Future prospects of reducing specific energy consumption in SeaWater Reverse Osmosis (SWRO) desalination plants

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Future prospects of reducing specific energy consumption in SeaWater Reverse Osmosis (SWRO) desalination plants

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Abstract

The minimum Specific Energy Consumptions (SECs) technically achievable by adopting different SeaWater Reverse Osmosis SWRO configurations are comparatively studied to assess the actual prospects to achieve values as low as 1 kWh/m^3. A thermodynamic analysis of a basic desalination process at different seawater conditions is performed. The case study of SWRO desalination is analysed in detail to obtain its actual minimum work required and the influence of design parameters. The effect of seawater salinity and temperature on the well known theoretical minimum work of solvent extraction is reported for comparing actual values of SEC of the SWRO desalination technology. The influence of main parameters on SEC is assessed, identifying the individual contribution to the exergy losses of main components namely, RO membranes, RO modules and pressure vessels, main pumps and energy recovery devices, together with the effect on SEC of the SWRO plant configuration (including single-stage and two-stages configurations). Opportunities of reducing SWRO SEC by innovative concepts are also discussed, with a detailed analysis of the potential of pressure retarded osmosis as an energy recovery device.

Keywords: seawater desalination, reverse osmosis, thermodynamic analysis, specific energy consumption.

1. INTRODUCTION

This paper deals with the comprehensive assessment of energy consumption of the Sea Water Reverse Osmosis (SWRO) desalination technology by means of joining points of view of thermodynamic and technology. In order to obtain general conclusions from the analysis conducted, wide ranges of both design and operating parameters are considered, based on SWRO plants with recent designs but also of plants that have been in operation for more than 15 years.

The main objective is to assess future prospects of reducing Specific Energy Consumption (SEC) in SWRO desalination plants. To this end, the minimum SEC inherent to the state-of-the-art is analysed along with the main aspects of SEC by means of its diagnosis. Not only configurations normally used are considered, but also innovative proposals from the literature and developing processes. Finally, actual prospects to achieve values as low as 1 kWh/m^3, milestone set by the H2020 [1], are discussed.

The diagnosis of the SEC of current SWRO desalination technology considers the following aspects:

- The well-known thermodynamic limit of solvent extraction from seawater, studied in subsection 3.1. It depends on the percentage of solvent extraction and on ambient conditions of temperature, pressure and seawater salinity.

- The SEC of an ideal SWRO desalination process carried out by ideal equipment, SEC0. This accounts for the thermodynamic limit plus the exergy losses due to the separation technology itself. Even though considering ideal membranes, the permeate flow passes through the membrane leaving a pressurised channel and entering the permeate channel at around ambient pressure. This pressure change directly depends on the SWRO configuration, consisting in either one or more passes, one or more stages. Therefore, the value of SEC0 minus the thermodynamic limit is attributable to the SWRO plant configuration. Subsection 3.2 analyses the main related issues.
- The value SEC minus SEC0 is attributable to exergy losses due to operation with non-ideal components. This strongly depends on design parameters of main plant component along with working parameters. Therefore, subsections 3.3 and 3.4 analyse the influence of main parameters on SEC identifying the individual contribution to the exergy losses of main components namely, RO membranes, feed-concentrate channels within the membrane modules and pressure vessels, main pump and energy recovery devices.

Subsection 3.5 analyses the effect on SEC of the plant configuration, comparing the thermodynamic limits of SWRO configurations with single-stage and two-stages. Moreover, the concept Closed Circuit Desalination, CCD-Desalitech [2] could have interesting prospects to significantly improve the SEC in spite of that energy recovery devices currently available are not suitable for this concept.

To sum up, based on this diagnosis, section 3.6 deals with identifying potential improvements of the SEC. Besides, regarding the assessment of opportunities of reducing SWRO SEC by innovative concepts, there are a number of recent patents related to the two-stages concept: Kurihara et al [3], Viera-Curbelo [4], Wittmann et al [5] and Zhou [6], among others. In addition, concerning developing processes, pressure retarded osmosis (PRO) [7-9] has been analysed in detail in section 4.

Finally, based on the aforementioned analyses, conclusions highlight future prospects of reducing energy consumption in SWRO desalination plants.

2. METHODOLOGY

First of all, the thermodynamic limit of the SEC considering product water as pure solvent is analysed as a function of the percentage of solvent extraction for a wide range of ambient temperature and seawater salinity. Table 1 shows exemplary cases [10] of seawater composition, pH and temperature in order to understand the influence of plant location. Besides that, a few data on extreme seawater conditions are reported by Sharqawy et al [11] namely, the shores lines of Kuwait and Saudi Arabia, 50 g/kg - g (salts)/kg (seawater) -; Australian Shark Bay, 70 g/kg, or desiccating seas like Dead Sea with salt content approaching saturation concentration. The apparent molar mass of sea salts considering as a whole amounts to $62.808 \cdot 10^{-3}$ kg/mol. Besides that, the composition referred to as Standard Seawater corresponds to 0.03516504 kg/kg of mass fraction [12].

Table 1 Exemplary cases of seawater composition in a number of plant locations [10].

Constituent	**Mediterra-nean**	**Persian Gulf**	**Read Sea**	**Caribbean**	**Pacific**	**Atlantic**	**Canary Islands**
Temperature	14ºC, 28ºC	16ºC, 34ºC	16ºC, 26ºC	26ºC	20ºC	20ºC	22ºC
pH	8.1	7.0	7.8	8.2	8.0	8.0	7.8
Ca^+, ppm	483	478	500	477	440	410	464
Mg^+, ppm	1557	1672	1540	1160	1300	1302	1526
Na^+, ppm	12200	14099	13300	11322	10200	10812	11700
K^-, ppm	481	530	490	386	380	389	429
CO_3^-, ppm	5	4.2	2.3	2.3	2.0	2.0	3.2
HCO_3^-, ppm	162	154	126.8	137	170	143	204
SO_4^{2-}, ppm	3186	3314	3240	2600	3000	2713	3059
Cl^-, ppm	22599	24927	23180	20034	18500	19441	21344
F^-, ppm	1.4	-	-	-	-	-	-
NO_3^-, ppm	-	-	-	-	-	-	-
B^+, ppm	5	5	5.3	5.3	4.5	4.5	4.5
SiO_2, ppm	1.6	-	-	-	-	-	-
TDS, ppm	**40686**	**45199**	**42389**	**36149**	**34000**	**35240**	**38739**

Regarding the thermodynamic limit of SEC, a basic desalination process within a control volume at steady state is considered. There is a single inlet flow of saline solution (Feed, F) and two outlet flows, a low concentration solution (Product, P) and a high concentration solution (Concentrate, C, or Blowdown, BD). The control volume consumes useful power, P_W, from a work source and interchanges thermal power, P_Q, with the ambient. If the product of the process is approximately pure water, desalination becomes a solvent extraction process. No hypotheses in relation to the separation technology are assumed at this stage.

The second stage of this study considers specific features of the desalination technology based on the RO concept. Figure 1 depicts a conceptual diagram of the core of the RO technology, consisting in the three basic processes shown. First process, pressurization of the seawater flow from ambient pressure up to any pressure (p_F) with the compliance of positive driven force of the RO process. Second, separation process through the RO membranes. Third, energy recovery from the pressurized concentrate stream by means of its expansion, thus resulting the outlet brine flow (blowdown). Main power consumption, attributable to process 1, is provided by both, an external work source and process 3. The latter means the energy recovery of the concentrate.

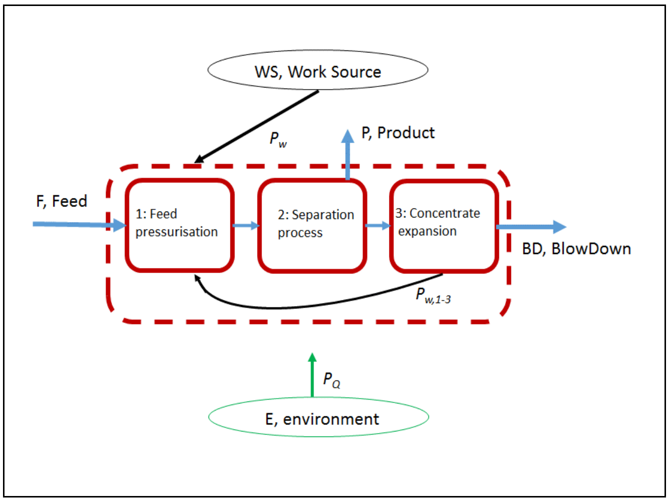


Figure 1. Conceptual diagram of a desalination process based on reverse osmosis.

Concerning the driving force of the RO process, RO membranes separates feed and permeate flows. Sal concentration of feed flow increases as permeate passes across the membrane and becomes concentrate flow (C) at the outlet of the membrane element series. The working condition required across the RO membranes at any point *x* of the OX-axis of the F-C channel (corresponding to the feed flow) is:

$$p_{F-C}(x) - p_P(x) > \Pi_{F-C}(x) - \Pi_P(x) \tag{1}$$

Where values of osmotic pressure correspond to the membrane surface – subscript *surf* -, being negligible the difference between bulk and surface in the product stream. The driving force of the RO process is known as Net Driving Pressure (NDP), which is defined as:

$$NDP(x) = [p_{F-C}(x) - p_P(x)] - \left[\Pi_{F-C,surf}(x) - \Pi_{P,surf}(x)\right] \tag{2}$$

Therefore, working pressure required at the feed inlet, p_{inlet}, of a serial of RO membrane elements as a whole should comply:

$$(p_{inlet} - \Delta p_{Loss}) - p_P > \Pi_{outlet,surf} - \Pi_P \tag{3}$$

where Δp_{Loss} corresponds to the total pressure losses through the feed-concentrate channel, subscript P corresponds to product flow and Π_{outlet} means the osmotic pressure of the concentrate outlet at the membrane surface. Thus, eq.3 determines the target feed pressurization in process 1.

Regarding process 2, the separation process could be implemented with a single pump, the High Pressure Pump (HPP). This process takes place within a serial connection of seawater membrane elements (First pass). Permeate quality decreases alongside the membrane series due to the fact that salt passage increases with salinity gradient across the membrane. Sometimes, the permeate production of the first pass requires further treatment by means of a second serial connection of brackish water membrane elements (Second pass). The second pass may treat all the permeate flow or only part of this. The second pass requires a feed pressure significantly lower than that of the first pass since permeate from the first pass exhibits low salt concentration (brackish water). Also the concentrate of the first pass could be further treated by a second serial connection of membrane elements (second stage). To install an additional pump (interstage pump) may be optional since the concentrate exits the first pass at a pressure slightly lower than that of the HPP outlet. Decision on installing this interstage pump depends on concentrate pressure in comparison to osmotic pressure at the tail of the membrane series. In these days the second stage is only normally used in Brackish Water Reverse Osmosis (BWRO) desalination. However, in the past, SWRO plants with second stage were common in The Canary Islands [13]. In case of installing two stages, the interstage pump could be replaced by a turbocharger to recover all the brine energy, thus the feed flow is pressurised only by the HPP [14] up to the working pressure of stage 1. Greenlee et al [15] report on some examples of SWRO plants along with pretreatment and posttreatment procedures.

In relation to process 3, there are diverse options of implementing the conceptual diagram shown in figure 2. In these days, two different Energy Recovery Devices (ERDs) could be used:

- Isobaric Chambers (ICHs) are the most efficient option. They pressurise part of the feed flow, around mass flow of concentrate, up to a pressure slightly below that of the concentrate at the membrane module outlet. Thus requiring a Booster Pump (BP) after the ICH. The rest of the feed flow, similar to that of product is pressurised by the High Pressure Pump (HPP) – see figure.2 -.
- TurboChargers (TCs), which normally act as booster pumps after the HPP. Both, TC and HPP pressurise the total feed flow, except if Danfoss iSave is used. The latter requires configuration of fig.3, an internal power consumption instead of a BP and exhibits 90% of energy efficiency.

With the aim of calculating the SEC with the present status of the SWRO desalination technology, modelling of the three basic process based on figure 2 diagram is carried out. In addition, the practical limit of the SWRO desalination SEC corresponds to the hypothesis of ideal components in order to perform ideal feed pressurization, separation by means of an ideal semipermeable membrane and energy recovery with no losses.

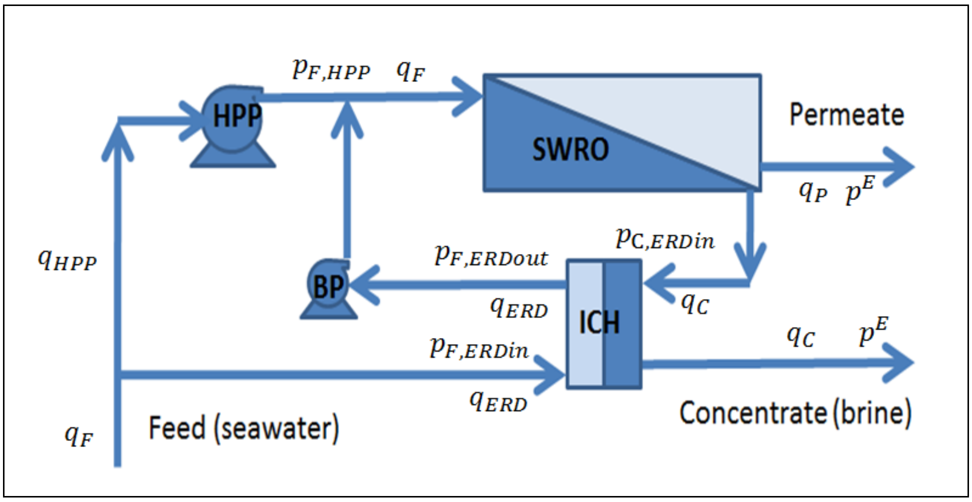


Figure 2. Diagram considered to SWRO modelling based on ERI-PX Energy Recovery Device (ERD).

3. DIAGNOSIS OF CURRENT SWRO DESALINATION TECHNOLOGY

3.1. Influence of seawater conditions on the theoretical minimum work of solvent extraction

In order to calculate the theoretical minimum work needed to a partial solvent separation from a seawater solution, the following hypothesis are required to apply the thermodynamic principles. First, work consumption is only that required to obtain the useful change of thermodynamic state, which is the change of salt concentration. Then, ambient temperature and pressure are assumed for feed, product and concentrate (blowdown). Second, the desalination process is reversible. Then, nil exergy destruction is assumed. Figures 3-4 show results of the calculation procedure described below to obtain the minimum net work, $P_{W,rev}$, required for partial solvent extraction at ambient temperature, T^E, and pressure, p^E, from seawater at ambient salinity, S^E, in J/kg, $P_{W,rev}/q_P$:

$$P_{W,rev}/q_P = \Delta_{des}ex_f \qquad (4)$$

where $\Delta_{des}ex_f$ represents the change of flow exergy, ex_f, per kg of product obtained, calculated from values of flow exergy of Product (P), Concentrate (C) and Feed (F) if BD does not achieve saturation concentration – superscript sat -:

$$\Delta_{des}ex_f \;\; (T^E, p^E, S^E, r_m < r_m^{sat}) \quad = ex_{f,P} + \left(\frac{1}{r_m} - 1\right) \cdot ex_{f,C} - \frac{1}{r_m} \cdot ex_{f,F} \qquad (5)$$

being r_m the ratio of mass flow rates (q) of product to feed:

$$r_m = \frac{q_P}{q_F} \qquad (6)$$

Hence,

$$\frac{q_C}{q_P} = \left(\frac{1}{r_m} - 1\right) \qquad (7)$$

Besides, by combining total and solute mass balances:

$$S_C = \frac{S_F}{1 - r_m} \qquad (8)$$

In this work r_v known as recovery rate, expresses the same ratio that r_m with volumetric flows. In eq. 5, flow exergy of feed is nil under the assumption of being seawater at ambient temperature and pressure. Alternatively to eq.4, the SEC is usually expressed in terms of kWh/m^3:

$$P_{W,rev}/q_{V,P} = \rho_P \cdot \Delta_{des} ex_f(T^E, p^E, S^E, r_m < r_m^{sat}) \quad (9)$$

where q_V and ρ mean volumetric flow and density, respectively. Sharqawy et al [11] obtained accurate correlations to calculate thermodynamic properties of seawater and in general of sea salt solutions. The reference state is saturated liquid water at triple point. Data of liquid water at 0.1 MPa were used to fit equations up to the normal boiling point. Upper temperatures were fit by means of properties at saturation pressure. Other authors proposed functions based on combining theoretical procedures and experimental data validation [16-19].

The following graphs allow the analysis of the effects of temperature and salt concentration on the SEC of a reversible process of solvent extraction. In figure 3, the salinity of standard seawater is assumed. The effect of salt concentration is shown in figure 4.

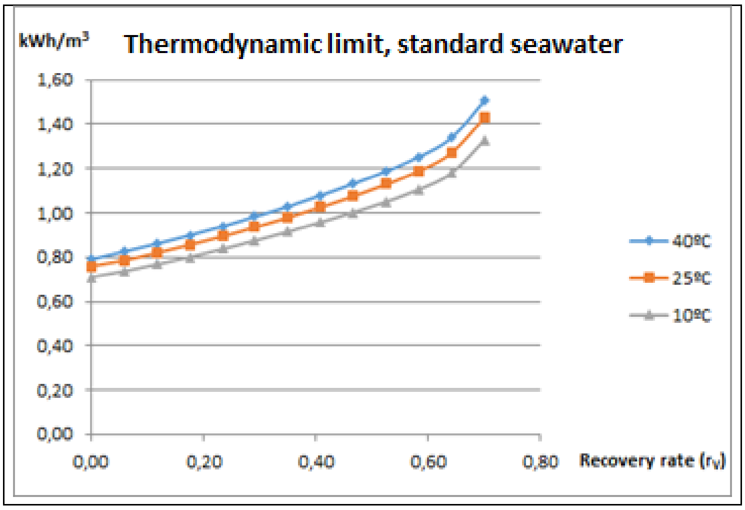


Figure 3. Specific work required to obtain pure water from seawater (Salinity 0.03510504 kg/kg) by means of a reversible desalination process at ambient temperature and pressure.

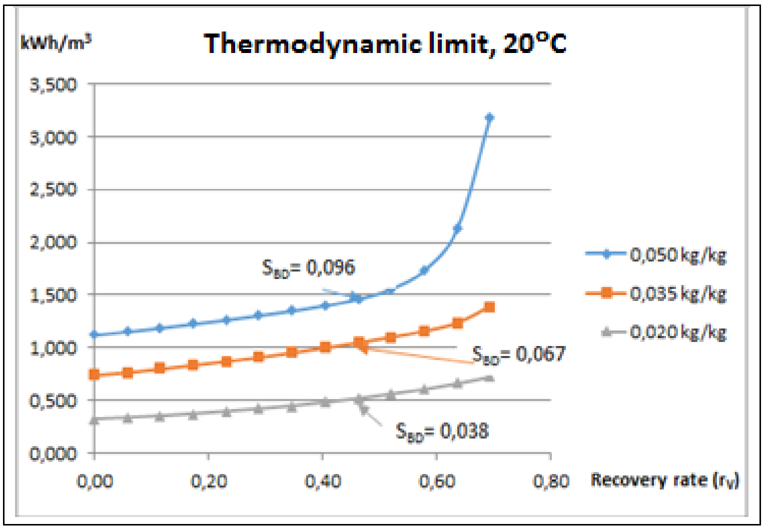


Figure 4. Specific work required to obtain pure water from seawater (20ºC) by means of a reversible desalination process at ambient temperature and pressure.

To sum up, if the recovery rate is 50%, the minimum theoretical energy required for solvent extraction is within 1.03-1.16 kWh/m^3 range for temperatures of 10ºC-40ºC and standard composition of seawater – see fig. 4 -. This range decreases up to 0.7-0.8 kWh/m^3 for recovery rate of 0%, which is the absolute minimum. Besides, the minimum theoretical energy for solvent extraction strongly depends on the seawater salt concentration, 0.5-1.5 kWh/m^3 is required for salinities of 0.020-0.050 kg/kg, 20ºC and 50% of recovery rate – see fig.4 -.

3. 2. Practical limit of SEC in current SWRO desalination technology

General equations of power consumption of HPP and BP (fig.2) are particularized by assuming the most favorable hypothesis in order to assess the practical limits of the SWRO desalination process (ideal SWRO process). General equations are reported below:

- Power consumption of the High Pressure Pump (HPP), in which the flow rate, $q_{V,HPP}$ increases its pressure from p^E to $p_{F,HPP}$, considering pump and engine efficiencies, η_{HPP} and η_{eng}, respectively.

$$P_{W,HPP} = \frac{q_{V,HPP} \cdot (p_{F,HPP} - p^E)}{\eta_{HPP} \cdot \eta_{eng}} \tag{10}$$

  The global mass balance relates mass flow rates involved as follows:

$$q_{V,F} \cdot \rho_F = q_{V,ERD} \cdot \rho_F + q_{V,HPP} \cdot \rho_F \tag{11}$$

- Power needed by the Booster Pump (BP) to increase the pressure of the flow rate of the seawater side of ERD, $q_{V,ERD}$. Its pressure increases from this side outlet, $p_{F,ERDout}$, to $p_{F,HPP}$:

$$P_{W,BP} = \frac{q_{V,ERD} \cdot (p_{F,HPP} - p_{F,ERDout})}{\eta_{BP} \cdot \eta_{eng}} \tag{12}$$

- Specific Energy Consumption is calculated by means of the following equation:

$$SEC_{net} = \frac{P_{W,HPP} + P_{W,BP}}{q_{V,P}} \tag{13}$$

  Representative values considered in this work to calculate the SEC are $\eta_{eng,HPP}$, 0.95; η_{BP}, 0.75, and $\eta_{eng,BP}$, 0.93.

- Concerning the Energy Recovery Device (ERD) based on ERI-PX [20-21], this consists in a number of units assembled in parallel with their performance parameters assumed by hypothesis as follows:
  - Average efficiency, Eff, 0.95 (peak efficiency 0.96-0.98 [14] no mixing is included in the model):

$$Eff = \frac{q_{V,ERD} \cdot p_{F,ERDout} + q_{V,C} \cdot p_{C,ERDout}}{q_{V,ERD} \cdot p_{F,ERDin} + q_{V,C} \cdot p_{C,ERDin}} \tag{14}$$

  - High Pressure flow Differential Pressure (HP_DP), 0.7 bar:

$$HP\_DP = p_{C,ERDin} - p_{F,ERDout} \tag{15}$$

  - Low Pressure flow Differential Pressure (LP_DP), 0.6 bar:

$$LP\_DP = p_{F,ERDin} - p_{C,ERDout} \tag{16}$$

  being operating conditions

$$p_{C,ERDout} \geq p^E; \; p_{F,ERDin} \geq LP\_DP \tag{17}$$

  The flow pressurized by the ERD, $q_{V,ERD}$ is calculated by combining equations 15-16:

$$q_{V,ERD} = q_{V,C} \cdot \frac{[(p_{F,ERDin}-LP\_DP)-p_{C,ERDin}\cdot Eff]}{[p_{F,ERDin}\cdot Eff-(p_{C,ERDin}-HP\_DP)]} \quad (18)$$

where the concentrate flow (C) is related to the product flow by means of r_m.

$$q_{V,C} = \left(\frac{1}{r_m}-1\right)\cdot\frac{q_{V,P}\cdot\rho_P}{\rho_C} \quad (19)$$

Therefore, the flow pressurized by the HPP, $q_{V,HPP}$, considering eq.9, is calculated by means of the following equations:

$$q_{V,HPP}\cdot\rho_F = q_{V,F}\cdot\rho_F - q_{V,ERD}\cdot\rho_F \quad (20)$$

$$q_{V,F} = \left(\frac{1}{r_m}\right)\cdot\frac{q_{V,P}\cdot\rho_P}{\rho_F} \quad (21)$$

Besides, pressure increasing required at the BP:

$$p_{F,HPP} - p_{F,ERDout} = p_{F,HPP} - \left(p_{C,ERDin} - HP\_DP\right) \quad (22)$$

$$p_{F,HPP} - p_{F,ERDout} = \Delta p_{Loss} + HP\_DP \quad (23)$$

- Working pressure at the inlet of the membrane series, $p_{F,HPP}$, (fig.3) should comply eq.3. The osmotic pressure Π is related to the osmotic coefficient of the solvent, ϕ, by means of:

$$\Pi = \phi\cdot\rho_w\cdot R\cdot T\cdot\frac{2\cdot S/(1-S)}{62.808\cdot 10^{-3}kg/mol} \quad (24)$$

where R means the universal gas constant, S is the salinity and ρ_w corresponds to the pure water density. Sarqawy [11] gives a correlation to calculate ϕ.

Table 2 gives hypotheses on ideal components namely, HPP, ERD and BP, to carry out an ideal SWRO desalination process. They are applied to calculate power consumptions of BP and HPP in order to assess the practical limit of the SEC, SEC0, of SWRO desalination. Results of SEC0 are reported in the following subsections in order to compare them to the actual SEC calculated within the framework of the parametric analysis performed.

Table 2. SWRO process under the most favourable hypothesis: Ideal components.

Energy recovery device, ERD (ERI-PX) - eqs. 14-18 -	$HP\_DP = 0 \Rightarrow \quad p_{F,ERDout} = p_{C,ERDin}$ $p_{C,ERDout} = p^E$ $LP\_DP = 0 \Rightarrow \quad p_{F,ERDin} = p^E$ $Eff = 1$ Therefore, eq. 19 becomes: $q_{V,ERD} = q_{V,C}$
Booster Pump, BP	BP parameters: $\eta_{BP} = 1; \eta_{eng} = 1$ Pressure increase (eq.23) becomes nil considering no losses: $p_{F,HPP} - p_{F,ERDout} = \Delta p_{Loss} + HP\_DP$ Hence (eq.12): $P_{W,BP} = 0\cdot kW$
High Pressure Pump, HPP	HPP parameters: $\eta_{HPP} = 1; \eta_{eng} = 1$ Operating pressure (eq.3):

	$(p_F - \Delta p_{Loss}) - p_P \geq \Pi_{C,surf} - \Pi_P$ With $\Delta p_{Loss} = 0$; $\Pi_P = 0$; $p_P = p^E$ and negligible polarization effect, thus S_C is used to calculate Π_C Eq. 3 become $p_{F,HPP} = \Pi_C + p^E$ Hence (eq.10): $P_{W,HPP} = \frac{(q_{V,F} - q_{V,C}) \cdot \Pi_C}{1 \cdot 1}$

3.3. Effect of membrane state of the art on SEC

At the opposite sides of the RO membrane there are:

- A Feed-Concentrate channel (F-C). The relatively high solvent flow through the membrane results in the effect known as concentration polarization. This consists in an increased salt concentration near the membrane surface, attributable to the fact that salt passage is quite small in comparison to the water transmembrane flow. Note that values of osmotic pressure in the NDP (eq.2) correspond to those of the membrane surface. The NDP mainly depends on the target product quality, economy of membrane area and membrane properties in relation to solvent and solute passage.
- A Permeate or product channel (P), which receives both water and salt flows coming through the membrane. These flows per unitary area are not constant, thus resulting in variable permeate quality alongside the axis of feed flow. However, salt flow in commercial membranes is quite small, so the value of permeate osmotic pressure is normally assumed to be nil. Due to the configuration of commercial membrane elements, pressure losses in the permeate channel are normally neglected.

This subsection presents representative results of a parametric analysis of the membrane state of the art on the SEC, considering different seawater conditions. Thermodynamic limit of SEC, $\Delta_{des}ex_f$, and SEC of an ideal SWRO process, SEC0, are shown for comparative assessments. Results obtained for different seawater conditions and 80% of HPP efficiency are depicted in figure 6 as function of the Tail Differential Pressure (TDP), defined as the NDP at the tail of the membrane series if concentration polarization is neglected. Thus, osmotic pressure of the concentrate outlet at the membrane surface can be calculated by eq.24 considering ambient temperature and salt concentration of the concentrate. Considering figure 2 and product as pure water, eq. 25 describes the TDP:

$$TDP = p_{C,ERDin} - p_P - \Pi_C \quad (25)$$

being nil its theoretical minimum value required to allow the RO process corresponding to ideal semipermeable membranes. Non ideal membranes allow salt passage. Therefore, in order to achieve the required low permeate salinity, the TDP should be increased to go up the water passage due to the enhanced NDP. Okamoto and Lienhard [22] thoroughly report on the effect of membrane permeability on SEC. Nanomaterials [23] and other innovative materials [24-26] represent significant opportunities to enhance the performance of membrane elements. A second membrane skid to treat the permeate should be necessary if the target permeate quality is not achieved, Tu et al [27] describe complex configurations in plants designed with the most restricted product quality.

A range of representative values of TDP could be 5-8 bar [10] in order to achieve required permeate quality within a range of recovery rate (r_V) of 42-50%.

Other parameters considering the analysis of figure 5 would be those of ERD (Eff, HP_DP and LP_DP), BP efficiency, pressure losses within the membrane module series and efficiency of pump engines. Their representative values corresponding to each component could be – see section 3.2 -:

- ERD: Eff, 0.95; HP_DP, 0.7, and LP_DP, 0.6 bar.
- BP: efficiency, η_{BP}, 0.75.
- Pump engines: Values of 0.95 in the HPP and 0.93 in the BP are assumed.

- Pressure losses associated to the membrane modules assembled within the Pressure Vessel (PV): 2 bar.

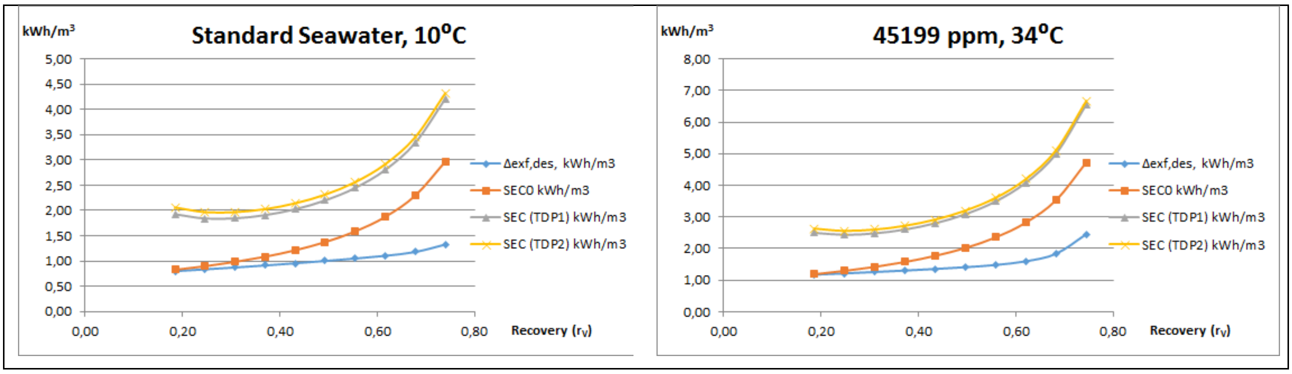


Figure 5. Specific Energy Consumption (SEC) with η_{HPP}= 80%, TDP$_1$= 5 bar and TDP$_2$= 8 bar; SEC0 (SEC of ideal SWRO process), and thermodynamic limit of seawater desalination, $\Delta_{des}ex_f$, for standard seawater at 10ºC and Persian Gulf conditions [10].

Results exhibit small influence of the TDP on the SEC in all conditions, less than 6% from TDP= 8 bar to TDP= 5 bar if r_v>40%. At representative values of recovery rate, r_v of 41-49%, the SEC decreases 0.038-0.039 kWh/m^3 per bar of TDP reduction, within the ranges analysed, 8-5 bar or 8-0 bar. Therefore, further improvements on membrane permeability would be important only on other OPerational EXpenditures (OPEX) parameters and on CAPital EXpenditures (CAPEX). This is consistent with conclusions reported by Zhu et al [28] and Okamoto and Lienhard [22].

3.4. Effect of HPP efficiency on SEC

The second parameter analysed is the HPP efficiency, η_{HPP}, being 80-90% a representative range of the current SWRO desalination plants, with the upper limit unavailable for large-capacity SWRO trains and 85% typical value for large-capacity plants. Figures 6-7 show the effect of pumping efficiency on SEC at different seawater conditions with TDP of 5 bar. Figures also show theoretical limit of solvent extraction as well as the minimum SEC of the SWRO technology, SEC0, to make easier further analyses.

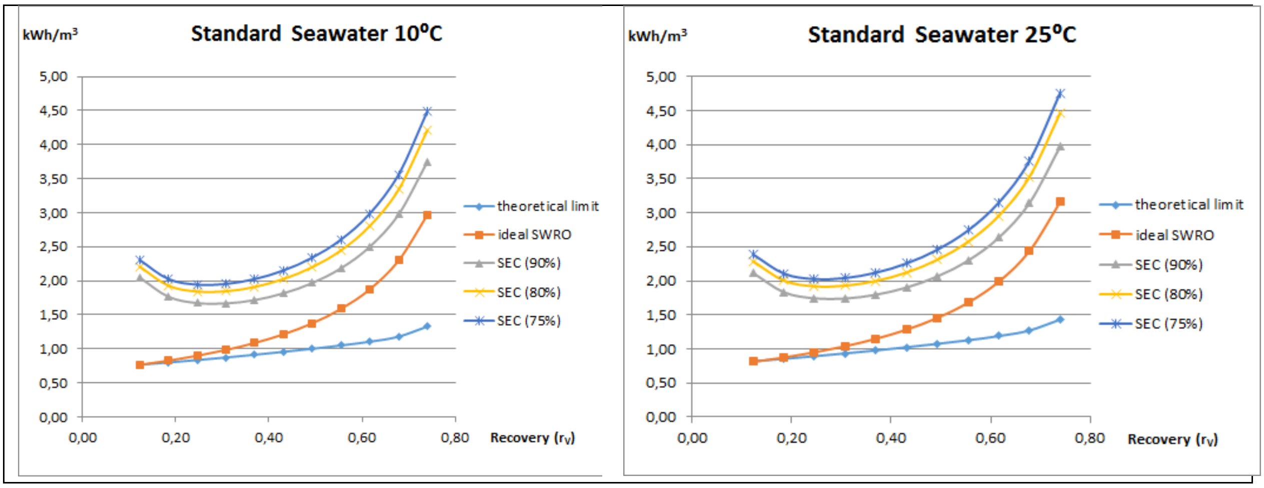


Figure 6. Specific energy consumption of SWRO desalination (TDP= 5 bar) for η_{HPP}= 75%, 80% and 90% in comparison to ideal SWRO process and thermodynamic limit.

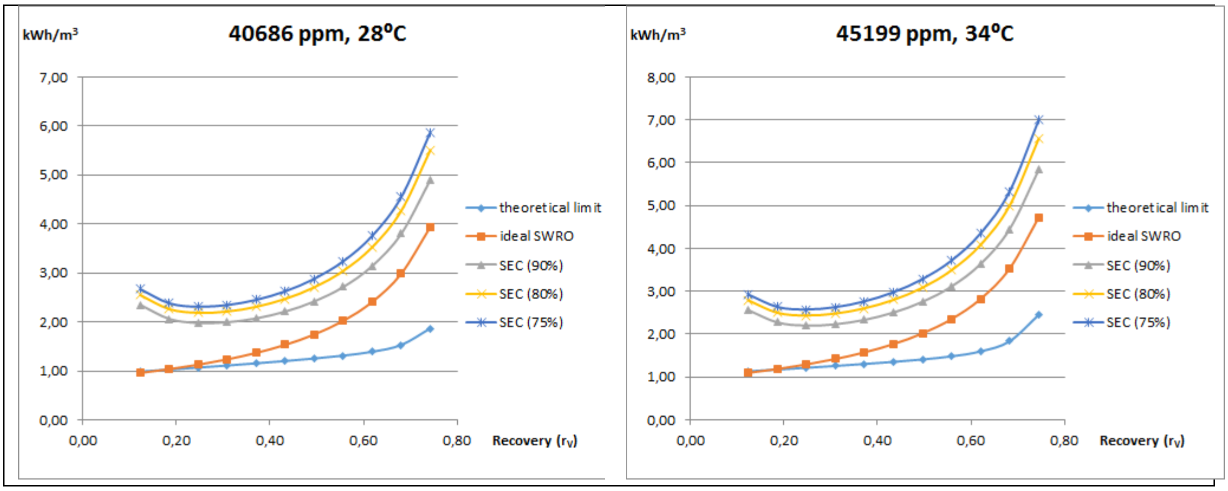


Figure 7. Specific energy consumption of SWRO desalination (TDP= 5 bar) for η_{HPP}= 75%, 80% and 90% in comparison to ideal SWRO process and thermodynamic limit. Cases of Mediterranean conditions depicted on the left and Persian Gulf on the right [Wilf, 2007].

Thermodynamic limit and SEC0 exhibit very similar values at recovery rates below 25% due to low salinity differences between concentrate and feed and low osmotic pressure of the concentrate. On the contrary, the SEC significantly increases as recovery rate decreases below 20% since even relatively small inefficiencies of the HPP are significant when pumping the corresponding high feed flows. Therefore, the use of SWRO technology at low recovery rates makes no sense, not only from the point of view of auxiliary energy consumption but also concerning main energy consumption. As expected, SECs of actual SWRO technology exhibit quite similar qualitative behavior in all plant locations. They show a minimum at around 25-30% of recovery rate and important increase with higher recovery rates. Besides that, the effect on the SEC of HPP efficiency from 75% to 90% (engine efficiency, η_{eng}= 95%) is around 0.5-0.8 kWh/m^3 for conventional SWRO configuration (one stage), depending on recovery rate, temperature and feed salinity.

Moreover, in SWRO configuration with single stage and one pass, the SEC ranged from 2.0-3.0 kWh/m^3 (recovery rate, 45%; efficiency of high pressure pump, 80%, efficiency of the engine, 95%). Around a 50% of the SEC in this case is attributable to the thermodynamic limit of a solvent extraction process at these specific conditions of salt concentration and temperatures. Besides, the SEC decreases up to 1.4-2.0 kWh/m^3 (SEC0) if ideal SWRO desalination process is considered, being 0.3-0.6 kWh/m^3 due to plant configuration – see SEC0 minus thermodynamic limit -.

3.5. Effect of plant configuration on SEC

Even though ideal feed pressurisation and brine energy recovery are technically possible, the single-stage concept results in pressurising all the feed flow up to a pressure higher than osmotic pressure of the concentrate (blowdown) – see figure 2 -. Nevertheless, the thermodynamic ideal limit (reversible process) means to reduce the NDP as much as possible. Therefore, an advance towards the thermodynamic limit should be to carry out the pressurisation process in multiple stages. Thus, the inter-stage pump is a Low Pressure Pump (LPP) that only pressurises the concentrate of the previous stage. Moreover, the corresponding pressure increase corresponds to the change of osmotic pressure between concentrate of adjacent stages. Regardless capital costs, multistage configurations would result in a significant reduction of energy consumption as Ahunbay [29] analysed. Up to recovery rates normally used in current SWRO technology, only two stages could be a reliable and might be a cost-effective option.

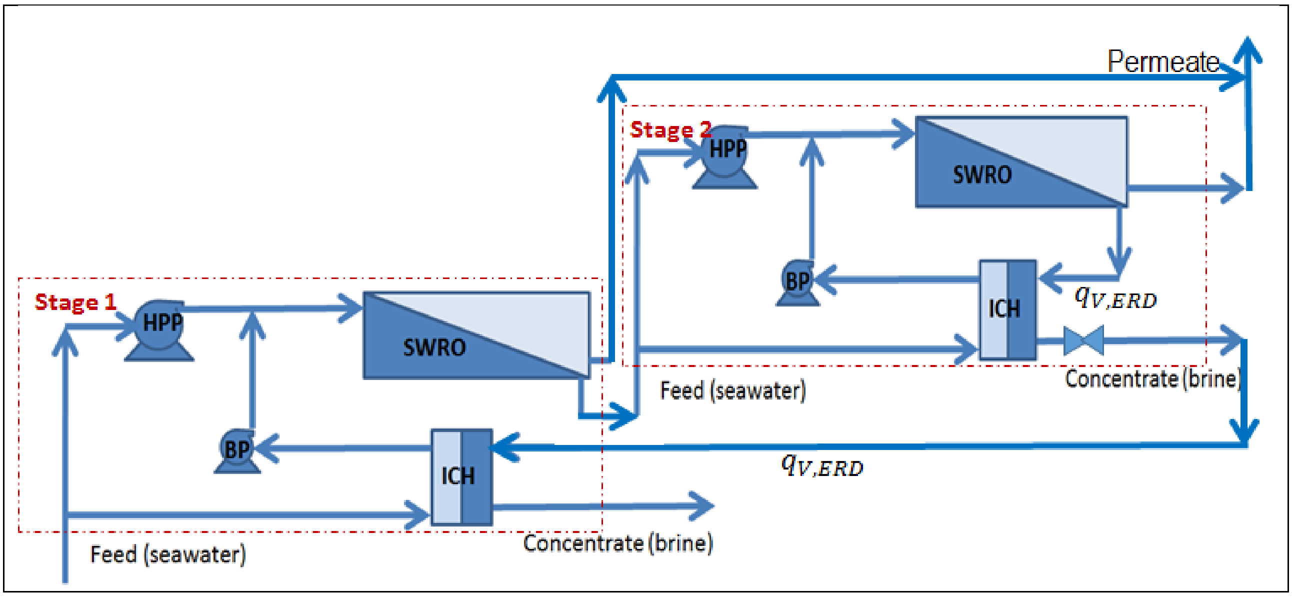


Figure 8. Conceptual figuration of SWRO desalination with two stages.

Note that the brine energy recovery is placed only at the brine outlet of the second stage since the concentrate of the first stage is the feed of the second stage. Two sets of ERI-PX should be installed and operated with same volumetric flow. Next equations describe the calculation of the power consumption in a two-stage SWRO configuration:

$$P_{W,HPP} = \frac{(q_{V,Fstg1} - q_{V,ERD}) \cdot (p_{F,stg1} - p^{E})}{\eta_{HPP} \cdot \eta_{eng,HPP}} \tag{26}$$

$$P_{W,LPPstg2} = \frac{(q_{V,Fstg2} - q_{V,ERD}) \cdot (p_{F,stg2} - p_{C,stg1})}{\eta_{LPPstg2} \cdot \eta_{eng,LPPstg2}} \tag{27}$$

$$\sum_{stg1,stg2} P_{W,BP} = \frac{q_{V,ERD} \cdot (\sum[LP\_DP + HP\_DP + \Delta p_{Loss}])}{\eta_{BPstg2} \cdot \eta_{eng,BPstg2}} \tag{28}$$

Where:

$$q_{V,F,stg1} = q_{V,F} \tag{29}$$

$$q_{V,C,stg2} = q_{V,C} \tag{30}$$

$$q_P = q_{P,stg1} + q_{P,stg2} \tag{31}$$

$$q_{V,Fstg2} = \frac{q_F - q_{P,stg1}}{\rho_{F,stg2}} \tag{32}$$

In addition, complementary equations are eqs. 6-8 considering the SWRO system as a whole along with eq.18, which is required for solving eqs. 26-28. Finally, in order to calculate SEC0, modelling of ideal components needs hypotheses summarized in table 3.

Table 3. Two-stages SWRO process: Thermodynamic hypothesis for ideal components.

Membrane series	○ Minimum working pressures: TDP_{stg1}= 0; TDP_{stg2}= 0
Energy recovery device, ERD	○ Feed flow (Eff=1; HP_DP= 0; LP_DP= 0): $$q_{V,ERD} = q_{V,C,stg2}$$ ○ Pump consumption: $P_{W,BP} = 0 \cdot kW$
Interstage pump, LPP	$$P_{W,LPPstg2} = \frac{(q_{V,Fstg2} - q_{V,C,stg2}) \cdot (\Pi_{C,stg2} - \Pi_{C,stg1})}{1 \cdot 1}$$
Main pump, HPP	$$P_{W,HPP} = \frac{(q_{V,Fstg1} - q_{V,C,stg2}) \cdot \Pi_{BD,stg1}}{1 \cdot 1}$$

Regarding SWRO desalination with two stages, the benefits on the SEC is analysed in this subsection for a wide range of temperatures, seawater salinities, recovery rates and pumping efficiencies by means of figures 9-11. The influence of the second stage increases with recovery rate and feed salinity. If operating with 60% of recovery rate is reliable, around 0.6-0.8 kWh/m^3 could be the energy saving due to including a second stage - HPP efficiency from 80% to 90% (η_{eng}= 95%) -. In all cases analysed, even if η_{HPP} is 90%, a range of 0.6-0.7 kWh/m^3 of the SEC is attributable to the inefficiency of equipment for 43-49% of recovery rate – see SEC minus SEC0 -. Besides that, 0.3-0.6 kWh/m^3 is due to plant configuration within the same range of recovery rate, being possible energy saving of 0.2-0.3 kWh/m^3 by adopting configurations with two stages – see SEC(1stg) minus SEC(2stg) in aforementioned figures -. Those values correspond around one half of the total amount attributable to plant configuration as reported in section 3.4.

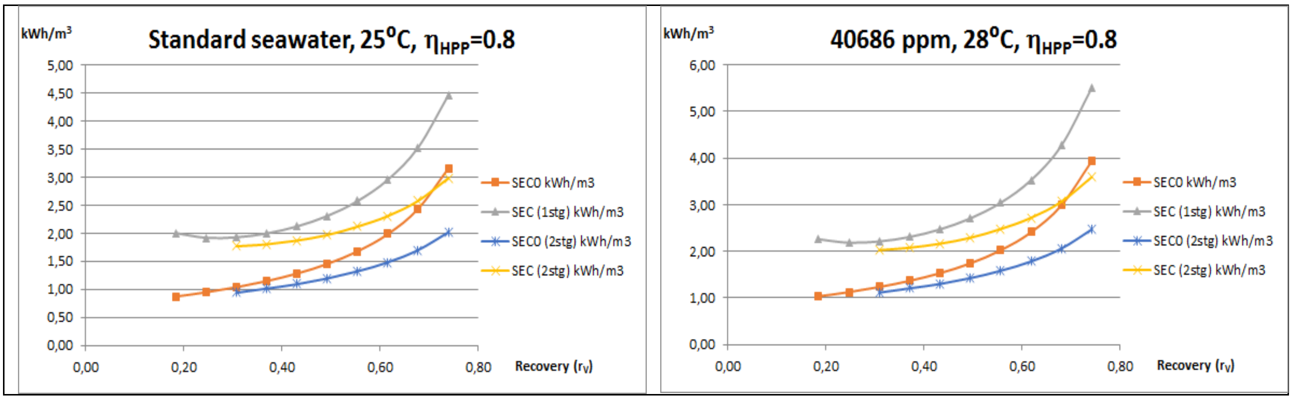


Figure 9. Specific Energy Consumption (SEC) with two stages in comparison conventional single-stage configuration, SEC (1stg), and to the ideal SWRO process with single stage, SEC0 (1stg) and double stage, SEC0 (2stg). Standard seawater salinity at 25°C on the left and Mediterranean conditions on the right [10].

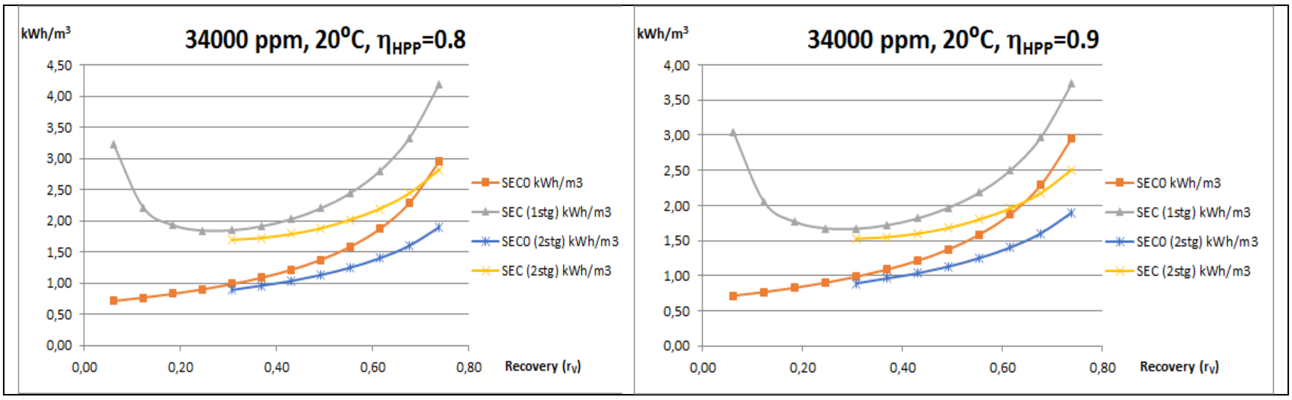


Figure 10. Specific Energy Consumption (SEC) with two stages in comparison conventional single-stage configuration, SEC (1stg), and to the ideal SWRO process with single stage, SEC0 (1stg) and double stage, SEC0 (2stg). Pacific conditions [10].

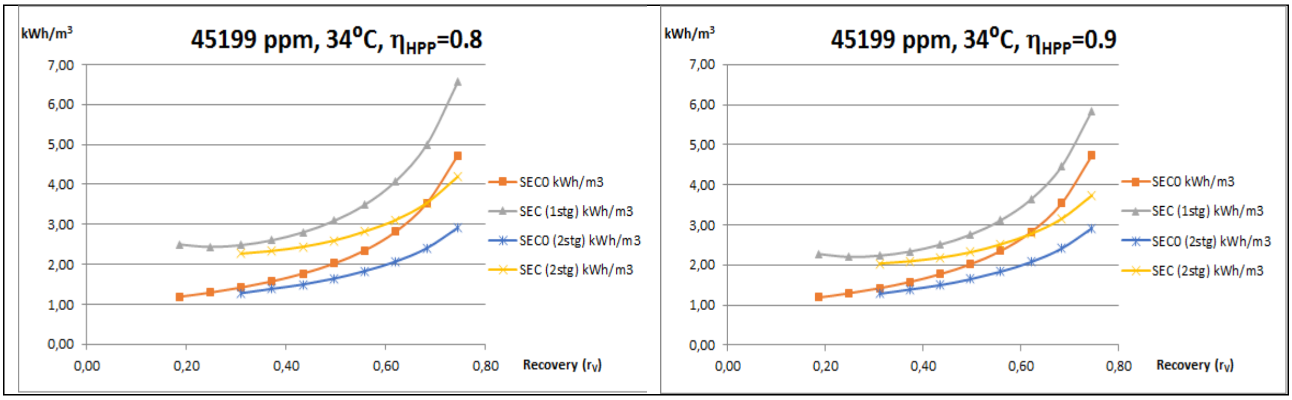


Figure 11. Specific Energy Consumption (SEC) with two stages in comparison conventional single-stage configuration, SEC (1stg), and to the ideal SWRO process with single stage, SEC0 (1stg) and double stage, SEC0 (2stg). Seawater conditions of Persian Gulf [10].

3.5.1 Desalitech- CCD configuration

Figure 12 depicts the configuration referred to as Desalitech-CCD (Closed Circuit Desalination) [2]. The HPP operates discontinuously to give to the BP the role of interstage pump. Therefore, this concept could take advantage of the multi-stage configuration thus reducing the NDP. Regardless CAPEX, this is a candidate SWRO configuration to reduce the SEC. The expected SEC should be ranged between two-stages and three-stages configurations. Nevertheless, it should be noted that the number of membrane elements, HPPs and BPs is similar than those of conventional two-stages configuration. Main technical problem of implementing CCD concept in SWRO applications is the complexity of a discontinuous energy recovery device. This fact makes unsuitable the commercially available energy recovery devices. However, novel designs in the near future could solve these technical problems.

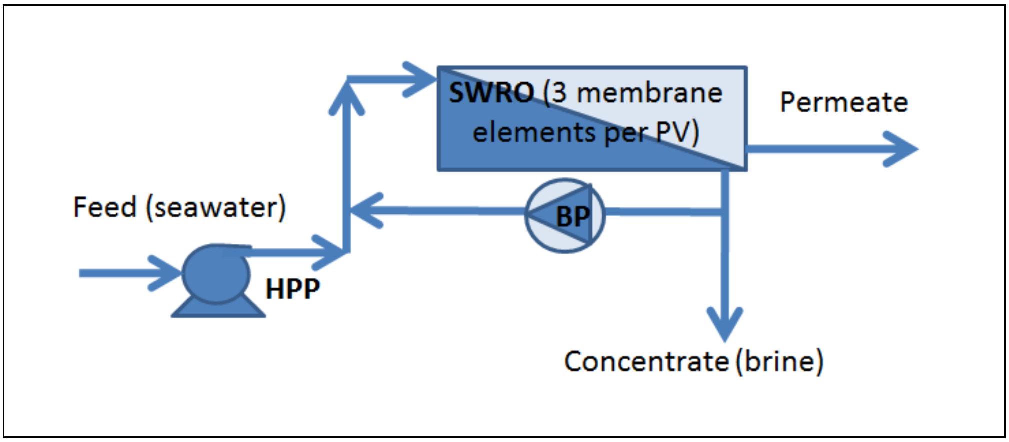


Figure 12. Desalitech-CCD (Closed Circuit Desalination) concept. Energy recovery from the brine is not shown in the figure.

3.6. SEC diagnosis: Opportunities of improving

- Exergy losses due to non-ideal equipment comprises, efficiencies below 100% in energy recovery devices, pumps and engines; limited water permeability in membranes as well as incomplete salt rejection, and pressure losses in the RO membrane modules. This amounts to SEC minus SEC0.
  Inefficiencies in feed pressurisation by the HPP includes those associated to both,
  - the required pressure increase to generate the reverse osmosis process, which depends on plant configuration as previously discussed.
  - the over pressurisation due to inefficiency of plant components, described below:
    - Pressure losses of feed flow circulation throughout the feed-concentrate channel results in requiring over pressurization of the feed flow.
    - The TDP – defined in section 3.3 - also results in an over pressurisation of the feed flow. This requirement is due to the actual performance of RO membranes associated to some effects namely, fouling, scaling, concentration polarisation and actual behaviour concerning water pass and salt rejection -.

  Moreover, the booster pump needed (figure.2) compensates:
  - Pressure losses within membrane modules assembled in series.
  - Inefficiencies of the energy recovery device at the high pressure side, known as HP_DP – see eq.15 -.

To sum up, next figures (13-16) analyse the effect of individual contributions to the SEC of a desalination plant, excluded all auxiliary energy consumptions. The total SEC consists in the following three main concepts:

- Thermodynamic limit, $\Delta_{des}ex_f$, associated to the changes in the thermodynamic state after the partial solvent extraction.
- Configuration, SEC0 - $\Delta_{des}ex_f$, corresponding to the selection of the SWRO plant configuration concerning number of stages and passes. This point affects to the actual NDP of the membrane separation process adopted.
- Non ideal components, SEC-SEC0, as follows:
  - Pressure Vessel (PV) in which membrane modules are assembled. This results in pressure losses in the feed flow, 1.65 bar is assumed.

- SWRO membranes, thus requiring operation with TDP above 0. In this case the effect of 7.2 bar is calculated.
- ERD, evaluated with Eff, 0.95; HP_DP, 0.7, and LP_DP, 0.6 bar, versus Eff, 1; HP_DP, 0, and LP_DP, 0 bar.
- The remaining energy consumption is attributed to the HPP, once discounted the inefficiency of the rest components namely, PV, membranes and ERD.

Other values considered are BP efficiency, 75% along with efficiency of engines: $\eta_{eng,HPP}$, 95%, and $\eta_{eng,BP}$, 93%.

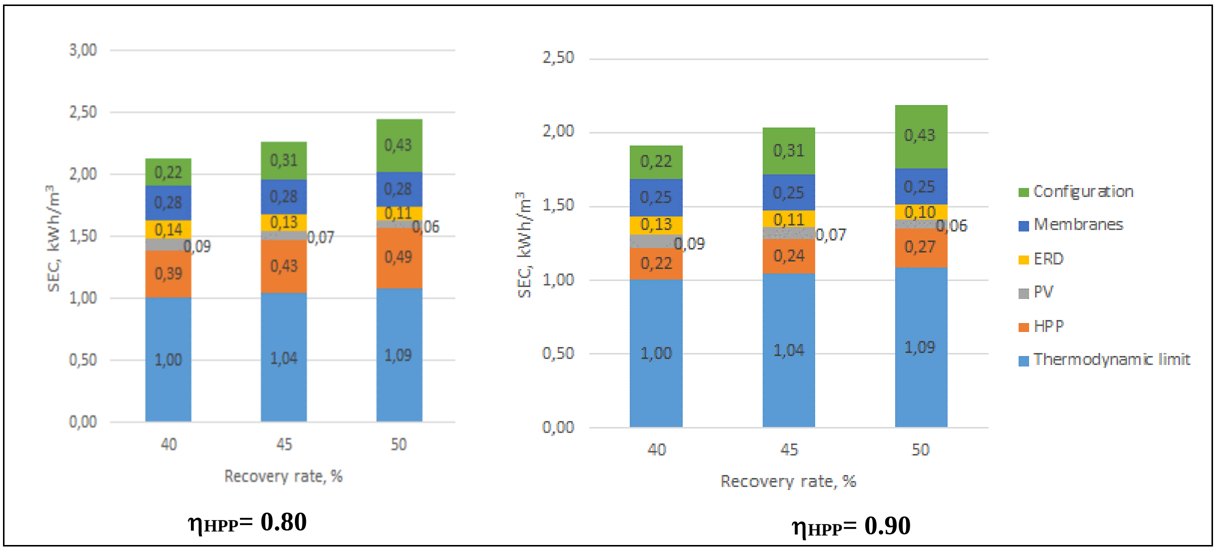


Figure 13. Seawater with 35000 ppm and 25°C: Effect on SEC of contributions of main items.

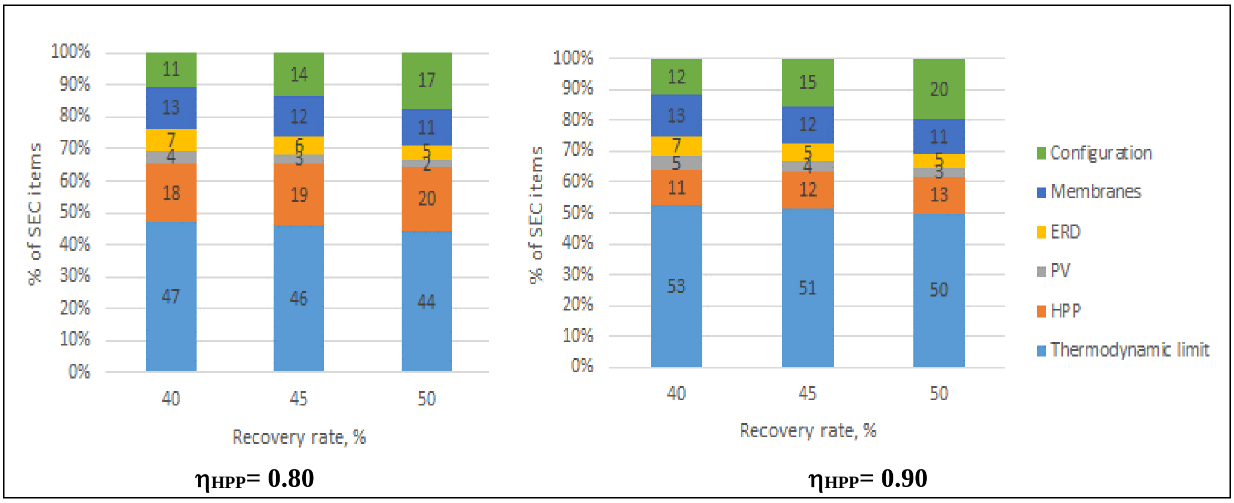


Figure 14. Seawater with 35000 ppm and 25°C: Effect on SEC of contributions of main items in terms of percentages. Source values of individual contribution in kWh/m^3 are shown (η_{HPP}= 0.90).

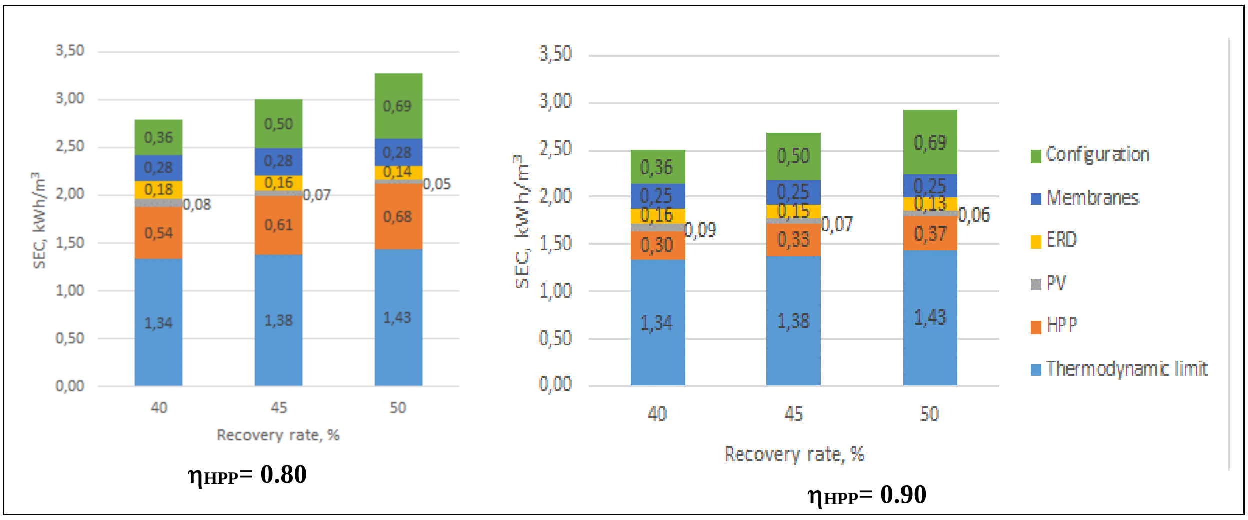


Figure 15. Persian Gulf [Wilf, 2007]: Effect on SEC of contributions of main items.

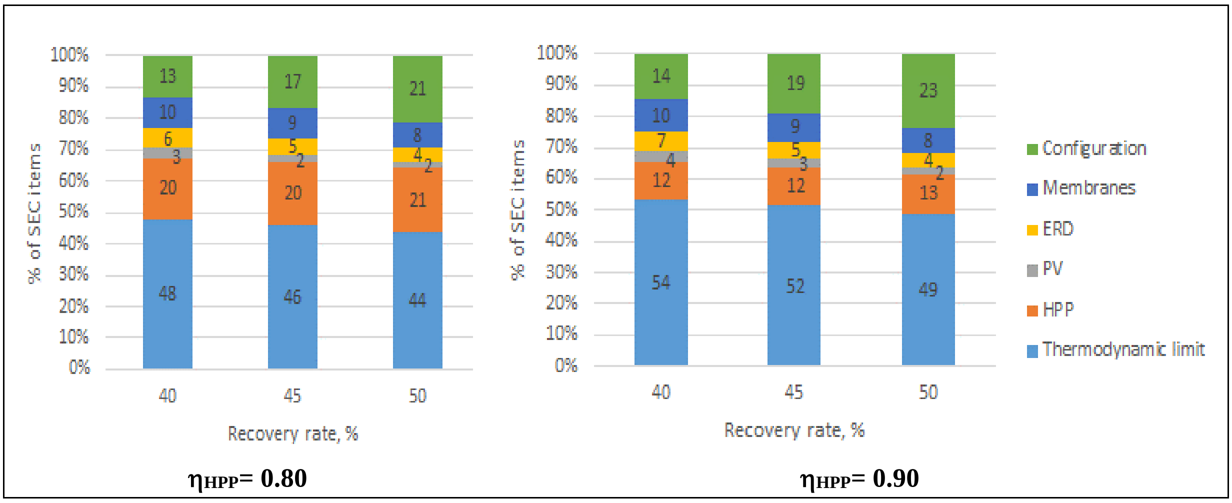


Figure 16. Persian Gulf [Wilf, 2007]: Effect on SEC of contributions of main items in terms of percentages. Source values of individual contribution in kWh/m^3 are shown (η_{HPP}= 0.90).

4. ASSESSMENT OF OPPORTUNITIES OF REDUCING SEC BY INNOVATIVE CONCEPTS

Pressure Retarded Osmosis (PRO) concept, based on energy production from salinity gradient, could act as an additional energy recovery in a SWRO desalination plant. To this end, it is assumed that an external aqueous flow with low osmotic pressure is available. Any aqueous effluent that could be rejected to the sea could be used, as treated wastewater or treated industrial effluents. No possible reuse of this flow as part of the SWRO permeate is considered in this work.

Spontaneous water flow through a PRO membrane from this external aqueous flow to a brine flow occurs if the NDP – eq.1 and 2 - between brine and external flows is negative. The transmembrane flow increases its pressure up to that of the brine flow, thus generating the corresponding energy from salinity gradient.

Figure 17 depicts the proposed configuration to integrate a PRO system in a SWRO desalination plant. Since the brine pressure at the SWRO membrane modules outlet is so high, the brine flow should be partially expanded prior the PRO system. This allows the osmotic pressure difference to be higher than the pressure difference between the concentrated and the external aqueous flows. Therefore, the brine flow of the PRO system inlet is the outlet of an energy recovery device of the SWRO desalination process – see turbocharger TC2 in figure 17 -. In the PRO system, some solvent of the aqueous effluent passes spontaneously thorough a membrane that separates this from the brine, thus increasing the mass flow rate of the pressurised brine flow up to q_{PRO}. As a result, the turbocharger TC1 processes higher brine flow than that of conventional SWRO plant. Consequently some additional energy saving is recovered when using the PRO system.

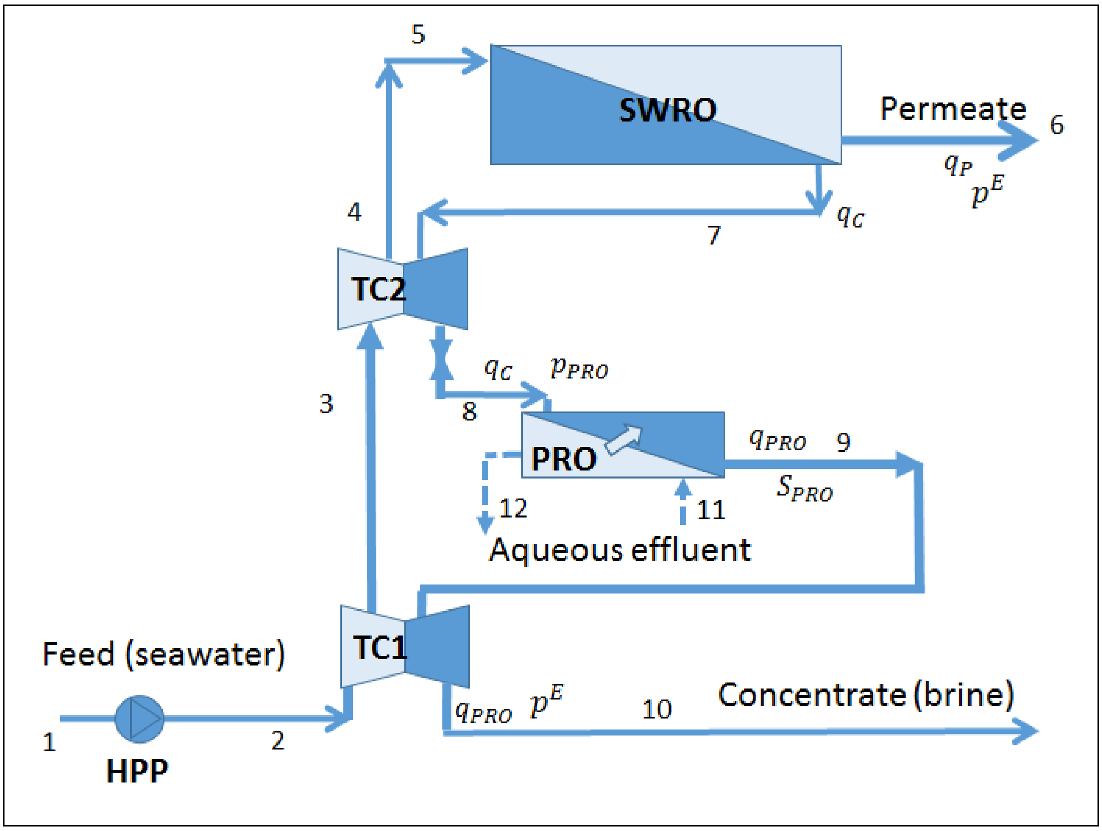


Figure 17. Configuration of SWRO desalination and PRO with an external aqueous effluent in order to decrease the SEC of the SWRO desalination process.

The main objective of this section is to perform a theoretical analysis due to the lack of experimental data of SWRO/PRO desalination plants. Thus, a configuration based on conventional turbochargers is considered in order to avoid power consumption or booster pumps required by iSave or ERI-PX isobaric chambers, respectively. However, a very high energy efficiency is assumed in the first phase of this study, 0.95, thus resulting in optimistic hypothesis considering current technology of conventional turbochargers but realistic for isobaric chambers. Thus, energy savings will be only attributable to the coupling of the PRO system. Some optimistic hypothesis are also adopted in relation to PRO systems as follows: no pressure losses, no polarisation effects and ideal salt rejection (nil salt passage).

The suitable selection of working pressure - p_{PRO} in figure 17 - depends on the overall system efficiency, membrane area economy, values of the driving force and maximum pressure that withstand current technology of PRO membranes as follows:

- The driving force of the spontaneous water transfer across the membrane is just the opposite of the NDP of the reverse osmosis:

$$\Pi_A - \Pi_B - (p_A - p_B) > 0 \quad (33)$$

corresponding the subscript A to the most concentrated solution. Therefore, the osmotic pressure difference sets the maximum gauge pressure of the brine in the PRO system, in a way that the water transferred (transmembrane flow) increases as the lower the brine working pressure is.

- The literature describes the optimisation of the energy production based on PRO. To maximise the power density **[30]** – i.e. minimise the membrane area -, the working pressure should be around one half of the difference of osmotic pressure across the membrane. Since osmotic pressures change throughout the membrane module due to the solvent transferred, average values at both sides of the membrane should be considered.

- Concerning the maximum working pressures [30], up to 30 or 48 bar have been experimentally achieved, but normally pressure below 12 bar are reported in the test campaigns, since the maximum pressure that withstand PRO membranes is usually limited.

Mass and exergy balances were carried out for a PRO process in which the inputs are blowdown (BD) of a seawater desalination process and treated wastewater or other aqueous flow. The part of the external aqueous flow that passes through the membrane is the transferred water (tw). Therefore, their respective mass flow rates, q_{BD} and q_{tw}, generates the outlet saline stream, q_{PRO}. The remaining aqueous flow could be recycled or discharged from the system. In this work, the recovery rate of the PRO process is defined by the ratio of either mass flow rate or volumetric flow:

$$r_{m,PRO} = \frac{q_{tw}}{q_{PRO}} \quad (34)$$

$$r_{V,PRO} = \frac{q_{V,tw}}{q_{V,PRO}} \quad (35)$$

Note that q_{tw} is the water that passes the PRO membrane and that the maximum gauge pressure achievable by the PRO outlet stream in an ideal process is the osmotic pressure difference of the brine at the PRO system outlet. Hence, the maximum working pressure depends not only on S_{PRO} but also on the salt concentration of the external aqueous flow. Besides that, the working pressure p_{PRO} should comply eq. 33 at both ends of the PRO system – see figure 17 -:

$$\Pi_9 - \Pi_{11} - (p_9 - p_{11}) > 0 \quad (36)$$

$$\Pi_8 - \Pi_{12} - (p_8 - p_{12}) > 0 \quad (37)$$

System model uses the following input parameters: q_P, T^E, S_{sw}, $r_{m,RO}$, $r_{m,PRO}$ and p_{PRO} as follows:

- PRO process:
  - Mass balances of solvent (water, w) and solute (s), respectively:

$$q_{tw} + q_C = q_{PRO} \quad (38)$$

$$q_{s,C} = q_{s,PRO} \quad (39)$$

    Hence, by combining eqs. 34 and 38:

$$\frac{q_C}{q_{PRO}} = 1 - r_{m,PRO} \quad (40)$$

  - Salinity of Concentrate (C) and the outlet stream of the PRO system:

$$S_{PRO} = \frac{q_{s,PRO}}{q_{PRO}} \quad (41)$$

$$S_C = \frac{q_{s,C}}{q_C} \tag{42}$$

Considering mass balance of solute (eq.39) and combining eqs.41-42:

$$S_{PRO} = \frac{q_C \cdot S_C}{q_{PRO}} \tag{43}$$

and finally, by using eq.40, eq,43 becomes:

$$S_{PRO} = \left(1 - r_{m,PRO}\right) \cdot S_C \tag{44}$$

- RO process - feed is seawater (sw) -:

$$S_C = \frac{S_{sw}}{1 - r_{m,RO}} \tag{45}$$

$$\frac{q_C}{q_P} = \left(\frac{1}{r_{m,RO}} - 1\right) \tag{46}$$

- Combination of PRO and RO processes:

$$S_{PRO} = \frac{\left(1 - r_{m,PRO}\right)}{\left(1 - r_{m,RO}\right)} S_{sw} \tag{47}$$

$$q_{V,PRO} = \left(\frac{1}{r_{m,RO}} - 1\right) \frac{q_P}{\rho_{PRO} \cdot \left(1 - r_{m,PRO}\right)} \tag{48}$$

Hence, if recovery rates of RO and PRO systems are the same, S_{PRO} becomes *Ssw*.

- Energy recovered at TurboCharger 1 (TC1) and TurboCharger 2 (TC2), respectively:

$$q_{V,F} \cdot \Delta p_{TC1} = \eta_{TC1} \cdot q_{V,PRO} \cdot (p_{PRO} - \Delta p_{Loss} - p^E) \tag{49}$$

$$q_{V,F} \cdot \Delta p_{TC2} = \eta_{TC2} \cdot q_{V,C} \cdot (p_C - p_{PRO}) \tag{50}$$

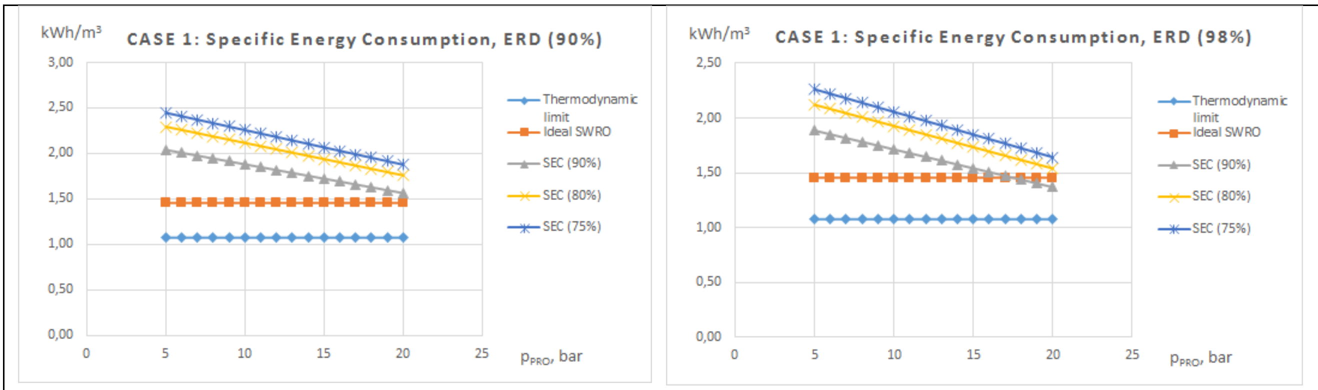
- SEC: The power consumption of the HPP is:

$$P_{W,HPP} = \frac{q_{V,F} \cdot \left(\{\Pi_C + TDP - p^E\} - \Delta p_{TC1} - \Delta p_{TC2}\right)}{\eta_{HPP} \cdot \eta_{eng}} \tag{51}$$

where pressure increase of feed flow at TC1 and TC2 are obtained by means of eqs. 49-50.

Theoretical results were calculated for different input parameters, such as: variable HPP efficiency, 0.75-0.90; BP efficiency, 0.75; engine efficiency, 0.95; pressure losses in RO membranes, 2 bar, and TDP, 5 bar. Different case studies (1-4) were analysed for salinity of standard seawater at 25ºC, and SWRO desalination with recovery rate $r_{m,RO}$, 0.48, and osmotic pressure of concentrate, Π_C, 53.1 bar. Case 1 considers $r_{m,PRO}$ of 0.5, thus resulting in optimum working pressure p_{PRO} of 19.5 bar for nil osmotic pressure of the external flow, Π_{11}. Optimum working pressure is one half of the arithmetic average of osmotic pressure in the concentrate channel. Besides, respective values for cases 2-4 are the following: $r_{m,PRO}$ of 0.35, 0.20 and 0.05, with optimum working pressures of 21.5 bar, 23.6 bar and 25.8 bar respectively. Moreover, in order to assess energy savings attributable to a PRO system coupled to the SWRO desalination, a conventional SWRO plant is being considered, with ERI-PX as energy recovery device with efficiency of 95%.

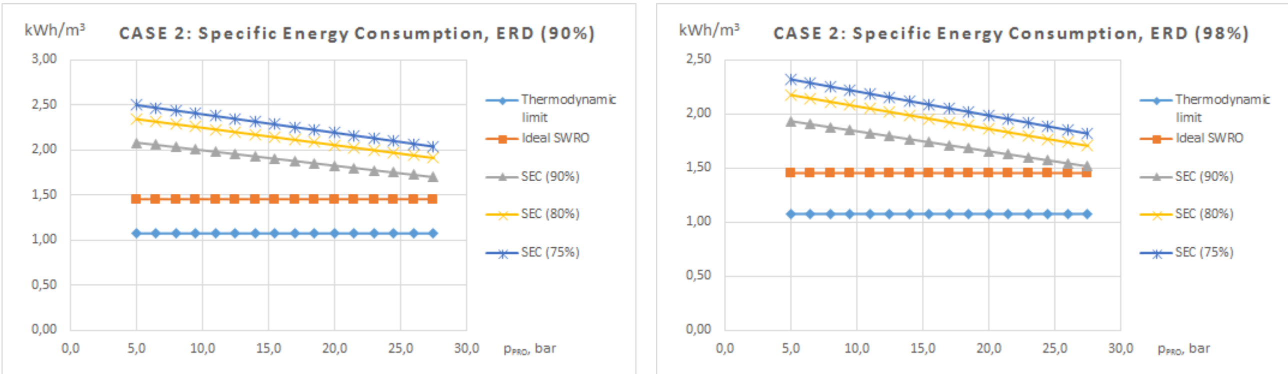
Regarding the efficiency of turbochargers, values of 0.90 and up to 0.98 were assumed in comparison to more realistic values as that of iSave, 0.90. Next figures (18-21) give results obtained providing detailed information in order to easily analyse different conditions of HPP efficiency (ideal, 90%, 80% and 75%) and working pressure of the PRO system considering different selection of PRO membrane (given maximum p_{PRO}) and external aqueous flow.



SEC vs. feed pressure
ERD (90%)

SEC vs. feed pressure
ERD (98%)

Figure 18. SEC results of case 1 ($r_{m,PRO}$= 0.50, optimum working pressure 19.5 bar). Realistic values of efficiency of turbochargers as Energy Recovery Device (ERD) on the left (90%) and optimistic values (98%) on the right.

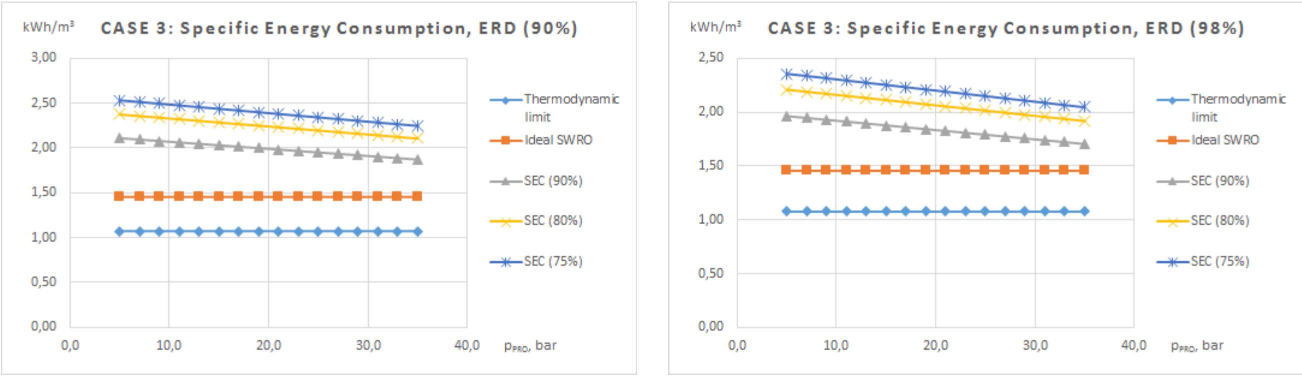


SEC vs. feed pressure
ERD (90%)

SEC vs. feed pressure
ERD (98%)

Figure 19. SEC results of case 2 ($r_{m,PRO}$= 0.35, optimum working pressure, 21.5 bar). Realistic values of efficiency of turbochargers as Energy Recovery Device (ERD) on the left (90%) and optimistic values (98%) on the right.

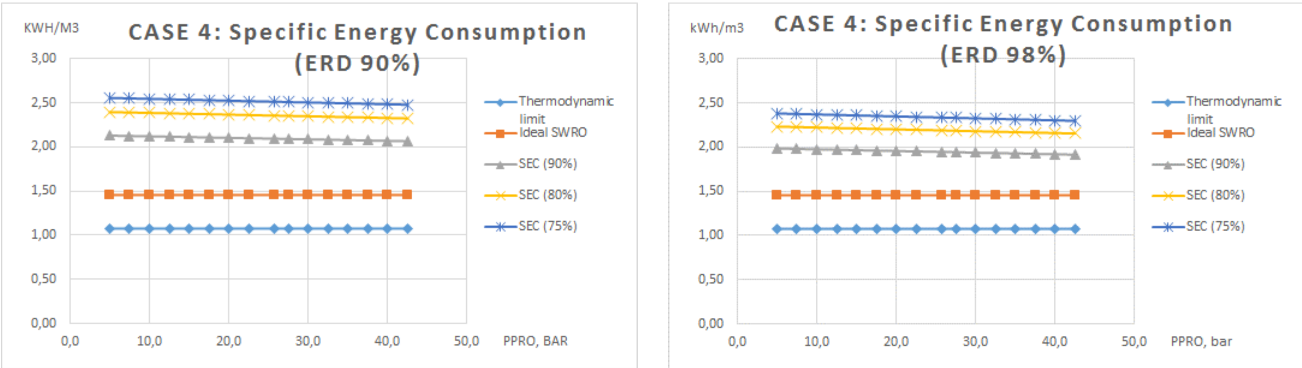
Note that ERD in conventional configuration exhibits 0.95 of efficiency, corresponding to ERI-PX. Thus, negative values of energy savings could be obtained for ERD of 90% in configurations SWRO/PRO. This means that conventional configurations is more efficient than those corresponding SWRO/PRO configurations (i.e. case 2 with 90% EDR). Considering energy savings of case 2 with PRO pressure 30 bar, 98% of efficiency in TCs and 90% of HPP efficiency, the SEC achieves values of the practical limit, SEC0.



SEC vs. feed pressure
ERD (90%)

SEC vs. feed pressure
ERD (98%)

Figure 20. SEC results of case 3 ($r_{m,PRO}$= 0.20, optimum working pressure, 23.6 bar). Realistic values of efficiency of turbochargers as Energy Recovery Device (ERD) on the left (90%) and optimistic values (98%) on the right.



SEC vs. feed pressure
ERD (90%)

SEC vs. feed pressure
ERD (98%)

Figure 21. SEC results of case 4 ($r_{m,PRO}$= 0.05, optimum working pressure 25.8 bar). Realistic values of efficiency of turbochargers as Energy Recovery Device (ERD) on the left (90%) and optimistic values (98%) on the right.

Concerning the analysis performed, it should be noted that the use of a seawater flow as external effluent instead of an aqueous flow with nil osmotic pressure only affects reducing the maximum achievable working pressure p_{PRO}. Up to 19.5 bar would be the practical limit (eqs.36-37) in the cases analysed for standard seawater at 25ºC and 48% of recovery rate (Π_{BD}= 53.1 bar). Respective practical limits would be around 11 bar, 19.5 bar in cases 3 (Π_{PRO}= 41 bar) and 4 (Π_{PRO}= 50 bar), corresponding to 0.16 and 0.11 kWh/m^3 of energy saving under optimistic hypothesis. Cases 1 and 2 do not allow the use of seawater as external flow. At a given working pressure, the driving force of the PRO process would be greater for a very low osmotic pressure external aqueous flow than for seawater, thus the latter requires greater membrane area to recover the same energy.

Finally, let´s consider favourable plant locations. Since the PRO system is based on salinity gradients, energy savings increase with osmotic pressure of the concentrate outlet of the SWRO membranes. Table 4 shows design parameters of four cases selected in order to study the use of PRO at high salinity conditions of Persian Gulf **[10].** The last columns give results of energy saving attributable to the PRO/SWRO system, also the SECs are given in brackets. They correspond to three different working pressure of the PRO system, 16 bar, 30 bar and 48 bar, respectively. The former is realistic with the current state of PRO membranes and an external aqueous flow with negligible osmotic pressure. The latter might be achieved in the near future for all commercial PRO membranes. Optimistic values of the energy efficiency of turbochargers, 0.98, are assumed. Cases 1-2 do not allow applications with seawater as external aqueous flow (eq. 36). On the contrary, cases 3-4 allows practical limits of 10 bar and 21 bar, respectively if they are operated with seawater, being negligible the benefits in terms of SEC, below 0.2 kWh/m^3.

Table 4. Main parameters of RO/PRO cases analysed for nil osmotic pressure of the external flow and salinity, 45199 ppm (Persian Gulf [10]; temperature, 34ºC; seawater osmotic pressure, Π_{sw}= 35 bar; recovery rate, $r_{m,RO}$= 0.42; Π_{BD}= 64.4 bar; η_{HPP}= 80%; η_{ERD}= 98%.

Case	$r_{m,PRO}$ kg/kg	Ratio $q_{V,PRO}/q_{V,P}$	S_{PRO} kg/kg	Π_{PRO} bar	Ratio $q_{V,tw}/q_{V,P}$	Energy saving and SEC, kWh/m^3		
						p_{PRO}= 16 bar	p_{PRO}= 30 bar	p_{PRO}= 48 bar
1	0.50	2.68	0.039	29.8	1.34	0.7 (SEC= 2.4)		
2	0.35	2.05	0.051	39.6	0.716	0.4 (SEC= 2.7)	0.8 (SEC= 2.3)	
3	0.20	1.65	0.062	49.8	0.330	0.2 (SEC= 2.9)	0.4 (SEC= 2.7)	
4	0.05	1.38	0.074	60.7	0.069	0.1 (SEC= 3.0)	0.2 (SEC= 2.9)	0.3 (SEC= 2.8)
Practical limit of working pressure: $p_{PRO} \approx \Pi_{PRO}$ - 5 bar Optimum working pressure for maximum economy of membrane area: 23.6 bar (case 1); 26.0 bar (case 2); 28.6 bar (case 3); 31.3 bar (case 4).								

In general terms, the larger the salinity gradient is in the PRO system (by means of either higher brine salinity and/or lower external aqueous flow salinity), the higher are the maximum achievable working pressure p_{PRO} and the potential of energy recovery in the PRO system (and reducing the SEC in the SWRO/PRO).

In SWRO membranes water permeabilities up to 2.5 L/h/m^2/bar are achieved, whereas PRO membranes exhibit greater values, as 3.6 L/h/m^2/bar reported by **Lui et al [31]**. If we consider water permeabilities of PRO membranes similar to those of SWRO membranes, the ratio $q_{V,tw}/q_{V,P}$ from table 4 would provide a gross estimation of the PRO membrane area required in comparison to SWRO membrane area installed. Precise estimations of required PRO membrane area depend on the driving force – i.e. working pressure and osmotic pressure at the inlets and outlets of the PRO system - along with water permeability. If the driving force within the PRO system is similar to that of the SWRO process, the ratio of water transferred would be similar to the ratio of membrane water permeabilities.

- Theoretically, PRO concept could be coupled to a conventional SWRO plant as an additional energy recovery device if an external aqueous solution is available. By means of a conventional turbocharger configuration, the energy recovered would lead to energy saving of about 0.3-0.6 kWh/m^3 if 17 bar of working pressure in the PRO system is achievable with η_{HPP}= 80% and η_{eng}= 95%.
- The integration of a PRO system in a SWRO plant with current technology may allow energy savings up to few tenths of kWh/m^3. This could represent for the SWRO plant to get SEC values of below 2 kwh/m^3

(figure 21) with η_{HPP}= 80% and η_{eng}= 95% with external flow as treated wastewater. With seawater as external flow, energy saving would be limited to around 0.10 kWh/m^3.

- When fully developed, the PRO technology could allow energy savings around 0.8 kWh/m^3 with very restrictive conditions of high salinity brine and treated wastewater as external flow. However, a significant increase of capital cost and plant complexity should be considered.
- Finally, SWRO/PRO should also be compared with conventional SWRO configurations based on two stages to point out recommendations on plant design. To this end, figures 9-11 show the analysis of using two stages configuration at different seawater conditions. These figures show that energy savings achieved by using PRO/SWRO, even if the most optimistic hypothesis are considered, might be similar to those attributable to two stages are assumed for PRO system. Therefore, considering the complexity due to including a PRO system in a SWRO plant, two staged configurations should be a better selection instead of adopting PRO energy recovery.

5. CONCLUSIONS

The analysis conducted points out some conclusions concerning the practical limits of energy consumption in SWRO desalination plants as follows. For representative value of recovery rate, 45%, - η_{HPP}= 80-90%; TDP= 7.2 bar -, within a range of salinities from standard seawater at 25ºC to 45199 ppm and 34ºC, the SEC comprises the following concepts:

- The thermodynamic limit of solvent separation, which represents the main contribution to SEC with 46-52%.
- Exergy losses directly related to the SWRO configuration adopted. This corresponds to ideal feed pressurisation and ideal energy recovery, thus being mainly attributable to the pressure reduction of permeate within the RO membranes, 14-19%.
- Exergy losses due to inefficiency of plant component as follows, membranes, 9-12%; energy recovery, 5-6%; pressure losses in the membrane series, 2-4%, and remaining contribution of high pressure pump inefficiency, from 12% (η_{HPP}= 90%) to 19-20% (η_{HPP}= 80%).

Current improvements on reliability of high efficiency HPP would have high impact on SEC by adopting them in large capacity desalination plants. On the contrary, low impact on SEC is expected in the near future for further developments in energy recovery devices and pressure losses within the membrane skid. Besides, advances in membrane permeability that ensure adequate permeate quality result in 0.038 kWh/m^3 per bar of net driving pressure decrease. In Atlantic conditions TDP of 5 bar is suitable with current membrane technology, thus low impact on SEC is expected in the near future for further developments in SWRO membranes, lower than 0.12 kWh/m^3 of energy saving if TDP could be reduced to 2 bar. However, same RO membranes would require higher TDP to achieve similar permeate quality in other plant locations. Therefore, higher impact would be likely obtained in plant locations with high salinity.

Considering plant configuration, innovations based on the second stage concept have the most interesting prospects of achieving low values of SEC. Among the innovative configurations described in the literature, the concept Desalitech-CCD seems to be the most suitable to achieve significant energy saving on SWRO process, regardless technical complexity. Nevertheless, the advantages in comparison to a conventional two stages configuration with inter-stage pump is not significant.

Concerning the use of energy from salinity gradient by means of Pressure Retarded Osmosis (PRO): The use of a PRO system integrated in a SWRO plant has been analysed in order to assess the potential energy consumption savings to produce desalinated water. Different operating conditions for the PRO system have been considered, with PRO operating pressure ranging from 5 to more than 30 bar as a theoretical analysis, thus regardless the mechanical stability or feasibility of the PRO system. The energy saved thanks to the PRO system is directly proportional to the transferred water and the operating pressure of the PRO system. Therefore, the larger the PRO system is (in terms of PRO membrane surface) the better in terms of energy savings for the SWRO plant. However, integrating a large PRO system means duplicating the membrane systems of the plant, that is, on the one hand the RO system and on the other the PRO system. This represents an important increase in terms of CAPEX and, without any doubt, more complexity in terms of the operation of the plant during transients but also under steady state conditions. Moreover, proposals of the literature that involve the use of treated wastewater as part of the fresh water production after passing through PRO membranes and SWRO membranes is not useful in SWRO plants. To reuse treated wastewater by a conventional two-pass BWRO desalination plant would be the best option. Finally, the benefits in terms of energy consumption reduction of integrating a PRO system in a SWRO plant turn to be similar to adding a second stage to a conventional RO plant. Therefore, the use of PRO systems in SWRO plants is not recommended.

Finally, the target energy consumption set by the EC at 1 kWh/m^3 is not technically realistic even though both, SWRO desalination with two stages and PRO are used along with advanced plant components.

GLOSSARY OF TERMS

Acronyms

BP	Booster Pump
BWRO	Brackish Water Reverse Osmosis
CAPEX	Capital Expenditures
CCD	Closed Circuit Desalination
EC	European Commission
ERD	Energy Recovery Device
HPP	High Pressure Pump
H2020	Horizon 2020
HP_DP	Differential Pressure of the High Pressure side of a ERD
ICH	Isobaric Chamber
LP_DP	Differential Pressure of the Low Pressure side of a ERD
LPP	Low Pressure Pump
NDP	Net Driving Pressure
OPEX	Operational Expenditures
PRO	Pressure Retarded Osmosis
PV	Pressure Vessel
RO	Reverse Osmosis
SEC	Specific Energy Consumption
SEC0	Specific Energy Consumption for ideal equipment
SWRO	SeaWater Reverse Osmosis
TC	TurboCharger
TDP	Tail Differential Pressure
TDS	Total Dissolved Solids

Symbols

Eff	Efficiency of the Energy Recovery Device, dimensionless
η	Efficiency of pumps and turbocharger, dimensionless
ex_f	Mass flow exergy, J/kg
$\Delta_{des}ex_f$	Change of flow exergy in a desalination process, J/kg

P_W	Power consumption, W
p	Pressure, Pa
Δp_{Loss}	Pressure losses through the feed-concentrate channel, Pa
Δp_{TC1}	Pressure increase at TurboCharger 1, Pa
Δp_{TC2}	Pressure increase at TurboCharger , Pa
Π	Osmotic pressure, Pa
ϕ	Osmotic coefficient of the solvent
q	Mass flow rate, kg/s
q_V	Volumetric flow rate, m^3/s
r_m	Ratio of mass flow rates of permeate to feed, dimensionless
r_v	Recovery rate (Ratio of flow rates of permeate to feed), dimensionless
R	Universal gas constant, J/(mol·K)
ρ	Density, kg/m^3
S	Salinity, kg/kg
T	Temperature, K (ºC)

Superscripts

E	Environmental conditions
sat	Conditions of brine saturation

Subscripts

A	high concentration side of a membrane element
B	low concentration side of a membrane element
BD	Blowdown (flow)
BP	Operating parameters of the Booster Pump
C	Concentrate (flow)
eng	engine
ERD	Operating parameters of the Energy Recovery Device
F	Feed (flow)
F-C	Feed-Concentrate (channel or flow)
HPP	Operating parameters of the High Pressure Pump
LPP	Operating parameters of the Low Pressure Pump
net	net
P	Product (flow)
PRO	properties at the outlet of the PRO system
RO	Operating parameters of the Reverso Osmosis system
rev	reversible process (thermodynamic limit)
surf	membrane surface
sw	seawater
s	sea salts
stg1	stage 1
stg2	stage 2
TC1	Operating parameters of the TurboCharger 1
TC2	Operating parameters of the TurboCharger 2
tw	transferred water at the PRO system
in or inlet	inlet
out or outlet	outlet
w	pure water

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