.05

When comparing the performance of this system with other published data in the literature it is important to note that most published results report effective PRO power only and omit net electric power. Operating conditions can be selected so as to favour the effective PRO power; however such improvement can ultimately be detrimental to net electric power. For example, in the case of this prototype, by adjusting operating conditions the effective PRO power can actually exceed the 5 W/m^2. The resulting net electric power however would be negative.

3.3. Osmotic power potential in Kuujjuarapik

The potential to use osmotic power for electrification of remote micro-grids can be illustrated by considering the particular community of Kuujjuarapik, which is located at the estuary between the Great Whale River and the Hudson Bay. The Kuujjuarapik grid is diesel powered. It has an annual electricity consumption of 11 GWh and a peak demand of 2 MW. Electricity is produced at a cost of 0.70 $/kWh and the related greenhouse gas emissions are on the order of 7400 equivalent CO_2 tonnes/year [5, 6]. The Great Whale River has an average discharge of 670 m^3/s, and as mentioned previously, has an average concentration and temperature around c_F=0.1 g/l and T = 0 °C. The Hudson Bay has an average concentration and temperature around c_D = 30 g/l and T = 0 °C.

Assuming that the system's energy extraction efficiency (0.05 kWh/m^3) remains constant with scale-up, the energy that could be extracted from the total discharge of the Great Whale River is 1056 GWh/yr, as shown in Table 4. Only a small fraction of this potential would suffice to meet the energy needs of Kuujjuarapik. A feed flow rate of 11.1 m^3/s diverted from the river and supplied to a PRO power station equipped with 2.4 x 10^6 m^2 of membrane surface area would be able to meet peak power demand for the community. This represents less than 2% of the river's average flow rate, which is within the limits for environmentally sustainable river use [27]. Assuming that capital costs are proportional to membrane surface area at an optimistic rate of 5 $\$/m^2$ and assuming a membrane life of 5 years [28], the electricity price of osmotic power in Kuujuarapik is projected at 0.13 $/kWh. This is much less than the current price of 0.70 $/kWh.

It is also encouraging to consider the potential improvements that can be realized by advances in membrane technology. The performance of the prototype, equipped with the target membrane is illustrated in Table 4. In this case, power and energy extraction efficiencies are approximately double those of the commercially available membrane. The result is an electricity price of 0.07 $/kWh, which would be competitive not only in remote regions but throughout Quebec.

Table 4. Potential for osmotic power system near the remote community of Kuujjuarapik

	Net power density (W/m^2)	Net energy density (kWh/m^3)	Energy potential (GWh/yr)	Required membrane area (m^2)	Required flow rate (m^3/s)	Capital cost ($/W)	Electricity price ($/kWh)
Selected membrane	0.85	0.05	1 056	2.35 x 10^6	11.1	5.88	0.13
Target membrane	1.68	0.11	2 324	1.19 x 10^6	5.6	2.98	0.07

4. Conclusion

The potential for salinity gradient power and in particular pressure retarded osmotic power to provide clean and renewable energy is promising. As illustrated with the case of Kuujjuarapik, PRO power has near-term potential for applications to remote communities. Using currently available membrane technology, electric power could optimistically be generated by PRO at prices significantly lower than with current diesel stations.

At first glance the environmental case for osmotic power is encouraging, although detailed impact and life cycle analysis are still required. PRO produces no greenhouse gas emissions during operation. It is a run-of-river system requiring no damns, and in cases like Kuujjuarapik, it is hoped that the diversion of only a small portion of flow will have little to no effect on local ecosystems. That being said, estuaries are often ecologically sensitive areas and as such further investigation is needed. Alternatively, anthropogenic sources of wastewater could possibly be used as feed solution, for example from municipal or industrial water treatment plants. PRO application for energy recovery in desalination plants is also promising.

It is hoped that niche markets such as these will provide the incentive for continued research and development in osmotic power technology. The energy prices of 0.07 $/kWh obtained by this study using the target membrane, suggest that in the near to medium future osmotic power can become competitive not only in niche markets but also in mainstream power generation markets. It is with this goal in mind that the OSMOP power plant is being developed. The preliminary design of the prototype has been completed as described herein, and the project is now in the financing stages.

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6. Acknowledgements

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada Chair titled "Design and Performance of Special Electrical Machines" established in 2009 at Concordia University, in part by the Fonds de Recherche du Québec - Nature et Technologies, in part by Mitacs and in part by Hydro-Québec. The authors would like to thank C.B. Laflamme from Hydro-Québec, G. Clairet and from H_2O Innovation and C. Mulligan and S. Abbasi from Concordia University for their collaboration in the OSMOP project.

7. Biography

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