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Improving the performance of reverse osmosis desalination process with pressure retarded osmosis

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Abstract

The interest on technologies using salinity gradient energy sources for reducing the energy consumption in seawater desalination processes is growing in the last years. One of the technologies able to harvest this kind of energy is pressure retarded osmosis. This work evaluates the performance of three different reverse osmosis – pressure retarded osmosis (RO-PRO) hybrid schemes for energy recovery in seawater desalination applications. The configurations considered have been taken from the patent of Sarp et al. (2016), selected as a relevant proposal from the literature survey. A fourth arrangement based on conventional RO process combined with brackish water RO (BWRO) is analysed for performance comparison with the schemes from the patent. Reverse osmosis system analysis (ROSA) software environment has been used to select the best RO configuration and operating conditions that best fit those reported in the patent. Two different cases are evaluated depending on the origin of the external low-salinity resource for the PRO process. In the case of industrial wastewater, due to regulations on wastewater reclamation, the best arrangement would be the first scheme proposed in the patent with a specific energy consumption of 1.54 kWh/m^3. Besides that, if urban treated wastewater is available as external resource, results obtained show that the scheme leading to the minimum specific energy consumption of the process (1.47 kWh/m^3) is the conventional seawater RO combined with BWRO.

Keywords: seawater desalination, pressure retarded osmosis, reverse osmosis, energy efficiency, industrial water reuse

HIGHLIGHTS:

- Assessment of PRO-SWRO schemes proposed in the literature for desalination is presented
- Urban and industrial wastewater as external resource for PRO process are evaluated
- The RO+PRO process is recommended if treated industrial wastewater is available

1. Introduction

The concern for the global warming and unsustainable growth of the energy consumption worldwide has raised great interest on renewable technologies as alternatives to conventional power plants based on fossil fuels. Among the available clean and environmentally friendly technologies (solar, wind, geothermal, etc.), those based on salinity gradient harnessing (blue energy) have become more attractive in the recent years, mainly due to the so far unexploited high potential of this source of energy, which is estimated in 2000 TWh/year [1]. There are two technologies able to extract this kind of energy: pressure retarded osmosis (PRO) and reverse electrodialysis (RED). Both processes extract energy from the controlled mixing of two solutions with different concentrations. The former uses osmotic membranes that allows the passage of water (permeate) while rejects the exchange of salt ions. Therefore, if a pressure lower than the osmotic pressure is applied to the concentrated solution (draw solution), the water transferred through the membrane from the dilute solution is "retarded" into pressurized high-salinity water. Then, the hydraulic pressure of this water volume is converted into mechanical energy in a hydraulic turbine, generating power. The RED technology, at the contrary, uses ion exchange membranes (IEMs) between a concentrate and a dilute salt solution to extract energy from the salinity gradient. Cationic and anionic IEMs are stacked in alternate positions forming channels for the concentrated and dilute solutions, with two electrodes at the sides. Cations and anions pass, respectively, through the cationic and anionic membranes. This exchange of ions is converted into exchange of electrons with a redox solution, generating a differential of potential at the electrodes when the circuit is closed. In this way, the electrochemical energy of the salinity gradient is converted directly into electricity. Nevertheless, in general, the PRO process provides higher efficiency and power density than RED, as stated by Yip & Elimelech [2].

The potential of the PRO process as a sustainable and emission-free energy source for power production or as energy recovery system has been highlighted by a number of authors from the middle of the twentieth century [3–11]. In 1981 Lee et al. [12] developed a model for predicting the performance of PRO membranes based on direct and reverse osmosis (RO) experimental data. They used flat sheet membranes and different water–brine pairings. It was found that concentration polarization within support layer reduced significantly the water flux. Also, an economic analysis revealed that using the couple fresh water-seawater PRO technology was not economically feasible with actual membranes, which should considerably improve their performance in order to reduce the cost of energy production. Nevertheless, for the fresh water–brine (25 wt% NaCl) case, the results obtained were competitive with other power production methods, under the economic assumptions made. In 1982, Mehta [13] investigated the performance of several hollow fibre and spiral wound membranes for RO and PRO applications, by conducting different experiments. Results obtained showed that spiral wound membranes could be used for PRO, but in order to be economically competitive, the performance of the membranes should be increased. Also, tests were done with commercial RO hollow fibre membranes for PRO applications, using potassium alum and high temperatures. Results revealed that the water flux was significantly lower than that of RO with NaCl solution at the same temperature.

Hybrid schemes between RO and PRO can help to minimize the energy consumption of the desalination process. The concentrated brine rejected from the RO can be used as the draw solution for the PRO, and the power produced by the PRO unit could reduce the pumping requirements of the RO. In addition, the dilution of the RO brine before being rejected to the sea can help to minimize the environmental impact of the desalination process.

The hybridization of SWRO processes with PRO with the aim of decreasing the specific energy consumption (SEC) has been widely reported in the recent literature. A significant number of papers have been published in this topic in the last years. A brief resume with some relevant publications is detailed hereafter.

Kim et al. [14] compared four RO-PRO hybrid arrangements to investigate the influence of the RO and PRO plant sizes, solutions concentration, and water and electricity prices on the water and energy return rate, a cost indicator concerning energy and water production. Results showed that the RO plant size had a stronger influence on the economic performance in comparison with the PRO plant size. Altaee et al. [15] assessed the performance of the PRO-RO process for seawater desalination and power generation. It was found that the PRO power production was improved when seawater with high total dissolved solids (TDS) was used, and with the increase of the feed and draw solutions flow rate. A maximum energy consumption reduction of 31% with respect the RO desalination system was obtained. Almansoori and Saif [16] analysed the design of PRO-RO schemes for the combined generation of water and power in desalination processes. A mixed integer non-linear programming model was developed and used to identify the optimal configuration and operating conditions. Results indicated that the RO process can be a feasible source for the PRO process. Prante et al. [17] modelled the specific energy consumption of the PRO-RO process and presented a module-based PRO model. A reduction of 40% in the energy consumption with respect standalone RO was found, 1.2 kWh/m^3 against 2 kWh/m^3 of RO (for 50% recovery). A sensitivity analysis revealed that a minimum SEC of 1 kWh/m^3 of permeate can be reached, with 50% recovery and a power density of 10 W/m^2.

Achilli et al. [18] experimentally evaluated the reduction in energy consumption of the RO desalination process hybridized with PRO. Three different configurations were assessed: standalone RO, RO-PX (isobaric pressure exchanger), and RO-PRO, with water recoveries of 20 and 30%. Simulated seawater of 35 – 37 g/L was used as RO feed solution and filtered municipal tap water was used for the PRO feed solution. The lowest SEC was observed for the RO-PRO configuration with a second PX (2.64 kWh/m^3 at 30% recovery) and the maximum power density achieved was 2.3 W/m^2. Altaee et al. [19] compared the performance of three different design arrangements for seawater desalination and power production: PRO-RO, forward osmosis (FO)-RO, and RO-PRO, using seawater and impaired water as the draw and feed solutions, respectively. The power generation efficiency of the RO-PRO scheme was higher than that of the PRO-RO, while the lowest energy consumption for desalination was achieved by the FO-RO process, followed by PRO-RO and RO-PRO. Kim et al. [20] analysed the energy consumption of an osmotic dilution process composed of a PRO-RO hybrid scheme, combining wastewater reuse and seawater desalination. Results reported a reduction of the SEC with respect the conventional RO process and with the combined forward osmosis scheme. Also, a significant decrease of the flux in the PRO due to the membrane inorganic fouling was identified.

Alternatives to the use of freshwater as feed solution to the PRO process have been evaluated in locations with water stress. In this respect, Wan and Chung [21] assessed the power generation with PRO using seawater brine from a RO plant as draw solution, and wastewater retentate from a RO water treatment plant as feed solution. A maximum power density of 4.6 W/m^2 was obtained, identifying the fouling on the porous substrate caused by the wastewater the main detrimental effect for the reduction of the power density. On the contrary, the effect of the RO brine on the process performance was small. Using ultrafiltration and nanofiltration pretreatments for the wastewater, the power density increased to 6.6 and 8.9 W/m^2, respectively. In addition, when deionized water was used as feed solution and RO brine as draw solution, a maximum power density of 21.1 W/m^2 was achieved. Zubair et al. [22] analysed the RO process applied to brackish water desalination by performing an exergetic evaluation of different energy recovering methods. The turbocharger, Pelton turbine, pressure exchanger and PRO were assessed, and results showed that the best option was coupling the RO with a PX, while the schemes with PRO provided performances equal or worse than the hydroturbine.

Choi et al. [23] presented a model to evaluate the performance and cost of a RO-PRO process. Results obtained showed that the water transport coefficient, internal concentration polarization, and seawater and feedwater TDS had a significant influence on the efficiency of the hybrid process. Also, from the economic analysis, the RO-PRO process was found to be competitive with the standalone RO process only for a high price of electricity, low price of PRO membranes, and high power density. Kurihara et al. [24] presented a performance analysis of the "Mega-ton Water System" formed by a large-capacity SWRO process (one million cubic meters) for seawater desalination and wastewater treatment system. The aims of the project were to reduce the energy consumption of the process, the environmental impact, and freshwater production costs. For that purpose, a PRO energy recovery system was proposed. The operation of a prototype plant during one year was studied. The maximum power density obtained was 13.5 W/m^2, and up to a 10% of energy saving with the PRO process was estimated, using 10-inch modules (Toyobo CTA Hollow Fibre). Wan et al. [25] developed an analytical model for predicting the PRO performance. They used the model to maximize the operating profit and recovery of a SWRO-PRO system. They found that it was possible to increase the recovery maintaining its profitability, to reduce the SEC of the desalination process by 35%, and to improve the operating profit of each m^3 of freshwater by 100% (taking into account the water and electricity price). Chung et al. [26] investigated the performance of a SWRO-PRO system for desalination and power production purposes, using a pilot-scale plant. In this case, the draw and feed solutions for the PRO were the RO brine and permeate, respectively. It was found that increasing the draw solution salinity and flow rate was beneficial for the process, while the maximum power density achieved was of 14 W/m^2 at 28 bar with a 70,000 mg/L NaCl solution. Senthil and Senthilmurugan [27] reported a theoretical assessment on the performance of six different SWRO-PRO hybrid schemes. The use of seawater and urban wastewater as feed of the PRO unit was analysed. The arrangement where the diluted RO brine was mixed with the feedwater of the SWRO process and with wastewater as the feedwater of the PRO unit provided the lowest SEC reduction with respect the stand-alone case (49%). For a production of 0.054 m^3/s and 0.1 g/L of feed solution concentration the optimal SEC was 0.842 kWh/m^3. Altaee et al. [28] theoretically analysed the design and operation of PRO-RO units for increasing the water recovery of the desalination process. RO brine was used as draw solution for the PRO process. Results showed that higher seawater salinities and RO freshwater recovery led to increase the power density. For 35 g/L seawater and recovery of 52% the power density obtained was 24 W/m^2, with 4.5 M NaCl draw solution. Up to 18% of increase in the water recovery was observed adding the PRO unit to the RO desalination process. Kim et al. [29] evaluated an hybrid scheme formed by RO, membrane distillation (MD) and PRO. This system decreased the SEC of the stand-alone RO desalination process and increased the dilution of the RO brine rejected to the environment. However, it was only recommended in locations where cheap or free thermal energy is available for the MD unit. Wan and Chung [30] investigated the reduction of energy consumption in the SWRO desalination process with PRO. Three different options were evaluated: stand-alone SWRO process, SWRO with two pressure exchangers, and SWRO with two pressure exchangers and PRO. For a 50% of freshwater recovery and using wastewater (or freshwater) as feed solution, the SEC obtained were 4.13, 2.27 and 1.14 kWh/m^3, respectively. It was highlighted that finding the optimal operating pressure for the PRO unit is crucial to maximize the power density and reduce the SEC of the integrated system. It was also recommended to develop new membranes able to work at the operating pressure with high water flux. Straub et al. [31] reviewed the use of PRO as energy recovery process in different configurations: in natural locations where river water and seawater meet, power plants using the osmotic energy with hypersaline solutions, and RO desalination plants. In the latter case, it was concluded that the RO-PRO was beneficial if large impaired water resources are available and moderate water recoveries are needed. Some practical problems that diminish the energy consumption reduction were discussed, such as the losses in the pressure exchangers and pumps and the fouling in the membranes. It was also indicated the possibility of directly produce water through the impaired water rather than use it in the RO desalination process.

Altaee et al. [32] studied the feasibility of the PRO process for power generation taking into account the input energy requirements and losses. The highest contribution to the energy loss was due to the concentration polarization (40% of the total). The feed and draw solution pretreatments represented 38% of the total energy input. The net power was negative when using seawater – river water as draw and feed solution, respectively, and it was positive for RO brine – wastewater. The Dead Sea seawater – RO brine provided the best results. However, due to the maximum pressure currently supported by commercial PRO membranes is around 30 bar, the optimal operating conditions for those high-concentrated solutions would be not feasible. Touati et al. [33] investigated the performance of two different RO-PRO schemes for a two-stage RO seawater desalination system, without using external water streams. The first scheme is composed of two RO stages and a PRO unit, being the draw and feed solutions the RO brine from the first and the second RO stages, respectively. In the second scheme the feed of the first PRO is pretreated seawater, while the draw solution of the second PRO device is the bleed of the first PRO. Results showed higher performance of the second configuration for recoveries between 40-50%. It was also found that the capacity of the SWRO plant and the concentration of the seawater had a great influence on the PRO performance. Altaee et al. [34] comparatively evaluated the energy production between PRO and dual stage PRO. In this scheme the draw solution is reused in a second PRO stage to further exploit the remaining salinity gradient. Several arrangements for the membrane modules and different draw and feed solutions were assessed. It was concluded that for a specific draw solution concentration the dual PRO scheme provided higher specific energy generation than the standalone PRO process with high feed concentration. Lee et al. [35] experimentally investigated the performance of thin-film composite hollow fibre membrane PRO modules on a SWRO pilot plant. Three feed pairs were tested: synthetic brine – tap water, real RO brine – tap water, and real RO brine – wastewater retentate. Power densities between 5 and 5.7 W/m^2 were obtained using a draw solution pressure of 15 bar, concentration 0.8 M, and 45% of recovery. Husnil et al. [36] analysed different configurations of the integrated production of water, salt and power by means of SWRO, PRO and electrodialysis units. The position of the RO and PRO units were evaluated with respect the main performance parameters. It was concluded that the highest power production and lower energy consumption for desalination was achieved when the RO unit was located before the PRO unit, although the permeate production was lower. Attarde et al. [37] analysed RO-PRO and FO-RO hybrid schemes for energy recovery in seawater desalination and wastewater treatment processes. The developed mathematical models for axial-flow and radial-flow hollow fibre modules to evaluate the system performance. Results obtained showed that about 25% of energy saving can be achieved with both hybrid schemes, with respect the conventional RO process, being the freshwater recovery of 50%.

Chae et al. [38] investigated SWRO-PRO and SWRO-MD-PRO hybrid processes by means of a proposed performance index that considers the energy recovered by the PRO and the energy consumed by the MD and RO processes. Simulations results indicated that the SWRO-MD-PRO scheme performed better than the SWRO-PRO when a cheap energy source was available for the MD. Li [39] carried out a performance optimization of a dual stage RO-PRO system for seawater desalination and power production. This scheme permits to apply a profile of hydraulic pressure along the stages, which is more convenient due to the osmotic pressure varies along the membranes. The SEC was minimized considering the total membrane area and water recovery. The best distribution of the membrane area and applied pressure were identified in the system, enhancing the energy efficiency of the process.

Wang et al. [40] performed an optimization study of the PRO process in order to reduce the SWRO energy consumption. A system-level process model was developed, and results showed that a significant reduction of the SEC could be achieved by increasing the permeate flow and operating pressure in the PRO unit. Nevertheless, the PRO membranes cannot achieve these conditions simultaneously. The increase of the PRO operating temperature help to increase the permeate flow under these conditions. Passing from 25 to 50 °C in a SWRO resulted in a reduction of the SEC of 14.4% for 0.6 M NaCl draw solution and of 18% for 1.4 M of NaCl draw solution. Soltani and Struchtrup [41] investigated the multistage PRO process in order to further enhance the process in comparison with the single stage PRO. A model was developed for the dual stage PRO plant and several arrangements were tested, maintaining the same membrane area. The effect of the concentration polarization, salt flux and pressure drop were considered in the model. It was observed that the specific energy produced could be enhanced by 8% with the dual stage PRO. Long et al. [42] developed a mathematical model for the PRO process to investigate the effect on the performance of different operating parameters. A sensitivity analysis revealed that the hydraulic pressure leading to the maximum power density and energy efficiency were not coincident.

Sarp et al. [43] proposes relevant RO-PRO configurations in the patent no. US 9,428,406 B2 to reduce the energy consumption in seawater desalination applications. However, no data of specific energy consumption are provided. This work has been selected, among the revised literature, to investigate the performance of the RO-PRO hybrid scheme and the energy consumption decrease by recovering osmotic energy from the rejected brine of the RO process. Specifically, the performance of three different PRO-RO configurations proposed in Ref. [43] have been assessed and a fourth configuration, based on the conventional SWRO combined with BWRO, is also proposed in order to make a fair comparison between the arrangements.

Reverse osmosis system analysis (ROSA) software environment [44] is used to select the RO membrane and configuration (number of pressure vessels and elements) which best fit the conditions provided in the patent. The values of the main variables (mass flow rate, pressure, concentration) for each stream of the patent are determined using the RO membrane configuration obtained and the data provided in the hybrid schemes. Finally, two different cases are evaluated depending on the origin of the external resource and the possibilities of water reclamation: industrial wastewater or pretreated urban wastewater.

2. Description of the system

Three different arrangements for the hybridization of a RO seawater desalination process and PRO have been selected from the existing literature [43] in order to reduce the overall specific energy consumption of the process. The three integrating schemes are detailed in the following subsections. For all the arrangements, according to said reference the mass balances applied are done assuming 100 m3/h of feed seawater with concentration of 40 g/L and temperature of 28ºC and recovery rate of the RO unit established as 50%.

2.1 First configuration

The first configuration, depicted in Fig. 1, is composed of a RO unit, a PRO system, two pressure exchangers (PX1 and PX2), one high-pressure pump (HP), two low-pressure pumps (LP1 and LP2), and a booster pump (BP). The inlet seawater, at ambient pressure, enters to the pressure exchanger PX2 where is pressurized up to 29.8 bar by the flow coming from the PRO process generated by dilution of the concentrated brine (draw solution). The pressurized inlet seawater is then divided in two equal streams: the first enters the pressure exchanger PX1 where gains pressure (up to 57.5 bar) due to the energy partially transferred by the RO brine outlet. The second stream is directed to the high-pressure pumps HP, where is pressurized up to the operating pressure of the desalination process (60 bar). This stream is mixed with the feed outlet of the PX1, after even its pressure by means of the booster pump BP1. This mixed stream (RO feed) enters the core of the RO unit, obtaining the permeate (product) and the rejected brine. This RO brine constitutes the draw solution of the PRO process. As this stream contains high-pressure energy (59 bar), it is partially transferred to the RO feedwater in the PX1. Before entering the PRO unit, it is slightly pressurized by the booster pump BP2. The dilute solution for the PRO unit, assumed to be pre-treated wastewater or brackish water, is pressurized from the atmospheric pressure to 5 bar in LP2. In this configuration a volumetric flow rate increase from the dilute solution of 80% is assumed for the PRO process. Part of the inlet dilute solution permeates to the pressurized draw solution, and the diluted draw solution at 30.7 bar enters the PX2 releasing its pressure energy to the feedwater. In this way, proposed by Sarp et al. [43], the PRO unit is used for reducing the pumping requirements of the RO desalination process and the concentration of the brine disposal.

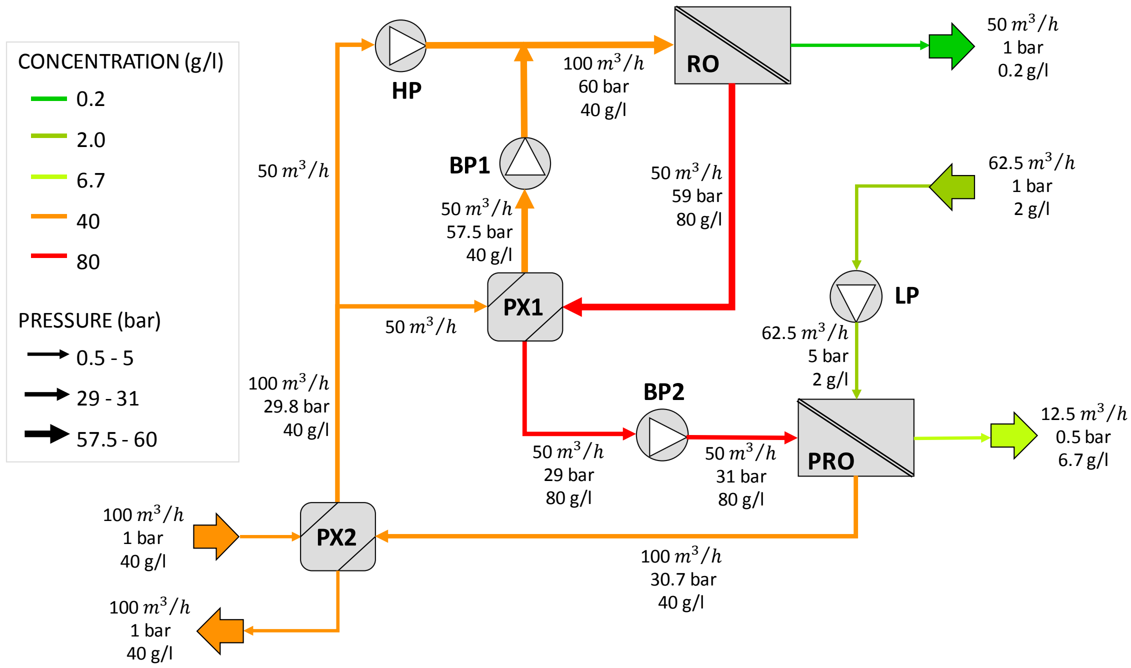

Fig. 1. Schematic diagram of the first SWRO+PRO arrangement proposed in the patent analysed.

2.2 Second configuration

The second RO-PRO scheme proposed in the patent is presented in *Fig. 2*. The feed seawater, at ambient pressure, is divided in two streams: the first one (15 m^3/h) is directed to the high-pressure RO pumps (HP2) where is pressurized up to 60 bar. The second stream (85 m^3/h) is driven to a pressure exchanger (PX2), increasing its pressure to 29.8 bar by partially recovering pressure from the dilute draw solution exiting the PRO unit. At the outlet, this stream is divided in two: part of it (35 m^3/h) is directed to the high-pressure pumps (HP1) of the RO unit, and the rest (50 m^3/h) to a pressure exchanger (PX1) used to recover pressure energy from the brine produced in the RO process. In PX1 this stream increases its pressure up to 57.5 bar and, using a booster pump (BP1), evens its pressure to the operating pressure of the RO process (60 bar). The three streams at 60 bar are then mixed and driven to the RO unit, where the permeate is produced and the concentrated brine is used to recover pressure energy in PX1.

After passing through the PX1, the RO brine at 29 bar increases its pressure in the low booster pump (BP2) up to 31 bar and is used as draw solution in the PRO unit. A volumetric flow rate increase from the dilute solution of 70% for the PRO process is assumed. The dilute feed solution of the PRO unit increases its pressure in the low-pressure pump (LP) up to 5 bar. Part of it permeates through the osmotic membranes and dilutes the draw solution gaining pressure up to 30.7 bar. This stream is used in PX2 to recover pressure energy and increase the pressure of the feed stream to the system. Finally, the diluted RO brine is rejected at ambient pressure.

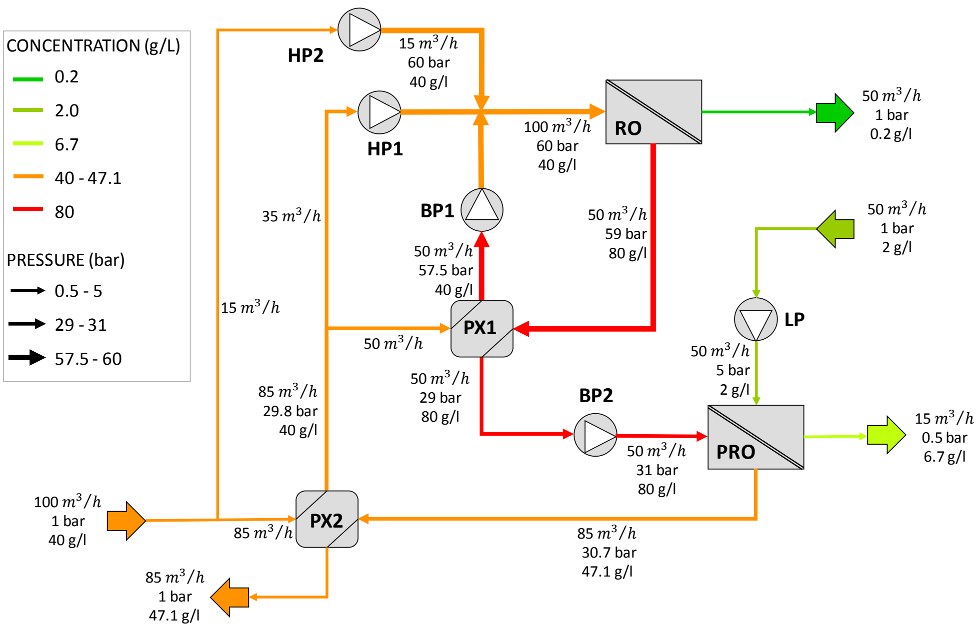

Fig. 2. Schematic diagram of the second SWRO+PRO arrangement proposed in the patent.

2.3 *Third configuration*

The third configuration proposed in the patent of Sarp et al. [43] is depicted in *Fig. 3*. This scheme is similar to the previous ones, although some differences can be observed. The feed seawater is split in two streams: a small part of this stream (25 m^3/h) goes to the pressure exchanger of the RO unit, PX1, where is pressurized up to 56.05 bar, and using the booster pump BP evens the RO operating pressure (60 bar). The other stream (75 m^3/h), is pressurized in PX2 up to 27.6 bar before entering the high-pressure RO pumps (HP), where is further pressurized to 60 bar. Both streams are then mixed at the inlet of the RO unit. At the outlet of the RO two streams are produced: the permeate flow, and the rejected brine, part of which (25 m^3/h) is used to recover pressure energy, and the other part (25 m^3/h) is mixed in the mixer (M) with the diluted brine at the outlet of the PX1. Note that respect the configuration 2, the booster pump associated to this stream is eliminated. The resulting stream, at 29.5 bar is the draw solution in the PRO unit. The dilute feed solution of the PRO is pressurized in the low-pressure pump LP up to 5 bar before entering the PRO unit, and part of it permeates to the concentrated side, hence gaining pressure. The diluted draw solution at the outlet of the PRO unit at 29 bar is split in two streams: the major part (75 m^3/h) is used in the PX2 to increase the pressure of the feed seawater, while the rest (10 m^3/h) is driven to a Pelton turbine to obtain mechanical energy. This configuration is the only one that has a hydraulic turbine and therefore the power produced can be used for pumping, reducing the SEC.

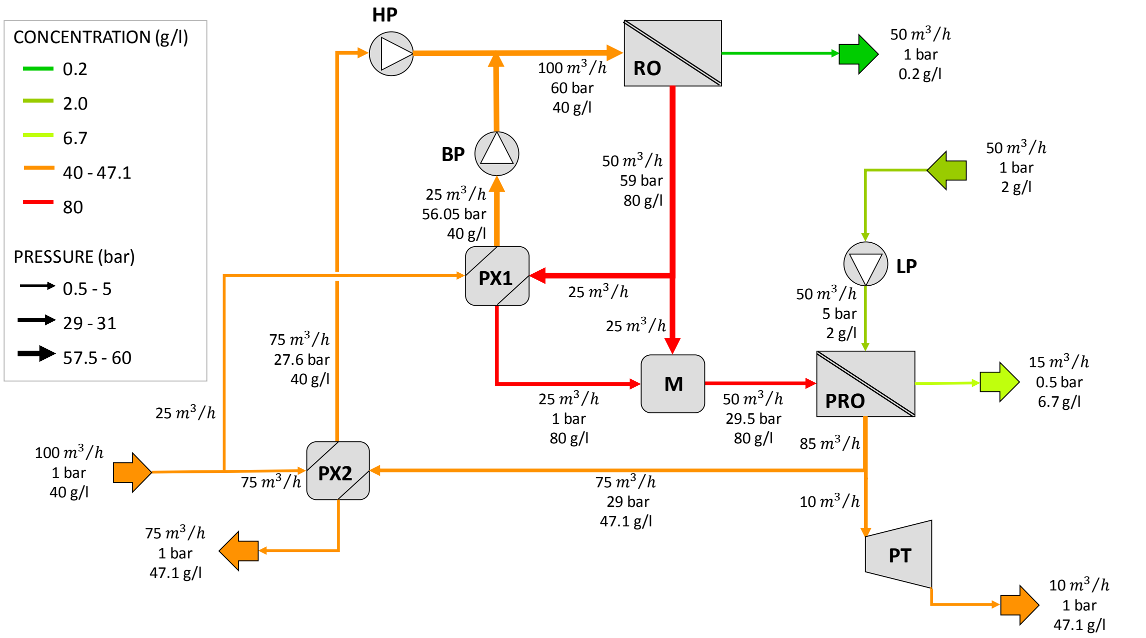

Fig. 3. Schematic diagram of the third SWRO+PRO arrangement proposed in the patent.

3. Materials and methods

The starting point of the analysis carried out consists in three configurations proposed in the literature in order to improve the energy performance of the SWRO desalination process as described in section 2. As a case base for allowing the assessment of the actual improvement, this paper considers a conventional configuration of SWRO desalination specifically designed to treat the same input flows. They are the same in all configurations:

- High salinity stream: volumetric flow, 62.5 m^3/h; pressure, 1 bar; salinity, 2 g/L.
- Low salinity stream: volumetric flow, 100 m^3/h; pressure, 1 bar; salinity, 40 g/L.

Therefore, a seawater RO scheme with the same inputs as those described in the patent is defined to perform a fair performance comparison of the three RO-PRO configurations with the single SWRO process. In order to make this standalone SWRO process similar to the other three configurations, an external brackish water stream should be added, with a volumetric flow rate of 50 m^3/h and a concentration of 2 g/L, in correspondence with the feedwater stream of the PRO process (see

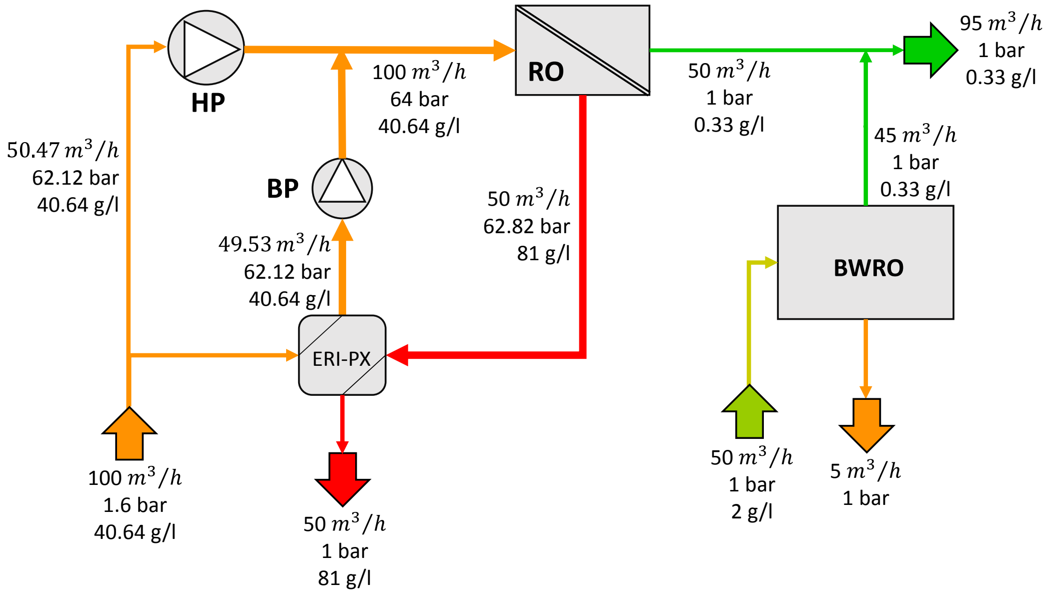

Fig. 4). This brackish water could be desalinated with a brackish water reverse osmosis (BWRO) system (see *Fig. 5*), which will be modelled by using Q+ software [45].

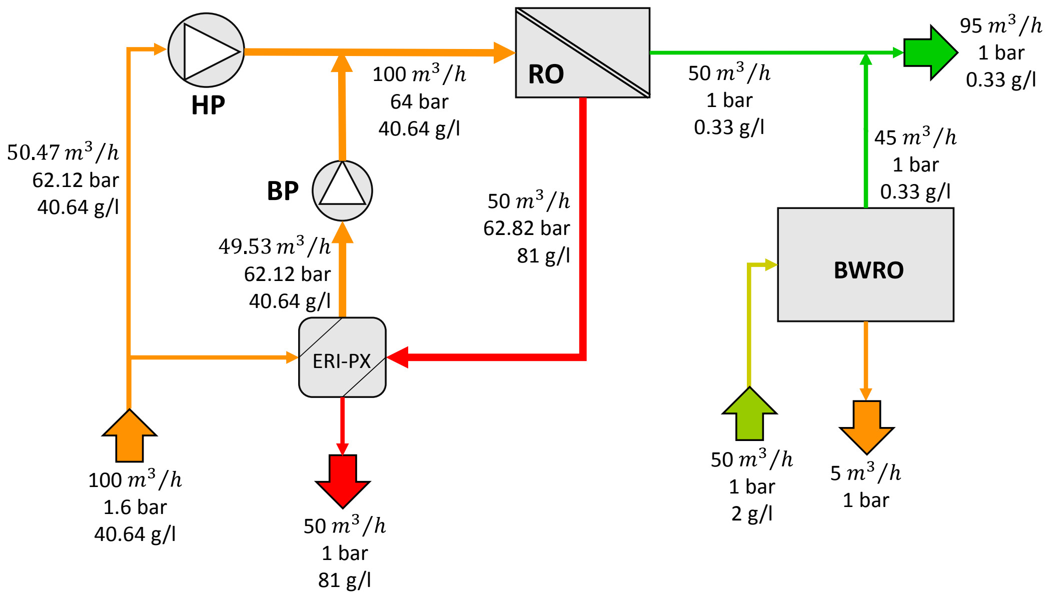

Fig. 4. Base case configuration of the SWRO desalination process without PRO and with BWRO depicted as a black box (see Fig. 5).

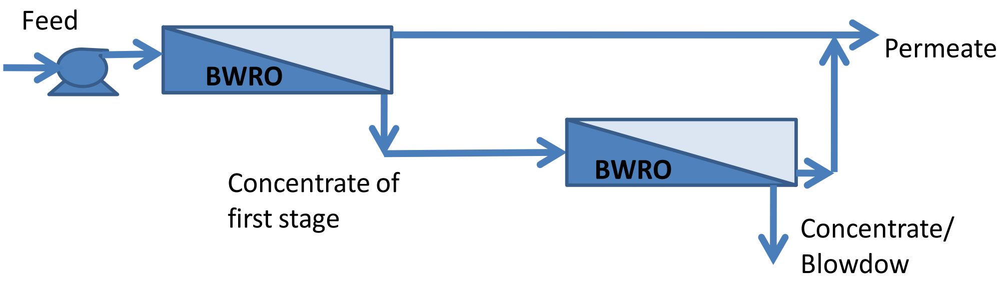

Fig. 5. Basic configuration of a BWRO desalination system.

Concerning the membrane skid in the SWRO desalination system, the design software ROSA [44] has been used to perform the best selection of design and operating parameters. Next section describes the analysis performed of each component. Besides that, in relation to the PRO units, operating parameters reported by Sarp et al. [43] were assumed as initial hypothesis regardless the design features of the system.

4. Calculation procedure

4.1 Selection of the SWRO design

The selection of the SWRO membrane has been made with ROSA software. The first step consisted in selecting the composition of the feed seawater. It has been considered Mediterranean seawater with a salinity of 40.6 g/L and a temperature of 28 °C [46]. The chemical composition of the seawater is presented in *Table 1*. SW30XLE–440i RO membranes from DOW FILMTEC^{TM}, one-pass and one stage configuration have been considered. Several configurations have been tested with ROSA to reach the desired specifications (50 m^3/h permeate flow, 50% recovery), varying the pressure vessel (PV) number and the number of membrane elements within a PV, resulting 13 PV with 7 elements each. The isentropic and mechanical efficiencies of the pumps have been selected as 85% and 95%, respectively, the flow factor (a factor considering the fouling of the membranes, aging, pressure and operation time) of 0.85, and in the case of the third configuration, the total efficiency of the Pelton turbine of 85%.

Table 1. Chemical composition of the feed seawater at 28 °C, pH=8.1, and with TDS=40,634.9 mg/L.

Ions	**mg/L**
Ammonium (NH_4^++NH_3)	0
Potassium (K)	485.34
Sodium (Na)	12,310.05
Magnesium (Mg)	1571.05
Calcium (Ca)	487.36
Strontium (Sr)	0
Barium (Ba)	0
Carbonate (CO_3)	32.24
Bicarbonate (HCO_3)	160.57
Nitrate (NO_3)	0
Chloride (Cl)	22,398.76
Fluoride (F)	1.39
Sulphate (SO_4)	3157.78
Silica (SiO_2)	1.61
Boron (B)	5.03

The results of the simulation carried out in ROSA with the values above-mentioned, i.e., 13 PV and 7 elements each, are depicted in *Table 2*, being in accordance with the results presented by Sarp et al. [43].

Table 2. ROSA simulation outputs for the SWRO system.

Concept	Value
System Details	
Feed Flow to Stage 1, m³/h	100.00
Feed Pressure, bar	64.00
Flow Factor	0.85
Chem. Dose	None
Total Active Area, m²	3719.72
Recovery rate, %	50.00
Feed Temperature, °C	28.0
Feed TDS, mg/l	40,634.96
Average Pass 1 Flux, L/(m²·h)	13.44
Osmotic Pressure:	
Feed, bar	29.08
Concentrate, bar	60.75
Average, bar	44.91
Power (no energy recovery), kW	209.18
Specific Energy (no energy recovery), kWh/m³	4.18
Stage 1 Details	
Element	SW30XLE-440i
#PV	13
#Ele	7
Number of Elements	91
Conc Flow, m³/h	50.00
Conc Press, bar	62.82
Perm Flow, m³/h	50.00
Perm Press, bar	1.00
Perm TDS, mg/l	331.03

4.2 *Selection of the BWRO design in the base case*

The configuration corresponding to the base case includes a BWRO unit. Typical BWRO systems have two membrane passes, therefore, the permeate crosses two membranes with pore size of RO. Actual regulations on the reuse (or reclamation) of wastewater requires two passes through membranes type forward osmosis, nanofiltration, pressure-retarded osmosis, or reverse osmosis. Therefore, this system would fulfil this requirement, and it would be suitable for desalting the feed stream for the PRO process of the patent in case of treated wastewater. Considering the BWRO process a specific energy consumption of 0.5 kWh/m^3 was obtained by using Q+ design software [45] with the following design and operating parameters:

- Brackish water: temperature, 28 °C; pH, 7.0; salinity, 2 g/kg; individual components and corresponding mass fraction from reference [46].
- Design parameters: feed water, 50 m^3/h, total recovery rate, 81%; pass 1 with 2 stages; pass 2 with 1 stage; pump isentropic efficiency, 85%, pump mechanical efficiency, 95%; energy recovery device, turbocharger with 90 % of efficiency.

Thus obtaining the following results:

- Permeate: 40.5 m^3/h.
- Specific energy consumption, 0.5 kWh/m^3.

4.3 *Isobaric pressure exchangers*

There are two pressure exchangers in all the three arrangements of the patent analysed, with different inlet and outlet flow rates. It has been assumed isobaric PXs due to their better performance [47–49]. Pressure exchangers from Energy Recovery Inc. (ERI) have been considered. The efficiency η_{PX} of the PX (provided by the manufacturer) is defined as depicted in Eq. (1):

$$\eta_{PX} = \frac{\sum(Pressure \cdot Flow)_{OUT}}{\sum(Pressure \cdot Flow)_{IN}} = \frac{(q_{sw}+L)\cdot(p_B - HPDP)\cdot 100kPa/bar + (q_B - L)\cdot(p_{sw} - LPDP)\cdot 100kPa/bar}{q_B \cdot p_B + q_{sw}\cdot p_{sw}} \quad (1)$$

where q (m^3/s) is the flow rate, p (bar) is the pressure, L (m^3/s) is the lubrication flow (considered null), $HPDP$ (bar) is the high-pressure differential pressure (defined by the manufacturer as the difference of pressure between the brine flow inlet and the seawater flow outlet), $LPDP$ (bar) is the low-pressure differential pressure (pressure difference between the seawater inlet and the brine flow outlet), HP refers to the high-pressure inlet stream, and LP refers to the low-pressure inlet stream. It has been assumed an efficiency of 97% for all the pressure exchangers. In addition, it has been assumed a HPDP of 0.7 bar and LPDP of 0.6 bar.

4.4 Specific energy consumption

The specific energy consumption (SEC, kWh/m^3) of the desalination process is determined with Eq. (2):

$$SEC = \frac{\sum P_{W,\,pumps} - P_{W,\,T}}{q_{V,permeate} \cdot 3600 s/h} \tag{2}$$

where $P_{W,pumps}$ (kW) is the power consumption of the pumps, $P_{W,\,T}$ (kW) is the power production of a Pelton turbine (only in configuration 3), and $q_{V,permeate}$ (m^3/s) is the volumetric flow rate of the permeate. The power consumption of each pump i has been calculated with Eq. (3):

$$P_{W,i} = \frac{q_{V,i} \cdot \Delta p_i \cdot 100\ kPa/bar}{\eta_{s,i} \cdot \eta_{m,i}} \tag{3}$$

where $q_{V,i}$ (m^3/s) is the volumetric flow rate, Δp_i (bar) is the pressure gain of the fluid in the pump, $\eta_{s,i}$ is the isentropic efficiency of the pump, and $\eta_{m,i}$ is the mechanical efficiency of the pump.

The power production of a Pelton turbine $P_{W,T}$ has been approximated as:

$$P_{W,T} = q_V \cdot \Delta p \cdot 100\ kPa/bar \cdot \eta_T \tag{4}$$

where η_T is the total efficiency of the turbine.

5. Results and discussion

5.1 Configurations of the patent

Fig. 6 shows the results for the first RO-PRO configuration proposed in the patent. All the streams have been defined by their volumetric flow rate, pressure and concentration. Values in blue depicts those which have been calculated while the values in black have been taken from the patent description. The pumping power consumption has been determined for all the pumps using the mass balance equations together with Eqs. (1)-(4). This highest power consumption is related to the high-pressure pump of the SWRO process (HP), reaching a value of 61.77 kW.

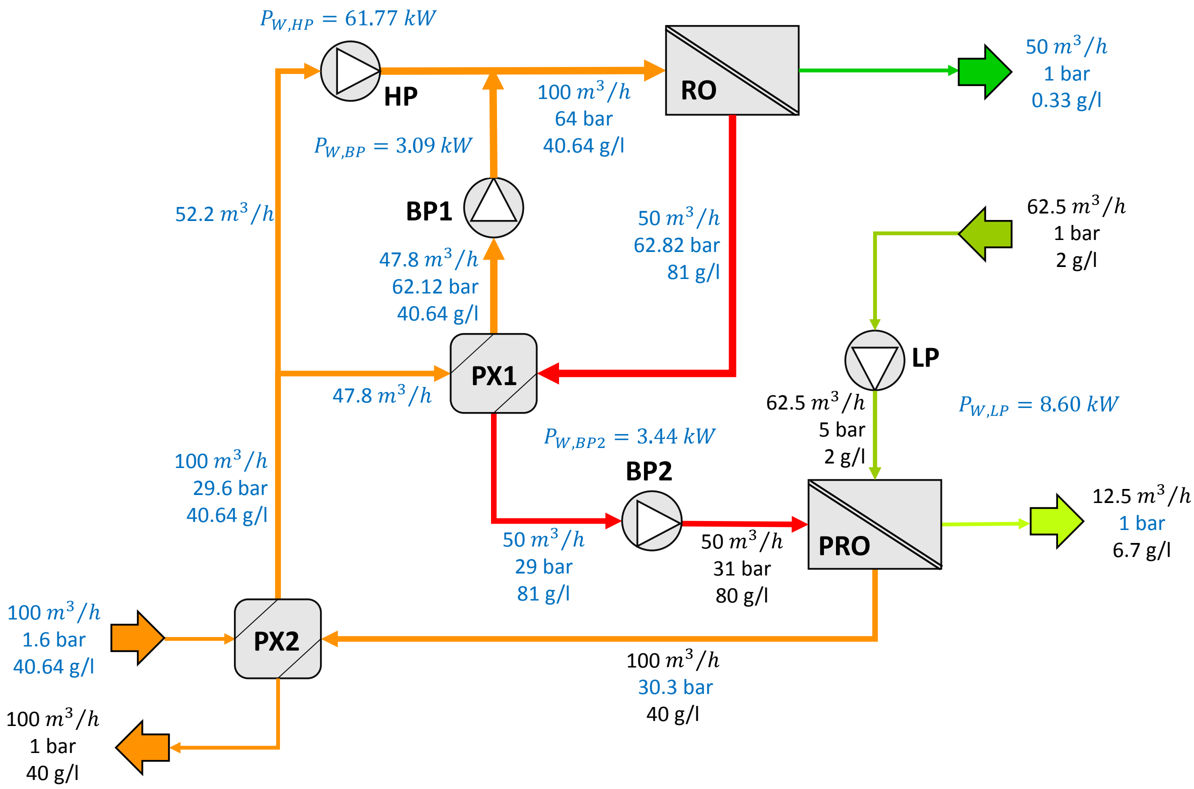

Fig. 6. Results for the first configuration of the patent. Black values are taken directly from the patent and blue values are calculated.

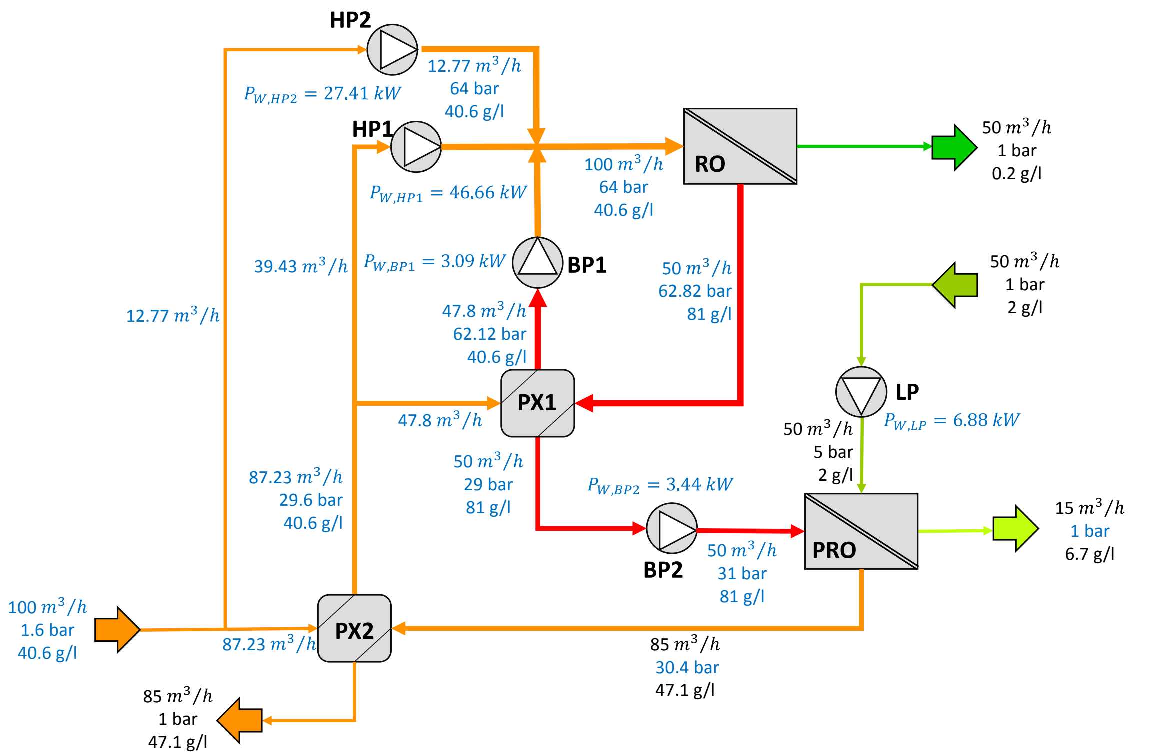

Fig. 7 depicts the results related to the second RO-PRO configuration. Note that in this scheme, there are two high-pressure pumps in the RO, with power consumption of 46.6 kW and 27.4 kW, for HP1 and HP2 pumps, respectively.

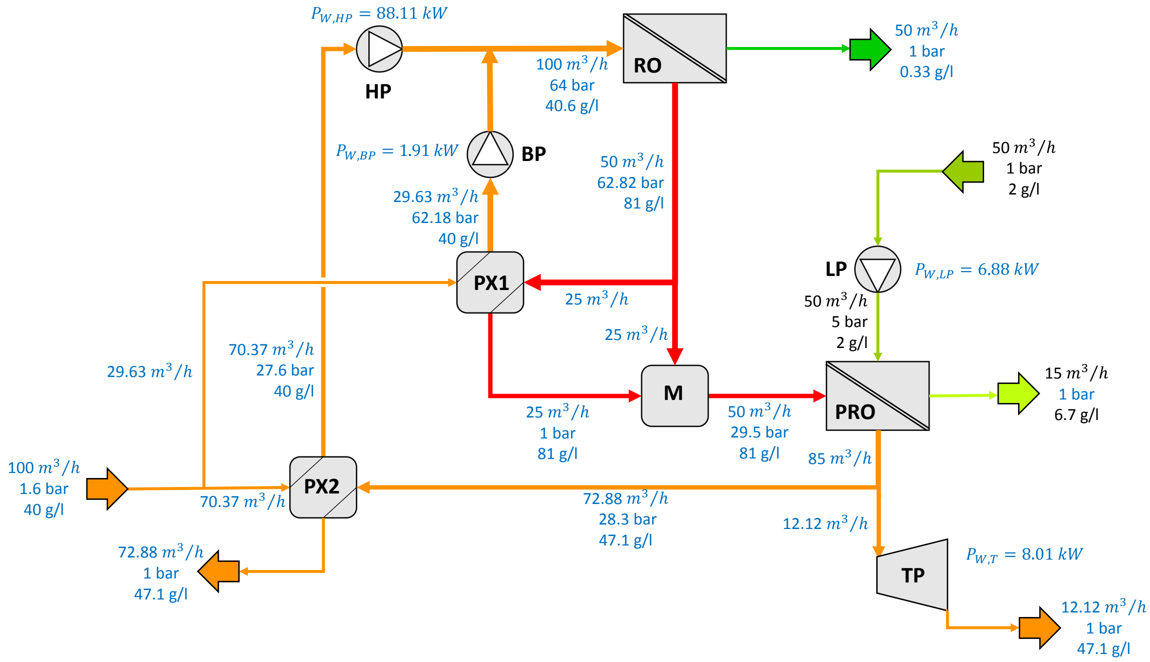

Fig. 8 shows the results for the third configuration of the patent where the second booster pump BP2 has been replaced by a mixer and part of the diluted PRO draw solution is sent to a Pelton turbine for power generation.

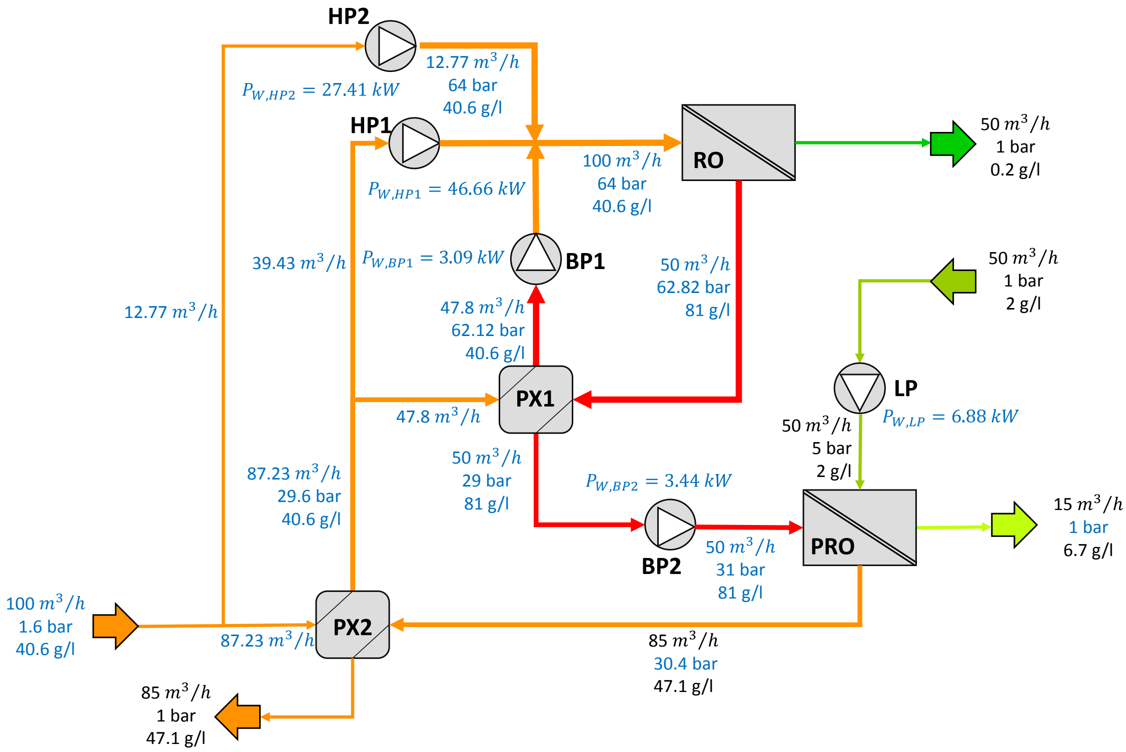

Fig. 7. Results for the second configuration of the patent. Black values are taken directly from the patent and blue values are calculated.

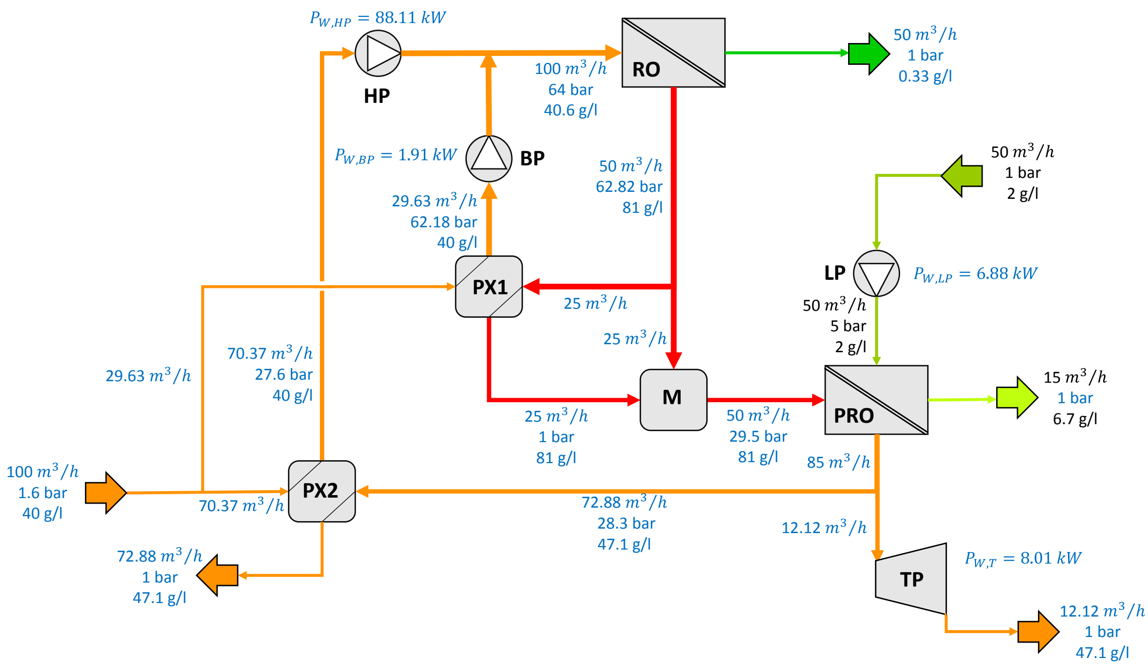

Fig. 8. Results for the third configuration of the patent. Black values are taken directly from the patent and blue values are calculated.

5.2 *Performance comparison for the configurations*

A resume of the results obtained for the three configurations presented in the patent and the base case introduced for comparison is depicted in *Table 3*.

Table 3. Comparison between the results obtained in the second, third configurations and base case.

	First config.	Second config.	Third config.	Base case
System	SWRO+PRO	SWRO+PRO	SWRO+PRO	SWRO+BWRO
Feed flow rate, 40 g/L (m^3/h)	100	100	100	100
Product flow rate - 0.32 g/L -, (m^3/h)	50	50	50	90.5
Membrane type	7xSW30XLE-440i 13 PV	7xSW30XLE-440i 13 PV	7xSW30XLE-440i 13 PV	7xSW30XLE-440i 13 PV
Recovery rate (%)	50	50	50	50% SWRO 81% BWRO
PRO feedwater	62.5 m^3/h 2 g/L 1 bar	50 m^3/h 2 g/L 1 bar	50 m^3/h 2 g/L 1 bar	50 m^3/h 2 g/L 1 bar
RO/PRO pumps (kW)	76.90	87.48	96.90	111.58
Pelton turbine (kW)	n/a	n/a	-8.01	n/a
BWRO SEC (kWh/m^3)	n/a	n/a	n/a	0.5
Total SEC (kWh/m^3)	1.54	1.75	1.78	1.47*

*The total SEC is determined weighting each contribution taking into account the different flow rates of permeate.

As it can be seen in *Table 3*, among the configurations presented in the patent, the first scheme results with the lowest SEC (1.54 kWh/m^3). In addition, this scheme does not have a hydraulic turbine associated, like in the third scheme, which reduce the capital and maintenance costs of the system.

The reuse of industrial wastewater is in general forbidden, and in this case the use of a BWRO system would be discarded. Therefore, the first scheme of the patent could be used with industrial wastewater if the PX2 were changed by a turbocharger, hence avoiding the mixing of streams. This configuration is the most energy-efficient.

Besides that, if the feed water of the PRO unit is treated wastewater, the best solution is the conventional SWRO process with the two-pass BWRO unit. When adding this external resource to the standalone SWRO base case, the freshwater production increases up to 90.5 m^3/h and the SEC reduces significantly (1.47 kWh/m^3).

Main points concerning the relevance of configurations proposed by Sharp analysed in this papers and the consistence of results obtained in this papers could be summarised as follows:

- Wan and Chung analyse RO/PRO systems considering seawater at 25ºC and salinity of 35 g/L. They obtain a SEC around 1.5 kWh/m^3 with a configuration similar to the second analysed in this paper if volumetric flow rates of seawater through HP2 and PX2 are similar to those of the second configuration. The lower SEC than that obtained could be attributable to BP1, BP2, LP shown in figure 2, which are not included in said reference. However, they are required to achieve the proper operating pressure of the respective streams. They amounts 0.27 kWh/m^3, corresponding to the sum of 0.6, 0.7 and 0.14 kWh/m^3 due to BP1, BP2 and LP respectively. Therefore, considering those additional components the total SEC would be around 1.77 kWh/m^3, which is consistent with our results.
- Wan and Chung also reports on SEC of 1.14 kWh/m^3 corresponding to a configuration quite similar to the first configuration if BP1, BP2, LP and PX2 are omitted. They considers the diluted draw solution as feed water of the RO system, thus resulting in no seawater input. Therefore, the global productive process does no consists in a seawater desalination process. On the contrary, desalinated water is thus obtained from the low salinity stream. Therefore, same effect could be obtained by means of BWRO with two passes with significant lower SEC.
- Senthil and Senthilmurugan [27] analysed six SWRO/PRO configurations including hydraulic turbine in order to produce electricity to be consumed by the SWRO process, thus reducing its specific energy consumption. Some of them are applicable to industrial wastewater by means of replacing one pressure exchanger by a turbocharger to avoid mixing. The specific energy consumption obtained for 32,000 mg/L ranged from 1.79 to 1.93 kWh/m^3. Therefore, Sarp et al [43] proposal including the hydraulic turbine (the third configuration) is superior.

6. Conclusions

A performance comparison of three PRO-RO schemes for energy recovery in seawater desalination application is carried out, based on the patent US 9,428,406 B2 of Sarp et al. [43], selected by the authors as a relevant proposal among the literature survey carried out. These hybrid schemes allow for energy consumption reduction of the overall process by recovering of part of the salinity gradient energy content between the RO brine and wastewater/brackish water. All three treat the same volumetric flow rate of seawater (40635 ppm) and low salinity water (2 g/l). In order to perform a fair comparison between the arrangements, another scheme using conventional SWRO and BWRO processes is included in the analysis.

Considering treated industrial wastewater as low salinity water source, the actual regulations forbid the reuse of this kind of wastewater. In this case, the first configuration is superior with regard to the energy efficiency. It uses this water stream to pressurize the feed seawater through a pressure exchanger. This kind of energy recovery produces a certain amount of mixing between the streams. To solve the problem of the regulation the second pressure exchanger (PX2) could be replaced by a turbocharger, which does not include any mixing between the solutions. However, it would also slightly increase the total SEC of the desalination process due to its lower efficiency – around 90% - compared to the PX – around 95-97% -. The best solution in this case would be the second configuration of the patent replacing the second PX by a turbocharger.

If the low salinity water source is treated urban wastewater, the actual regulations on non-industrial wastewater reclamation two membrane passes of NF, RO, PRO or FO are mandatory. This requisite is fulfilled by the two passes BWRO. In this case the best solution with lower specific energy consumption would be the conventional SWRO process with the two-pass BWRO. The integration of both systems achieves a specific energy consumption of 1.47 kWh/m^3. Besides, the scheme of the patent providing the lowest specific energy consumption (1.54 kWh/m^3) is the first one, followed by the second and third configurations (1.75 and 1.78 kWh/m^3, respectively), with a slightly higher values.

Symbols

$HDPD$	High-pressure flow differential pressure, bar
$LDPD$	Low-pressure flow differential pressure, bar
L	Lubrication flow, m^3/h
p	Pressure, bar
P	Power, kW
q	Volumetric flow rate, m^3/s
SEC	Specific thermal energy consumption, kWh/m^3

Acronyms and abbreviations

BP	Booster Pump
BW	Brackish Water
ERI	Energy Recovery Inc.
HP	High Pressure
IEM	Ion Exchange Membrane
LP	Low Pressure
M	Mixer
MD	Membrane Distillation
NF	Nanofiltration
PRO	Pressure-Retarded Osmosis
PV	Pressure Vessel
PX	Pressure eXchanger
RED	Reverse Electrodyalisis
RO	Reverse Osmosis
ROSA	Reverse Osmosis System Analysis
SEC	Specific Energy Consumption
SW	Seawater
TDS	Total Dissolved Solids

Subscripts

B	Brine
HP	High Pressure
LP	Low Pressure
m	Mechanic
p	Pressure
PX	Pressure eXchanger
s	Isentropic
sw	Seawater
T	Total or Turbine
V	Volumetric
W	Work

Greek

η Efficiency

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