A comparison of reverse electrodialysis and pressure retarded osmosis as technologies for salinity gradient power

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Abstract

The global salinity gradient power (SGP) potential is between 1 650 - 2 000 $\frac{\text{TWH}}{\text{a}}$ and can be converted by mixing two solutions with different salinities. The harnessing of SGP for conversion into power can be accomplished by means of pressure retarded osmosis (PRO) and reverse electrodialysis (RED). PRO and RED are membrane-based technologies and have different working principles. PRO uses a semipermeable membrane to seperate a concentrated salt solution from a diluted solution. The diluted solution flows through the semipermeable membrane towards the concentrated solution, which increases the pressure within the concentrated solution chamber. The pressure is balanced by a turbine and electricity is generated. RED uses the transport of ions through cation and anion exchange membranes. The chambers between the membranes are alternately filled with a concentrated and diluted solution. The salinity gradient difference is the driving force in transporting ions that results in an electric potential, which is then converted to electricity. The comparison shows that there are two different fields of application for PRO and RED. PRO is especially suitable at extracting salinity energy from large concentration differences. In contrast, RED are not effect by increasing concentration differences. So PRO are supposed to focus on applications with brines or waste water and RED on applications with river water and seawater. Moreover, just a few measured values from processes under real conditions are available, which makes it difficult to compare PRO and RED.

Keywords: osmotic power, salinity gradient power, salinity gradient energy, blue energy, pressure retarded osmosis, reverse electrodialysis

1 Introduction

The Covid-19 pandemic has caused high disruption to the energy sector. It is estimated that global energy demand is expected to fall by 5 % and energy-related CO_2 emissions by 7 %. The estimated decline of 8 % in oil demand and 7 % in coal use contrasts with a slight rise in the contribution of renewable energies. Especially an increase of solar and wind power is predicted [1] but both technologies are dependent on the present weather conditions, hence require back up supplies from other sources. Unlike wind and solar power, salinity gradient power (SGP)[1] has the characteristic of a base load source of renewable energy. Therefore SGP is able to generate a constant and reliable supply of power and has also a low environmental impact [2, 3].

SGP is generated by converting the chemical potential difference between two salt solutions with different concentrations into electrical or mechanical energy. It is a clean and sustainable energy source with no toxic gas emissions. SGP is available where salt solutions of different salinity mix, for example where fresh river water flows into the sea, or where industrial brine is discharged [3, 4]. The global energy potential is estimated to be between 1 650 - 2 000 $\frac{\text{TWH}}{\text{a}}$ [2, 4]. The harnessing of this energy for conversion into power can be accomplished by means of pressure retarded osmosis (PRO) and reverse electrodialysis (RED). PRO and RED are the two promising technologies which are at the most advanced stage of development [4]. This short review analyses technical, economical and other aspects in order to show which technology has more promising future prospects. At first PRO and RED are briefly explained. Then follows the comparison with focus on the literature. After that pilot power plants are presented and a conclusion is drawn.

2 Pressure Retarded Osmosis

The energy released through the mixing of fresh water and salt water can be explained using the osmosis effect. Osmosis is the transport of water across a semipermeable membrane from a solution of a lower salt concentration (feed solution) to a solution of a higher salt concentration (draw solution) [2]. The semipermeable membrane retains the passage of salts.

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[1] Also known as salinity gradient energy, osmotic power, blue energy

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The chemical potential difference between both solutions creates a driving force. The water of the feed solution diffuses through the membrane toward the draw solution in order to equalize the chemical potential difference [3]. In PRO, an external hydraulic pressure is applied to the draw solution side. The transport of water molecules into draw solution side leads to the increase of flow rate since the volume is controlled. Then a turbine and generator can be introduced to generate power using the pressurized flow of the diluted draw solution (Figure 1) [5]. The osmotic pressure of a solution can be calculated using the van't Hoff equation, as shown below [3]:

$$\Pi = i \cdot c \cdot R \cdot T \quad (1)$$

Π	Osmotic pressure (Pa)
i	Number of osmotically active particles
c_j	Molar Concentration ($\frac{\text{kmol}}{\text{m}^3}$)
R	Universal gas constant (8314 $\frac{\text{Nm}}{\text{kmol}\cdot\text{K}}$)
T	Absolute temperature (K)

For sea water, for example, where the sodium chloride (NaCl) solution ranges from 0.51 - 0.68 $\frac{\text{kmol}}{\text{m}^3}$ and $i = 2$, the osmotic pressure, for a temperature of 25 °C, is between 2.5 and 3.4 MPa [2].

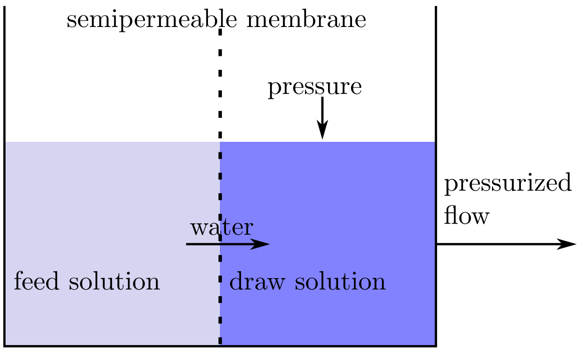

Fig. 1: Pressure retarded osmosis process [5].

3 Reverse Electrodialysis

In RED, the energy of mixing two solutions with different salinity is extracted through the transport of ions. Figure 2 shows the schematic illustration of RED. A concentrated salt solution (e.g. sea water) and a diluted salt solution (e.g. river water) are separated by an alternating series of cation and anion exchange membranes (CEM and AEM). The AEM contain fixed positive charges only allow the selective transport of anions toward the anode, whereas the CEM contain fixed negative charges only allow the selective passage of cations towards the cathode [3]. Salinity gradient and charge segregation induced by ion exchange membranes generate an electrochemical potential. The electrochemical potential difference causes the transport of ions through the membranes. For a sodium chloride solution, sodium ions permeate through the CEM in the direction of the cathode, and chloride ions permeate through the AEM in the direction of the anode. The ionic current is converted into electrical current by redox reactions that occur at the electrodes at the outside of the stack. The redox couple is used to reduce the transfer of electrons. The electrons released at the anode are subsequently transported through an external circuit containing an external load, to the cathode [3, 5].

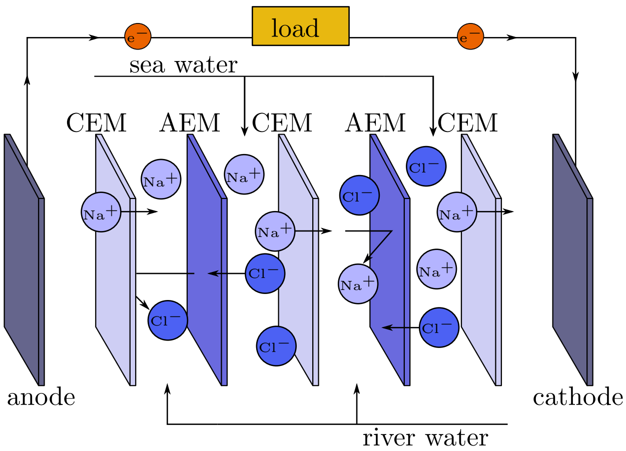

Fig. 2: Schematic illustration of RED. The redox pair helping ionic current to electron flows in the wire, the electrode rinse solution and the brackish water are not depicted [3, 5]. Acronyms: CEM (cation exchange membrane), AEM (anion exchange membrane), Na^+ (sodium-ion), Cl^- (chloride-ion), e^- (electron).

4 Comparison of PRO and RED

In the literature are several publications which only focus on PRO or RED [2, 4, 6, 7] but only a few articles compare these two processes [8, 9]. If only one technology is considered in an article, a comparison is not that easy. There are several reasons for this, for example

- efficiency losses,
- salinities and
- comparative values

are dealt with differently. For PRO the efficiency losses due to conversion of hydrostatic potential energy to electrical energy by a turbine and generator have taken into account. For RED the efficiency losses due to electrode reactions have taken into account. Furthermore, it is important to use the same mixtures of sodium chloride solutions. For PRO the salt concentrations of the diluted solutions are often kept considerably low whereas for RED the salt concentrations of the diluted solutions are higher. Moreover,

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the only reported measure of performance for each process is often the power density. However, for a comparison several variables have to be considered [8].
Based on this, Post et al. [8] and Yip and Elimelech [9] developed methods which allows a comparison of PRO and RED under equal conditions. In addition to the power density the authors considered the efficiency. The power density ($\frac{\mathrm{W}}{\mathrm{m}^2}$) is defined as the power produced per unit membrane area and is a measure of how quickly the membranes convert salinity energy to useful work. The efficiency (%) is the ratio of power produced to the amount of free energy which can be obtained from mixing two solutions with different salinities [8, 9].
The study by Post et al. [8] refers to the state-of-the art of PRO and RED in 2006. For power generation from mixing river water and seawater, the results show a higher power density and a higher efficiency for RED. For power generation from mixing a brine and less concentrated water, both are higher for PRO. In further steps the future potential of PRO and RED was considered. Higher performances was achieved for both techniques. According to Post et al., the development should focus on

- membrane characteristics for PRO (i.e. increasing the water permeability of the membrane skin and optimization of the porous support) and
- system characteristics for RED (i.e. optimization of the internal resistance, which is mainly determined by the width of the spacers) [8]

in order to achieve the potential performances. Referring to economic aspects, they assumed two to three times higher membrane costs for RED. However, the installed costs (including membranes, pumps, turbines) were estimated in the same order of magnitude but they assumed decreasing membrane costs for RED. Post et al. assumed in their model a co-current system which is not necessarily applied in practical operation. They also neglected efficiency losses (e.g. friction losses, pump and turbine efficiencies) which have different kinds of effect to PRO than RED [8].
The method of Yip and Elimelech [9] centers on membrane-based performance and was published in 2014. According to the authors, PRO is able to achieve greater efficiency and higher power density performance for a range of salinity gradients, compared to RED. PRO is especially suitable at extracting salinity energy from large concentration differences because PRO effectively uses larger salinity differences for driving force augmentation. As reported by Yip end Elimelech, RED is unable to gain appreciable power density benefits from salinity gradient increases, regardless of membrane transport properties. Furthermore the authors mention that the selectivity of the ion exchange membranes decrease at high solution concentrations, which leads to low efficiencies. So the application of RED energy production is restricted to relatively small salinity gradients. Referring to the economic aspects, Yip and Elimelch calculated higher costs for the ion exchange membranes employed in RED stacks than the semipermeable membranes in PRO modules. According to Yip and Elimelch the development should focus on greater permselectivity and higher conductivity for RED. For PRO, the authors see insufficient membrane robustness to withstand the high pressures due to large salinity gradients. In the study by Yip and Elimelch components like water turbines and pumps were neglected for PRO. This components are significant for converting mechanical energy to electrical energy. In comparison, RED employ a redox couple to convert salinity energy to electrical without mechanical components but also require pumping energy to circulate the solutions through the stack. In addition, foulants were not considered in the input streams, although this reduces the productivity [9].
Both studies come to similar results. However, a closer comparison is achieved when PRO and RED are considered under real operating conditions in pilot power plants.

4.1 PRO pilot power plant

In 2009, the first PRO pilot power plant was opened by the company Statkraft in Tofte (Norway). The pilot plant is equipped with 2 000 m^2 of membranes and has a power density of 1 $\frac{\mathrm{W}}{\mathrm{m}^2}$. The plant is described to utilize 20 $\frac{\mathrm{l}}{\mathrm{s}}$ seawater and 13 $\frac{\mathrm{l}}{\mathrm{s}}$ river water. Crucial for the power performance and reduction of membrane fouling is the pre-treatment of the incoming solutions. Rivers contain significant amounts of organic matter and silt, which contents vary considerably during the seasons. Therefore the pre-treatment for river water consists of a 50-µm pore size filter and a ultrafiltration plant. The pre-treatment of river water is more complex than with seawater because the seawater is supplied through water pipes approximately 35 m below sea level. The pre-treatment based solely on a 50 µm pore size filter. Due to the filtrations and standard maintenance cycle of the membranes, the performance is sustained for 7 - 10 years. The goal of the Statkraft power plant is to reach a power density of 5 $\frac{\mathrm{W}}{\mathrm{m}^2}$. A power density of 1 $\frac{\mathrm{W}}{\mathrm{m}^2}$ is not economical. This low power density requires a large area of membranes in order to produce an appreciable power output. For instance, the total membrane area for a 2 MW power plant would have to be 2 km^2 which results in high costs so the business is not financially profitable [2].
The goal of Statkraft, a power density of 5 $\frac{\mathrm{W}}{\mathrm{m}^2}$, could not be achieved so the pilot power plant was closed in December 2013. Statkraft justified that the technology was not sufficiently developed to become competitive at that time [10].

4.2 RED pilot power plant

The Ettore-Infersa saltworks in Marsala (Italy) is one of the most important areas in the Mediterranean Sea for the production of sea salt. Since 2014 the first RED pilot power plant for power production from saline waters and concentrated brines is located in this area. Figure 3 shows the schematic overview of the RED power plant. The seawater flows into brine basins. Due to evaporation, salt concentration increases along the basins ending with a brine saturated in NaCl. The use of brine for RED power production does not compromise the salt production process of the saltworks. The daily volumes required for the RED

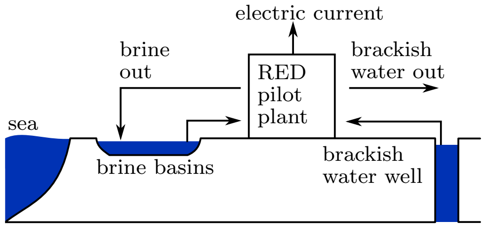

Fig. 3: Schematic overview of the RED power plant in Marsala (Italy) [7].

plant are negligible compared to the total volume of the basins and used brine can be recycled to the basins. A process-scale up of 3 - 4 orders of magnitude in this site considered technologically feasible and well integrated within the conventional production cycle. The installed RED module is equipped with 125 cell pairs and has a total membrane area of 48 m^2. The experimental campaign was from May 2014 to September 2014. The results are shown in Table 1. The yield and efficiency in Table 1 refer to the feed

power (W)	power density $(\frac{W}{m^2})$	yield $\frac{kWh}{m^3}$	efficiency (%)
35 - 40	1,5 - 1,7	0,03 - 0,06	2 - 3

Tab. 1: Performance indicators of the RED pilot power plant [7].

solution. The net power output oscillated around an average of 25 W. The efficiency is relatively lower than commonly presented values for the RED process (i.e. a range from 10 to 20 %). This is due to the use of highly concentrated brine which leads to a reduction of the membranes permselectivity. The future target was a power capacity of the plant with a magnitude of 1 kW and more than 400 m^2 membrane area [7]. In 2016 a power capacity of 700 W was extracted when using artificial solutions, whereas 50 % decrease in power density was observed when using real solutions like brines seen above [11].
In 2013 started another project at Breezanddijk on the Afsluitsdijk (The Netherlands). In this project a RED pilot power plant with a capacity of 50 kW was build. The installed plant generates electricity by mixing salt water from the North Sea and fresh water from Lake Issel. One goal of the project is to upscale the power plant to 1 MW [4].

5 Discussion and conclusion

In Figure 4 and Figure 5 the results of the studies by Post et al. as well as Yip and Elimelech are quantified. However, the results are not supposed to be overestimated, because the studies were published in different years and the authors applied different models. In another study, a model was developed

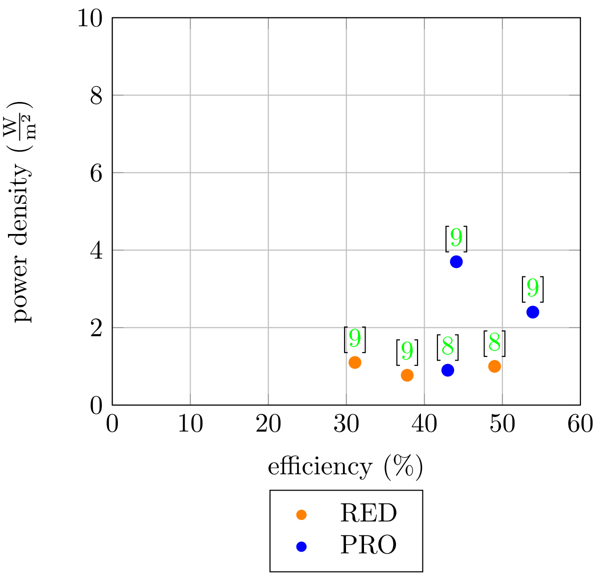

Fig. 4: PRO and RED with seawater and river water as solutions. Diluted solution in the range of 0,0015 - 0,05 $\frac{mol}{l}$ and the concentrated solution in range of 0,5 - 0,6 $\frac{mol}{l}$ [8, 9].

in which full-scale system losses were considered for PRO and RED. The authors wanted to achieve practical values for power density and efficiency. Table 2 shows that the power densities are in range with the results shown in Figure 4 but the efficiencies are lower.
The initial task was to enable a comparison between

technology	power density $(\frac{W}{m^2})$	efficiency (%)
PRO	2,5	10 - 30
RED	2,0	10 - 20

Tab. 2: Power densities and efficiencies referring to the calculation of Feinberg et al. for river water and seawater [12].

PRO and RED. In this context, the power density and efficiency was considered by analyzing studies. However, PRO and RED have a trade-off between

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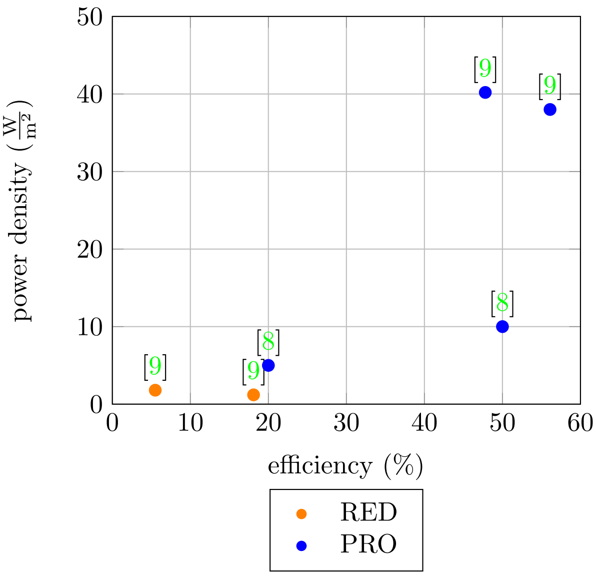

Fig. 5: PRO and RED for higher differences. Diluted solution in the range of 0,017 - 0,05 $\frac{mol}{l}$ and the concentrated solution in range of 4 - 5 $\frac{mol}{l}$ [8, 9].

efficiency and power density. For example, the use of more permeable but less selective membranes increase power density. But due to the uncontrolled mixing, the entropy production increases as well and efficiency is sacrificed [9]. Therefore, power densities and efficiencies vary depending on the selected membranes. Moreover the power density seems to be an unsuitable parameter for comparing PRO and RED. For example both technologies could produce the same power density, yet exhibit different power outputs, efficiencies and system sizes [12].
Finally, the energy costs and the capital cost are the most important factors in comparison between PRO and RED and, ultimately, between SGP and other forms of electricity generation. Since it would not be economically viable to seek complete mixing, the most cost-effective system lengths will lie somewhere between the maximum power density and efficiency [12]. Helfer et al. and Tufa et al. elaborated the costs from the literature (Table 3)[2]. The costs depending on the membrane costs, the solutions and other aspects which specify a wide range [2, 4]. For

technology	capital costs ($\frac{EUR}{kW}$)	energy costs ($\frac{EUR}{kWh}$)
PRO	3 093 - 309 334	0,05 - 0,94
RED	4 500	0,07 - 0,18

Tab. 3: Capital and energy costs for PRO and RED [2, 4].

RED, the capital costs were estimated within the project on the Afsluitsdijk and refer to a 200 kW plant. A calculation for a 200 MW plant resulted in same capital costs ($\frac{EUR}{kW}$). With a load factor of round about 90 %, such a RED plant delivers 1,6 million MWh to the public network. This amount of energy requires between 140 - 240 wind turbines (3 - 5 MW per plant, load factor between 25 - 30 %). The capital costs for wind turbines can be estimated between 1 000 - 2 000 $\frac{EUR}{kW}$, so the investment costs are 700 - 1 400 million euro. The investment costs for the 200 MW RED plant are 900 million euro, so both technologies are comparable [13].
However it is just as difficult to compare the costs as it is difficult to compare power densities and efficiencies because the values referring to different studies with different parameters. Measured values under real operating conditions are required for a comparison of PRO and RED. However, there are only a few power plants running under real operating conditions. An evaluation based on the current number is not sufficient to allow a good evaluation of the technologies. Considering only pilot plants, two promising projects exist for RED. But both projects are still in the testing stage and not commercial. Referring to PRO, the largest power plant has already been closed for economic reasons.
Despite all the challenges, a field of application for SGP will be found because of the need of base-load energy sources. This study has shown that there are different fields of application for PRO and RED. PRO is especially suitable at extracting salinity energy from large concentration differences. In contrast, the power density of RED does not increase strongly with increasing concentration differences. So PRO are supposed to focus on application with brines and RED on applications with river and seawater.

6 Outlook

In this work, only PRO and RED were considered in order to harness salinity gradient power. However, PRO and RED are not the only technologies for salinity gradient power. Future work should also focus on other technologies. For example, researchers of the university of Stanford presented a mixing entropy battery (MEB) in 2019. MEB uses battery electrodes to convert salinity gradient energy into electricity. MEB does not need membranes or turbines and have passed a practical test with waste water and seawater [14].
In addition, the use of hybrid systems can be very efficient. For example, a hybrid RED/ED system can harness salinity gradient power and enable desalination in the process of wastewater treatment [15].
Results from previous studies showed that for PRO and RED the membranes are the key factor. In 2019, researchers of the Rutgers University may have achieved a breakthrough in membrane science. They have found a solution how to use the potential of a

[2] The costs were converted from dollar to euro.

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membrane with a boron nitride nanotube (BNNT). One square centimeter of such membrane could produce 30 MWh per year [16].
Following studies should always keep an eye on current developments. As soon as improvements are achieved in membrane science, the possibility of economic power supply due to PRO and RED increases.

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