The potential of chemical-osmotic energy for renewable power generation

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Abstract: This paper presents a study on the potential of osmotic energy for power production. The study includes both pilot plant testing and theoretical modelling including cost estimation. A projected cost of 30 $/MWh of clean electricity could be achieved by using a Hydro-Osmotic Power (HOP) plant if a suitable membrane is used and the osmotic potential difference between the two solutions is greater than 25 bar; a condition that can be achieved in a number of ways.

Results have shown that the membrane system account for 50% - 80% of the HOP plant cost depending on the osmotic pressure difference level. Thus, further development in membrane technology and identifying suitable membranes would have significant impact on the feasibility of the process and the route to market. The results have shown the strong dependency of the produeced power cost on the membrane permeability. The results have also shown that a substantial reduction in the membrane area requirment for a given power output can be acheived as the osmotic pressure differnece between the two solutions increases beyoned 50 bar.

Keywords: *Osmotic Power, Salinity Gradient, Osmotic Energy, Renewable Energy*

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1. Introduction

The world's searching for cost-effective renewable energy (RE) sources is continuous and has taken many dimensions and directions. This has become more so, given the current urgency of climate change, dwindling world supplies of conventional fossil fuels, and increased oil prices. Alternative energy sources, including solar, wind, tidal wave, and biomass, have been used to provide secure, sustainable and adequate energy sources. However, expensive equipment and high installation costs of these technologies, coupled with the uneven availability distribution, have prevented them, so far, from being used widely. Affordable, clean, secure, and adequate energy sources remain one of the world's biggest challenges. Similarly, we have the great challenge of sufficient world freshwater availability.

Recent R&D activities at the Centre for Osmosis Research and Applications (CORA) at the University Surrey, and in collaboration with Modern Water plc, have investigated the potential of a relatively unexplored, renewable clean energy source with little or no environmental impacts, namely the Osmotic Energy (OE), or the power of osmosis [1,2]. Osmotic Energy is produced by the osmotic pressure difference between two miscible solutions of different potential energy due to, e.g., the concentration gradient. It is released in the process of mixing a low concentration solution and a high concentration solution, such as in the mixing of freshwater, which is relatively of low osmotic pressure, and seawater, which normally has higher osmotic pressure, through a semi-permeable membrane. The membrane retains the solute movement between the two solutions and only allows pure water. In an osmotic power plant, a large percentage of the osmotic potential difference, or the chemical energy of fresh water is converted into hydraulic pressure.

Theoretically, most of the consumed mechanical energy in the Reverse Osmosis (RO) process is stored in the concentrated solution in the forms of kinetic energy (hydraulic pressure) and osmotic or chemical energy (chemical potential). However, some of the energy dissipates in a form of heat at the high pressure pumps or in the frictional losses through and along the membrane. Up to 50% of this osmotic energy or chemical energy stored in the concentrated solution (brine), which is otherwise wasted, can be converted into mechanical energy through a Pressure Retarded Osmosis (PRO) process and recovered into hydropower [3-5]. This recovered pressure can be used to generate electricity using a hydro-turbine and generator in a similar way to conventional hydropower plants.

For example, each cubic meter of freshwater that runs into the sea with a salinity of about 35 g/*l* has, in theory, a chemical potential difference of about 0.7 kWh of energy [6]. This is because the osmotic pressure difference between seawater and freshwater is around 27 bars, which is theoretically equivalent to a 270 m waterfall. Therefore, each cubic meter of freshwater that runs into the sea could produce 0.7 kW of electricity (based on water flow through the membrane of 1 m^3/h). However, for higher salinity solutions, such as the Dead Sea or other salty lakes (e.g. salinity is higher than 20%), the chemical potential difference is higher and the produced power would be higher. The power production potential, is a function of the solutes concentration difference between two solutions, and does not require one to be freshwater, and the other to be salty water.

The generated hydraulic pressure can be utilised for the production of electricity by utilising the concept of the PRO by using a hydro-turbine and a generator in a form of land based Hydro-Osmotic Power (HOP) plant [7-9], or sub-sea or seabed-anchored plant, termed a Submarine Hydro Electric Osmotic Power Plant (SHEOPP) [10]. The generated hydraulic pressure can also be directly used through PES for pumping or other purposes [11].

The potential of osmotic energy is huge. According to Statkraft, the Norwegian power company, an osmosis-power plant could produce eco-electricity for $50-100 per MWh [12]. Its potential can be increased by combination with other renewable energy sources, such as solar, wind, tidal wave, biomass, and low-grade excess heat to further concentrate salty solutions. The global resource has been estimated at 2.6 TW [13]. The technical potential has been estimated at 2000 TWh/a [14]. Bearing in mind that these figures were derived, based purely on operation between the osmotic potentials of fresh and seawater. Additional opportunities are offered, as briefly mentioned in the introduction, by discharges from the desalination industry.

An economic assessment of a 48 MWe power plant, using the brine from an RO-concentrated seawater plant, estimated the cost of produced electricity at about 28 $/MWh [15,16]. This figure compares to about 29, 22, 12, and 5 $/MWh to produce electricity from nuclear, coal, natural gas and hydropower plants, respectively.

1.1. Open and Closed Cycle HOP Processes

There are a number of ways to recover the osmotic or the chemical energy of concentrated and salty solutions.. For the case of seawater and freshwater, e.g. up to 50% of the OE can be recovered across a semi-permeable membrane in an open cycle system. The low salinity water, Feed Water (FW), is fed at low osmotic and hydraulic pressures to one side of an Osmotic Membrane Unit (OMU), while a Draw Solution (DS), e.g. seawater or brine, is fed to the other side at higher osmotic and hydraulic pressures, where the hydraulic pressure of the DS is normally lower than the osmotic pressure. The discharged concentrated FW is circulated to the freshwater source, while the diluted DS is used to operate a turbine in order to generate power. A more efficient process can be achieved by recycling some of the pressurised solution, leaving the OMU and through a PES to assist in pumping the brine to the OMU. This process is applied when there is a continuous supply of freshwater and seawater, e.g., at a river run-off point to a sea or to a salty lake [12].

Alternatively, a closed cycle HOP plant has also been proposed [1, 10], where a DS can replace the seawater. The draw agent is retained in the system by using a Regeneration Unit (RU), which may be another separation technique, such as evaporation, crystallization, or membrane separation. In the closed cycle HOP plant, the generated hydraulic pressure can be used to produce electricity in a similar way to the open cycle system or could be transferred to other liquids through a PES for pumping processes. The efficiency of the closed HOP system depends on the availability of a low-grade energy source and/or renewable energy sources for the regeneration of the osmotic agents. Examples of renewable energy sources include, solar, geothermal, and wind for evaporation in hot and dry climates or cold temperature for crystallisation in cold climates, and/or waste heat from power and chemical plants anywhere. Recent development has been carried out to the closed-cycle process by usimg ammonia-carbon dioxide solution as DS, which is regenerated by thermal separation [17].

2. Commercial Potential and Cost Estimation

Research and development activities at CORA, and in collaboration with Modern Water plc, have shown that the potential of the hydro-osmotic power (HOP) is far greater than what had been previously assessed by other workers in this field [3,12,18]. CORA activities have involved both pilot plant testing and theoretical studies to investigate the potential of osmotic energy. For a closed-cycle HOP plant, several design and economic parameters have been assumed to carry out the calculations.

For two different, but constant, system permeabilities (A_w), 0.1 and 1 l/m^2.h.bar , Fig. 5 shows the total capital cost, the cost of the produced electricity, and the total required membrane area by using a closed cycle plant for 25 MW net electricity production. The resutls are obtianed for a rnage of osmotic pressure differences, $\Delta\Pi_f$, between the inlet concentrated, DS, and the inlet dilute, FW, to the osmotic membreane unit, OMU. The regenration unit has been assumed to be as another osmotic (FO) unit with similar membrane permeability.

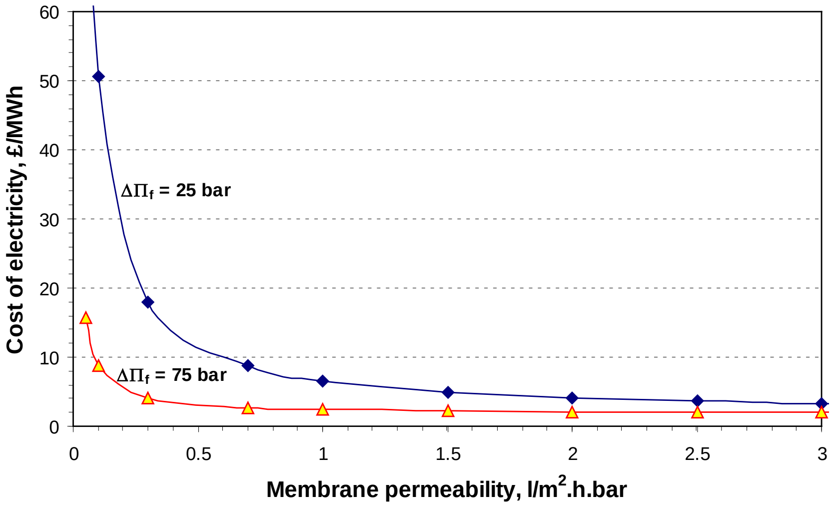

Fig. 5. The estimated cost of electricity of the proposed closed cycle HOP plant for 25 MW net power production at two osmotic pressure differnces $\Delta\Pi_f$) at the FO unit, 25 and 75 bars, by utilising 15 bars hydraulic pressure at the DS side, as a function of the membrane permeability.

It can be clearly noted the high effect of the membrane permeability on the total capital cost due to membrane contribution. The results also show that a substantial reduction in the membrane area requirment for a given power output can be acheived as the osmotic pressure differnece increases beyoned 50 bar. The cost breakdown for such a plant is calculated. More clearly, Fig. 5 shows the cost of electricity as a function of the membrane permeability for two cases of $\Delta\Pi_f$, e.g. 25 and 75 bar, respectively.

The results suggest that for osmotic pressure difference higher than 50 bar, increasing the membrane permeability beyoned 0.3 l/m^2.h.bar has little or no effect on the overall cost of the produced electricity.

3. Experimental Setup

Several pilot plant runs have been carried out with variable DS inlet hydraulic pressure at constant temperature (25^{o}C) and feed flow rates using an OMU module having high surface area (more than 100 m^2). The pilot plant setup is schematically shown in Fig. 2. A controllable needle valve was used to replace the turbine generator assembly. The DS and FW used were aqueous solutions of NaCl salt at different concentrations to simulate fresh water (280 ppm), brackish water (6,900 ppm), seawater (~35,000 ppm), and high salinity water (145,000 ppm).

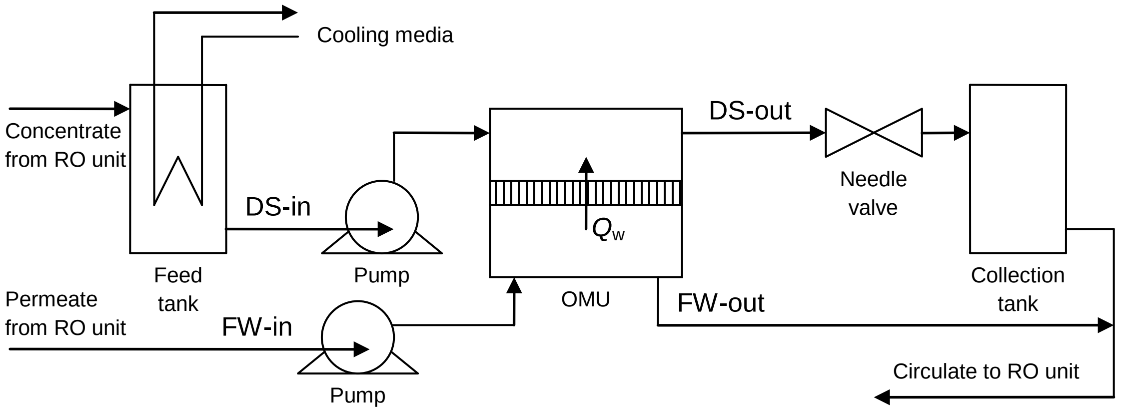

Fig. 2. Schematic diagram for the pilot plant setup.

Table 1 shows the main operational conditions of these three experiments. The discharges from the OMU were circulated to an RO unit to regenerate the concentrated DS as well as the diluted FW. A cooling for the feed tank has been used to control the increase of temperature during operation.

Table 1. The operational conditions for the pilot plant runs

Experiment no.	FW-in		DS-in		$\Delta\Pi_f$, bar
	Concentration, ppm	Flow rate*, l/min	Concentration, ppm	Flow rate, l/min	
1	240	11.1	34560	9.8	27.4
2	6900	10.9	145000	5.5	125.3
3	6900	9.5	34690	5.5	22.1

* Average value

The inlet FW is fed to the module at constant hydraulic pressure, though its flowrate was variable depending on the rate of membrane flux. The concentration measurements at the different locations of the process were obtained by using a portable conductivity meter, while flowrate and pressure measurements were taken from online digital flow meters and pressure gauges, respectively.

4. Results and Discussion

Firstly, the pure water permeability has been measured for the membrane (A_{wm}) by using pure water as feed (into the DS side) at 25^{o}C. The test has been carried out by modifying the OMU to an RO setup. The A_{wm} found to be decreasing with ΔP within the experimental range of 5 to 30 bars, according to the following relationship:

$$A_{wm} = 0.3265 - 0.0045\ \ln(\Delta P) \qquad (1)$$

The system permeability (A_w) has then been experimentally determined in a PRO setup as the product from dividing the measured water flux by the net driving pressure ($\Delta\Pi$-ΔP). Each experiment has been referred to by its number as indicated in Table 1. The A_{wm} is also shown in this figure for comparison. The A_{wm} is the upper limit for the A_w; it departs from A_{wm} as the entered solutions become more concentrated or as the ΔP increases. This indicates the effect of the A_{ws}, which is estimated by using Equations (1) and plotted in Fig. 3 as a function of the DS inlet hydraulic pressure.

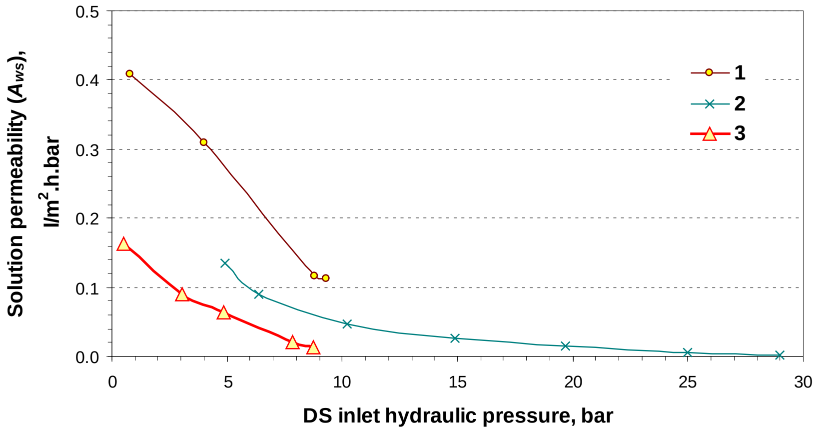

Fig. 3. The solution permeability coefficient (A_{ws}) as a function of the DS inlet hydraulic pressure.

From a comparison between the obtained values for A_{wm} and A_{ws}, the controlling phase for water transfer can be predicted. It can be noted from the case of experiment 1, where freshwater was used as FW and seawater as DS, that the membrane phase controls water transfer at low hydraulic pressures, as A_{wm} value is lower than that of A_{ws}, while at higher hydraulic pressures, the solution phase appear to be the controlling one. In the other two cases of experiments 2 and 3, where higher concentration solutions were used on both sides of the membrane, the A_{ws} was always lower than A_{wm}, which refer to the higher effect of the solution.

The following figures illustrate the calculated P_G, ρ_E, E_S, and W, (The gross power production, energy density, specific energy production and the power obtained from the PRO process respectively) as a function of the hydraulic pressure of the inlet DS. Results shown in Fig. 5 that the produced gross power, P_G, increases as the osmotic pressure (or the solute concentration) difference between the inlet FW and the inlet DS increases. Values of up to 90 watts were obtained when using freshwater as FW and seawater as DS.

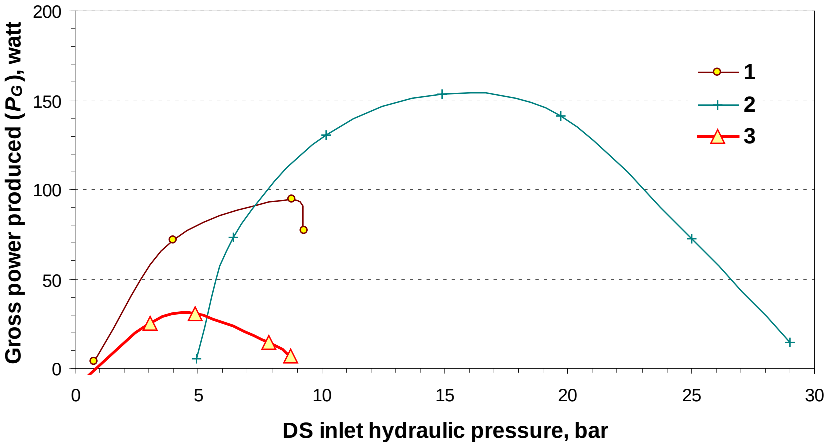

Fig. 4. Gross power produced (P_G) as a function of the DS inlet hydraulic pressure.

By using brackish water as FW with the same DS, less P_G was produced with maximum obtained values of up to 30 watts, while by utilising brackish water as FW and high salinity water as DS, the maximum P_G produced was more than 150 watts.

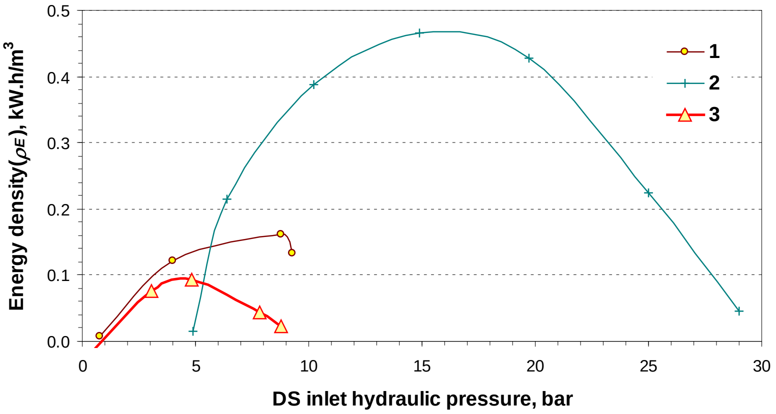

Fig.5. Energy Density (ρ_E) of the Ds as a function of its inlet hydraulic pressure for different osmotic-systems.

The effect of the hydraulic pressure at the DS side on P_G has been found to be dependant on the DS and the FW inlet concentrations, i.e. $\Delta\Pi_f$. However, different results are expected to be obtained with different membrane modules even if similar solutions and operational conditions are utilised. Practically, it has been found that the maximum value of the P_G is achieved when the hydraulic pressure drop at the DS side ($P_{DS\text{-}in}$-$P_{DS\text{-}out}$) becomes at minimum.

Fig. 5 shows the energy density (ρ_E) (in kWh/m^3 or J/m^3) of the input DS as a function of its inlet hydraulic pressure. Results show that the ρ_E, similarly to P_G, increases as the osmotic pressure difference between the FW and the DS increases. Fig. 6 shows the specific power production (E_S) of the system, based on the permeate rate, as a function of the DS feed hydraulic pressure. Results show that the E_S increases as the feed hydraulic pressure of the DS increases; however, it decreases when P_G becomes low and by increasing $\Delta\Pi_f$.

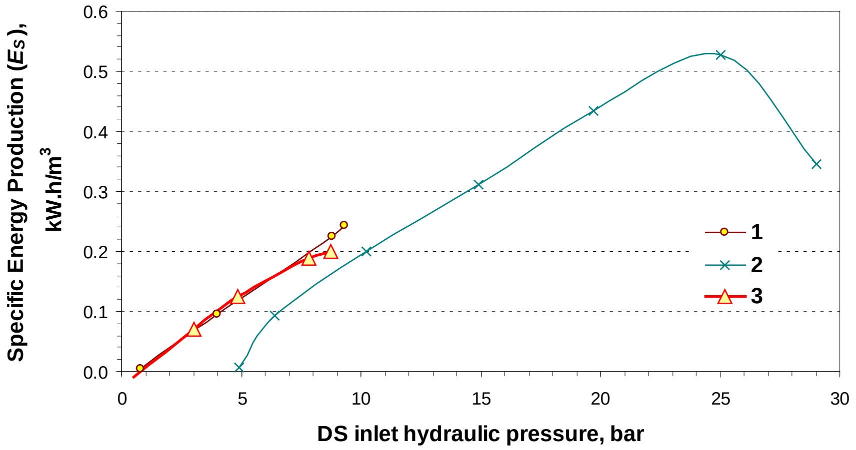

Fig. 6. Specific Energy Production (E_S) as a function of the DS inlet hydraulic pressure for different osmotic systems.

5. Conclusions

In this study both theoretical and experimental investigations of the potential of the osmotic energy (salinity gradient) for power generation have been carried out. The results indicate a high potential of the osmotic energy for power generation using the Hydro Osmotic Process. Several theoretical calculations have been presented, which show e.g. that a clean electricity could be produced using the HOP process at a projected cost of 30 \$/MWh, if a suitable membrane is used, and the osmotic potential difference between the two solutions is greater than 25 bar; a condition that can be readily achieved in many sites around the world. The results also illustrate the effect of the membrane permeability and the osmotic pressure difference across the membrane in the osmotic membrane unit (OMU) on the HOP plant cost and productivity.

This study further presents the pilot plant results under different operational conditions. The experiments show the effect of the physical properties of the FW and the DS solutions on the water permeability across the semi-permeable membrane in PRO processes. The permeability of the membrane is a critical issue when the HOP process feasibility is being evaluated. Increasing of the membrane permeability decreases the capital cost and increases the productivity. The interaction between the fluid properties and the membrane properties need to be considered when these processes are to be developed in future.

It has been experimentally found that the gross power produced is obtained when the hydraulic pressure drop at the draw solution side of the OMU becomes minimal.

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