

Multiple staging of pressure retarded osmosis: Impact on the energy generation

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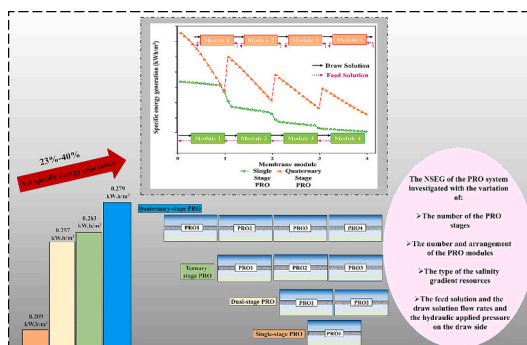
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HIGHLIGHTS

- The plug flow PRO model is used to build multistage PRO scenarios.
- The highest energy generation was in the 4-stage PRO due to reduced concentration polarization.
- Dead Sea-wastewater salinity gradients net specific energy was 0.82 kWh/m³.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:

Pressure retarded osmosis
Multistage
Net specific energy generation
Recovery rate
And power density

ABSTRACT

As pressure retarded osmosis (PRO) is getting more attention for sustainable energy generation, further investigation to enhance its efficiency is required. Applying a multiple-stage PRO scenario is one suggestion to boost the generated energy in the PRO process. This research evaluates the benefit of multiple stages of pressure retarded osmosis on specific energy generation. Single, dual, ternary, and quaternary pressure retarded osmosis stages were investigated for power generation using four membrane modules in the PRO process. Eight designs were proposed to cover the arrangement of the membrane modules in a single, dual, ternary and quaternary PRO process and estimate the net-specific energy generation of pressure retarded osmosis. For each design, the variation in the total energy input and the total energy output of single and multistage pressure retarded osmosis processes were calculated. The water flux and the power density enhanced with the number of stages for the investigated multistage PRO scenarios. The maximum water flux and power density resulted in four PRO stages of values equal to 6 L/m².h and 15 W/m², respectively. For the Dead Sea-reverse osmosis brine salinity gradient, a 33.96 % rise in the net specific energy generation is observed in the quaternary-stages pressure retarded osmosis scenario. The Dead Sea and wastewater salinity gradients produced the highest net specific energy generation of 0.82 kWh/m³ over the other investigated types of salinity gradients.

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<https://doi.org/10.1016/j.desal.2023.117199>

Received 23 August 2023; Received in revised form 14 November 2023; Accepted 29 November 2023

Available online 30 November 2023

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1. Introduction

In nonideal pressure retarded osmosis (PRO), the energy of mixing a salinity gradient source is partially converted to hydraulic energy [1,2]. The draw solution gets diluted while the feed solution concentration intensifies after leaving the PRO unit. The simultaneous decrease and increase in the draw and feed solutions during the osmotically driven membrane processes will adversely impact the water flux and process efficiency [3]. For example, in a single PRO stage (SSPRO), only a part of

the draw solution's osmotic energy will be harvested due to the increase in the feed solution concentration caused by freshwater transport through the PRO membrane [4]. Increasing the salinity of the feed solution will compromise the osmotic driving power, and the permeation flux enters the turbine unit for energy generation. Therefore, a multi-stage PRO scenario was suggested to improve the PRO efficiency compared to the SSPRO [4–6]. The multistage PRO scenario uses a new feed solution in each stage to eliminate the effect of increased feed solution concentration in the previous stage on the osmotic driving force

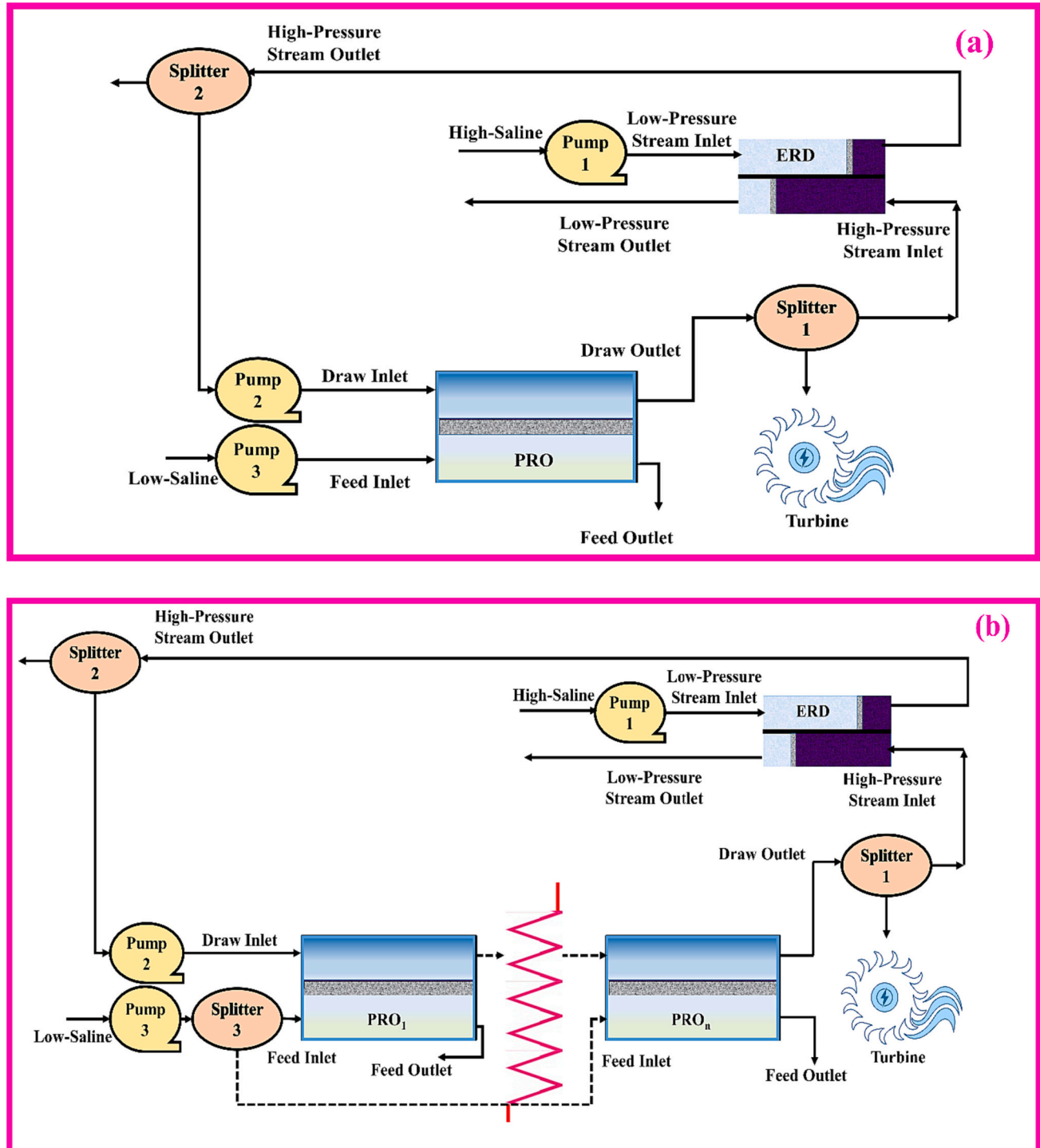


Fig. 1. (a) Single-stage PRO (SSPRO) for energy generation, (b) multistage PRO for energy generation, where PRO₁ represents the first PRO stage, and PRO_n represents the last PRO stage, and (c) the specific energy of the Dead sea-wastewater salinity gradients of Dual-stage PRO (DSPRO) design with the membrane module.

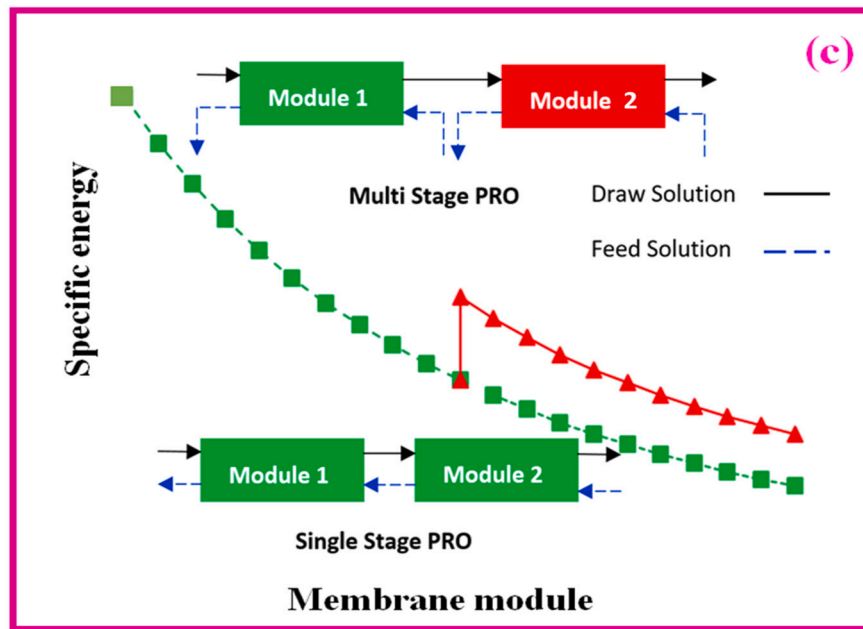


Fig. 1. (continued).

[7,8]. In the single-stage PRO, the draw solution is pressurized and fed into the PRO membrane for freshwater extraction from the feed solution (Fig. 1a). The pressurized flow splits into two parts after leaving the PRO membrane; the first part goes to a Pressure Exchanger (PX) to pressurize the seawater feed whereas the second part goes to turbine for power generation. In the dual PRO, the first stage is similar to the single-stage PRO process, with the difference that the pressurized draw solution from the first PRO module goes to a second PRO module to combine with a new feed solution (Fig. 1b). A considerable freshwater permeation from the feed to the draw solution is expected in the second PRO stage due to the osmotic pressure gradient restoration across the membrane (Fig. 1c). After leaving the second PRO module, the entire seawater flow goes to a turbine system for power generation. This arrangement will facilitate harvesting the remaining draw solution osmotic energy in subsequent PRO stages. Due to the intense concentration polarization at the feed side, the performance of the multistage PRO scenario becomes more efficient at high draw solution concentrations. Accordingly, using new feed water in each stage will alleviate the vestige of concentration polarization and the fouling phenomena on the membrane [7]. Besides, pumping a new feed solution in each stage will regenerate the osmotic driving power across the membrane and the water flux [6,8].

The dual-stage PRO (DSPRO) system is investigated broadly in the literature [4,7,9–17] due to the possibility of utilizing the DSPRO system with a variety of feed solution nature and applying different membrane types in each stage [11]. Altaee et al. [7] reported an 18 % increase in energy generation and a 43 % increase in the power density by a DSPRO compared to an SSPRO. Additionally, the authors noticed a reduction in the impact of concentration polarization when dealing with DSPRO. Unfortunately, these studies did not determine net energy generation [7,11]. Another study implied that the specific energy of the DSPRO system was 8 % higher than the corresponding one of the SSPRO system [16]. Nevertheless, the study did not investigate a higher number of PRO stages. In another study, four different designs of the DSPRO system were introduced for power generation [18]. The first design was similar to the SSPRO system, as the feed solution was fed from stage one to stage two. New feed and draw solutions were sent to the second stage in the second design. In the third design, a new feed solution was utilized in stage two, while the less concentrated draw solution leaving stage one was sent to stage two. The results revealed that the second design's power density was below the SSPRO systems. It has been suggested that

the mean power density of the first and third designs was elevated at a higher dimensionless flow rate. Nevertheless, the power density is a good indicator of the performance of the PRO. Still, it is not the best factor to describe the net available energy of the PRO system [19]. The power density relates to the maximum power harvested per membrane unit area. Nevertheless, the net specific power is the difference between the energy output and the energy input. Using PRO requires pumping energy, whereas ignoring this fact would overestimate the efficiency of the PRO system. Also, utilizing multistage PRO with the exact amount of pumping energy compared to the single-stage is promising for generating higher net specific energy. A recent study [20] reported an extremely high power density of around 90 W/m²; however, the study did not consider the net available energy.

Madsen et al. [21] also reported the advantages of utilizing a dual-stage PRO system when coupled with a geothermal heat system for energy generation. Two configurations were suggested; the first used lower applied pressure for the draw solution of the second PRO stage, while the second configuration used the same applied pressure for the draw solution of both PRO stages. The generated energy increased to 46 % when using the first dual-stage PRO configuration. A double energy generation was noticed when using the second dual-stage PRO configuration compared to a single PRO system. However, the study did not consider optimization to determine the maximum energy generated through the different PRO systems.

Sarp et al. [22] examined the influence of the variation of the feed solution pressure of a multistage PRO system on the process performance. Four PRO stages were designed in series with fresh feed solutions for each PRO stage. The optimum power recovery was obtained by varying the feed solution's hydraulic pressure in each stage of the PRO, where the draw solution was a hypersaline solution of up to 300 g/L. Even though the study optimized feed solution hydraulic pressure, the evaluation of the net energy generation was not included. A multistage PRO design was investigated in one research [23], where hydro-turbines were included in each stage for energy production. Single, dual, and three PRO stages were studied. The results conducted higher net specific energy generation for the three PRO stages, followed by the DSPRO and the SSPRO. The driving force represented by the salinity gradient among the osmotic pressure and the hydraulic pressure was elevated in the three PRO stages than in dual or single PRO stages. Bharadwaj and co-workers optimized energy recovery through a multistage PRO system

[24]. The authors reported that the multistage PRO system could collect higher energy than the single PRO. The highest energy recovered occurred when using one membrane module, followed by three membrane modules in DSPRO. The results reported that the enhancement of the energy recovery was reduced when the number of stages was increased to more than three PRO stages. Multiple PRO stages were added in series in another study [25], where a new feed solution was added in each stage, and the draw solution was sent from one stage to another. This system configuration was compared to a single PRO stage with multiple modules, where the final outlet draw solution was partially circulated to the initial draw solution. The outcomes reported that the variation of the proportion of the feed outlet flow rate to the draw inlet flow rate did not influence the specific energy of the multistage PRO system. In contrast, the variation in the flow ratio affected the specific energy of the single-stage PRO process. A 10.71 % increase in the generated specific energy was reported when using the multistage PRO system over the single-stage PRO system.

To date, the advantage of utilizing a multistage PRO system for maximizing net energy generation is not reported. As mentioned earlier, some studies did not determine the evaluation of net energy generation [13,22], other studies only compared SSPRO to DSPRO [4,7,18], and some studies did not consider the variation of the multistage PRO system parameters for the maximum energy generation [21,23]. The pumping energy consumed in the multistage PRO should not be ignored. Increasing the number of PRO stages could boost the total energy generation and the total energy consumed by the pumps, signifying the importance of investigating the multistage PRO system by evaluating the net-specific energy generation, where the total energy used is considered. The impact of salinity gradient resources on energy generation should be examined.

Besides the PRO stage configuration, the operating conditions of the single and multistage PRO, such as the feed and draw flow rates and the applied pressure on the draw side, are critical in maximizing the net energy generation and process performance. The study assessed the net specific energy generation (NSEG) of the multistage PRO compared to a single-stage PRO. The PRO membranes in the single, dual, ternary, and quaternary PRO stages (SSPRO, DSPRO, TSPRO, and QSPRO, respectively) were four, arranged in the configurations illustrated in Table 1. For instance, the TSPRO scenario has three designs for stage configu-

PRO membrane. According to the authors' knowledge, there is no study yet in the literature that has investigated the net-specific energy generation of a multistage PRO scenario with different module arrangements and various salinity gradients by studying the operating parameters' variation on the best multistage PRO model.

2. Methodology

The four PRO designs with the possible membrane modules' configurations are shown in Table 1. It's worth noting that the SSPRO and the QSPRO have one arrangement only, as the SSPRO has four membrane modules in one stage, while the QSPRO has a single membrane module for each of its four stages. The suggested model of SSPRO and multistage PRO scenarios, including the PRO unit/s, pumps, turbines, splitters, and energy recovery device (ERD), are shown in Fig. 1. The mathematical models for the pump, splitter, turbine, and energy recovery device were separately built and designed by Dymola software and discussed in detail in our previous study [8]. The pumps' efficiency is 80 %, and the ERD efficiency is 96 %. The PRO system model was built and validated using the Modelica language through Dymola software, where more details about it are included in our previous study [8]. The PRO system has been modeled and simulated through Dymola, and a brief explanation is introduced next.

2.1. The Mathematical model of the PRO

A radial plug flow model is selected to define the flow of the PRO unit in this study. The feed solution moves in the radial direction, whereas the draw solution moves in the axial direction. A hollow fiber (HF) membrane is the used module. The mathematical approach for the HF membrane module is described in reference [26], where more details can be found. The solution-diffusion model represents the feed and draws solutions flowing through the membrane. The internal and external concentration polarization effects are determined in the PRO mathematical model [26]. The reverse salt flux (J_s) and the pressure drop in both the radial and the axial directions are also included in the model. The mass transfer coefficient for the feed solution (k_f) and for the draw solution (k_d) is considered through the model [8,26]. The following equation can find the PRO water flux (J_w).

$$J_w = A_w \left(\frac{\left(\frac{nRTC_{Di} \left(1 + \frac{Q_{Di}}{Q_{Do}} \right)}{2} \right) \exp\left(\frac{-J_w}{k_d}\right) - \left(\frac{nRTC_{Fi} \left(1 + \frac{Q_{Fi}}{Q_{Fo}} \right)}{2} \right) \exp\left(J_w \left(K + \frac{1}{k_f} \right)\right)}{1 + \frac{B}{J_w} \left(\exp\left(J_w \left(K + \frac{1}{k_f} \right)\right) - \exp\left(\frac{-J_w}{k_d}\right) \right)} - \Delta P \right) \quad (1)$$

rations (Table 1). TSPRO [1,2] represents three PRO stages, where one membrane module is in the first and the second stage, while two membrane modules are used in the third stage. The NSEG of the best PRO stage configuration will be evaluated for several salinity gradient resources. The research questions are i) What is the effect of PRO multistaging on power generation, and ii) What is the net energy generation by the single and multistage PRO scenarios? The study hypothesized that the NSEG of multistage PRO designs (Table 1) is the variation between the energy generation by the hydro turbine and pump energy consumption, assuming that the feed and draw solution flow rates are equal and hence the pretreatment energy. The study also hypothesized the potential for custom-designing the PRO membrane to withstand elevated feed pressures, given the absence of any existing commercial

where A_w is for the water permeability coefficient, n is for the number of the ions in the salt solution, R is for the universal gas constant, T is for the temperature, C_{Di} and C_{Fi} are for the initial salinity of the draw solution and the feed solution, respectively, Q_{Di} , Q_{Do} , Q_{Fi} , and Q_{Fo} are for the initial and outlet flow rates of the draw and feed solutions, respectively, B is for the salt permeability coefficient, K is the solute resistivity in the membrane support layer, k_f is the mass transfer on the feed side, and ΔP is for the applied pressure difference of the draw and the feed solutions. In this study, the draw solution pressure was equal to the average osmotic pressure difference across the membrane, $\Delta P = \Delta \pi/2$, to maximize the power density [11].

The overall mass balance for the draw and the feed solutions is given below:

Table 1

The membrane module arrangement in the various stages of the multistage PRO scenario.

PRO stages	Abbreviation	Membrane modules in stage one	Membrane modules in stage two	Membrane modules in stage three	Membrane modules in stage four
SSPRO	SSPRO	4	0	0	0
DSPRO	DSPRO [1,3]	3	1	0	0
	DSPRO [1,3]	1	3	0	0
	DSPRO [2]	2	2	0	0
TSPRO	TSPRO [1,2]	2	1	1	0
	TSPRO [1,2]	1	2	1	0
	TSPRO [1,2]	1	1	2	0
QSPRO	QSPRO	1	1	1	1

$$Q_{Fo} = Q_{Fi} - (J_w * A_m) \quad (2)$$

$$Q_{Do} = Q_{Di} + (J_w * A_m) \quad (3)$$

where A_m is the membrane surface area of the PRO membrane. The solute mass balances for the feed and the draw solutions are given below:

$$Q_{Fo} C_{Fo} = Q_{Fi} C_{Fi} - (J_w * A_m) \quad (4)$$

$$Q_{Do} C_{Do} = Q_{Di} C_{Di} + (J_w * A_m) \quad (5)$$

Simulation results of a single PRO membrane module using the suggested model are included in Appendix A.

The power density (W) is calculated from the membrane flux multiplied (J_w) by the hydraulic pressure difference across the PRO membrane (ΔP):

$$W = J_w \Delta P \quad (6)$$

The permeation rate (Q_p) is determined for a single PRO system as follows.

$$Q_p = J_w * A_m \quad (7)$$

where A_m is the area of a single PRO membrane in m^2 .

The significance of the internal concentrative concentration polarization (ICCP) with mass transfer on the feed side on the system behaviour is also included and explained through the following expression [26].

$$ICCP = \exp\left(J_w \left(K + \frac{1}{k_f}\right)\right) \quad (8)$$

The water flux of each PRO stage ($J_{wn,avg}$) in the multistage PRO scenarios is determined as the average value of the water flux of each membrane module in that stage, as follows.

$$J_{wn,avg} = \frac{\sum_{j=1}^m J_{wj}}{m} \quad (9)$$

where J_{wj} is the water flux in the j membrane module, m is the number of the membrane modules in each PRO stage of the multistage PRO scenarios, and n is the number of the PRO stages.

The power density of each PRO stage ($W_{n,avg}$) in the multistage PRO scenarios is determined as the average value of the power density of each membrane module in that stage, as follows.

$$W_{n,avg} = \frac{\sum_{j=1}^m W_j}{m} \quad (10)$$

where W_j is the power density in the j membrane module, m is the number of the membrane modules in each PRO stage of the multistage PRO scenarios, and n is the number of the PRO stages.

The internal concentrative concentration polarization, including mass transfer on the feed side, is determined for each membrane module in each PRO stage in the multistage PRO scenarios. After that, the

average internal concentrative concentration polarization ($ICCP_{n,avg}$) in each PRO stage (n) of the multistage PRO scenarios is calculated as follows.

$$ICCP_{n,avg} = \frac{\sum_{j=1}^m ICCP_j}{m} \quad (11)$$

where $ICCP_j$ is the average internal concentrative concentration polarization in the j membrane module in each PRO stage of the multistage PRO scenarios.

The permeation rate of each PRO stage (Q_{pn}) in the multistage PRO scenarios is calculated as the summation of the permeation rate in each membrane module in that stage, as follows.

$$Q_{pn} = \sum_{j=1}^m Q_{pj} \quad (12)$$

where Q_{pj} is the permeation rate in the j membrane module. This study used Hagen-Poiseuille and Ergun equations to determine the pressure drop in the feed and the draw side of the PRO module. More information about the pressure drop models is found in the literature [8]. Generally, the pressure drop in the PRO module was insignificant, which agrees with the findings [8].

The model used in this study is based on the performance of a commercial Toyobo PRO module instead of a laboratory-made membrane. The water permeability of commercial PRO membrane is about ($1 * 10^{-7}$ m/bar.s), slightly lower than FO membranes such as Aquaporin and Porifera, affecting the power generation by the module.

Furthermore, experimental data validated the PRO model for a Toyobo HF module utilizing Dymola. The experiments were conducted in the Water and Energy Nexus Laboratory, Indian Institute of Technology Guwahati. The effective length of the membrane module is 0.78 m, and 63 m^2 is the membrane area. The agreement between the

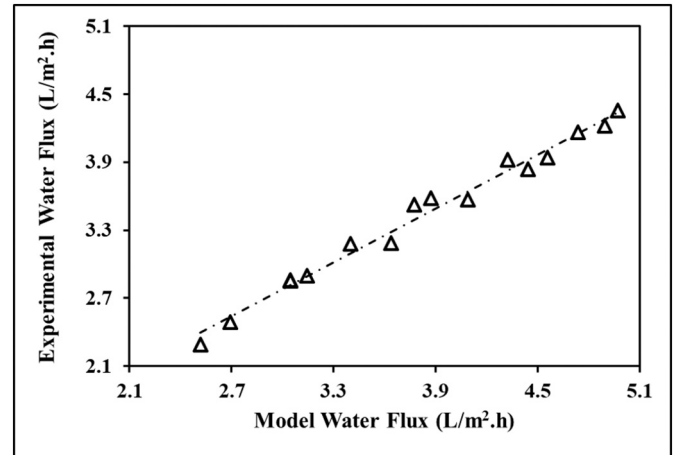


Fig. 2. The model water flux versus the experimental water flux of the PRO model.

modeled and experimental water flux was high, with an error of no $>15\%$ [8]. The evaluated membrane parameters are 3.6×10^{-4} m/bar.h for the water permeability coefficient, 6.2×10^{-9} for the salt permeability coefficient, and $880 \mu\text{m}$ for the membrane structural parameter. Moreover, the model has been validated by another experimental data for the Toyoboo hollow fiber membrane module of 70.5 m^2 area, with tap water as the feed solution and 1 M NaCl draw solution [27]. The hydraulic pressure on the draw side ranged between 5 and 30 bar, while the pressure on the feed side ranged between 3 and 7 bar. The feed and draw solutions' flow rates were set between 0.48 and $0.72 \text{ m}^3/\text{h}$. The agreement between the modeling and experimental results is shown in Fig. 2, where no $>14\%$ error was found.

2.2. The multistage PRO system design

In osmotically driven membrane processes, the osmotic driving force undergoes attenuation through the module due to the dilution of the draw solution and the increase in the intensity of the feed solution concentration. Increased feed solution concentration results from freshwater transport to the draw solution, compromising the process efficiency. Previous studies demonstrated the effectiveness of multistaging the PRO to reduce the influence of the increase in the feed solution concentration on energy generation [4]. Unlike the SSPRO process, a new feed solution is fed for each stage of the multistage PRO process. Combining the initial draw solution with a new feed solution will partially restore the osmotic gradient through the PRO membrane, leading to a higher water flux (Fig. 1a).

The SSPRO scenario for energy generation is shown in Fig. 1a. A part of the less concentrated draw stream leaving the PRO unit is sent to the ERD. The energy of the less concentrated draw solution is extracted through the ERD when the pressurized high-saline is used as the low-pressure feed stream for the ERD. Then, the high-pressure stream leaving the ERD is fed to the PRO system to represent the inlet draw solution. The low-saline stream is pressurized through a pump (Pump 2) and utilized as the feed solution of the PRO unit. The other portion of the diluted draw stream and a limited portion ($<0.5\%$) of the high-pressure stream-out from the ERD are sent to turbines for energy generation. The flow layout of the multistage PRO for energy generation is shown in Fig. 1b. PRO₁ represents the first PRO stage, while PRO_n represents the last PRO stage. PRO_n would be PRO₂ for DSPRO, PRO₃ for TSPRO, and PRO₄ for QSPRO. A similar flow path is noticed for the multistage PRO scenario compared to the single PRO scenario.

Fig. 1c shows the significance of utilizing a DSPRO scenario compared to an SSPRO scenario of producing higher specific energy. Adding fresh feed solution to the second stage in the DSPRO causes a sudden increase in the specific energy compared to the SSPRO of the same number of membrane modules, highlighting the advantage of considering multistage PRO designs for the specific energy rise.

Nevertheless, the multistage PRO consists of more than one PRO stage. Additionally, pump 3 is used to pressurize the low-saline feed stream, and then splitter 3 is responsible for dividing the stream equally into the PRO stages. This proposed design of the multistage PRO scenario is utilized to fix equal flow rates of the draw inlet stream sending to the first PRO stage and the low-saline stream (Fig. 1).

The multistage PRO would have two, three, or four stages in this study. The multistage PRO scenario is designed to send the less concentrated draw solution from the previous stage to present the inlet draw solution of the following PRO stage. Furthermore, the feed solution is freshly supplied at each PRO stage (Fig. 1b) to regenerate the osmotic power gradient among the PRO membrane. At the last PRO stage (PRO_n), the diluted draw solution will be divided and sent to a turbine and an ERD. The diluted draw stream will exchange energy with a pressurized high-saline solution in the ERD. After that, $>99\%$ of the pressurized stream leaving the ERD will present the draw solution inlet to the first PRO stage, while the rest will be sent to another turbine to gather the unused left energy.

The design of the multistage PRO of sending the entire less concentrated draw stream to the next stage is preferable to enhance the water flux in the following PRO stage. Altaee and Hilal [11] reported that utilizing such a design for DSPRO increased the power density by 17.4% compared to splitting the diluted draw stream and sending a portion to the next stage, sending the rest to an ERD. Additionally, the authors noticed a reduction in the specific energy consumption while utilizing the discussed DSPRO design. Recharging the feed solution for each PRO stage in the multistage PRO causes a boost in the permeation rate and, consequently, the dilution in the draw side [25].

2.3. The design operating conditions

The power density and net specific energy generation of the SSPRO and the multistage PRO scenarios were investigated through the use of Dead Sea water of 292.20 g/L and RO Brine of 70.13 g/L as the high-saline and low-saline solutions (Fig. 1). It is noteworthy that Dead Sea has been suggested in many studies as the draw solution in the PRO system because of its high osmotic pressure and relevance to combine with myriad feed solutions such as combined with wastewater, seawater, or even RO brine [4,28]. The draw solution of PRO stage one is the high-pressure outlet stream from the ERD (Fig. 1b). Each PRO stage uses a fresh feed solution. The pressure on the draw solution is 90 bar, while the feed solution pressure is 1 bar. The draw and feed solutions' total inlet flow rate (Q_{tot}) is fixed at $2 \text{ m}^3/\text{h}$ for the SSPRO and the multistage PRO designs. For instance, in the SSPRO, the draw inlet flow rate and the feed inlet flow rate are equal ($1 \text{ m}^3/\text{h}$ each). In contrast, for DSPRO, the draw inlet flow rate is equal to $1 \text{ m}^3/\text{h}$, which is equivalent to the summation of the feed inlet flow rate to the first and the second PRO stages, where the feed inlet flow rate of each stage is $0.5 \text{ m}^3/\text{h}$. The solution's temperature is assumed to be room temperature (298 K). The net energy generation (NSEG) (kWh/m^3) is the difference between the energy generated in the turbine and the energy consumed for pumping the draw and feed solution. NSEG is calculated and compared for each PRO scenario.

$$\text{NSEG} = \frac{1}{Q_{\text{tot}}} \left(\sum_{i=1}^{TN} E_{\text{Turbine}} - \sum_{i=1}^{PN} E_{\text{Pump}} \right) \quad (13)$$

where E_{Turbine} and E_{Pump} are the energy generated through the turbines in kW and energy consumed through pumping in kW, TN is the number of turbines in the PRO scenario, and PN is the pumps' number in the PRO scenario. E_{Turbine} is the energy out and is equal to the permeate flow in the PRO module multiplied by the hydraulic pressure of the draw solution. The energy consumed by the pumps, E_{Pump} , presents the input energy required for feed and draw solution pumping into the PRO system, and it is equal to the feed or the draw solution flow rate multiplied by the feed pressure. Besides, the pump efficiency was assumed to be 0.8 in this study. The pump head loss was accounted for in the model and calculated as the difference between pressure out and pressure in. Then, the power consumed was calculated as = (inlet flowrate * head loss)/efficiency.

Fixing the total feed and the draw solution initial flow rates is critical for major comprehension of the advantage of the PRO system with the highest NSEG. Moreover, the total water flux and the total power density of the multistage PRO scenarios are defined as follows.

$$J_{\text{wtot}} = \sum_{i=1}^{i=n} J_{\text{wi}} \quad (14)$$

$$W_{\text{tot}} = \sum_{i=1}^{i=n} W_i \quad (15)$$

J_{wi} is the water flux in stage i of the multistage PRO scenario, and W_i is the power density resulting in stage i .

It should be noted that The SSPRO and multistage PRO costs are not

significantly different since they use the same number of PRO elements. There may be a slight cost difference between SSPRO and multistage PRO pressure vessels; however, it will not significantly impact overall costs since pressure vessels typically last the plant's lifetime.

3. Results and discussion

Four scenarios of PRO systems are investigated in the current study, with eight PRO designs (Table 1). SSPRO scenario with four membrane modules is the first scenario. The second and third scenarios of the DSPRO and the TSPRO have three designs, each to investigate different membrane module arrangements. The fourth QSPRO scenario has one design with a single membrane module in each stage. The same type of high-saline and low-saline solutions were used for all designs but with different numbers of PRO stages in each design. For the multistage PRO scenarios, an extra pump is necessary to pump the fresh feed solution to each stage. However, the multistage PRO scenarios maximize the energy harvested from the draw solution when paired with a new feed stream in the subsequent PRO stages. The water flux (J_w), power density (W), and NSEG were calculated for each of the eight PRO designs and compared in this section.

3.1. The comparison of the SSPRO and multistage PRO scenarios

3.1.1. Water flux and power density

The impact of adding more stages to the PRO system compared to the SSPRO is investigated and discussed here. The hydraulic pressure in the SSPRO and multistage PRO systems was equal to $\Delta\pi/2$. Although the draw solution osmotic pressure changes along the PRO module and from one PRO module to another, the hydraulic pressure remains constant to reduce energy losses. Therefore, the designed hydraulic pressure of the SSPRO and multistage PRO will be carried from the first to the tail PRO module without modification. The permeation flow is the parameter influenced by the variation in the number of PRO stages and membrane module configuration in the stages. Fig. 3a shows the permeation flow at each PRO stage of the SSPRO and the multistage PRO scenarios. As can be noticed, the permeation flow increased with the PRO stages in the multistage PRO scenarios. Increasing the PRO stages, with a new feed at each stage, enhances the permeation flow. Compared to the SSPRO configuration, the percentage increase in the total permeation flow in the DSPRO [2], TSPRO [1,2], and QSPRO designs is 9.96 %, 10.15 %, and 15.53 %, respectively. The permeation flow varied depending on the PRO configurations (Fig. 3a); for instance, the DSPRO [2] design produces 0.37 m³/h permeation flow compared to 0.33 m³/h and 0.34 m³/h for the DSPRO [1,3] and DSPRO [1,3] designs.

Fig. 3b shows the average water flux at each PRO stage of the SSPRO and the multistage PRO scenarios. $J_{w1,avg}$, $J_{w2,avg}$, $J_{w3,avg}$, and $J_{w4,avg}$ is the water flux at the first, the second, the third, and the fourth PRO stage, respectively. The figure shows that the amount of water flux increased with the PRO stages. For instance, the DSPRO scenarios produce higher water flux than the SSPRO scenario, which agrees with the literature [7]. The percentage increase in the water flux by using DSPRO [1,3], DSPRO [1,3], and DSPRO [2] compared to the SSPRO scenario is 124 %, 175 %, and 120 %, respectively. Nevertheless, the water flux of each DSPRO design varied with the membrane modules' configurations. The DSPRO [1,3] attained the highest $J_{w1,avg}$, and the lowest $J_{w2,avg}$ compared to the DSPRO [1,3] and the DSPRO [2] scenarios. The DSPRO [1,3] exhibited the highest total water flux compared to the DSPRO [1,3] and [2] due to the highest osmotic pressure difference (Fig. 3c). The osmotic pressure gradient in stage two of DSPRO [1,3] is 149.3 bar, while in stage two of DSPRO [1,3] and DSPRO [2] is 139.9 bar and 141.1 bar, respectively. In the PRO stage one of the DSPRO [1,3], the internal concentrative concentration polarization ($ICCP_{1,avg}$) was more significant than in the DSPRO [1,3] and DSPRO [2] due to higher water flux, then decreased in the PRO stage two ($ICCP_{2,avg}$) of the DSPRO [1,3] compared to the DSPRO [1,3] and DSPRO [2] (Fig. 3d) as water flux

decreased.

Interestingly, adding a third PRO stage caused a further improvement in the water flux. For instance, the percentage rise in the water flux of the TSPRO [1,2], TSPRO [1,2], and TSPRO [1,2] compared to the SSPRO scenario is 236 %, 260 %, and 280 %, respectively (Fig. 3b). Over the three TSPRO designs, the TSPRO [1,2] design shows the highest $J_{w1,avg}$, while the TSPRO [1,2] shows the highest $J_{w2,avg}$ and the TSPRO [1,2] shows the highest $J_{w3,avg}$. The variation in the water flux occurred due to the change in the membrane configurations of the TRSPRO scenario. For instance, it has been noticed that having one membrane module in stage one of the TSPRO produced higher $J_{w1,avg}$, and having one membrane module in stage two of the TSPRO produced higher $J_{w2,avg}$ (Fig. 3b). Additionally, the results present that the highest the water flux in a PRO stage of the TSPRO of any configuration is the highest the $ICCP_{avg}$ of that stage. As shown in Fig. 3e, the $ICCP_{1,avg}$ is higher than the $ICCP_{2,avg}$ and $ICCP_{3,avg}$ of the TSPRO [1,2], as a result of $J_{w1,avg}$ is higher than $J_{w2,avg}$ and $J_{w3,avg}$ of the TSPRO [1,2] (Fig. 3b). The TSPRO [1,2] design is preferable over the TSPRO [1,2], and TSPRO [1,2] designs for producing greater water flux (Fig. 3b) and having the highest permeation flow (Fig. 3a). The better water flux in the TSPRO [1,2] configuration can be attributed to the greater osmotic pressure difference compared to the other TSPRO configurations (Fig. 3c), where higher osmotic pressure difference causes an increase in the PRO water flux [29]. For instance, the percentage increase in $\Delta\pi_3$ of TSPRO [1,2] compared to TSPRO [1,2] and TSPRO [1,2] is 1.7 %, and 2.2 %, respectively.

Finally, the QSPRO shows the highest permeation flow of 0.38 m³/h, around a 15.53 % greater permeation flow than the SSPRO scenario. Additionally, it has the highest amount of water flux of 6.01 L/m².h, around 362 % higher than the water flux from the SSPRO scenario. The QSPRO design achieved greater water flux due to the higher osmotic pressure gradient than the other PRO designs. (Fig. 3c). The QSPRO design shows higher $\Delta\pi_2$ (2.4 %-12.2) and $\Delta\pi_3$ (3.5 %-5.8 %) in comparison to the DSPRO designs and the TSPRO designs (Fig. 3c). The internal concentrative concentration polarization results in the first, second, third, and fourth PRO stages of the QSPRO are shown in Fig. 3f. It can be noticed that the internal concentrative concentration polarization values are decreasing gradually from stage one to stage four in the QSPRO design. The finding points out the advantage of adding more PRO stages, where each stage will face less ICCP, and it agrees with the behaviour of the permeation flow and water flux of the QSPRO, where the permeation flow and the water flux decreased gradually from stage one to stage four. The higher the water flux, the higher the permeation from the feed side to the draw side, increasing the concentration at the membrane's feed side and consequently increasing the ICCP [30].

Fig. 3c shows the advantage of utilizing multistage PRO in increasing the osmotic pressure gradient. The osmotic pressure difference increases due to the fresh feed introduced to the additional PRO stages. For instance, using the DSPRO [1,3] design caused an 81 % rise in the osmotic pressure gradient compared to the SSPRO. Having TSPRO [1,2] enhanced the osmotic pressure difference of around 155 % compared to the SSPRO. The highest increase in the osmotic pressure difference was for the QSPRO, 228 % compared to the SSPRO. Different membrane modules' arrangements showed different osmotic pressure differences. For instance, the osmotic pressure difference of the second stage of the DSPRO [1,3] is lower than that of the other dual-stage configurations (DSPRO [1,3] and DSPRO [2]), as shown in Fig. 3c. This can be explained by the further draw solution dilution in the three membrane modules in the first stage of the DSPRO [1,3] design compared to the other two PRO configurations (DSPRO [1,3] and DSPRO [2]). Draw solution dilution in the second stage of the DSPRO [1,3] reduced the osmotic pressure difference in this stage.

Fig. 3g represents the hydraulic pressure difference in each stage of the SSPRO and the multistage PRO scenarios. It is worth noting that the applied pressure difference in each stage is determined by the difference between the average hydraulic pressure on the draw side and the



Fig. 3. (a) The permeation flow in the first, second, third, and fourth PRO stages (Q_{p1} , Q_{p2} , Q_{p3} , and Q_{p4} , respectively) in the single-stage PRO (SSPRO) and the multistage PRO scenarios, (b) the average water flux in the first, second, third, and fourth PRO stages ($J_{w1,avg}$, $J_{w2,avg}$, $J_{w3,avg}$, and $J_{w4,avg}$, respectively) in the single-stage PRO (SSPRO) and the multistage PRO scenarios, (c) the total water flux ($J_{w,tot}$) and the osmotic pressure difference in the first, second, third, and fourth PRO stages ($\Delta\pi_1$, $\Delta\pi_2$, $\Delta\pi_3$, and $\Delta\pi_4$, respectively) of the SSPRO and the multistage PRO scenarios, (d) the average internal concentration polarization in the first and the second PRO stages ($ICCP_{1,avg}$ and $ICCP_{2,avg}$, respectively) in the dual-stage PRO (DSPRO) scenarios, (e) the average internal concentration polarization in the first, the second, and the third PRO stages ($ICCP_{1,avg}$, $ICCP_{2,avg}$, and $ICCP_{3,avg}$, respectively) in the ternary-stage PRO (TSPRO) scenarios, (f) the average internal concentration polarization in the first, the second, the third, and the fourth PRO stages ($ICCP_{1,avg}$, $ICCP_{2,avg}$, $ICCP_{3,avg}$, and $ICCP_{4,avg}$, respectively) in the quaternary-stage PRO (QSPRO) scenario, and (g) the hydraulic pressure difference in the first, second, third, and fourth PRO stages (ΔP_1 , ΔP_2 , ΔP_3 , and ΔP_4 , respectively) of the SSPRO and the multistage PRO scenarios.

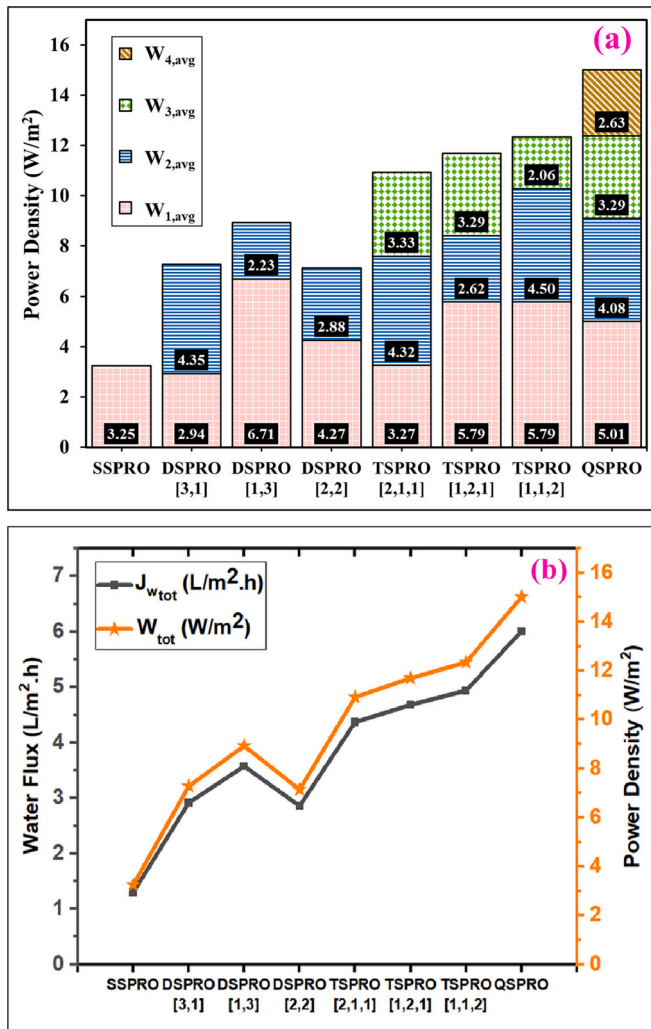


Fig. 4. (a) The power density in the first, second, third and fourth PRO stages (W_1 , W_2 , W_3 , and W_4 , respectively) of the single-stage PRO (SSPPRO) and the multistage PRO scenarios, and (b) the total water flux ($J_{w,tot}$) and the total power density (W_{tot}) of the single-stage PRO (SSPPRO) and the multistage PRO scenarios.

average hydraulic pressure on the feed side, where the pressure drop on both sides is considered. It can be noticed that the hydraulic pressure variation between the multistage scenarios and the SSPPRO scenario is $<1.5\%$ because the applied hydraulic pressure on the draw and the feed side were fixed for all of the scenarios.

The PRO process operates with consistent hydraulic pressure [22], yet the freshwater transport causes fluctuations in the driving force within the PRO module. These fluctuations in draw and feed solution concentration ultimately impact the power density of the PRO process. The variation in the number of PRO stages and the membrane modules' configuration in the stages influence the power density. Fig. 4a displays the average power density of the first, second, third, and fourth PRO stages ($W_{1,avg}$, $W_{2,avg}$, $W_{3,avg}$, and $W_{4,avg}$, respectively) of the SSPPRO and the multistage PRO scenarios. The power density of the SSPPRO scenario is 3.25 W/m^2 . A higher power density was obtained in the multistage PRO scenarios. The DSPRO design [1,3] shows the highest W_1 and the lowest W_2 compared to the DSPRO design [1,3] and the DSPRO design [2]. The profile of the total power density results follows the total water flux trend in the PRO designs (Fig. 4b). Generally, the power density is controlled by the water flux and the difference in the applied pressure (Eq. (6)).

Furthermore, adding a third PRO stage caused a rise in the power

density. For instance, the percentage rise in the average power density of the TSPRO design [1,2], TSPRO design [1,2], and TSPRO design [1,2] compared to the DSPRO design [1,3] is 22 %, 31 %, and 38 %, respectively (Fig. 4a). The TSPRO [1,2] is preferable over the other TSPRO designs for producing higher power density. Over the three TSPRO designs, the TSPRO design [1,2] shows the highest $W_{1,avg}$, while the TSPRO design [1,2] shows the highest $W_{2,avg}$, and the TSPRO design [1,2] shows the highest $W_{3,avg}$. The variation in the total power density through the different TRSPRO designs was affected by the variation in the total water flux (Fig. 4b). It can be noticed (Fig. 4b) that the power density increases with more PRO stages, which agrees with Chung et al. [31] study. Finally, the QSPRO shows the highest total power density of 15.02 W/m^2 , around 362 % more than the power density produced through the SSPPRO scenario.

3.1.2. The NSEG results

The single and multistage PRO designs used the same draw and feed solution flow rates; hence, the required pretreatment energy of the draw and feed solutions is equal. Fig. 5 represents the energy generated through the turbines, the energy consumed through pumping, and the net specific energy generation of the SSPPRO and the multistage PRO scenarios. E_{Turbine} ranges between 0.63 kW and 0.77 kW for the SSPPRO and the QSPRO scenarios, respectively. As the PRO stages increased, the amount of energy generated also increased according to the higher permeation flow and power generation in the PRO process. Further, the amount of energy consumed through pumping is fixed for the investigated designs because all scenarios utilize the exact amount of the inlet feed and draw solution flow rates. Accordingly, the NSEG will be enhanced with adding more PRO stages (Fig. 5). The NSEG for SSPPRO, DSPRO design [1,3], DSPRO design [1,3], DSPRO design [2], TSPRO design [1,2], TSPRO design [1,2], TSPRO design [1,2], and QSPRO design are 0.209, 0.230, 0.235, 0.257, 0.258, 0.261, 0.263, and 0.279 kW.h/m^3 , respectively. Presenting two membrane modules in each PRO stage of the DSPRO scenario caused a 23.41 % rise in the NSEG compared to the NSEG of the SSPPRO (Table 2). The NSEG increase in the DSPRO compared to an SSPPRO ranged from 10 % to 23 %. A similar result is reported in the literature [4], where the authors reported that around 12 % to 16 % was the increase in the specific energy due to using a DSPRO scenario. It is worth pointing out that the PRO module configuration of the DSPRO directly affected the NSEG. For instance, using the DSPRO design [1,3] instead of the DSPRO design [2] reduces the NSEG by around 11.98 %. As mentioned above, different membrane modules' configurations affected the permeation flow in the PRO stages (Fig. 3a). For instance, it was noticed that the DSPRO design [2]

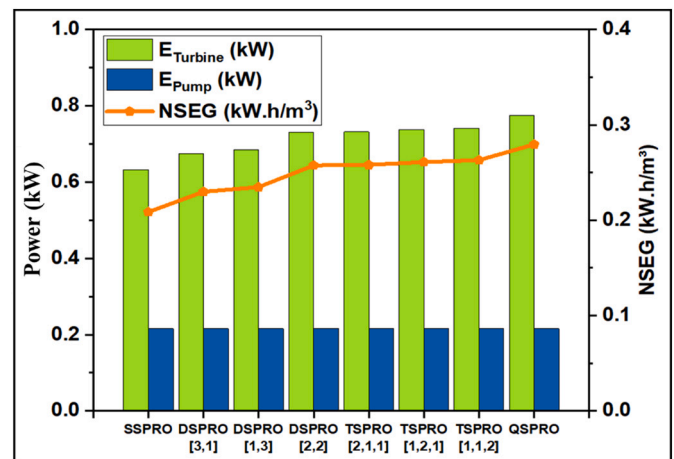


Fig. 5. The energy generated by the turbines (E_{Turbine}), the energy consumed by the pumps (E_{Pump}), and the net specific energy generation (NSEG) of the single-stage PRO (SSPPRO) and the multistage PRO scenarios.

Table 2

The percentage increase in the NSEG using the multistage PRO scenarios compared to the single-stage PRO (SSPRO) scenario.

Multistage PRO scenario		% Increase in the NSEG
Dual-stage PRO	DSPRO [3,1]	10.20
	DSPRO [1,3]	12.51
	DSPRO [2,2]	23.41
Ternary-stage PRO	TSPRO [2,1,1]	23.69
	TSPRO [1,2,1]	25.12
	TSPRO [1,1,2]	26.10
Quaternary-stage PRO	QSPRO	33.96

produced the highest permeation compared to the DSPRO design [1,3] and the DSPRO design [1,3] (Fig. 3a), explaining why the DSPRO design [2] produced higher NSEG.

Additionally, the same trend is noticed for the TSPRO designs, where a 26.10 % increase in the NSEG (Table 2) was achieved in the TSPRO design [1,2] compared to the SSPRO (Fig. 5). Results showed that having two membrane modules in PRO₁, one membrane module in PRO₂, and one membrane module in PRO₃ (i.e., TSPRO design [1,2]) is the less favourable configuration over the other two TSPRO designs (Fig. 5). By changing the modules' configuration to TSPRO design [1,2], higher water flux, power density (Fig. 4b), and permeation rate (Fig. 3a) was achieved, causing an increase in the NSEG. Furthermore, it has been noticed that the water flux and the membrane area govern the permeation flow along the PRO system. For instance, having more membrane modules in one PRO stage increases the permeation flow of that stage (Fig. 3a). The best-performance membrane configuration was in the QSPRO; a 33.96 % increase in the NSEG was attained compared to the SSPRO (Table 2).

Permeation flow, water flux, and internal concentrative concentration polarization are the key parameters that impact the amount of NSEG produced in the PRO. These parameters are affected by the number of PRO stages in the system and the membrane modules' configuration. For instance, although the power density in the DSPRO design [2] was not the best-performing PRO design, it produced the highest NSEG in the DSPRO scenario. The situation differed for the three TSPRO designs, where the TSPRO design [1,2] showed the highest permeation flow, water flux, and internal concentrative concentration polarization than the other two TSPRO designs. That explains why the TSPRO design [1,2] has the highest NSEG than the two TSPRO designs.

It is worth noting that the membrane cost will be equal for all of the investigated multistage PRO scenarios, as they all contain four membrane modules. The HF membrane module (HP5230SI) PRO's price, as Toyoboo gave and mentioned in our previous study [8], equals \$ 5193 US/membrane element. Then, the cost of the four membranes will be \$ 20,772 US.

Besides the advantages of employing multistage PRO systems, it is essential to consider their main limitations. For instance, a balance between the number of the PRO stages and the feed and the draw initial flow rates should be investigated. Adding more than four PRO stages would require increasing the feed and drawing solutions' initial flow rates. On the other hand, increasing the flow rates would increase the total consumed energy, impacting the net-specific energy generation. Moreover, the capital cost of the multistage PRO systems would vary based on the number of used PRO units. For instance, the cost of the PRO

membrane module's pressure vessel will impact the system's cost analysis. The QSPRO will be more expensive than the TSPRO, the DSPRO, and the SSPRO systems. Therefore, a critical cost analysis should determine the capital and operational costs before choosing how many PRO stages would be used. A power plant of a multistage PRO system would have turbines, pumps, pressure vessels, and water tanks. Accordingly, the availability of empty land should also be considered based on the number of PRO stages that would be used. Accordingly, a commercial power plant with PRO technology is not available yet, and further optimization and cost analysis of a full-scale plant are required [32,33].

After comparing the PRO designs' permeation flow, water flux, internal concentrative concentration polarization, and power density, the QSPRO scenario is the best-performance scenario for NSEG (Table 2). Consequently, this scenario will be further investigated with different salinity gradients.

3.2. Impact of the salinity gradient resource

The salinity gradient resource is one of the significant parameters that dominate the process efficiency of the PRO system [28,34]. It presents the driving force behind the water flow from the feed solution to the draw solution in the PRO according to the osmotic pressure gradient between the two solutions. Accordingly, this section studies the influence of the salinity gradient resource on the NSEG in the QSPRO scenario. Five salinity gradient resources were considered: Dead Sea-wastewater (DS-WW), Dead Sea-seawater (DS-SW), RO brine-wastewater (ROB-WW), seawater-wastewater (SW-WW), and Dead Sea with RO brine (DS-ROB). The selected feed and draw solutions represent the most available water bodies for energy generation by the PRO process [35–38]. The inlet feed and the draw solutions' flow rates were 1 m³/h, the applied pressure on the feed side (1 bar) and the solutions' temperature (298 K) were the same as the used ones for the DS-ROB (Subsection 2.3). Table 3 shows the salinity gradient resources, the resources' salinity concentration, and the applied pressure on the draw side. The applied pressure on the draw side for the DS-WW is half the osmotic pressure of the salinity gradient resource [39].

As the salinity gradient resources change, the performance of the QSPRO scenario changes.

Fig. 6a shows the permeation flow of the investigated salinity gradient resources' PRO1, PRO2, PRO3, and PRO4 designs. The DS-WW salinity gradient shows the highest Q_{p1} , Q_{p2} , Q_{p3} , and Q_{p4} compared to the other salinity resources (Fig. 6a). Compared to the DS-WW, the percentage drop in the permeation flow is 29.66 %, 46.03 %, 19.41 %, and 43.55 % for the DS-SW, DS-ROB, ROB-WW, and SW-WW salinity gradient resources. Additionally, the DS-WW has the highest water flux (Fig. 6b) and the highest osmotic pressure difference (Fig. 6c), potentially maximizing the energy output.

Fig. 6b displays the water fluxes (J_{w1} , J_{w2} , J_{w3} , and J_{w4}) for the PRO₁, PRO₂, PRO₃, and PRO₄ for the investigated salinity gradient resources. The highest total water flux is for the DS-WW, followed by ROB-WW, DS-SW, SW-WW, and DS-ROB. The DS-WW shows the highest J_{w1} , J_{w2} , J_{w3} , and J_{w4} compared to the other salinity resources (Fig. 6b) because of its highest osmotic pressure-driven force (Fig. 6c). The highest osmotic pressure gradient across the membrane, the highest water flux [4,7]. Compared to the DS-WW, the percentage drop in the total water flux is

Table 3

The salinity and the applied pressure on the draw side of the investigated salinity gradient resources.

Salinity gradient resources	Abbreviation	Resources' salinity (g/L)	Applied pressure on the draw side (bar)
Dead Sea-Wastewater	DS-WW	292.20–1.16	121
Dead Sea- Seawater	DS-SW	292.20–35.06	108
Dead Sea-RO Brine	DS-ROB	292.20–70.13	90
RO Brine-Wastewater	ROB-WW	70.13–1.16	29
Sea Water-Wastewater	SW-WW	35.06–1.16	16

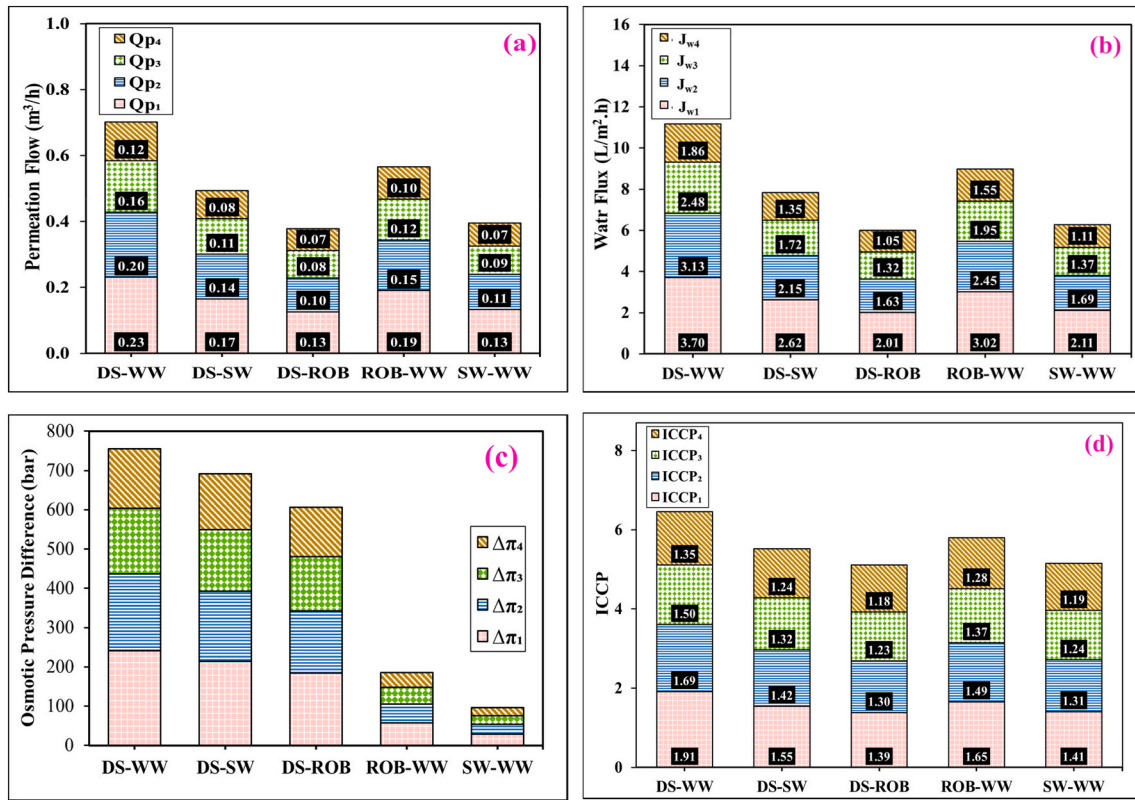


Fig. 6. (a) The permeation flow in the first, second, third, and fourth PRO stages (Q_{p1} , Q_{p2} , Q_{p3} , and Q_{p4} , respectively) in the quaternary-stage PRO (QSPRO) scenario for DS-WW, DS-SW, DS-ROB, ROB-WW, and SW-WW salinity resources, (b) the water flux in the first, second, third and fourth PRO stages (J_{w1} , J_{w2} , J_{w3} , and J_{w4} , respectively) in the quaternary-stage PRO (QSPRO) scenario for DS-WW, DS-SW, DS-ROB, ROB-WW, and SW-WW salinity resources, (c) the osmotic pressure difference in the first, second, third and fourth PRO stages ($\Delta\pi_1$, $\Delta\pi_2$, $\Delta\pi_3$, and $\Delta\pi_4$, respectively) of the quaternary-stage PRO (QSPRO) scenario for DS-WW, DS-SW, DS-ROB, ROB-WW, and SW-WW salinity resources, and (d) the internal concentrative concentration polarization in the first, second, third and fourth PRO stages ($ICCP_1$, $ICCP_2$, $ICCP_3$, and $ICCP_4$, respectively) of the quaternary-stage PRO (QSPRO) scenario for DS-WW, DS-SW, DS-ROB, ROB-WW, and SW-WW salinity resources.

29.91 %, 46.22 %, 19.69 %, and 43.75 % for the DS-SW, DS-ROB, ROB-WW, and SW-WW salinity gradient resources. At the same time, the internal concentrative concentration polarization is also affected by the permeation flow across the membrane. For instance, as shown in Fig. 6b, the ROB-WW shows the second-highest water flux compared to the DS-SW, DS-ROB, and SW-WW, which is responsible for the severe ICCP of ROB-WW compared to DS-SW, DS-ROB, and SW-WW salinity gradients (Fig. 6d).

The PRO system's osmotic pressure gradient across the membrane significantly impacts the produced energy. Fig. 7a displays the osmotic pressure gradient across the membrane of the QSPRO scenario for the five salinity gradient resources. The highest osmotic pressure gradient is for the DS-WW resource, while the lowest is for the SW-WW resources. The variance between the osmotic pressure of the feed and the draw solution explains the results in Fig. 7a. The energy generated, consumed by the pumps, and the NSEG of the QSPRO scenario for the investigated salinity gradient resources are shown in Fig. 7b. The energy consumed by the pumps depends on the salinity gradients. It ranges between 0.269 kW for the DS-WW and 0.205 kW for the SW-WW salinity gradient. The maximum energy generated through turbines is 1.91 kW for the DS-WW salinity gradient resources. The highest osmotic pressure gradient (Fig. 7a) and the highest applied pressure on the draw side (Table 2) resulted in the highest NSEG. Around 0.82 kWh/m³ is the NSEG produced in the QSPRO scenario using the DS-WW salinity gradient (Fig. 7b). The NSEG decreased by 41.73 %, 65.97 %, 86.44 %, and 99.15 % when DS-SW, DS-ROB, ROB-WW, and SW-WW salinity gradients were used instead of the DS-WW salinity gradient.

3.3. Impact of operating parameters on DS-WW QSPRO performance

According to section 3.2, the QSPRO scenario with DS-WW showed the highest NSEG of around 0.82 kWh/m³. To further enhance the QSPRO system performance, this subsection investigated the influence of the feed and the draw solutions flow rates and the applied draw solution pressure (Fig. 1b) on the energy generated by the turbines ($E_{Turbine}$), the energy consumed in the pumps (E_{Pump}), and the NSEG. The feed and draw solutions flow rates and the applied draw solution pressure govern the energy generation and consumption in the PRO process [40–42].

Fig. 8a shows the $E_{Turbine}$, E_{Pump} , and NSEG of the QSPRO scenario at different feed solution (WW) flow rates. Increasing the feed solution flow rate from 0.93 to 1.14 m³/h caused an increase in the energy generated by the turbines from 1.88 kW to 1.96 kW, about 5 %. Increasing the feed flow rate in the QSPRO scenario was responsible for the rise in the water flux at each PRO stage since water flux in the PRO system rises with the feed solution flow rate [27] as more water would be available for the permeation. Therefore, increasing the feed flow rate explains the boost in the water flux and, consequently, the increase in the energy generated by the turbines.

Besides, E_{Pump} increased by 2 % due to the feed flow rate increase from 0.93 to 1.14 m³/h, since the higher the flow rate, the higher the energy consumed through pumping [43]. Even though the energy consumed through pumping was increased, the net energy, Eq. (13), increased due to the considerable increase in the energy generated compared to the energy consumed. Fig. 8a shows that the NSEG dropped due to the increased feed solution flow rate. The decrease in the NSEG can be explained by Eq. (13) since the NSEG is inversely related to the

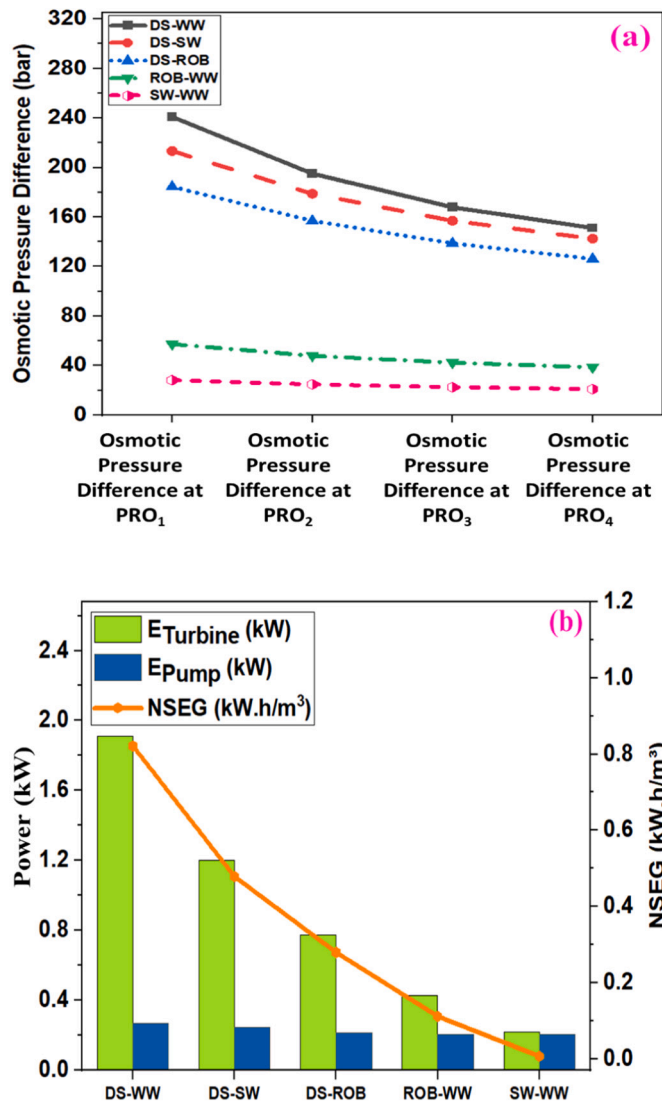


Fig. 7. (a) The osmotic pressure difference at PRO₁, PRO₂, PRO₃, and PRO₄ of the quaternary-stage PRO (QSPRO) scenario for DS-WW, DS-SW, DS-ROB, ROB-WW, and SW-WW salinity resources, and (b) the energy generated by the turbines (E_{Turbine}), the energy consumed by the pumps (E_{Pump}), and the net specific energy generation (NSEG) of the quaternary-stage PRO (QSPRO) scenario for DS-WW, DS-SW, DS-ROB, ROB-WW, and SW-WW salinity resources.

total feed and draw flow rates (Q_{tot}). There was a 22 % increase in the feed solution flow rate when the feed solution flow rate increased from 0.93 to 1.14 m³/h. Thus, the lower the feed solution flow rate is, the higher the NSEG (Table 4).

The profile of NSEG followed the same trend when the draw solution flow rate increased from 0.93 to 1.14 m³/h. The E_{Turbine} and the E_{Pump} increased with the draw solution flow rate (Fig. 8b). A 22 % rise in the draw solution flow rate caused a 10 % increase in the E_{Turbine} and a 19 % increase in the E_{Pump} . The higher the draw solution flow rate, the lower the impact of the draw dilution effect on the water flux [44]. The increased water flux improved the E_{Turbine} generated in the PRO process. Previous research reported a direct relation between the draw solution flow rate and the water flux of the PRO system [27,30,45,46]. However, the NSEG decreased from 0.824 kWh/m³ to 0.806 kWh/m³ (Fig. 8b) due to the increase in the total draw solution flow rate, as shown in Eq. (13). Enhancing the net specific energy harvested by the PRO required less draw solution flow rate (Table 4).

Fig. 8c displays the impact of varying the applied pressure on the draw side (Pump 2, Fig. 1b) on the QSPRO system performance.

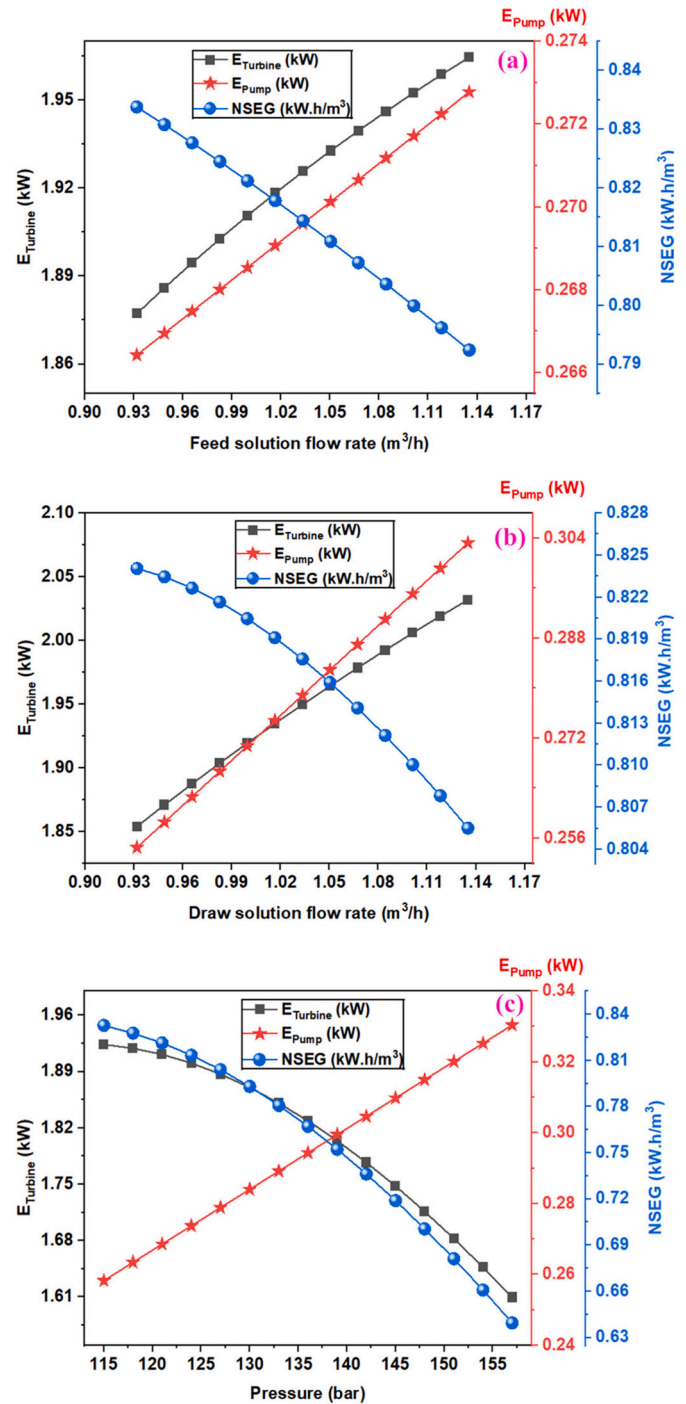


Fig. 8. (a), (b), and (c) the impact of the variation of the feed solution flow rate, the draw solution flow rate, and the applied pressure on the energy generated by the turbines (E_{Turbine}), the energy consumed by the pumps (E_{Pump}), and the net specific energy generation (NSEG) of the quaternary-stage PRO (QSPRO) scenario for DS-WW salinity resources, respectively.

Undoubtedly, increased E_{Pump} was noticed with the increased applied pressure. A 37 % increase in the applied pressure caused a rise in E_{Pump} from 0.258 kW to 0.330 kW (Fig. 8c). In contrast, the results showed a 16 % drop in the E_{Turbine} with the increase in the applied pressure (Table 4) due to the drop in the water flux in the PRO stages of the QSPRO [47–49]. Additionally, the higher the applied pressure on the PRO membrane, the greater the membrane fouling [50,51], impacting the PRO water flux. Approximately 23 % reduction in the NSEG

Table 4The percentage change in the E_{Turbine} , E_{pump} , net energy, and NSEG as the quaternary-stage PRO (QSPRO) scenario parameters changed.

Parameter changed	Range	% Change in the E_{Turbine}	% Change in the E_{pump}	%Change in the net energy	% Change in the NSEG
Feed flow rate	$1 > \frac{Q_{\text{Fi}}}{Q_{\text{Di}}} > 0.93$	−1.75	−0.79	−1.91	1.53
	$1 < \frac{Q_{\text{Fi}}}{Q_{\text{Di}}} < 1.14$	2.82	1.58	3.03	−3.51
Draw flow rate	$1 > \frac{Q_{\text{Di}}}{Q_{\text{Fi}}} > 0.93$	−3.41	−6.00	−2.98	0.44
	$1 < \frac{Q_{\text{Di}}}{Q_{\text{Fi}}} < 1.14$	5.87	11.99	4.86	−1.82
Hydraulic pressure on the draw side	$\frac{\Delta\pi}{2} > \Delta P > 0.95 \times \frac{\Delta\pi}{2}$	0.65	−3.84	1.39	1.39
	$\frac{\Delta\pi}{2} < \Delta P < 1.30 \times \frac{\Delta\pi}{2}$	−15.79	23.04	−22.14	−22.14

occurred with increased draw solution pressure. It can be noticed that the variation of the applied pressure on the draw side has the highest impact on the QSPRO system performance compared to the feed and draw solutions flow rates.

Generally, multistage PRO scenarios are more efficient than single-stage PRO due to the lower ICCP on the feed side in the additional stages. Dividing the feed solution into the PRO stages attenuates the impact of ICCP, improving water flux and, eventually, energy generation. The QSPRO configuration achieved the highest energy generation due to the greater permeation flow caused by using a fresh feed solution in each stage (Fig. 3). Dead Sea-wastewater salinity gradients exhibited the highest osmotic pressure driving force and NSEG compared to other salinity gradients. Table 4 shows the results of the variation of the operating conditions on the QSPRO system using Dead Sea-wastewater as the salinity gradient resource. Varying the feed and draw solution flow rates and draw solution pressure led to an insignificant drop in the NSEG. Therefore, using a feed-to-draw flow rate ratio of <1 and a draw solution pressure slightly lower than the average osmotic pressure difference of the salinity gradient offers the best operating condition in the multistage PRO process (Table 4). For instance, reducing $\frac{Q_{\text{Fi}}}{Q_{\text{Di}}}$ from 1 to 0.93 (reducing the feed flow rate and using a draw flow rate was $1 \text{ m}^3/\text{h}$) caused a 1.53 % increase in the NSEG. A similar trend was noticed when $\frac{Q_{\text{Di}}}{Q_{\text{Fi}}}$ was reduced from 1 to 0.93 by reducing the draw flow rate and using $1 \text{ m}^3/\text{h}$ feed flow rate caused a 0.44 % increase in the NSEG. In contrast, a 1.39 % increase in the NSEG occurred when the applied hydraulic pressure was 0.95 of the average osmotic pressure difference (Table 4). However, the highest impact on the NSEG was noticed when the applied pressure increased from $\frac{\Delta\pi}{2}$ to $1.30 \times \frac{\Delta\pi}{2}$, causing a 22.14 % drop in the NSEG. Accordingly, the applied hydraulic pressure is the most influential parameter on the NSEG, and it is preferred to be equal to or slightly less than $\Delta\pi/2$.

4. Conclusion

This study focuses on determining the NSEG of SSPRO, DSPRO, TSPRO, and QSPRO of DS-ROB as salinity gradients. The results showed that the NSEG of the QSPRO scenario is 33.96 % higher than its corresponding SSPRO scenario. Moreover, it has been noticed that the water flux and the power density are increasing by adding more PRO stages to the system. For instance, the QSPRO scenario will produce 362 % higher water flux than the SSPRO scenario. Adding more PRO stages reduces the inverse effect of the internal concentration polarization on the multistage PRO performance. It will enhance the multistage PRO systems' water flux, power density, and NSEG.

Five salinity gradients are investigated using the QSPRO scenario. The DS-WW salinity gradients of the QSPRO scenario presented the highest produced water flux over the DS-SW, DS-ROB, ROB-WW, and SW-WW. Additionally, the DS-WW has the highest osmotic pressure gradient and the highest applied pressure on the draw side. These results clarify that the DS-WW of the QSPRO scenario produced the highest

NSEG of about 0.82 kW.h/m^3 .

The variation of the feed solution flow rate, the draw solution flow rate, and the applied pressure on the QSPRO system productivity are also evaluated. The results show that the applied pressure has the most dominant impact on the behaviour of the QSPRO scenario compared to the feed solution and the draw solution flow rates. A 37 % increase in the applied pressure caused a 23 % drop in the NSEG. On the other hand, the reduction in the NSEG was 5 % and 2 %, with a 22 % rise in the feed solution flow rate and the draw solution flow rate, respectively, indicating the significance of choosing the best parameters for maximizing the NSEG of the QSPRO scenario. It has been concluded that the highest impact on the NSEG was noticed when the applied pressure increased from $\frac{\Delta\pi}{2}$ to $1.30 \times \frac{\Delta\pi}{2}$, causing a 22.14 % drop in the NSEG. Accordingly, the applied hydraulic pressure is the most influential parameter on the NSEG, and it is preferred to be equal to or slightly less than half of the osmotic pressure difference. The outcomes of this study aim to enhance comprehension among researchers and scientists regarding the merits of employing a multistage PRO instead of a single-stage PRO in water treatment. Conducting a pilot plant investigation is essential for interpreting the advantages associated with the multistage PRO process, and it is strongly advised that such studies be undertaken to verify the findings of this study.

CRediT authorship contribution statement

Nahawand: Conceptualization, Data collection, Data Analysis, Writing – original draft, writing – review and editing. **Ibrar Ibrar:** Interpretation of results, Supervision, Data collection, editing, writing –original and review, Data analysis. **Ali Altaee:** Supervision, Conceptualization, Data Analysis, Writing – review and editing. **Senthilmurugan Subbiah:** Conceptualization, data analysis. **John L. Zhou:** Supervision, Writing – review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The authors wish to acknowledge their gratitude for the assistance provided by an Australian Government Research Training Program Scholarship. The Dymola software is presented by the Department of Science and Technology, Government of India, Project Number No. DST/TMIWT/2K16/73 (G).

Appendix A

The following table represents the results of the simulation of the suggested PRO model used in this study.

Table A.1

The outputs and the parameters of the PRO process simulation.

Input	Value
Feed inlet flow rate, Q_{Fi} (m ³ /h)	1
Feed inlet concentration, C_{Fi} (g/L)	70.13
Feed inlet pressure, P_{Fi} (bar)	1
Draw inlet flow rate, Q_{Di} (m ³ /h)	1
Draw inlet concentration, C_{Di} (g/L)	292.20
Draw inlet pressure, P_{Di} (bar)	90
Parameter	Value
Area of the single membrane, A_m (m ²)	63
Vont's Hoff factor, i	2
Universal gas constant, R (m ³ .bar/(mol.K)	0.00008314
The molecular weight of NaCl, M_{wt} (g/mol)	58.5
Constant in mass transfer coefficient relation, x (bar.s/m ⁴)	0.002068
Constant in mass transfer coefficient relation, y	0.501
Membrane water permeability, A_w (m/(bar.s))	1×10^{-7}
Membrane salt permeability, B (m/s)	6.235×10^{-9}
Membrane structural parameter S (m)	880×10^{-6}
Output	Value
Feed outlet flow rate, Q_{Fo} (m ³ /h)	0.76
Feed outlet concentration, C_{Fo} (g/L)	880.01
Draw outlet flow rate, Q_{Do} (m ³ /h)	1.24
Draw outlet concentration, C_{Do} (g/L)	243.116
Feed outlet pressure, P_{Fo} (bar)	0.81
Draw outlet pressure, P_{Do} (bar)	89.89

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