

Article

Techno-Economic Feasibility Study of a Hypersaline Pressure-Retarded Osmosis Power Plants: Dead Sea–Red Sea Conveyor

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Abstract: In this study, three pressure retarded osmosis (PRO) power plants are proposed to be built on the Red Sea–Dead Sea (RSDS) water conveyance project, to generate power from the salinity gradient between two water streams at different salt concentrations. The first two proposed plants are to be built after sea water reverse osmosis (SWRO) desalination plants, where Red Sea water and the rejected brine from SWRO plants are used as feed and draw solutions, respectively. In the third proposed plant, Red Sea water and Dead Sea water will be used. Results showed that the three proposed plants are technically feasible while the third plant is the only one that is economically feasible with a 134.5 MW capacity and a 0.056 \$/KWh levelized cost of electricity (LCE). The power generated from the third PRO power plant accounts for about 24.7% of the power needed for the RSDS project that can be used to power SWRO-2 in order to reduce the electricity consumption by 49.3%. If the generated power from the proposed PRO plant is sold to the Jordanian national electricity grid at the current selling price in accordance with Jordanian prices of electricity, a saving of about 21.2% can be attained. It is found that using the power generated by the current proposed plants for desalination project purposes will significantly reduce the price of desalinated water produced from SWRO desalination plants.

Keywords: renewable energy; power generation; osmotic power; blue energy; pressure retarded osmosis (PRO); sea water reverse osmosis (SWRO)

1. Introduction

Blue energy is one of the renewable energy sources that has a great potential to generate power by mixing two solutions of different salt concentrations. One of the most widely investigated processes to harvest the salinity gradient power is pressure retarded osmosis (PRO). Increasing demand on traditional energy sources, such as fossil fuels, encouraged researchers to search for other sources of energy, such as renewable energy and alternatives, especially after the oil crises in 1973, 1990, and 2000s, and the Kyoto protocol in 1997.

Renewable energy sources, such as solar and wind, are non-dispatchable due to its fluctuating nature. They depend on the availability of solar radiation, wind speed, and other factors, therefore the reliance on them is limited without the support of proper energy storage systems, which still have a low efficiency and high cost. Osmotic power (blue energy) is one type of dispatchable renewable energy sources that can generate power continually. It is estimated that the global potential of osmotic power from flowing rivers into the seas is calculated to be two TW, about 980 GW of which can be harnessed [1,2].

The concept of generating power by mixing salt and fresh water was first introduced in 1954 [3]. Succeeding the oil crises in 1973, the term pressure retarded osmosis (PRO) was introduced and

followed by a series of theoretical and experimental investigations by Loeb et al. [4–9]. They studied the technical and the economic feasibility of mixing freshwater with seawater by using a hollow-fiber reverse osmosis (RO) membrane where fresh water flows through the bore and the seawater flows on the active layer side of the membranes. Their results show that the seawater reverse osmosis membranes that were designed for water desalination are not suitable for PRO applications because of the thick support layer and their hydrophobicity. Since then, the RO membrane has developed into a thinner support layer with decreased hydrophobicity [10].

Generating osmotic energy from a sea water/river water resource scheme is the most known and studied scheme [11–14]. However, the power density and water flux based on this scheme is not viable with present commercial PRO membranes because of their limited water permeability and the thick support layer that significantly reduces the osmotic pressure difference [15]. Conversely, studies on generating osmotic energy from hypersaline water bodies are very limited because of their scarce availability and the presence of the logistics and geographical constraints. This scheme produces higher osmotic pressure differentials and hence increases the water flux and the power density of the system. In this scheme, sea water could be used as a feed solution mixed with higher concentrated brine as a draw solution. Some studies investigated this way to exploit the osmotic energy from the brines of desalination plants [16–18], and hypersaline water from salt lakes [11,13,19–22].

Exploiting osmotic energy using the PRO process from hypersaline water resources requires membranes with a high hydraulic operating pressure to withstand the high osmotic pressure difference. Current available PRO membranes can operate on a maximum pressure difference of 13 bar, which is far below the required operating pressure for hypersaline PRO power plants, as in this study, while RO membranes can withstand pressures up to 120 bar [23]. Experimental results available from using RO membranes in hypersaline PRO applications are very limited. The first experimental study was conducted by Mehta and Loeb in 1978 using an RO aromatic polyamide hollow fiber membrane [7–9] and they reported that the actual power generated was far below the expected theoretical potential where the water flux extremely decreased after two hours. They reported an operating pressure of 40.5 bar, power density of 3.3 Wm^{-2} , and water flux of $2.92 \text{ Lm}^{-2}\text{h}^{-1}$. Current RO membranes have shown a huge improvement over the last few decades in terms of water flux, operating pressure, and cost [14]. Efraty [24] used a modified commercial thin film composite (TFC) RO membrane SW30-HR reported in Reference [15]. He reported that pairing river water with hypersaline domains (33% NaCl) under an operating pressure of 92.5 bar will yield a power density of 696 Wm^{-2} and a water flux of $712 \text{ Lm}^{-2}\text{h}^{-1}$.

The idea of generating power using a PRO process from the Dead Sea was first introduced and investigated by Loeb [21]. Using a hollow fiber RO membrane by mixing sea water with the Dead Sea water and a concentrated brine RO desalination plant with the Dead Sea, his finding shows the technical feasibility of generating 130 MW and 48 MW PRO power plants, respectively, and the economic feasibility of the energy cost was 0.058 \$/KWh and 0.07 \$/KWh, respectively. However, Loeb's findings were idealistic based on assumed water inflows and a suboptimal RO membrane in 1998. Furthermore, Loeb's economic analysis was based on RO desalination plants at that time.

In this study, we analyze possible scenarios to exploit osmotic energy for power generation using a PRO process from the on-going Red Sea–Dead Sea Water Conveyance Project (RSDS) [25] based on the available data from the project and a recent modified commercial RO membrane [15]. This study also examines the techno-economic feasibility of these scenarios and their potential to power the RO desalination plants that will be built in this project.

Presently, there is no PRO plant for commercial use built. The first PRO prototype power plant with a 2 kW capacity was built by Statkraft in Norway in 2009 for research purposes. The plant utilized 13 L/s of river water and 20 L/s of seawater with a 2000 m² membrane [25]. The prototype proves that the PRO process can be implemented at a large scale for power generation purposes.

In the present study, three PRO power plants are proposed to be built in the RSDS project. The RSDS project planned to be built in the next few years is as mentioned in the memorandum

of understanding that has been signed in 2013 between the countries bordering the Dead Sea [25]. The first PRO power plant inflows are Red Sea water as a feed solution and the first sea water reverse osmosis (SWRO) plant brine is used as a draw solution. The second PRO power plant inflows are the diluted water from the Red Sea and the first SWRO plant brine is used as a feed solution, and the second SWRO plant brine is used as a feed solution. The third PRO power plant inflows are the diluted water from the second PRO as a feed solution and the Dead Sea water is used as a draw solution. All economical and technical aspects related to the design of the PRO power plants are considered in this study including the pumping system, membranes, turbine-generator set, pressure exchangers, and the pre-treatment system.

2. Materials and Methods

2.1. Red Sea–Dead Sea Water Conveyance Project

The Dead Sea is considered the lowest spot on earth, more than 400 m below sea level. It is one of the saltiest water bodies in the world; its water is ten times more saline than ocean water. The Dead Sea and its unique environment are changing, as the water level is dropping due to a significant evaporation rate (754 MCM/year), consumption of Dead Sea water as a raw material for the chemical industries (650 MCM/year), and the diversion of about 85% of the Jordan River [25], which is the main water body feeding the Dead Sea. Consequently, this means a reduction in the surface area of over 3 km² per year and dropping water level about 1 m per year. As a result, water level has fallen from 394 m below sea level in the 1960s to about 427 m below sea level at the end of 2014 [26]. If no action is taken to remedy the situation, the Dead Sea will reach a new level at an elevation that is about 40 m below the current level, as can be seen in Figure 1. The further decline of the Sea's level is likely to cause more severe environmental, economic, and cultural damages [25].

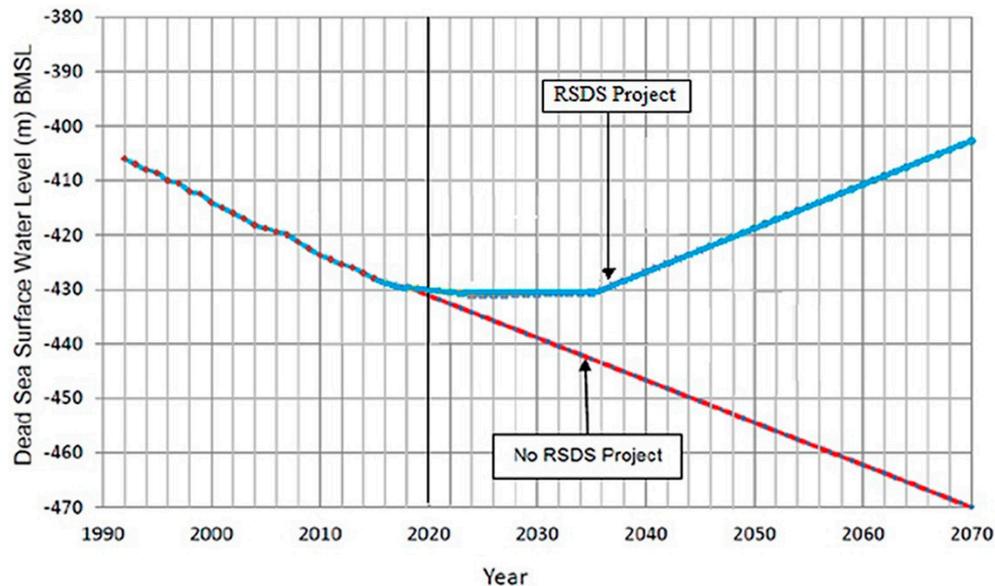


Figure 1. Predicted Dead Sea levels for different intake volumes [26].

The big difference in elevation between the Dead Sea and the Red Sea has long been attractive to build a water conveyance project because of the gravity flow advantage and the considerable potential for hydropower generation. In 2013, the three Dead Sea bordering countries signed a memorandum of understanding to start implementing the Red Sea–Dead Sea project (RSDS). The proposed project is a water infrastructure project designed to convey about 1220 MCM of Red Sea water to the Dead Sea annually in order to provide the beneficiary countries bordering Dead Sea with potable water and to

save the Dead Sea from environmental degradation by increasing Dead Sea water level from -428 m up to -406 m [25].

The proposed project infrastructure includes two large-scale sea water reverse osmosis (SWRO) desalination plants with a total capacity of 930 MCM of fresh water annually, two hydropower plants with total 150 MW power capacity, a pre-treatment plant, and pump stations (Figure 2).

The proposed RSDS project is designed to allow a phased implementation schedule. In the first phase, a SWRO-1 plant will be constructed over the next few years to provide beneficiary countries with 80 MCM of fresh water. The second and third phases are planned to cause a stabilizing effect on the Dead Sea water level, and the last two phases are introduced to increase the water level as shown in Figure 2. The two hydropower plants, pretreatment system, and SWRO-2 plant will be built during these phases.

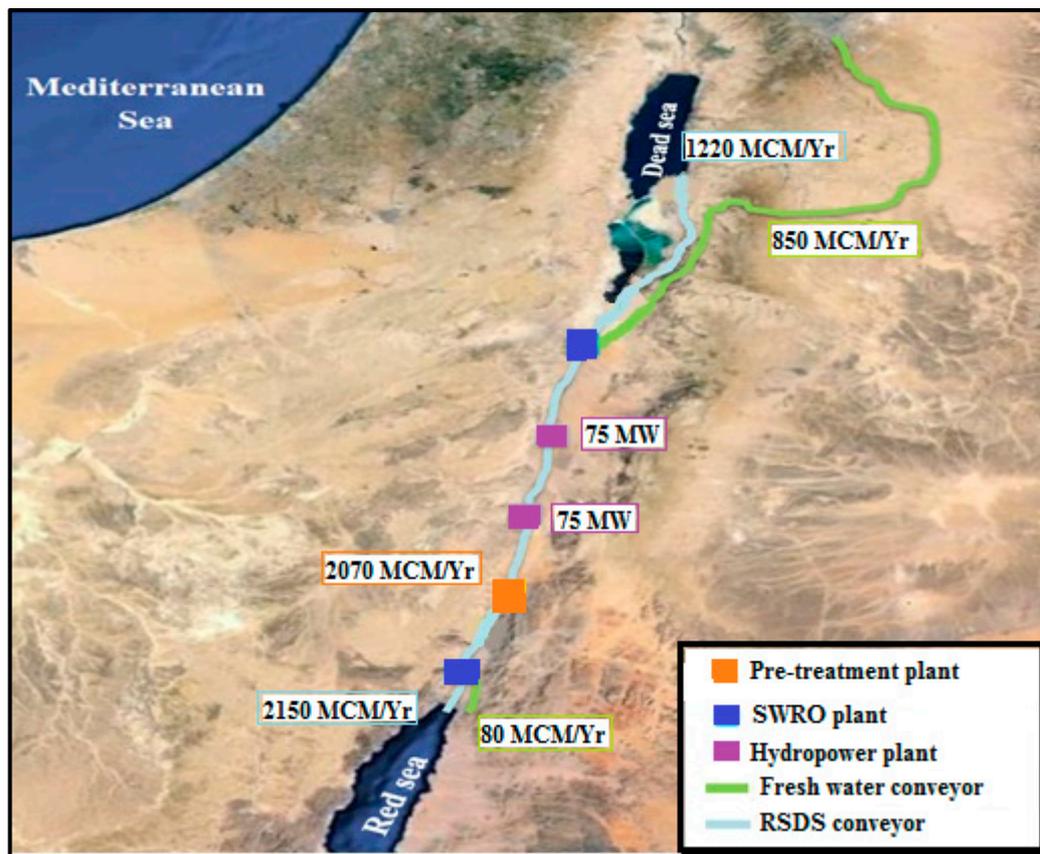


Figure 2. Schematic of Red Sea—Dead Sea Conveyance Project and amounts of annual flow rates.

2.2. PRO Power Plant Modeling

In the PRO plant, a draw solution with a volumetric flow rate of V_D and osmotic pressure π_D is pressurized to a hydrostatic pressure P_h using pumps. The feed solution enters the membrane vessel with a volumetric flow rate V_F . As π_D is larger than the feed solution osmotic pressure, π_F , the draw solution permeates through the membrane to the high concentration side at a ΔV volume flow rate (Figure 3). As a result, the volume flow rate of the draw solution increases. This pressurized solution is split into two flows: 2/3 of the flow will drive the pressure exchanger, and the rest will drive the hydro turbine to generate power [27]. A pressure exchanger was found to be the best option in the PRO plant as an energy recovery device. It was proved that pressure exchangers can save about 60% of the energy input in SWRO desalination plants [28].

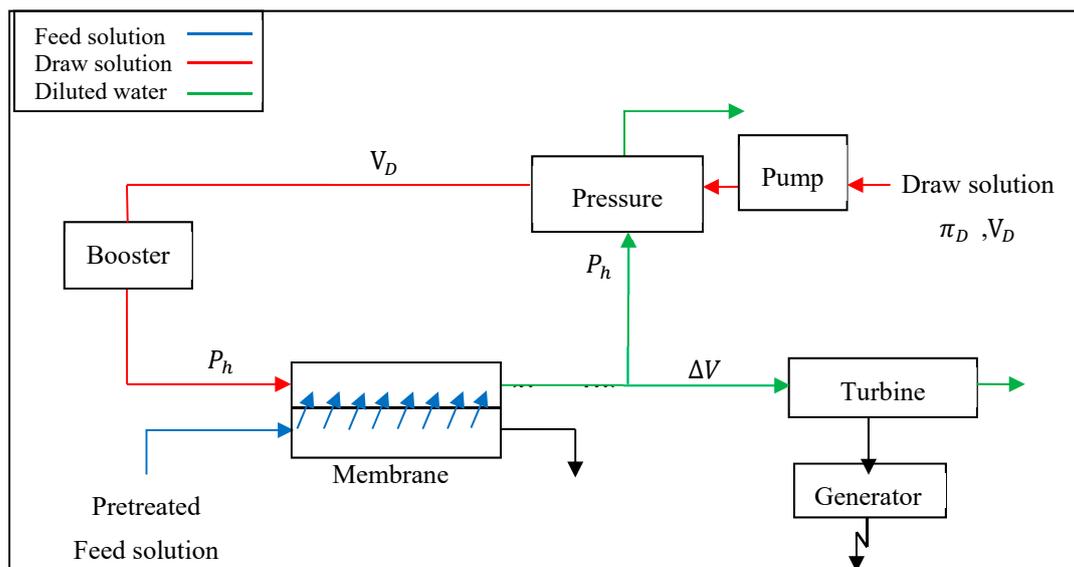


Figure 3. Schematic diagram of power production from PRO power plant.

Osmotic pressure, π , of a solution can be determined using the Van't Hoff equation [14]:

$$\pi = \sum \Phi I c R T \quad (1)$$

where Φ is the osmotic reflection coefficient, I is the ionic concentration per dissociated solute molecule, c is the molar concentration of the salt ions (mol/L), R is the gas constant (0.08314472 L·bar/K·mol), and T is the temperature (K).

The concentration of salt in hypersaline water sources is 240–340 g/L [14]. Using the Van't Hoff equation and the data in Table 1, the estimated osmotic pressure of the Dead Sea as a hypersaline water source is found to be 240 bar at 293 K. This result is compared to 225 bar as estimated by Kelada [29].

Table 1. Dead Sea salt composition [30].

Salt	Φ	I	Mass Composition (g/L)	Molar Weight (g/mol)	c (mol/L)	$\Phi * I * c$
NaCl	0.93	2	91.8	58.44	1.55	2.883
CaCl ₂	0.86	3	52.4	111	0.47	1.2126
MgCl ₂	0.89	3	190.2	95.2	1.995	5.3266
KCl	0.92	2	15.9	74.55	0.2132	0.3922

For oceans around the globe, NaCl is the dominant salt and its concentration ranges between 30 to 40 g/L (3–4%) [11]. Meanwhile, the Red Sea salinity ranges between 4.2 and 4.5%, since it is located in a desert zone with high evaporation rate [25]. Using the Van't Hoff equation with 4.44% salinity (44.4 g/L) at 293 K, the osmotic pressure is calculated and found to be 34.4 bar. An approximation for π may be made by assuming that 1 g/L of total dissolved solids (TDS) equals about 0.76 bar of osmotic pressure. This approximation was used to calculate the osmotic pressure of RSDS conveyance water shown in Figure 4.

In this study, three PRO power plants are proposed. The first plant is proposed to be built after SWRO-1 where the flow intakes are the Red Sea water and the first SWRO brine. For the second PRO plant, proposed to be built after SWRO-2, the flow intakes are the treated water and the second SWRO brine. The third one is before the Dead Sea where the flow intakes are the final Red Sea mixed flow with Dead Sea water, as shown in Figure 4.

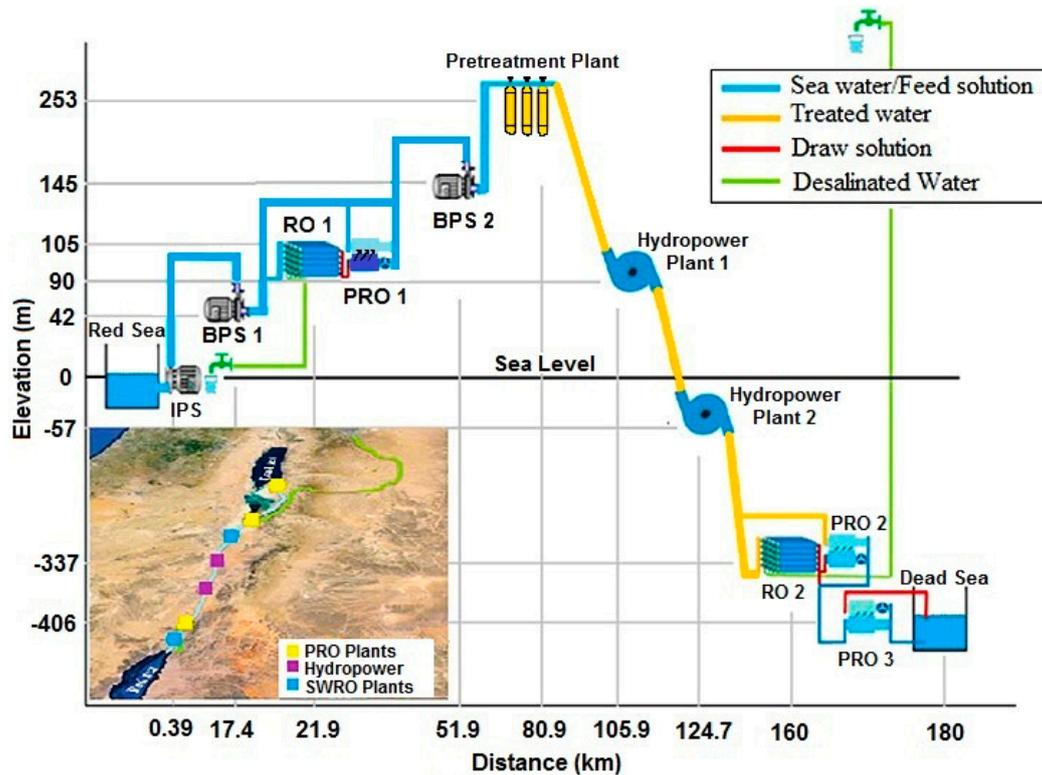


Figure 4. Flow diagram of the proposed RSDS project with three proposed PRO plants (RSDS infrastructure with distance and elevation [26]).

The draw solution flow rates, V_D , and feed solution flow rates, V_F , were determined based on the Jordan Red Sea Project report [26], which is explained in Figure 5. The feed solution flow rate, V_F , for PRO 1 is calculated based on a recovery rate of 50%, which will permeate through the membrane because of the limited amount of draw solution that enters the plant, while in PRO 2 and PRO 3, flow rates are fully used as the feed solution since larger amounts of draw solution flow rates are entering these plants. The permeated flow rate through the membrane, ΔV , for the three proposed PRO plants is calculated based on a desirable ($V_D/\Delta V$) ratio in PRO plants [14].

Since the streams entering and leaving SWRO and PRO plants are always mixed, the TDS values are always changing. To determine the osmotic pressure (π) for the feed and draw solutions of the three PRO plants, TDS must be known. This can be achieved by knowing the flow amounts as shown in Figure 5, and the TDS of the Red Sea, which is equal to 44.4 g/L, and the TDS of the desalinated water, which is approximately negligible.

For example, the draw solution of the first PRO plant is the brine from SWRO-1. This is equal to 80 MCM/yr. The water entering the SWRO-1 is Red Sea water at rate of 160 MCM/year, and the desalinated water is 80 MCM/year. Therefore, the brine TDS is $44.4 \text{ g/L} \times 2 = 88.8 \text{ g/L}$, and $\pi = 88.8 \times 0.76 = 67.5 \text{ bar}$. The calculated results of the feed, draw, and permeate solutions flow rates as well as feed and draw osmotic pressures of the three proposed PRO power plants are presented in Table 2.

Table 2. Data for the three proposed PRO power plants.

Parameter	PRO 1	PRO 2	PRO 3
V_F (m ³ /s)	2.5368	11.7326	38.685
V_D (m ³ /s)	2.5368	12	40
ΔV (m ³ /s)	1.2684	6	20
π_D (bar)	67.5	70.1	240
π_F (bar)	34.4	35.04	59.4

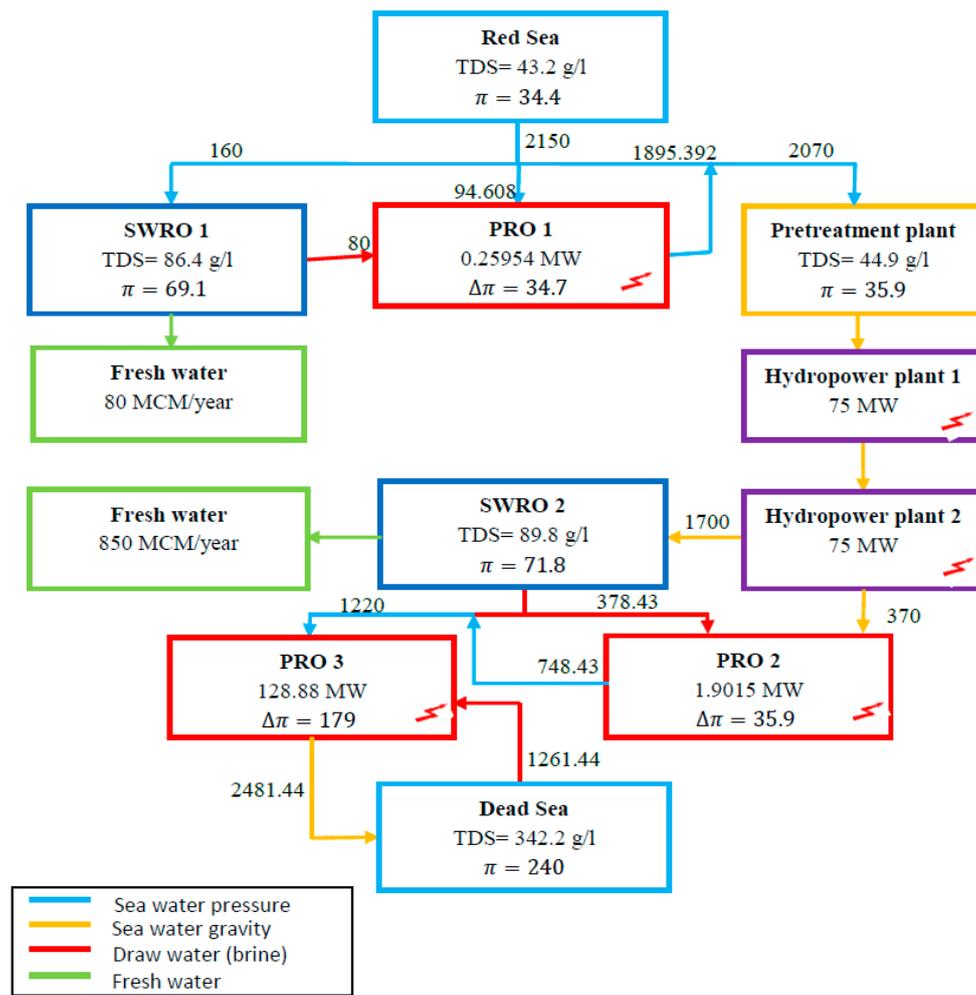


Figure 5. Flow chart of the flow streams for the proposed RSDS project and the three proposed PRO plants. (Flow rates are shown beside arrows [26]. All flow rates are in MCM/year).

For steady power generation, steady flow has to be maintained. To do so, the hydrostatic pressure difference ΔP_h and osmotic pressure difference $\Delta\pi$ must be kept constant. Equation (2) shows the mathematical expression for the flow through membrane [31]:

$$J_w = A(\Delta\pi - \Delta P_h) \quad (2)$$

where J_w is water flux ($\text{m}^3/\text{m}^2 \cdot \text{s}$), and A is the water permeability coefficient of membrane ($\text{m}^3/\text{m}^2 \cdot \text{s} \cdot \text{bar}$). Power density, W , is the power generated per unit area membrane (W/m^2), mathematically:

$$W = J_w \Delta P_h \quad (3)$$

The optimum hydrostatic pressure that should be applied is $\Delta P_h = \frac{\Delta\pi}{2}$. Therefore, the maximum power density, W_{max} , is:

$$W_{max} = \frac{A(\Delta\pi)^2}{4} \quad (4)$$

The maximum power, PW_{max} , for 100% efficiency mechanical components and without considering any losses and parasitic power consumption is:

$$PW_{max} = P_h \Delta V \quad (5)$$

The actual power output of a PRO plant depends on the non-ideal performance of the different components that are used and on the parasitic energy losses. These components are the:

- Membrane
- Mechanical components like turbines, pumps, pressure exchangers, and generators.
- Piping system
- Pre-treatment system.

2.2.1. Membrane

The most critical step in the designing of PRO plant is selecting the proper type of membrane. The actual performance of the membrane depends on different factors. One of the most important factors that reduces the performance of membrane is the concentration polarization that occurs at the boundary layer of the membrane due to accumulation of salts. Membranes are composed mainly of an active layer and porous support layer. The active layer is used to separate water and salt (0.1 to 2 μm), whereas the support layer provides strength to withstand the high pressure and is much thicker than the active layer. Accumulation of salts on the feed solution side is called internal concentration polarization (ICP) and it is a function of the support layer thickness, porosity, and tortuosity [15]. Accumulation on the draw solution side is called external concentration polarization (ECP); thus, the actual membrane performance occurs at the active layer, as shown in Figure 6.

Another important factor that also reduces membrane performance is the reverse salt flux, J_s , where small amount of salt flows through the membrane from the draw solution to the feed solution. To study the non-ideal effects of the membrane, some information about the membrane structure (i.e., thickness, porosity, and tortuosity) should be known under test conditions.

Membranes for such applications should withstand high pressures. The optimum hydrostatic pressure that will be used to pressurize the draw solution, P_h , is half of osmotic pressure difference $\Delta\pi$, as mentioned in Table 4. However, PRO membranes are designed to withstand hydrostatic pressure up to 15 bar, since it is used for river water and seawater applications (i.e., $\Delta\pi \leq 30$ bar) [14]. Such operating pressure is not suitable for very high PRO applications, as in the current study.

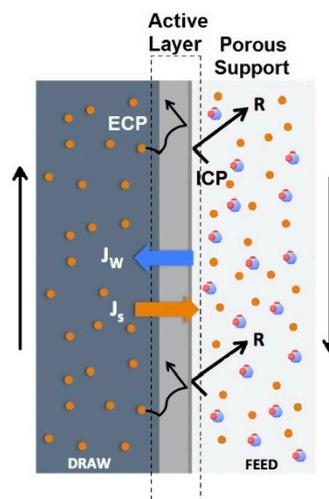


Figure 6. Schematic illustration of the concentration polarization profile for a typical membrane under PRO mode [32].

Most seawater RO membranes operate at the range of 55–83 bar at a feed solution concentration of 32 g/L [11]. Yet, high pressure membranes are specially manufactured to operate at higher pressures up to 120 bar and higher feed solution concentrations up to (58–87 g/L) [23]. In this study, seawater RO membranes are used to withstand the high osmotic pressure difference (240 bar) calculated using Equation (1). Such membranes are designed for a brine conversion SWRO process. Using RO

membranes for PRO applications was first investigated by Loeb et al. [4–9]. They concluded that using RO membranes for PRO applications reduce the water flux significantly because of the internal concentration polarization.

However, in the last decade, the idea of using RO membranes for PRO applications has been raised again and investigated by chemically modifying the active layer of commercial RO membranes. Such studies are very limited and still under research and development [13–15,24,33]. The selected membrane in this study is a commercially modified RO polyamide thin-film composite membrane TFC-RO SW30-HR [15]. This membrane is chemically modified to be used for PRO application at higher pressures. The characteristics of this membrane are listed on Table 3. Despite there being other RO membrane options commercially available that withstand higher pressures than SW30-HR, these membranes are not modified for PRO applications, and their characteristics and intrinsic values under test conditions are not available for public. However, the SW30-HR membrane is found to be the only RO membrane in the literature modified to work under PRO applications. Efraty [24] used the SW30-HR membrane in a closed-circuit PRO. He reported that pairing river water with hypersaline domains (33% NaCl) under an operating pressure of 92.5 bar will yield a power density of 696 Wm^{-2} and a water flux of $712 \text{ Lm}^{-2}\text{h}^{-1}$.

Table 3. Selected membrane properties [15].

Intrinsic Water Permeability A ($\text{L/m}^2 \cdot \text{h} \cdot \text{bar}$)	Solute Permeability Coefficient B ($\text{L/m}^2 \cdot \text{h}$)	Max Operating Pressure (bar)	Salt Rejection R (%)	$Pd/\text{Element}$ (bar)	Feed Solution Concentration (ppm)	Cost $\$/\text{m}^2$
7.70 ± 0.34	7.67 ± 0.49	93	86.4 ± 2.4	1	3000	≈ 25

This type of membrane was assumed to be a good choice for the PRO plant since it was approved for such conditions in PRO mode. In PRO mode, unlike RO mode, the active layer of membrane faces the draw solution side (high concentration), which means more salt accumulation that increases the ECP. ICP was assumed to have no effect on membrane performance because the properties of the membrane in Table 3 shows the membrane performance in RO mode, i.e., the water in the feed solution side of Figure 6 is brine that will be desalinated in RO mode, which is similar to the case in PRO.

The other factor that reduces the output power from the PRO plant is the pressure drop Pd in the membrane elements. The power losses in membrane elements due to the pressure drop PW_{L_m} can be described using Equation (6). Assuming four elements will be in each pressure vessel, then, the total pressure drop Pd is 4 bars.

$$PW_{L_m} = Pd \times \Delta V \quad (6)$$

The amount of permeated water through membrane ΔV is given by:

$$\Delta V = J_w a_m \quad (7)$$

The equation above is used to calculate the membrane area a_m . The power density of the membrane for the three PRO plants is shown in Table 4.

Table 4. Calculated membrane parameters and cost for the three PRO plants.

Parameter	PRO 1	PRO 2	PRO 3
P_h (bar)	16.55	17.53	90.3
W_{max} (W/m^2)	1.97	2.2	58.7
J_w ($\text{L}/\text{m}^2 \cdot \text{h}$)	4.3	4.5	23.4
a_m (m^2)	1,064,500	4,753,800	3,076,200
C_m ($\$$)	26,611,000	118,840,000	76,904,000
PW_{max} (MW)	2.1	10.52	180.6
PW_{L_m} (MW)	0.51	2.4	8

2.2.2. Mechanical Components and Piping System

The inefficiencies of mechanical components and the pressure drop in the piping system reduce the output power from the PRO plant. The pressure drop in the piping system due to friction in the pipe and fittings H is assumed to be 1 bar. The capital cost of the piping system C_p is assumed to be 1% of the capital cost C_c of the PRO plant [34].

Turbines used in PRO plants are impulse turbines, such turbines are used for high head and low flow rate applications. A Pelton turbine is the best to be used in PRO power plants [35].

Equation (8) is an empirical formula that is used to calculate the cost of a Pelton turbine-generator set C_{tg} [36].

$$C_{tg} = (2n_{tg}) \times 8300 \times f \times (V_t \times h)^{0.54} \quad (8)$$

where n_{tg} represents the number of turbine and generator sets that can be known from V_t and ΔV flow rates, V_t represents the water flow rate entering one turbine that can be known from the flow rate ΔV that will enter the turbine, h is the total hydraulic head of water entering Pelton turbine i.e., ($h = \frac{P_h - H - Pd}{0.098}$), and f is the Pound to U.S. Dollar conversion factor. These data for each PRO power plant are given in Table 5.

Table 5. Turbine-generator set parameters.

Parameter	PRO 1	PRO 2	PRO 3
V_t (m ³ /s)	1.2684	1	1
n_{tg} (-)	1	6	20
h (m)	118	128	870.4

Power loss due to inefficiencies of turbines and generators $PW_{L_{tg}}$ can be described using Equation (9):

$$PW_{L_{tg}} = PW_{max} \times (1 - \eta_{tg}) \quad (9)$$

The efficiency of a Pelton turbine can reach up to 97% [37], and the generator efficiency can also reach up to 98%. Therefore, the total efficiency of a turbine generator set η_{tg} is 95%. Table 6 represents the power loss of a turbine generator set for the three plants.

The use of pressure exchangers reduces the consumption power in the plant. Pressure exchangers have high efficiencies up to 97% [38], and Equation (10) can be used to estimate the capital cost of pressure exchangers C_{px} [39]:

$$C_{px} = 19802.4 \times (V_D \times 3600)^{0.58} \quad (10)$$

The pressure drop in the pressure exchanger P_{px} due to the inefficiency is given by Equation (11). This pressure drop will be compensated by the use of a booster pump.

$$P_{px} = P_h(1 - \eta_{px}) \quad (11)$$

Axial piston pumps are used in high pressure applications [40], and their average efficiency η_{pu} is 85%. The cost of the pumping system C_{pu} can be calculated by using Equation (12) [39]:

$$C_{pu} = 19802.4 \times ((V_F + V_D) \times 3600)^{0.58} \quad (12)$$

To calculate the consumption power in the feed, draw, and booster water pumping systems ($PW_{L_{Fpu}}$, $PW_{L_{Dpu}}$ and $PW_{L_{Bpu}}$), Equations (13)–(15) are used, respectively. Equation (17) is the sum of all the power consumption used for pumping system; the results are shown in Tables 6 and 7.

$$PW_{L_{Fpu}} = \frac{V_F \times H}{\eta_{pu}} \quad (13)$$

$$PW_{L_Dpu} = \frac{V_D \times H}{\eta_{pu}} \quad (14)$$

$$PW_{L_Bpu} = \frac{V_D \times (H + P_{px})}{\eta_{pu}} \quad (15)$$

$$PW_{L_pu} = PW_{L_Fpu} + PW_{L_Dpu} + PW_{L_Bpu} \quad (16)$$

$$PW_{L_pu} = \frac{H(V_F + 2V_D) + (V_D \times P_{px})}{\eta_{pu}} \quad (17)$$

2.2.3. Pre-Treatment System

In any membrane system, fouling is considered a key issue that affects the productivity and costs [14,41]. Water entering PRO power plant contains different types of colloidal, suspended, soluble, and organic matter. The accumulation of this matter on the membrane causes fouling, especially on the feed solution side as it faces the porous support layer. Thus, a pre-treatment system is important to sustain the membrane performance for long periods. The energy applied for a pre-treatment system reduces the net power from the plant. Moreover, the pre-treatment will add an additional capital cost. Based on the Stat Kraft field test [41], micro-filtration was considered as a good option for the pre-treatment of water in PRO plants. The pre-treatment system capital cost C_{pt} can be estimated using Equation (18), where the micro-filtration cost factor C_f is 0.1 €/m³ [41]:

$$C_{pt} = C_f \times F \times ((V_F + V_D) \times y)^b \quad (18)$$

The symbol b represents a scale factor, and in the case of a PRO plant, the relationship between the plant capacity and the flow rate through the pre-treatment facility is linear. Thus, the scale factor is equal to 1. F represents the Euro to U.S. Dollar conversion factor and y represents second to year conversion factor. The total power consumption of pre-treatment system PW_{L_pt} can be calculated using the following equation [42].

$$PW_{L_pt} = P_{mf} \times (V_F + V_D) \quad (19)$$

where P_{mf} represents minimum pressure of micro-filtration in pre-treatment system.

3. Results and Discussion

To calculate the net output power PW_{net} from the PRO plant, power losses and parasitic power consumption are subtracted from the maximum theoretical power:

$$PW_{net} = PW_{max} - PW_{L_m} - PW_{L_tg} - PW_{L_pu} - PW_{L_pt} \quad (20)$$

The capital cost of the plant is the sum of all components cost as shown in Equation (21):

$$C_c = C_m + C_{Pi} + C_{tg} + C_{px} + C_{Pu} + C_{pt} \quad (21)$$

Table 6 presents the results of the modeled PRO plant capacity, with the maximum theoretical power of the plant calculated using Equation (4).

Results show that the first and second PRO plants have low efficiency, since the osmotic pressure difference is low and the SWRO membrane designed for brine desalination has a low water permeability coefficient compared to other PRO membranes.

Furthermore, the power needed for pumping in these two plants is considerably high compared to generated power, which is about 40%, as illustrated in Figure 7. However, calculated results for the third PRO power plant show that the plant can generate 1.178 TWh per year, which is about 6% of the

total electrical consumption in Jordan [43]. The plant efficiency is 74.5%, which is better than thermal and renewable power plants, except hydropower plants [35].

Table 6. PRO power plants power generation capacities and losses.

PRO Plant	PW_{max} MW	PW_{L_m} MW	$PW_{L_{tg}}$ MW	$PW_{L_{pu}}$ MW	PW_{pt} MW	PW_{net} MW	E GWh/Year	η %
First	2.1	0.51	0.105	1.04	0.15	0.295	2.584	14
Second	10.52	2.4	0.526	4.2	0.712	2.682	23.494	25.5
Third	180.6	8	9.03	26.71	2.36	134.5	1178.22	74.5

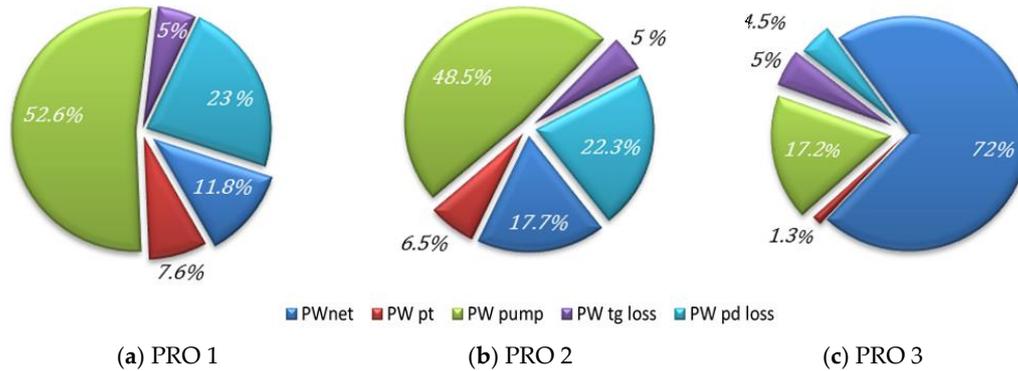


Figure 7. Percentage of the different power losses and net power production from the three PRO power plants.

The capital cost of the membrane, piping system, turbine generator set, pressure exchangers, pumps, and pre-treatment system are shown in Table 7.

Table 7. Cost calculations of the three PRO power plants.

PRO Plant	C_m \$	C_{pi} \$	C_{tg} \$	C_{px} \$	C_{pu} \$	C_{pt} \$	C_c \$	C_c \$/KW
First	26,611,000	554,276	389,567	3,925,177	5,867,548	18,080,118	55,427,626	187,890
Second	118,840,000	2,319,043	2,148,089	9,667,148	14,357,326	84,572,734	231,904,340	86,466
Third	76,904,000	4,299,704	20,159,786	19,434,263	28,773,362	280,399,348	429,970,463	3196

Capital costs for the three power plants per unit of KW installation indicate that the first and second PRO power plants are not economically feasible compared to other types of renewable power plants. In contrast, the third PRO power plant is highly competitive, as shown in Figure 8.

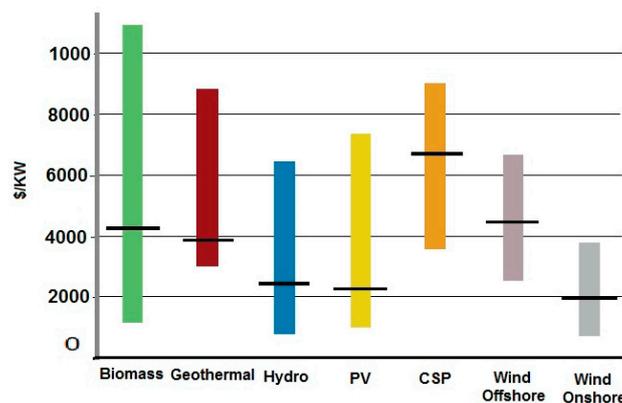


Figure 8. Typical ranges and weighted averages for the total capital costs of renewable power generation technologies (2017) [44].

The capital costs of the systems used in PRO plants as a percentage of the total capital cost are shown in Figure 9. As indicated, for the first and second PRO plants, the major cost is the membrane system because of a low osmotic pressure difference compared to the third plant where the pretreatment system accounts for 63.8% of the total capital cost of the plant. Though, pre-treatment reduces fouling and sustains membrane performance for 7 to 10 years [14].

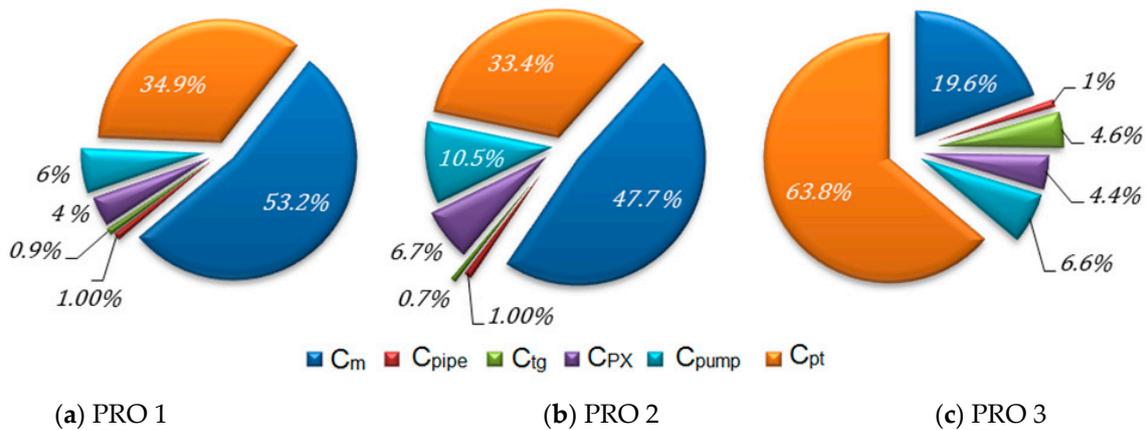


Figure 9. Percentage of capital costs for three PRO power plants.

The membrane area calculated for the third PRO plant is a considerably large area. In such cases, some authors used a scale-up factor to reduce the capital cost of membrane. Loeb [21] used a 0.8 exponential scale-up cost factor, where the membrane cost reduced from 42 \$/m² to 18.6 \$/m².

Making a decision regarding an energy option is not made solely on the basis of its technical feasibility; the economic feasibility also plays a vital role. Economically, several methods can be used to determine the economic feasibility of any power generation project. The levelized cost of electricity (LCOE) is one of the best economic indicators that is used widely for decision-making. Calculating LCOE requires both fixed and variable costs. Fixed costs are the PRO investment cost and the variable cost indicates operation and maintenance cost.

LCOE is the main parameter to study the economic competitiveness of any electricity generation system. It represents the ratio of the total cost of the electricity generated to the total electric energy output (\$/KWh) [45]. This is given using Equation (22):

$$LCOE = \frac{C_c + C_{O\&M} \frac{(1+i)^N - 1}{(1+i)^N \times i}}{E \frac{(1+i)^N - 1}{(1+i)^N \times i}} \quad (22)$$

Total cost of the electricity generated includes the capital cost and operation and maintenance cost of the plant during its life. For the calculation, the life of the plant N is assumed to be 20 years with an interest rate i of 6% and E is the energy generated per year (8760 h). The annual operation and maintenance cost $C_{O\&M}$ consists of the membrane replacement cost, labor, and maintenance cost, which can be calculated using Equation (23). The expected membrane lifetime L_m for a PRO plant is 5 years, and the maintenance and labor costs are estimated to be 2% and 1% of the total capital cost, respectively [46]. LCOE and operation and maintenance costs are shown in Table 8.

$$C_{O\&M} = \left(\frac{C_m \times \frac{N}{L_m}}{N} \right) + (0.02C_c) + (0.01C_c) \quad (23)$$

It can be seen that the first and second plants are not economically feasible, while the third PRO plant is highly competitive compared to other types of renewable energy sources, as indicated in Figure 10.

Table 8. Operation and maintenance costs and LCOE.

PRO Plant	Membrane Replacement (\$/Year)	Maintenance Cost (\$/Year)	Labor Cost (\$/Year)	$C_{O\&M}$ (\$/Year)	LCOE (\$/KWh)
First	5,322,200	1,108,552	554,276	6,985,028	4.57
Second	23,768,000	4,638,087	2,319,043	30,725,130	2.16
Third	15,380,800	8,599,409	4,299,704	28,279,913	0.056

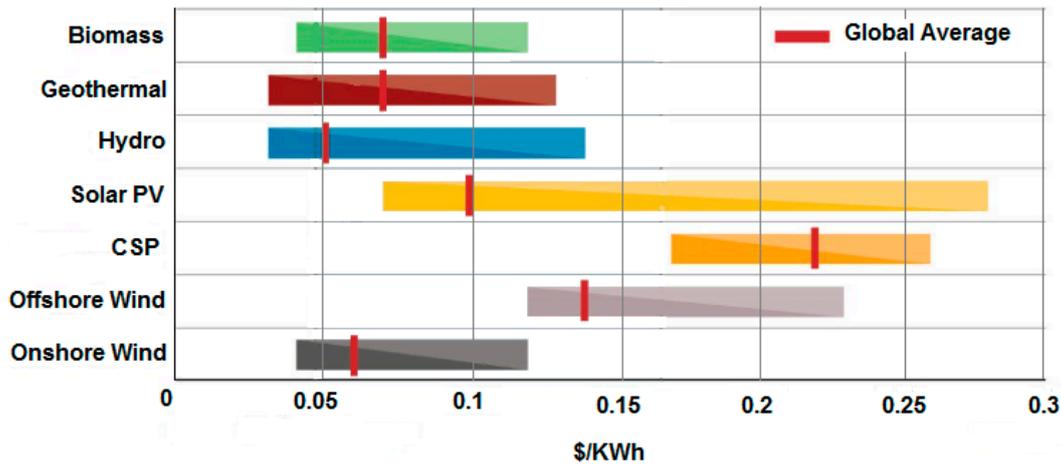


Figure 10. The levelized cost of electricity (LCOE) of renewable power generation technologies and their weighted average (2017) [44].

Other important criteria in deciding the economic merit of a project is the payback period (PBP). By rearranging Equation (22), PBP can be obtained from Equation (24). Where S is the selling price of electricity:

$$PBP = \frac{\ln\left(\frac{S \times E - C_{O\&M}}{(S \times E - C_{O\&M}) - i \times C_c}\right)}{\ln(1 + i)} \tag{24}$$

Payback period (PBP) is an important economic indicator for the decision-making of a project, which consequently affects the selling price of electricity. According to renewable energy regulations in Jordan [47], the electricity selling price from renewable energy sources ranges between \$0.08 for biogas and \$0.19 from concentrated solar power for each KWh. Assuming a 0.135 \$/KWh selling price for produced electricity from PRO, the PBP will be about 4 years. Figure 11 shows how the selling price of electricity affects the payback period of the third PRO plant.

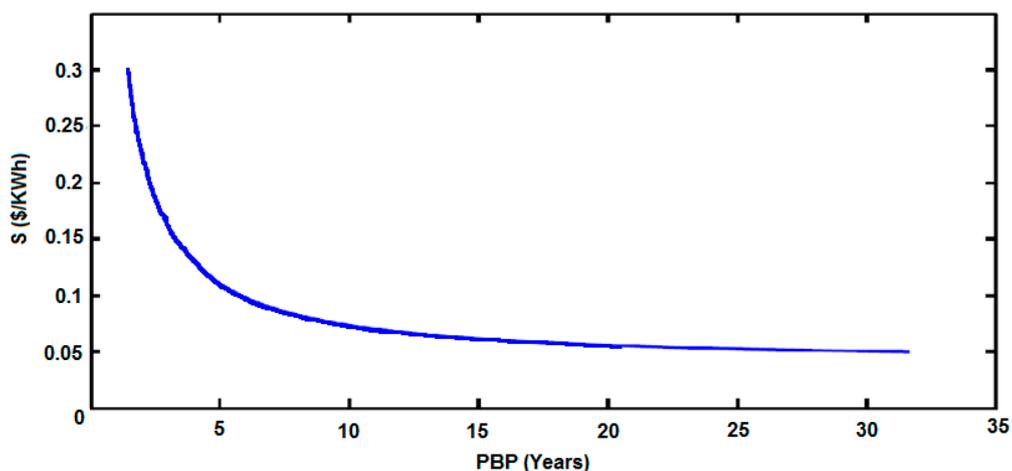


Figure 11. Payback period as a function of the selling price of electricity for PRO-3.

The report of the RSDS project [26] estimated that the power needed for the project is 522 MW of electricity, and the SWRO-2 alone consumes 255.397 MW. The third PRO plant accounts for about 24.7% of the power needed for the project. According to the Jordan electricity tariff for the industrial sector, electricity costs for SWRO-2 are calculated to be 749,750,729 \$/year. If the power generated from third PRO power plant is used to power SWRO-2, the electricity costs will be reduced to 380,215,732 \$/year, making a save of about 49.3%. If the generated power from the PRO plant is sold to a national grid at a selling price of 0.135 \$/KWh, the revenue is 159,059,700 \$/year, saving about 21.2% of the electricity cost needed to power SWRO-2. Thus, using the power generated for project purposes is recommended from an economic point of view, which can significantly reduce the price of desalinated water produced from SWRO desalination plants.

4. Conclusions

In this work, three PRO power plants are proposed to be built on Red Sea–Dead Sea conveyance project RSDS. Draw solutions for the first two plants are the brine rejected from the SWRO desalination plants and the feed solutions are the Red Sea water flowing in the conveyer. The third PRO plant solution water is the Dead Sea water and the feed water is the water from conveyer. Calculated results show that all plants are technically feasible to generate power but only the third plant is economically feasible. The main reason is that this PRO power plant operates at a high osmotic pressure difference, which maximizes the power density and reduces the area of the membrane needed, as clearly shown in Table 6. The other reason is that no costs for the intake and outfall systems were calculated, which accounts for more than 60% of the total capital cost of the plant [14,42].

Economic indicators results for capital cost, LCOE, and payback period of an acceptable selling price of electricity showed that the PRO plant is highly competitive with other sources of renewable energy. Comparing the third PRO plant efficiency of 74.5% with other renewable energy power plants shows that the PRO plant has the highest efficiency after the hydroelectric power plants. The other technical advantage of PRO power plants over other types of renewable energy sources like wind and solar is the dispatchable generation, which can be controlled by using proper valves and controlling water flow. Furthermore, the PRO power plant capacity factor can reach 100% by maintaining a permeation rate of water and applied hydraulic pressure. This can be achieved by using a pre-treatment system and cleaning the membrane systematically.

This study also shows that there are other factors that affect the performance and cost of PRO power plants other than the membrane system, namely, the pumping system and pretreatment system. Since the third PRO plant accounts for about 24.7% of the power needed for the project, the power generated from the third PRO power plant can be used to power SWRO-2 in order to reduce the electricity costs by 49.3%. If the generated power from the third PRO plant is sold to the Jordanian national electricity grid at a selling price in accordance with Jordanian prices of electricity, a saving of about 21.2% can be attained. Thus, using the power generated for project purposes is recommended from an economic point of view, which can significantly reduce the price of desalinated water produced from SWRO desalination plants.

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