Desalination and Water Treatment
www.deswater.com
doi:10.5004/dwt.2017.21409

88 (2017) 25–32
September

Scenarios of RO brines valorization in power plants

Alia Rehouma, Ahmed Hannachi*

GPSI, National Engineering School of Gabes, University of Gabes, Street of Omar Ibn El Khattab, 6029 Gabes, Tunisia, Tel. +216 75392100, Fax +216 75392190, email: ahmed.hannachi@enig.rnu.tn (A. Hannachi)

Received 1 August 2016; Accepted 27 July 2017

ABSTRACT

In this work we propose and compare three scenarios of reverse osmosis (RO) brines valorization in power plants. The comparison focuses on energy consumption and environmental considerations. The first scenario is based on using seawater reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO) brines to generate power using pressure retarded osmosis (PRO) which is a membrane based process that converts the osmotic energy into electrical energy. In the second scenario the BWRO brine is used to dilute the SWRO inlet seawater. This will reduce specific energy consumption by reducing the feed pressure applied to the system. It will also ameliorate permeate quality and reduce brine salinity. The third scenario is a combination of the first and the second scenarios. The specific energy gain in the second valorization scenario is the highest representing 14% of the actual energy used for desalinating seawater. It is about 7.6 times higher than in the first valorization scenario. The last scenario looks the best from an environmental consideration as the brine has the lowest salinity at the expense of a drop of only about a third of the energy savings in the second scenario.

Keywords: Seawater desalination; Reverse osmosis brines; Valorization scenarios; Pressure retarded osmosis; Simulation; Energy consumption; Brine salinity

1. Introduction

Reverse osmosis (RO) technology offers a solution for the shortage of fresh water resources worldwide, through its capacity to treat all kinds of water such as seawater, wastewater, ground water and surface water [1,2]. Within the last decade, RO has been established as the preferred method for water desalination. However, it is an energy intensive process and generates a saline concentrate that ultimately requires disposal. As a result of increased interest in RO desalination, the concern about potential environmental problems has grown. Brine disposal costs are high today and account for 5–33% of total desalination cost [3]. This cost depends on the quality of the concentrate, treatment level before disposal, disposal method and the volume or quantity of concentrate. Disposal costs for inland desalination plants are even higher than those for plants discharging brine into the sea [4]. Some of the options for brine disposal from inland desalination plants are deep well injection, evaporation ponds, discharge into surface water bodies, disposal to municipal sewers, concentration into solid salts and irrigation of plants tolerant to high salinity.

Seawater reverse osmosis (SWRO) desalination plants extract large volumes of seawater. Very often only less than 50% of these huge water fluxes are converted to desalinated water. The rest is discharged as dense brine concentrates back the sea not very far from the seawater intake [2]. It is widely suggested that desalination plant brines have a strong potential to detrimentally impact both physicochemical and ecological attributes of receiving environments. Environmental impact of SWRO desalination plants is mainly associated with the discharge into the sea of the brine produced. Particularly for the Mediterranean Sea, brine disposal could be a serious threat to Posidonia oceanica, the most abundant sea grass species in the region. This endogenous variety exists from surface to depths of 40 m and covers about 40,000 km^2 of the sea floor hosting a

*Corresponding author.

Presented at the EDS conference on Desalination for the Environment: Clean Water and Energy, Rome, Italy, 22-26 May 2016

1944-3994 / 1944-3986

very rich and diverse ecosystem [5]. Posidonia oceanica is very sensitive to brine discharges from desalination plants. To limit SWRO adverse effects on sea ecosystems, brine is diluted before its disposal.

Due to the environmental problems that brine disposal can cause and because of the high disposal costs, many technologies have been developed for brine recovery. Beneficial reuse of RO brines has become an important aspect of desalination, especially in more economically challenged areas or inland regions with limited disposal options. Under certain conditions, brines from desalination plants can have useful applications. Examples are evaporation ponds to produce salt or chemicals for industry and renewable energy generation involving Pressure retarded osmosis (PRO) systems [6]. PRO is a membrane based process that converts the osmotic energy into electrical energy exploiting salinity differences between concentrated solution, called draw solution (DS), and diluted solution, referred to as feed solution (FS). Both solutions are separated by a semi permeable membrane. The osmotic pressure difference that exists between the fluids drives water to permeate through the membrane from the feed over to the draw side where a hydraulic pressure lower than the osmotic pressure difference is applied. The pressurized volume in DS compartment can be converted into electricity by discharging the effluent through turbines [7,8]. RO brines could be valorized as DS and used to produce energy in PRO systems [7,9].

PRO units using RO brines present the advantage of a lower capital costs for the solution intake systems seeing the proximity of DS and FS sources. The capital costs for the solution intake systems are the costs for constructing piping and pumping. Depending on the distance of the power plant relative to the fresh and salt water sources, the capital cost of the intake system can make up a large portion of the total capital cost especially when FS and DS sources are far from the PRO unit [10]. Moreover, RO brines allow for foulants free PRO system avoiding pretreatment processes for feed and draw fluxes already handled by the SWRO pretreatment operation.

Two scenarios are possible: simple PRO system and closed loop PRO (CLPRO) system which assume continuous regeneration of draw solution. CLPRO is adopted when no continuous source of DS is available. When RO brines are continuously available, there is no need to use CLPRO process [11].

Various scales of PRO processes are at the heart of several international research programs focusing on improving the economic efficiency of desalination, and reducing the environmental impacts originated from SWRO brine discharge. Carravetta et al. proposed different scenarios to reduce SWRO cost through coupling SWRO to PRO allowing achieving considerable energy savings [12].

Further research is needed for conceiving environmentally friendly and economically viable management options for RO brines. The present study focuses on brine valorization and its contribution to significantly reduce energy consumption in processes that integrate desalination units. Power plants are among these processes where highly pure water needs to be produced often with at least a two stage membrane treatment. More investigation is needed to assess energy consumption for brine valorization scenarios. Thus, the objective of this work is to compare three scenarios for brine recovery in a power plant located in the southern Mediterranean Sea. The focus will be put on energy consumption, environmental and technical issues.

2. Materials and methods

In this work the case study of a 400 MW power plant is considered. It is relative to the combined cycle power plant implemented in Ghannouch at the south of Tunisia. The process scheme is shown in Fig. 1. In the power plant, pretreated seawater by coagulation-flocculation undergoes a RO process (SWRO) yielding an intermediate water quality which is subject to a second treatment by a similar process, referred to as brackish water reverse osmosis (BWRO) [9]. The latter process permeate is further polished through a mixed bed ion exchange resins (MBIExR) in order to produce ultra-pure water, with a conductivity below 1 μS/cm, for the boilers. RO processes generate two different brines that are usually discharged to the Mediterranean Sea. The salinities of SWRO and BWRO brines are 65 g/L and 1.2 g/L, respectively. The SW brine feeds a pressure exchanger (PX) before being rejected.

Performances of brine valorization processes will be based on simulation of all involved membrane processes. Because, the investigated power plant is using DOW SW and BW membranes, RO simulations were conducted using reverse osmosis system analysis design software (ROSA) developed for DOW FILMTEC™ membrane elements. Simulations were conducted using seawater and brackish water qualities that were provided by the power plant laboratory. The simulation tool provides many results, of which the focus will be on specific energy consumption, concentrate and permeate qualities, feed pressure.

For PRO process simulation, a computer program was developed. The developed tool allows optimizing module geometry, feed and draw water velocities and hydraulic pressure in order to reach maximum energy production. Given any set of operating conditions, the simulation program provides concentrations of draw and feed solutions, pressure losses along membrane module, feed and draw solution flow rates and velocities, flux solvent and power density. The computational algorithm used for assessing the best operating experimental domain is shown in Fig. 2.

3. Case studies

As previously mentioned three brine reuse scenarios will be considered. The first scenario is based on using a hybrid SWRO-BWRO-PRO process. In the second scenario, the BWRO brine is used to dilute the SWRO inlet seawater. The third scenario is a combination of the first and the second scenarios.

3.1. First scenario: SWRO and BWRO brines reuse for power production

SWRO and BWRO are used to generate pure water in the power plant. These two membrane processes generate brines of very different concentrations. They may be connected to PRO systems as feed and draw solutions. Draw solution refers to the high concentration side (SWRO brine)

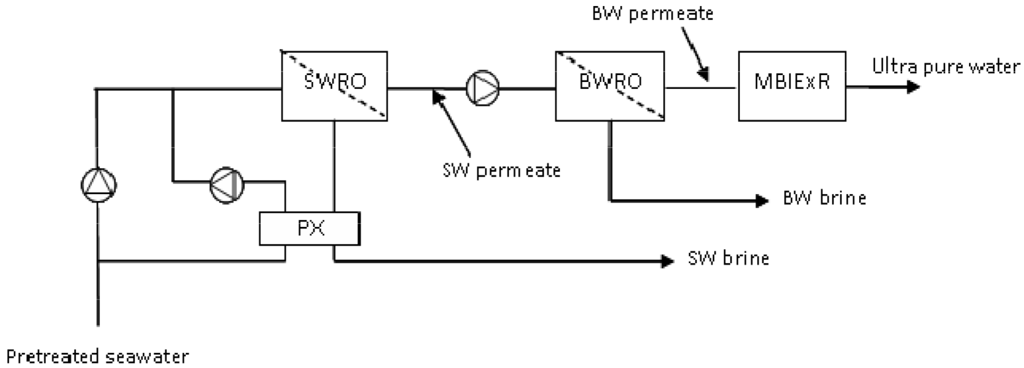

Fig. 1. Flow sheet of ultra-pure water production process.

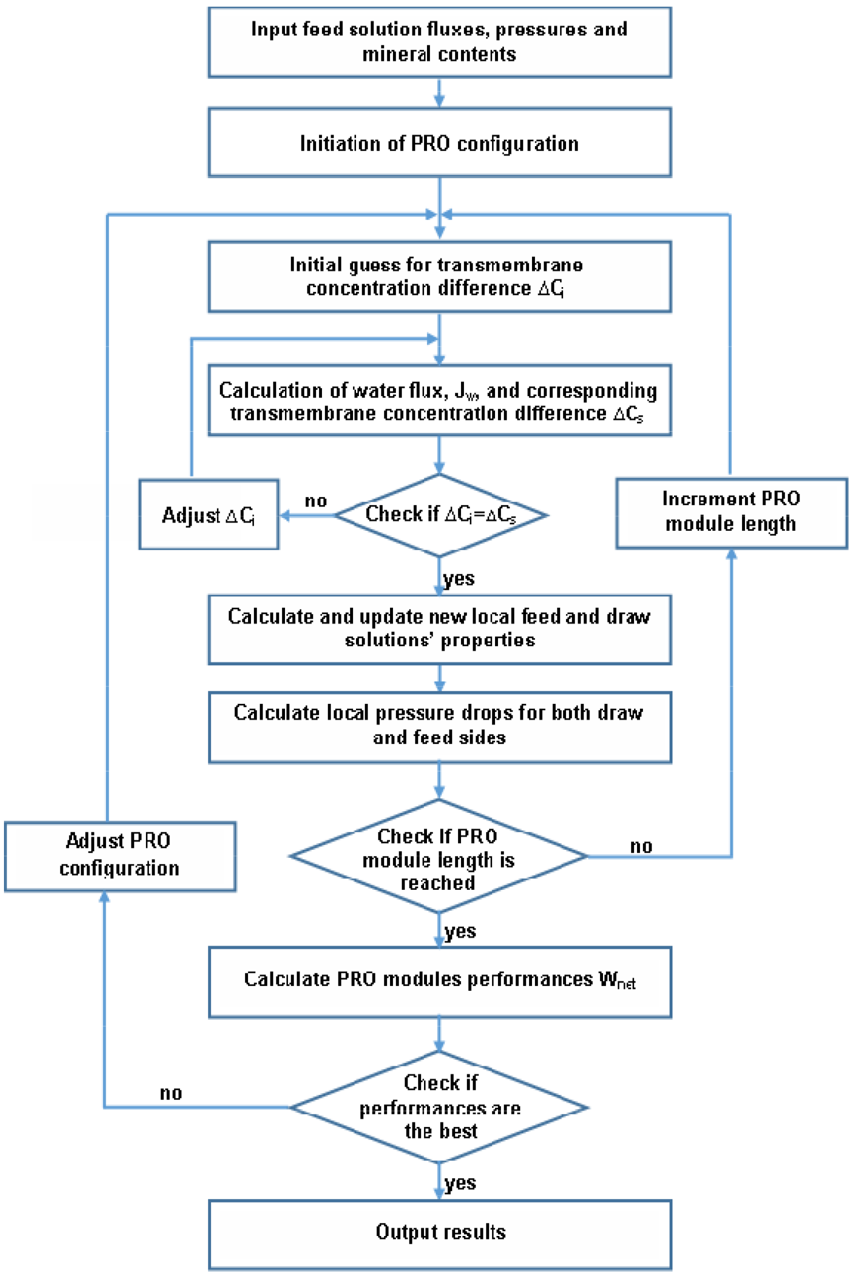

Fig. 2. PRO calculation algorithm.

and feed solution to the low concentration side (BWRO brine). In this scenario SWRO and BWRO brines are used as shown in Fig. 3 to generate power using a PRO system.

The main feature of this hybrid system is the insertion of PRO system and electricity generator hydro turbine (HT). In addition to the existing desalination unit pressure exchange (PX1), a second pressure exchanger (PX2) is annexed to the PRO system allowing recovering the hydraulic pressure of part of the exiting draw solution.

Unlike what has been reported in the literature for brine use, the PRO system is fed with brines of SWRO and BWRO. The concentration difference of these two streams allows harvesting some electrical energy. The osmotic pressure difference that exists between the fluids drives water to permeate through the semi permeable PRO membrane from the feed over to the draw side. The driving force decreases as the draw solution gets diluted. Thus the contact area between feed and draw side should be limited. An optimal length can be determined. The quantity of energy produced depends on feed and draw solution concentrations, hydraulic pressure applied, geometry considered and membrane properties.

Like similar membrane processes, membrane properties are the key in the success of a PRO operation. The performance of such process is related to the achieved power density. An ideal PRO membrane should have high water permeability and salt rejection [13–16]. These membrane properties are referred to as *A* and *B* respectively. The PRO membrane should also have a robust mechanical strength to withstand high pressures. Salt transfer between sides of a PRO membrane is related to structural membrane properties referred to as *S*. Ideally, low *S* is relative to membranes allowing small build-up of salts in theirs porous layers [7]. Recently developed hollow fiber membranes have shown excellent performance under experimental conditions [17]. In this work a cellulose triacetate hollow fiber membranes with A=1.87 10^{-12}; B=1.11 10^{-7} and S=678 10^{-6} m are considered [18].

The computer code developed for simulation PRO systems is based on modeling steady state transfer of species between draw and feed solutions through membranes accounting for conservation equations. Since hallow fiber modules are considered, a pseudo one dimensional model accounting for non-ideal phenomena like internal and external concentrations' polarizations, pressure drops as well as mechanical losses in the system, was developed. Pressure drops in the system occur in pipes and valves and along membranes.

The PRO system net power produced W_{net} is expressed as:

$$W_{net} = W - w_{PL} \tag{1}$$

where w_{PL}: accounts for all electrical losses, W: is the converted part of hydraulic pressure conveyed to the generator. W is related to the water flux through the membrane, J_w, via the following equation:

$$W = \Delta P \cdot J_w \cdot \eta_T \cdot \eta_G \tag{2}$$

where ΔP is the hydraulic pressure applied to the draw side, η_T and η_G are turbine and generator yields, respectively.

The water flux through the membrane is given by:

$$J_w = A \cdot \left(\Delta\pi - \Delta P\right) \tag{3}$$

where $\Delta\pi$: is the osmotic pressure difference between feed and draw solutions defined by:

$$\Delta\pi = i \cdot \Delta C_{bulk} \cdot R \cdot \frac{T}{M} \tag{4}$$

where i: is the Van't Hoff coefficient, R: is the ideal gas constant, T: is the liquid absolute temperature, M is the molecular weight of solutes and ΔC_{bulk} is the difference between draw and feed bulk concentrations. $\Delta\pi$ calculation requires determination of ΔC_{bulk} which may be found by iterative calculation as described in Naguib et al.'s work [18].

3.2. Second scenario: BWRO brine recycling

In the second scenario, as shown in Fig. 4, the BWRO brine which has a salinity of 1.2 g/L is used to dilute the

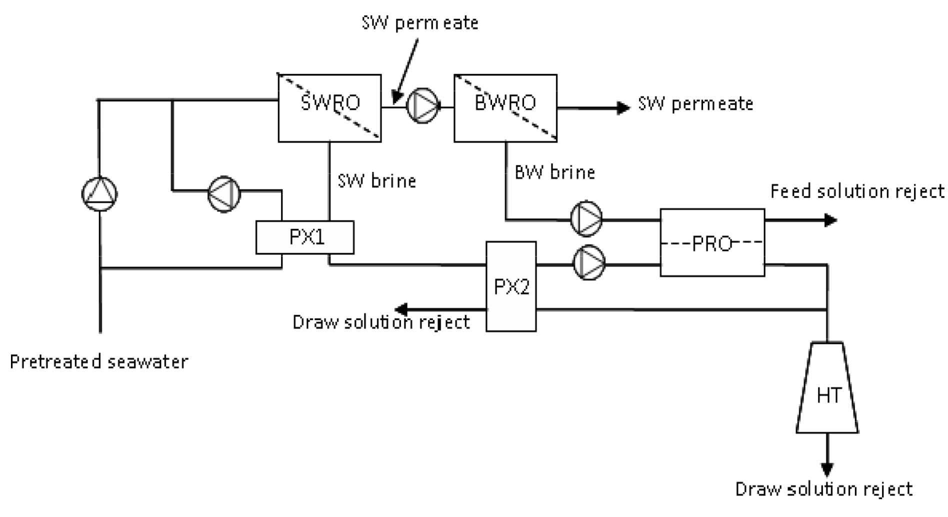

Fig. 3. Flow sheet of SWRO and PRO hybrid process.

SWRO inlet seawater. This will lead to decrease of the required pressure because of less saline inlet water. It will then contribute to reduce the energy consumption for water desalination. Desalination system energy consumption assessment was based on simulation using ROSA software. It is worthy to note that an iterative procedure is needed as the inlet feed concentration depends on that of the brine.

3.3 Third scenario: RO, PRO hybrid system with BWRO brine recycling

The third scenario combines the first and the second one. The process flow sheet is similar to the one given in Fig. 3. However, the difference lies in the fact that the PRO draw solution reject will be connected to SW feed system as in Fig. 3 for the BW brine.

4. Results and discussion

4.1. First scenario

Using the developed calculation program, PRO modules geometry and operational parameters were optimized in order to find best configuration for maximum energy production. Results are shown in Table 1.

The module length was determined in order to ensure considerable water flux all along the hallow fiber membranes. Predicted power density and brine salinity as function of membrane length are illustrated in Fig. 5. This figure hints that for PRO modules of 2 m length, there is a compromise between high power densities and diluted brine. This result is also inferred from Fig. 6 where the hydraulic pressure and the net power generated are presented for various PRO modules lengths. The net power generated can be obtained by increasing total membrane surface via multiplying the number of membranes in parallel so that feed and draw solution flow rates are also increased to match the brine streams exiting SWRO and BWRO units. This scenario presents the advantage that foulants contained in feed and draw fluxes are already retained by SWRO pretreatment process. So, PRO membranes are less exposed to fouling by inorganic matter, natural organic matter and other foulants.

Feed and draw solution concentration profiles are presented in Fig. 7. Due to membrane permeability, water drips from feed to draw solution so that draw solution is diluted by about 23% reaching 50 g/L concentration before being discharged into the sea. Feed solution concentration increases to about 3 g/L as a result of water migration and undesirable salt diffusion from the draw solution side through the membrane. The power plant discharge to the environment is a mixture of PRO feed and draw exit solutions. This will make this discharge scenario better than the actual brine discharge system for the power plant.

Table 1
Membrane properties and optimal parameters.

Inner radius of hollow fiber, *r* (mm)	0.25
Outer radius of hollow fiber, *R* (mm)	0.35
Feed solution velocity (m/s)	0.09
Draw solution velocity (m/s)	0.11
Membrane length (m)	2
Hydraulic pressure (bar)	23

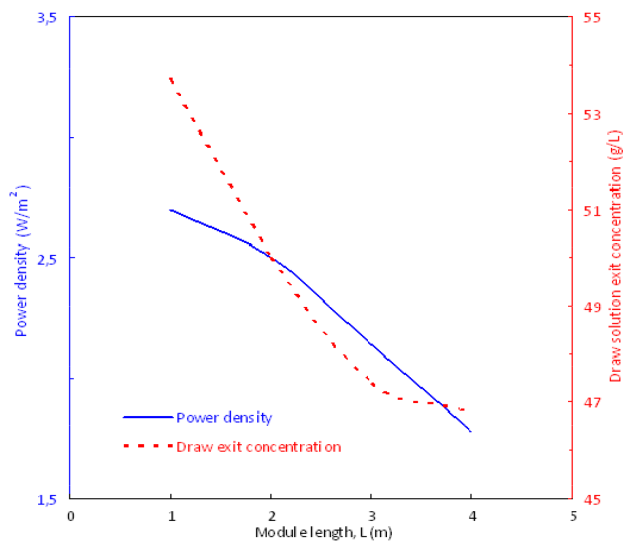

Fig. 5. Power density and draw solution exit concentration vs. PRO module length.

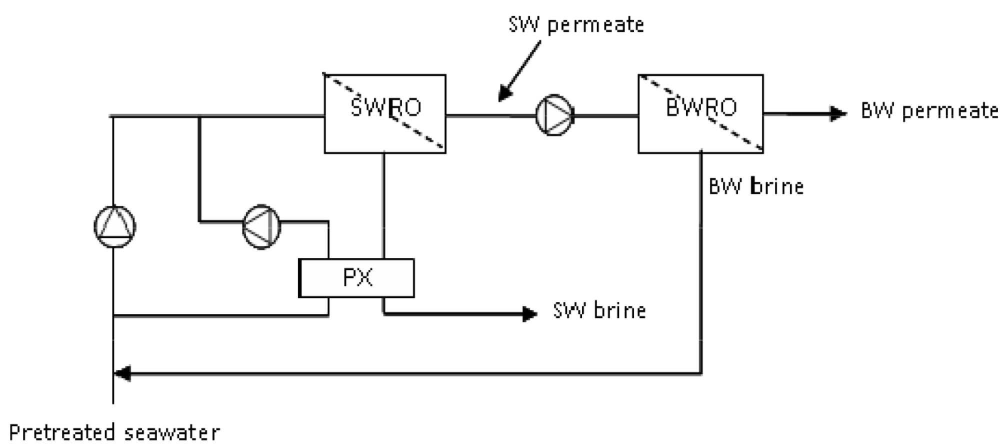

Fig. 4. Brine recycling flow sheet.

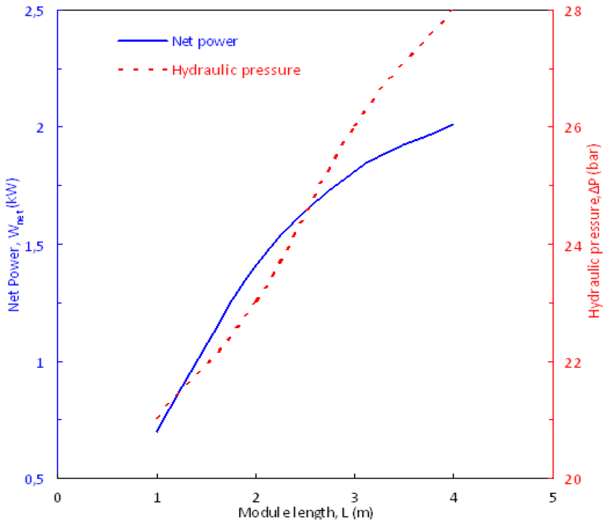

Fig. 6. Net power and hydraulic pressure vs. PRO module length.

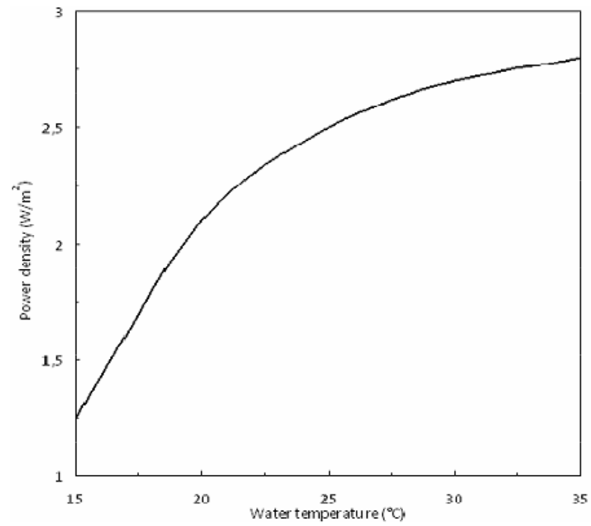

Fig. 8. Impact of temperature on power density.

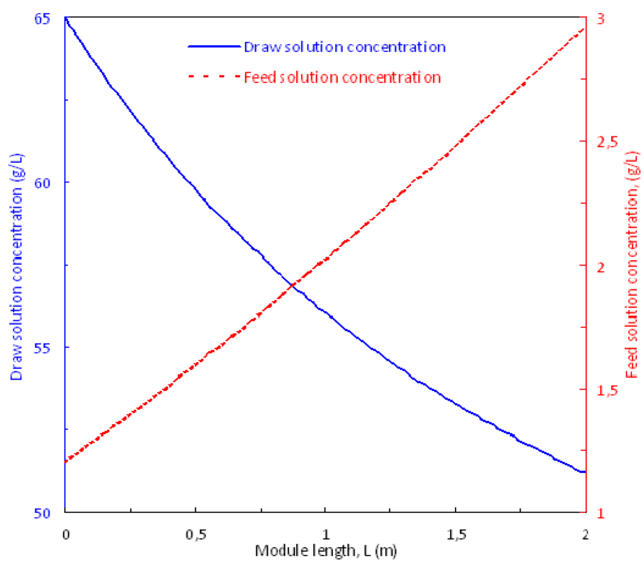

Fig. 7. Feed and draw concentration profiles along PRO modules.

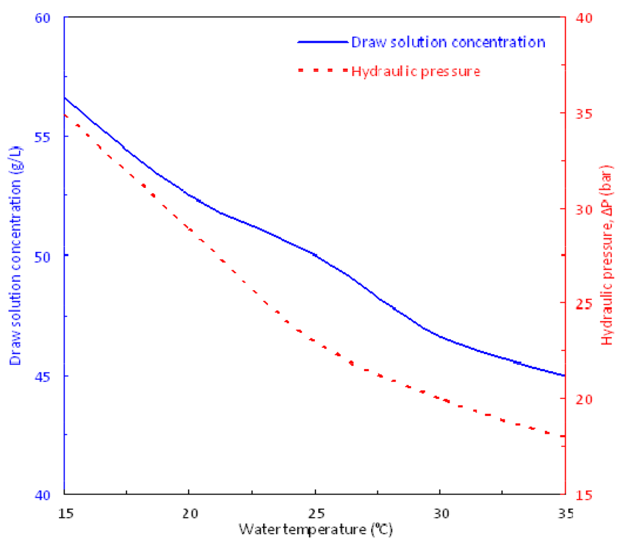

Fig. 9. Impact of temperature on hydraulic pressure and draw solution exit concentration.

The adopted PRO system configuration corresponds to arrays of vessels containing two membrane modules, of 1 m length, in series. The optimized power density for the PRO configuration is 2.5 W/m² corresponding to 1.411 kW with a total membrane surface of 564 m². This limited value of power density is a consequence of the limited water flux along the membrane induced by membrane properties. Our values for water flux and power density are comparable with figures shown in Straub et al.'s work using the same membrane properties and similar feed and draw solution concentrations [19]. However, the achieved power density is lower than that obtained with membranes having better properties. Indeed, as reported by Saito et al. a power density of 7.7 W/m² was attained with a pilot hollow fiber membrane PRO unit at an applied hydraulic pressure of 25 bar, using SWRO brine and treated sewage effluent [20]. Kurihara et al. found that the power density may reach 13.3 W/m² at an applied pressure of 30 bar using the same draw and feed solutions [21]. In fact power density figures may vary considerably with membrane properties, draw and feed solutions' natures as well as PRO system size and configuration. In our case, the power density was limited because of the BWRO brine characteristics (salinity and flow rate) for the investigated ultra-pure water production process in the power plant. The PRO draw and feed solutions flow rates are 9.6 m³/h and 8.2 m³/h, respectively.

In fact seawater temperature is not constant and varies between 13°C in winter and 35°C in summer [22]. The effect of seawater temperatures variation was also investigated. The results are shown in Figs. 8 and 9. PRO system performances vary considerably between winter and summer time. At 15°C, the net power density is about 1.25 W/m² and the discharged brine concentration reaches 56.6 g/L with an applied pressure of 35 bar. At 35ºC, the net power density is doubled with a much lower brine concentration reaching 45 g/L with and applied pressure of only 18 bar. As shown, generated power density and rejected draw concentration are very sensitive to operational temperature. This can be explained by the fact that the viscosity of water changes very much with temperature. These results indicate that PRO performances are very dependent on operational parameters. That's why, module configuration, membrane properties and applied pressure should be optimized for the best yearly average temperature.

As conclusion, even at the best operational conditions, PRO system produces small quantities of energy with a power density of 2.5 W/m^2 which is much below the 5 W/m^2 efficiency threshold reported by Skilhagen [23]. However, this scenario has a beneficial environmental impact as the brine concentration drops from 65 g/L to 50 g/L. The net power production of the PRO system is only about 1411 W. For this reason, another scenario for brine valorization was proposed.

4.2. Second scenario

In this scenario, the BWRO brine is mixed with the inlet SWRO unit. Dilution reduces RO specific energy consumption by reducing the required feed pressure applied to the system. This will also improve permeate quality and will reduce brine salinity. Simulations using ROSA software have been conducted. Table 2 illustrates the impact of dilution on water salinity and some other operational parameters.

In addition to power consumption reduction, dilution gives better quality of permeate and brine of both SWRO and BWRO stages. The SWRO brine concentration drops by more than 14.5% in comparison with the real case. The specific energy gain in this valorization scenario is about 14% of the actual energy used for desalinating seawater. It is about 7.6 times higher than the gain in the first valorization scenario. However, in this studied case, the first scenario is interesting as it reduces brine salinity by 23.1% versus only 14.5 % by the second scenario.

4.3. Third scenario

In this scenario combines the features of the first two scenarios. The BWRO and SWRO brines feed the PRO system and the PRO diluted stream is re-injected with the seawater feeding the SWRO unit. Simulations using commercial RO system and the developed computer program for PRO system were conducted to assess the performances of this valorization scenario. A comparison of the power gain and brine discharge salinity for the three scenarios is shown in table 3.

For environmental considerations, the third scenario is the best because it leads to a brine TDS decrease of 32.3% to a value of 44 g/L vs. 65 g/L in the actual case. Energy savings mount to about 9.2% of total energy consumption for desalinating seawater in the power plant. This represents about 2/3 of the energy reduction in the second scenario. What would be interesting to know is if the excess energy consumption is worth the brine salinity drop between the third and second scenario.

5. Conclusion

Simulations were conducted using RO commercial software and developed program for PRO systems. The simulation tools were used to compare performances of three scenarios of brine valorization in power plants. After optimizing the PRO modules configuration, the best valorization scenario for environmental considerations corresponds to an hybrid SWRO-BWRO-PRO process with reinjection of PRO feed solution. On the other hand, the second scenario involving BW brine recycling leads to the lowest energy consumption.

Table2
Comparison of some operational parameters in the power plant in the case of the second scenario

	Without dilution		With dilution	
	Permeate	Concentrate	Permeate	Concentrate
TDS (mg/L)	273	65600	213	57920
Flow rate (m^3/h)	22	33	25	37.5
SWRO applied pressure (bar)	54		50	
Specific energy (kW/m^3)	4.69		4.35	

Table 3
Comparison of the power gain and brine discharge salinity for the three scenarios

Brine valorization Scenario	–	1	2	3
Power plant configuration	SWRO-BWRO	SWRO-BWRO-PRO	SWRO-BWRO & brine reuse	SWRO-BWRO-PRO & brine reuse
Rejected solution salinity (g/L)	65	50	55.6	44
SWRO applied pressure (bar)	54	54	46.5	50
Total power consumption (kW)	103.3	101.4	88.8	93.8

References

[1] R.A. Al-Juboori, T. Yusaf, Biofouling in RO system: Mechanisms, monitoring and controlling, Desalination, 302 (2012) 1–23.

[2] J.D. Bene, G. Jirka, J. Largier, Ocean brine disposal, Desalination, 97 (1994) 365–372.

[3] M. Ahmed, A. Arakel, D. Hoey, M. Coleman, Integrated power, water and salt generation: a discussion paper, Desalination, 134 (2001) 37–45.

[4] J.M. Arnal, M. Sancho, I. Iborra, J. Gozalvez, Concentration of brines from RO desalination plants by natural evaporation, Desalination, 182 (2005) 435–439.

[5] J. Morillo, J. Usero, D. Rosado, H. El Bakouri, A. Riaza, F.-J. Bernaola, Comparative study of brine management technologies for desalination plants, Desalination, 336 (2014) 32–49.

[6] M. Ahmed, W. Shayya, D. Hoey, J. Al-Handaly, Brine disposal from inland desalination plants: research needs assessment, Water Int., (2002) 37–41.

[7] S. Sarp, Z. Li, J. Saththasivama, Pressure retarded osmosis (PRO): past experiences, current developments, and future prospects, Desalination, 389 (2016) 2–14.

[8] J. Lee, S. Kim, Predicting power density of pressure retarded osmosis (PRO) membranes using a new characterization method based on a single PRO test, Desalination, 389 (2016) 224–234.

[9] A. Rehouma, B. Najar, N. Abderrahim, A. Hannachi, Recovering reverse osmosis effluents for electrical energy production, Proc. Tunisian Days for Alternative Water Sources (JTSAE'15), 18–20 December 2015, Mahdia, Tunisia.

[10] T.T.D. Tran, K. Park, A.D. Smith, System scaling approach and thermoeconomic analysis of a pressure retarded osmosis system for power production with hypersaline draw solution: A Great Salt Lake case study, Energy, 126 (2017) 97–111.

[11] A. Altaee, P. Palenzuela, G. Zaragoza, A.A. Alanezi, Single and dual stage closed-loop pressure retarded osmosis for power generation: Feasibility and performance, Appl. Energy, 191 (2017) 328–345.

[12] A. Carravetta, O. Fecarotta, U.M. Golia, M. La Rocca, R. Martino, R. Padulano, Tucciarelli, Optimization of osmotic desalination plants for water supply networks, Water Resour. Manage., 30 (2016) 3965–3978.

[13] G. Han, S. Zhang, X. Li, T.-S. Chung, High performance thin film composite pressure retarded osmosis (PRO) membranes for renewable salinity-gradient energy generation, J. Membr. Sci., 440 (2013) 108–121.

[14] T.S. Chung, X. Li, R.C. Ong, Q. Ge, H. Wang, G. Han, Emerging forward osmosis (FO) technologies and challenges ahead for clean water and clean energy applications, Curr. Opin. Chem. Eng., 1 (2012) 246–257.

[15] X. Li, S. Zhang, F. Fu, T.S. Chung, Deformation and reinforcement of thin-film composite (TFC) polyamide-imide (PAI) membranes for osmotic power generation, J. Membr. Sci., 434 (2013) 204–217.

[16] G. Han, P. Wang, T.S. Chung, Highly robust thin-film composite pressure retarded osmosis (PRO) hollow fiber membranes with high power densities for renewable salinity-gradient energy generation, Environ. Sci. Technol., 47 (2013) 8070–8077.

[17] K.-V. Peinemann, K. Gerstandt, S.E. Skilhagen, T. Thorsen, T. Holt, In: K.-V. Peinemann, S.P. Nunes, Membranes for energy conversion, Vol. 2, Wiley-VCH Verlag GmbH & Co. KGaA, (2008) 263–273.

[18] M.F. Naguib, J. Maisonneuve, C.B. Laflamme, P. Pillay, Modeling pressure-retarded osmotic power in commercial length Membranes, Renew. Energy, 76 (2015) 619–627.

[19] A.P. Straub, A. Deshmukh, M. Elimelech, Pressure-retarded osmosis for power generation from salinity gradients: Is it viable? Energy Environ. Sci., 9 (2016) 31–48.

[20] K. Saito, M. Irie, S. Zaitsu, H. Sakai, H. Hayashi, A. Tanioka, Power generation with salinity gradient by pressure retarded osmosis using concentrated brine from SWRO system and treated sewage as pure water, Desal. Water Treat., 41 (2012) 114–121.

[21] M. Kurihara, H. Sakai, A. Tanioka, H.H Tomioka, Role of pressure-retarded osmosis (PRO) in the mega-ton water project, Desal. Water Treat., 57 (2016) 26518–26528.

[22] A. Rehouma, A. Rhouma, A. Hannachi, Improvement of reverse osmosis seawater desalination performances by feed water solar heating, Proceedings of Tunisia-Japan Symposium: R&D on Energy and Materials Sciences (TJS2014), 28–30 November 2014, Gammart, Tunisia.

[23] S.E. Skilhagen, Osmotic power-a new, renewable energy source, Desal. Water Treat., 15 (2010) 271–278.