Final Master's Project
Master's Degree in Thermal Energy Systems

Energy-savings in seawater reverse osmosis plant using energy recovery device: Simulations on Morocco's Atlantic part

Author: Oussama El Hamidi
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Department of Energy Engineering
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El tribunal nombrado para juzgar el Proyecto arriba indicado, compuesto por los siguientes miembros:

Presidente:

Vocales:

Secretario:

Acuerdan otorgarle la calificación de:

Sevilla, 2020

El Secretario del Tribunal

A mi familia

A mis maestros

Acknowledgements

Alhamdulillahi Rabil Alamin.

Eternal thanks to all my family, for bestowing me the chance to live in the middle of an environment full of peace, high manners, respect and generosity. Especially to my mother and father, who have been able to support me along these 28 years with love, the only thing needed to be happy and to thrive.

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I dedicate this Master's Thesis to all of them.

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Gracias eternas a toda mi familia, por haberme brindado la suerte de vivir en medio de un ambiente lleno de paz, altos modales, respeto y generosidad. Especialmente a mi madre y mi padre, quienes me han apoyado a lo largo de estos 28 años con amor, lo único necesario para ser feliz y prosperar.

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Dedico esta Tesis de fin de Máster a todos ellos.

Abstract

This Master's Thesis is the continuation of a previous work which dealt with the advantages of using energy recovery devices (ERD-PX) in seawater reverse osmosis desalination plants (SWRO) that I performed in my Master's Degree in Thermal Energy Systems. Now in this work, I will expand the study incorporating the pressure exchanger (PX) in a SWRO plant design to calculate how much is the **energy savings** associated with the use of this device. I'll make this calculation in different scenarios, by varying quality parameters of feed water and efficiency of the devices used. For that purpose, I will use WAVE, Dupont's software which is beyond public domain to performe the simulations, and a simple Excel program from my own made to calculate the specific energy consumption when the PX is implemented.

At the end, we would obtain results from four scenarios, that help us to be able to know in advance how much energy savings we're going to have depending on the future plant location (quality parameters of feed water) and depending on the available budget to carry out the work (procurement of equipement with normal energy efficiency or with high energy efficiency).

Resumen

Esta Tesis es la continuación de un trabajo que trataba de las ventajas del uso de los dispositivos de recuperación de energía (ERI-PX) en plantas de desalación por ósmosis inversa (SWRO), que realicé en el “Máster en Sistemas en Enegía Térmica”. Ahora en esta Tesis voy a ampliar el trabajo incorporando el PX en el diseño de una planta de SWRO para calcular cuánto es el **ahorro energético** que supone el uso de este equipo. Haré este cálculo en distintos escenarios, variando parámetros de agua de mar y modelos de equipos utilizados. Para ello utilizaremos WAVE, software concebido por Dupont de dominio público para hacer las simulaciones, y un programa en Excel de elaboración propia para calcular el consumo específico de energía cuando se usa el PX.

Al final obtendremos resultados de cuatro escenarios, que nos sirven para poder conocer de antemano qué ahorros vamos a tener dependiendo de la localización de la futura planta (parámetros de agua de mar) y del presupuesto disponible para ejecutar la obra (adquisición de equipos normales o equipos de alta eficiencia energética).

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1 PREFACE

Water is essential to life, and access to sufficient quantities of safe water for drinking and domestic uses and also for commercial and industrial applications is essential for healthful living, enhanced quality of life and well-being, and the opportunity to achieve human and economic development. Many world regions are grossly deficient in the availability of water of sufficient quantity as well as quality. People in many areas of the world have historically suffered from inadequate access to safe water. Some must walk long distances just to obtain sufficient water to sustain life. As a result, they have had to endure health consequences and have not had the opportunity to develop their resources and capabilities to achieve major improvements in their well-being. With growth of the world population, the availability of the limited quantities of fresh water continually decreases.

Most of the world's water is seawater or brackish water, and groundwater that is high in total dissolved solids and either undesirable or unavailable for beneficial uses without the application of technologies capable of removing large portions of the salinity and dissolved solids. Commercial desalination technologies were introduced about 50 years ago and were able to expand access to water, but at high cost. Developments of significant new and improved technologies have now significantly broadened the opportunities to access large quantities of safe water in many parts of the world. Costs are still significant compared with those associated with freshwater sources, but there has been a major cost reduction trend. The desalination option is now much more widely available and probably the principal source of "new" water in the world. Even so, when the alternative is no water or inadequate water quantity for needs and significant harm to health and welfare, greater cost is endurable in many circumstances (Cotruvo, y otros, 2011).

2 INTRODUCTION

Desalination is increasingly being touted as a solution to the world water crisis in the 21st century. Considering that almost one quarter of the world's population lives less than 25 km from the coast, seawater could become one of the main sources of freshwater in the near future (Rodríguez, 2011). At present, membrane reverse osmosis (RO) desalination is the fastest growing technology for the production of fresh water from saline water sources and has become a basis of water production in many parts of the Middle East, North Africa, Australia and Europe. Reverse osmosis desalination plants use less energy to produce the same volume of fresh water than thermal desalination facilities. Therefore, **this Master's thesis focuses exclusively on the reverse osmosis desalination technology**.

Nowadays, more than 19,000 desalination plants worldwide produce a total of 99.8 million cubic meters per day (m3/day) of fresh water from seawater and brackish water (GWI, 2017) and provide approximately 1% of the world's drinking water supply. The number and size of desalination projects worldwide have been growing at a rate of 5% - 6% per year since 2010, which corresponds to an addition of 3.0 – 4.0 million m3/day of newly installed desalination plant fresh water production capacity every year.

In this context, principal objective of this work, as anticipated, is to be able to know in advance how much energy savings we're going to have depending on the SWRO plant location (quality parameters of feed water) and depending on the available budget to carry out the work (procurement of equipement with normal energy efficiency or with high energy efficiency). For this principal purpose, next specific goals are carried out:

- Define the commertial devices with the best energy efficiency in todays market:
    - High pressure pump from two different suppliers:
        - Flowserve: normal efficiency device
        - Danfoss Axial Pressure Pump (APP): high efficiency device
    - Booster pump, different models from same supplier:
        - ERI model VP-4671: normal efficiency device
        - ERI model VP-XP 150x200: high efficiency device
    - Energy recovery device, different models from same supplier:
        - ERI model PX-220: normal efficiency device
        - ERI PX-Q300: high efficiency device
    - Membrane, different models from same supplier:
        - Dupont-FilmTec model SW30XHR-440: normal efficiency device
        - Dupont-Filmtec model SW30HRLE-440i: high efficiency device
- To calculate specific energy consumption (SEC) in the following situations:
    - Unfavourable feed water conditions (high TDS concentration and low temperature) and favourable feed water conditions (low TDS concentration and high temperature).
    - Normal efficiency devices and high efficiency devices.
    - With combinations of situations above, we're going to have 4 SEC cases without PX.
- After that, we will calculate the SEC for the 4 cases above, but implementing the PX device.

3 DESALINATION PLANTS CATEGORIES

Source water salinity is one of the most important factors determining desalination project design and costs (AWWA, 2007) and (Papapetrou, y otros, 2017). Based on the salinity of the source water they process, desalination plants can be divided into three broad categories: low-salinity and high-salinity brackish water desalination plants, and seawater desalination plants (Table 1).

Low-salinity brackish water (BW) desalination plants often have a relatively simple single-stage RO system configuration and are typically designed to treat water of total dissolved solids (TDS) concentration between 500 and 2,500 mg/L.

High-salinity BWRO plants are configured to process brackish source waters with TDS content in a range of 2,500 – 10,000 mg/L.

Seawater desalination projects are designed to process source water of salinity between 15,000 and 46,000 mg/L.

Table 1. Desalination plants categories

Salinity	Brakish Water low-salinity	Brakish Water high-salinity	Brakish Water high-salinity / Seawater	Seawater
Total dissolved solids (TDS)	500-2500	2500-10000	10000-15000	15000-46000

Approximately 75% (1.6 million m3/day) of the new globally installed desalination plant capacity for the period of June 2016 to July 2017 (2.14 million m3/day) was for seawater desalination and only 15% (0.32 million m3/day) was for brackish water desalination (GWI, 2017). The remaining 10% (0.32 million m3/day) of the desalination plants have applied other water treatment technologies such as electrodialysis reversal (EDR), ion exchange (IX), forward osmosis (FO), and capacitive deionization (CDI).

Only 1.1% of the worldwide water resources are located in brackish water aquifers while 97.5% of the planet's water is in the oceans and seas. Therefore, this Thesis focuses mainly on seawater reverse osmosis technology.

4 REVERSE OSMOSIS TECHNOLOGY

Osmosis is a phenomenon where pure water flows from a dilute solution through a semi permeable membrane to a higher concentrated solution as illustrated in Figure 1. Semi permeable means that the membrane will allow small molecules and ions to pass through it but acts as a barrier to larger molecules or dissolved substances. To illustrate this, assume that a semi permeable membrane is placed between two compartments in a tank (see Figure 1). Assume the membrane is permeable to water, but not to salt. If we place a salt solution in one compartment and pure water solution in the other one, the system will try to reach equilibrium by having the same concentration on both sides of the membrane. The only possible way to do this is for water to pass from the pure water compartment to the saltwater compartment.

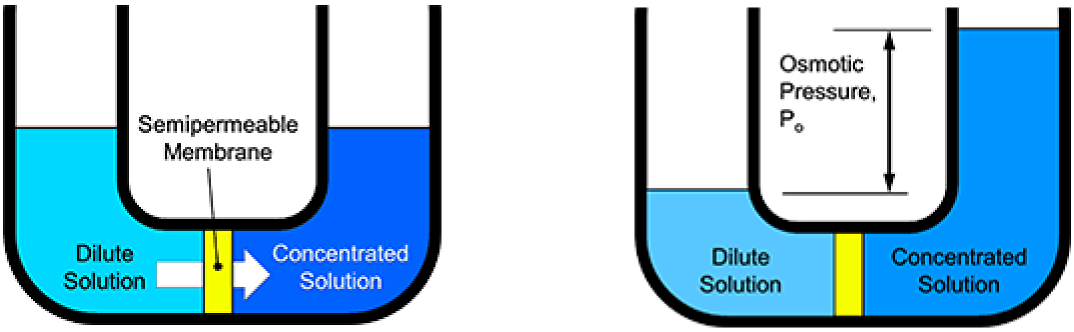

Figure 1. Osmosis process

As water passes through the membrane to the salt solution, the level of liquid in the saltwater compartment will rise until enough pressure, caused by the difference in levels between the two compartments, is generated to stop the osmosis. In the equilibrium state between a saline solution and its pure solvent, this pressure is called osmotic pressure. In Figure 1, the difference of pressures shown by the difference of levels equals the difference of osmotic pressures of concentrated and dilute solutions.

If pressure greater than the osmotic pressure is applied to the high concentration the direction of water flow through the membrane can be reversed. This is called Reverse Osmosis (abbreviated RO) as illustrated in Figure 2. Note that this reversed flow produces pure water from the salt solution, since the membrane is not permeable to salt.

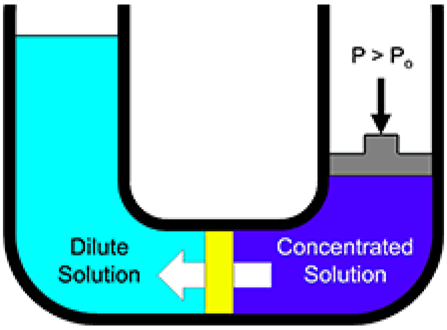

Figure 2. Reverse Osmosis process

Figure 3 illustrates the basic RO process, which includes pre-treatment, membrane transport, and post-treatment prior to distribution. RO processes can produce water with TDS in the range 10–500 mg/L.

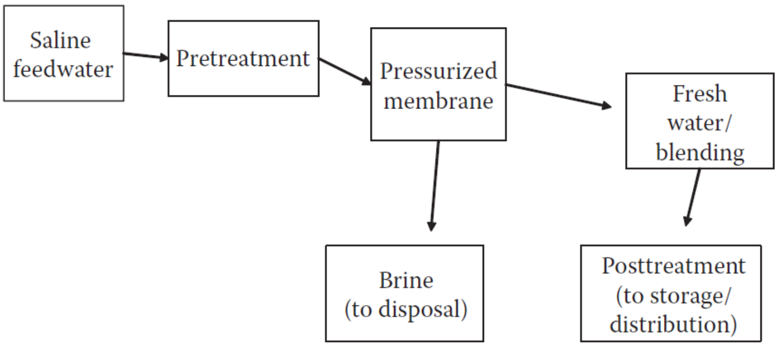

Figure 3. Reverse osmosis desalination process outline

Since 2010, reverse osmosis (RO) desalination has been the main technology of choice for production of fresh water from saline water worldwide (Figure 4).

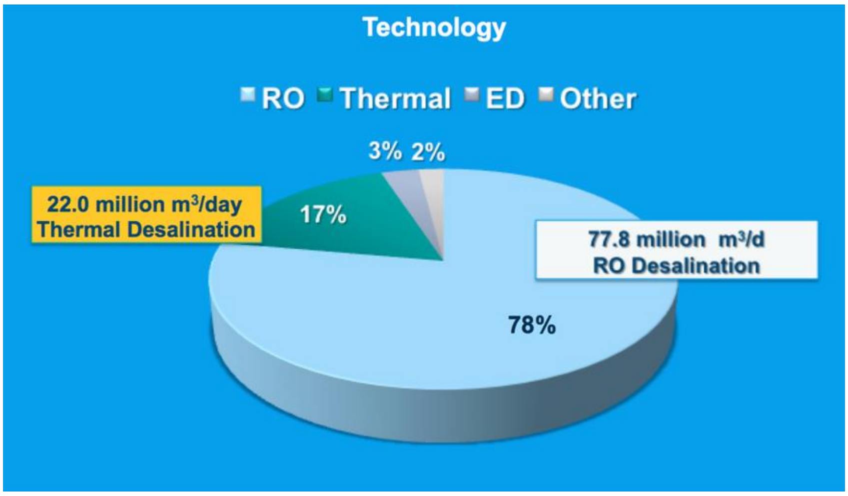

Figure 4. Breakdown of installed desalination plants worldwide by technology (2017) (Voutchkov, 2019)

At present, over 50% of the existing desalination plants are located in the Middle East and North Africa (MENA) region. The majority of the plants built in this region over the past 5 years' employ seawater RO (SWRO) membrane desalination (Figure 5) for production of fresh water The steady trend of increasing use of SWRO membrane desalination in the MENA region is mainly attributed to the lower energy use, high efficiency, and lower fresh water production costs associated with this technology as compared to thermal desalination (Voutchkov, 2019).

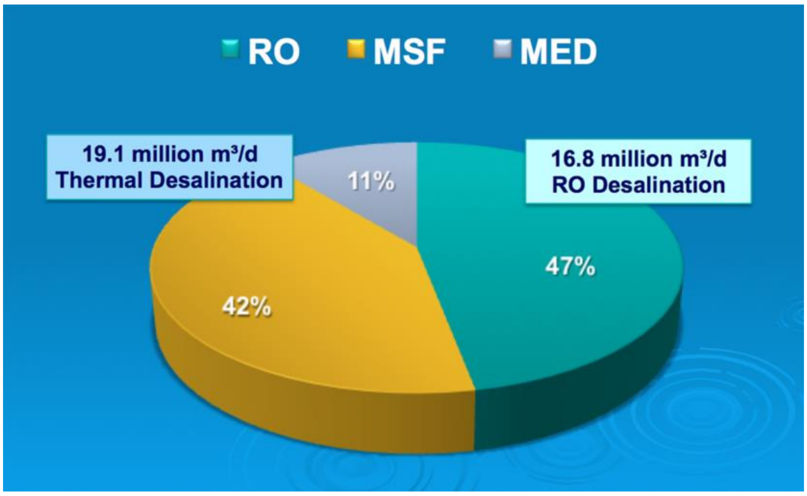

Figure 5. Breakdown of installed desalination plants in MENA by technology (2017)

5 SOURCE WATER QUALITY

The key source water quality parameters that impact desalination system design, operations, and cost of water production are total dissolved solids (TDS), temperature, turbidity, silt density index (SDI), organic content, nutrients, algae, bacteria, boron, silica, barium, calcium, and magnesium. Of these parameters, seawater TDS and temperature are the two key source water quality parameters that have the most significant influence on costs of water production by seawater desalination (Voutchkov, 2019). Table 2 presents typical TDS concentration and temperature of various seawater sources.

Table 2. Salinity and Temperature of Various Seawater Sources

Seawater Source	Total Dissolved Solids Concentration (g/L)	Temperature ºC
Pacific and Atlantic oceans	33 - 39 (avg. 35)	14 - 30 (avg. 18)
Caribbean	35 -38 (avg. 36)	16 - 35 (avg. 26)
Mediterranean	38 - 41 (avg. 40)	16 - 28 (avg. 24)
Gulf of Oman/Indian Ocean	39 - 42 (avg. 40)	22 - 35 (avg. 30)
Red Sea	40 - 42 (avg. 41)	24 - 33 (avg. 28)
Arabian Gulf	42 - 46 (avg. 44)	22 - 35 (avg. 26)

Note: Seawater TDS and temperature may be outside the table ranges for a site-specific location.

1 g/L = 1000 ppm

6 SEA WATER REVERSE OSMOSIS SYSTEMS

6.1. Single-Pass SWRO systems

Single-pass SWRO systems are designed to produce desalinated seawater (permeate) in one step using only a single set of RO trains operating in parallel. Under a typical single-stage SWRO system configuration, each RO train has a dedicated system of transfer pump for pretreated seawater followed by a high-pressure RO feed pump. The high-pressure feed pump motor/operation is coupled with that of energy recovery equipment (see Figure 6).

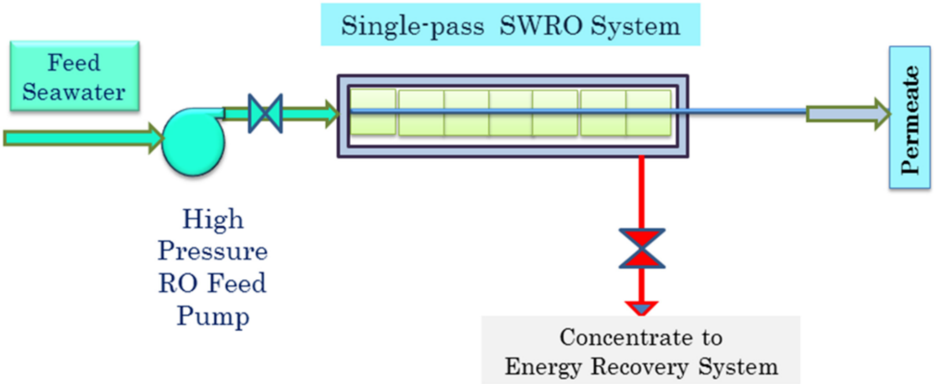

Figure 6. Conceptual diagram of a single-pass system without energy recovery

Single-stage SWRO systems are widely used for production of desalinated water. However, these systems have product water quality limitations. Even if using the highest-rejection RO membrane elements commercially available today (nominal minimum rejection of 99.85%), the single-stage SWRO desalination systems typically cannot consistently yield permeate with TDS concentration lower than 200 mg/L, chloride level of less than 100 mg/L, and boron concentration lower than 0.5 mg/L, especially when source water temperatures exceed 18 – 20ºC. If enhanced boron removal is needed in such systems, high boron rejection membranes are used, and/or sodium hydroxide and antiscalant might be added to the RO system feed water to increase pH to 8.8 or more, which in turn improves boron rejection. However, the conventional solution is to treat the permeate of the seawater RO desalination with a brackish water RO desalination system. This combined system as a whole is referred to as two-pass RO system. Besides, other related concept is based on two-stages, in which two membrane element series are coupled being the concentrate of the first serie (first stage) treated by the second membrane serie (second stage). This conventional solution is detailed in the following paragraphs.

6.2. Two-Pass SWRO systems

Two-pass SWRO systems are typically used when either the source seawater salinity is relatively high (e.g., exceeds 35,000 mg/L) and/or the product water quality requirements are very stringent. For example, if high-salinity/high-temperature source water (such as Red Sea and Arabian Gulf seawater) is used in combination with standard-rejection (99.6%-99.8%) SWRO membranes, then single-pass SWRO systems may not be able to produce permeate suitable for drinking water use. In this case, two-pass SWRO systems are applied for potable water production. RO systems with two or more passes are also widely used for production of high-purity industrial water.

The two-pass SWRO systems typically consist of a combination of a single-pass SWRO system and a two-stage brackish water RO (BWRO) system connected as follows. Permeate from the SWRO system (i.e., first pass) is directed for further treatment to the BWRO system (i.e., second pass) to produce a high-quality TDS permeate. The concentrate from the second-pass BWRO system is returned to the feed of the first-pass SWRO system to maximize the overall desalination system production capacity and efficiency. Two-pass SWRO systems are classified in two main groups: full two-pass systems and partial two-pass systems.

In full two-pass SWRO membrane systems (see Figure 7), the source seawater is first treated by a set SWRO membrane trains (referred to as first RO pass) and then the entire volume of desalinated water from the first pass is processed through a second set of brackish water desalination membrane trains. If enhanced boron removal is needed, sodium hydroxide and antiscalant are added to the feed permeate of the second RO pass to increase pH and improve boron rejection. If the required product quality is achieved by treating part of the permeate production of the first pass the configuration is called partial twp-pass. Desalination systems can employ either the same membrane elements throughout the entire serie of membrane elements assembled within a pressure vessel or internally staged membrane configuration within the vessels, by using different models.

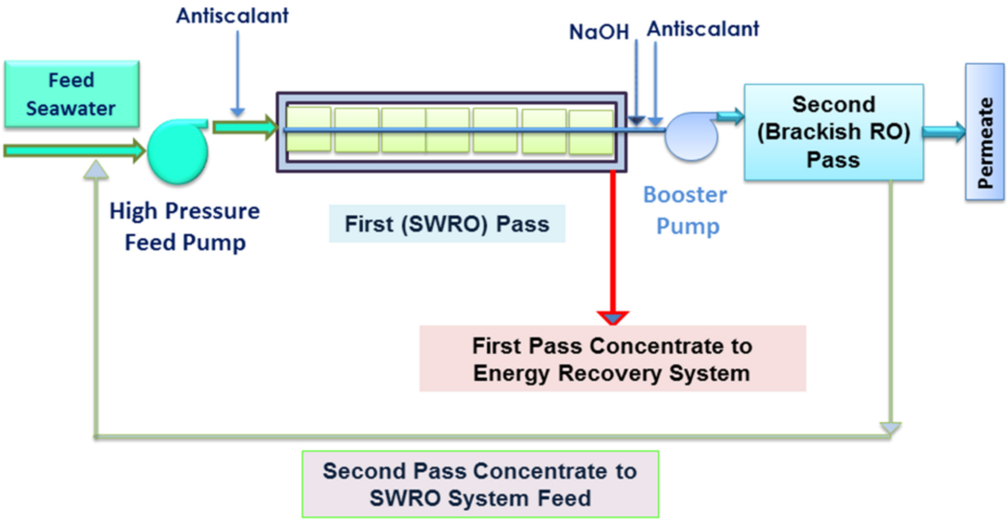

Figure 7. Schematic of full two-pass SWRO system

6.3. Split-Partial Two-Pass SWRO systems

In split-partial two-pass systems the second RO pass typically processes only a portion (50%–75%) of the permeate generated by the first pass. The rest of the low-salinity permeate is produced by the front (feed) SWRO elements of the first pass. This low-salinity permeate is collected and without additional desalination it is directly blended with permeate produced by the second RO pass (see Figure 8).

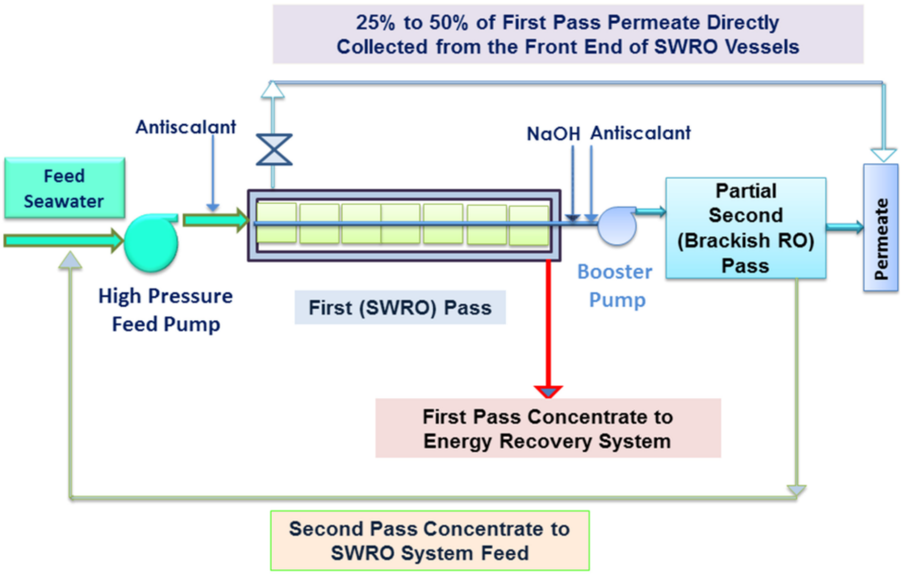

Figure 8. Schematic of split-partial two-pass SWRO system

As depicted in Figure 8, the second-pass concentrate is returned to the feed of the first RO system pass. When the desalination system is designed for enhanced boron removal, this concentrate will have pH of 9.5 to 11 and potentially could cause precipitation of calcium carbonate on the membranes. In order to avoid this challenge, typically antiscalant is added to the feed of the partial second-pass (brackish RO) system.

While the recycling of the second-pass concentrate returns to feed of the first pass, salinity of this global feed reaching membranes is slightly lower because of the low level salinity of the brackish RO concentrate.

Under the split-partial two-pass configuration the volume of permeate pumped to the second RO pass and the size of this pass are typically 20%-50% smaller than the volume pumped to the second RO pass under conventional full two-pass operation. Since pumping energy is directly proportional to flow, the energy costs for the second-pass feed pumps (low pressure pumps) are reduced proportionally, i.e., eith 20%-50%.

For an SWRO system operating at 45% recovery, such savings will amount to 14%-22% of the energy of the first-pass RO pump. The concentrate returned from the second pass carries only 1%-2% of additional salinity to the first-pass RO feed, which reduces the energy benefit from such recovery proportionally – i.e., by 1%-2% only. As a result, the overall energy savings of the use of split-partial two-pass RO system as compared to conventional two-pass RO system are between 12% and 20%.

The first pass of this two-pass system occasionally employs hybrid membrane configuration with the first two or three SWRO elements being high-rejection/low productivity and the remaining elements being low-rejection/high-productivity SWRO membranes.

7 ENERGY RECOVERY SYSTEM

In the typical operation of SWRO, the high pressure pump is the main power consumer. The pressure of brine produced is in the range of 52-65 bar, which is only around 1.5-2 bar smaller than the feed pressure. As such, a huge amount of energy is wasted if the brine is discharged directly without recovery. The advances made in the design of ERDs have been beneficial for the desalination industry to reduce the energy consumption of seawater desalination by more than 60% over the counterpart system without the devices. Two types of ERDs, namely centrifugal and isobaric have been commonly used in SWRO. On the other hand, isobaric ERDs which play important roles in reducing the specific energy consumption of SWRO desalination system have progressed significantly in recent years (Matsuura, Ismail, & Ng).

The ERI PX® - Energy Recovery Inc., Pressure Exchanger system comes under the method of hydraulic driven pumping operating in parallel (see Figure 9).

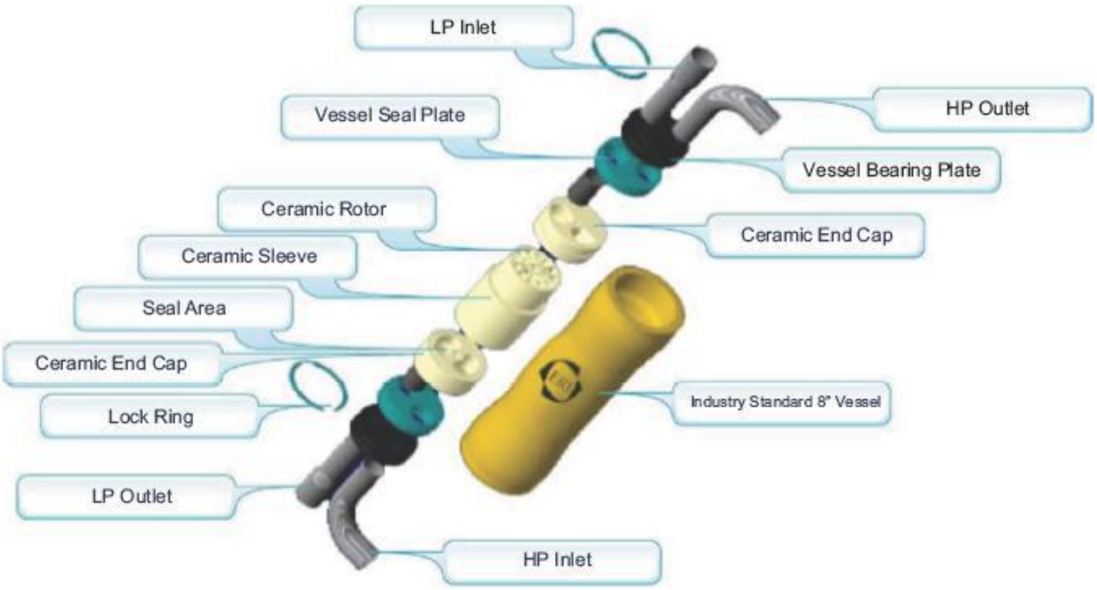

Figure 9. ERI Pressure Exchanger Exploded View

By full advantage of ERDs, major savings in energy consumption in the desalination process can be achieved. For SWRO plants where the plants operate at 50% recovery, energy is recovered from the concentrate using ERDs and supplied back to the feed stream or to inter stage booster pumps. As an indispensable equipment for SWRO system, ERDs can significantly reduce the energy consumption by means of transferring the pressure energy in the reject stream to the seawater feed (see Figure 10).

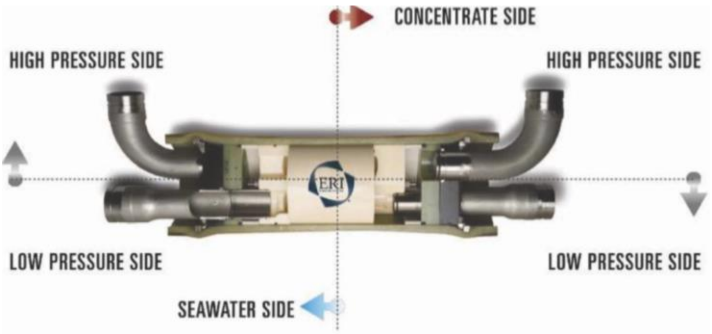

Figure 10. View from Inside Pressure Vessel

Figure 11, Figure 12 and Figure 13 shows efficiencies of the principal energy recovery devices from Energy Recovery Inc. manufacturer.

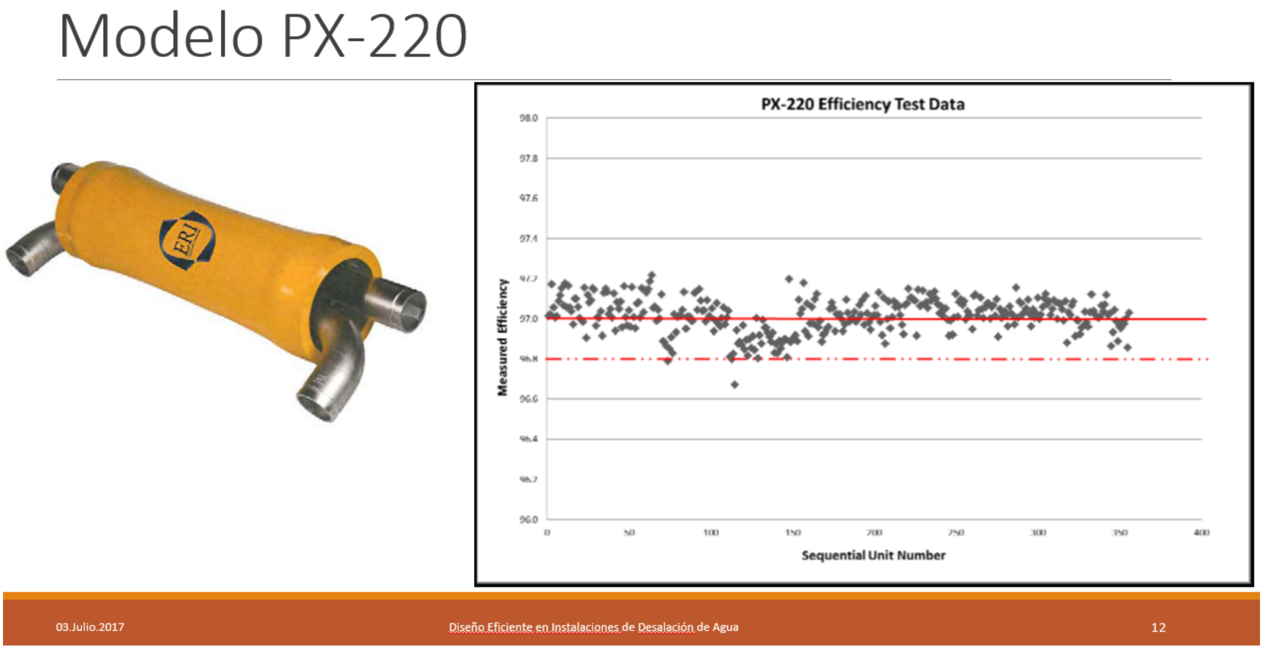

Figure 11. PX-220 Efficiency Test Data. ERI (Inc., 2018)

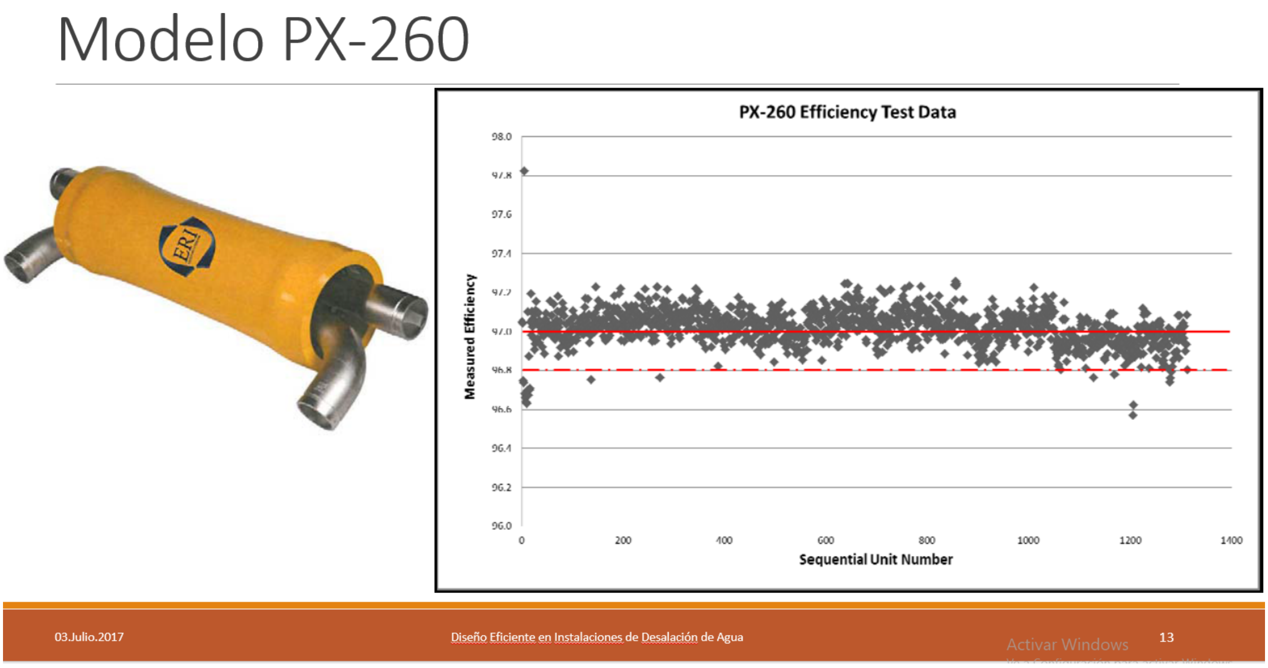

Figure 12. PX-260 Efficiency Test Data. ERI (Inc., 2018)

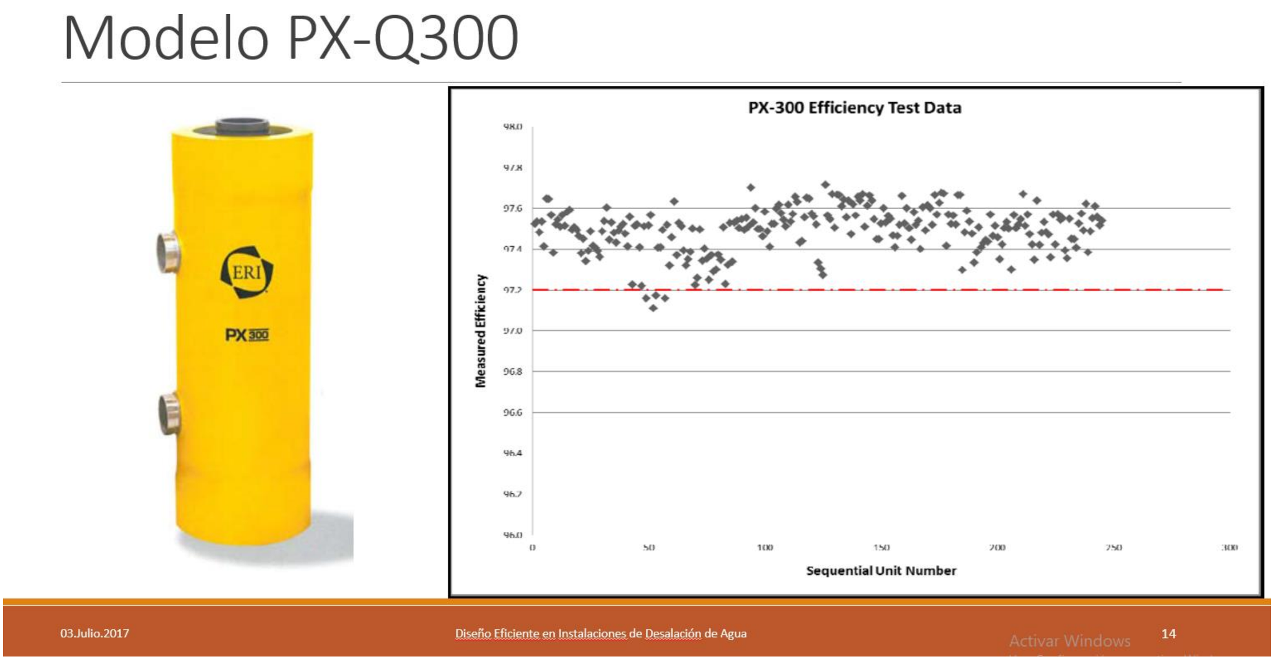

Figure 13. PX-300 Efficiency Test Data. ERI (Inc., 2018)

Next Figure 14 shows efficiency's comparatives between the three principal pressure exchangers models mentioned above.

PX models comparison

PX model	Flow [m3/h]	Minimum efficiency %	Maximum efficiency %
PX-220	40-50	96.670	97.217
PX-260	40-50	96.570	97.825
PX-Q300	45-68	96.8	98

PX-220 & PX-260 → Single pressure exchange per rotor duct per revolution

PX-Q300 → Two pressure exchanges per rotor duct per revolution

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Figure 14. PX comparative of efficiencies (Inc., 2018)

8 MEMBRANE PERFORMANCE

SWRO membrane performance is a function of a number of design and operating variables including membrane type, feedwater temperature, salinity and dissolved solids composition, permeate quality requirements, and membrane flux and membrane conversion or recovery rate. The composition of the membrane feedwater is affected by mixing in the ERD, and thus is a function of the composition of the brine reject flowing from the membranes. Because membrane selectivity varies with membrane type, flux and ion type, the composition of the brine differs from the composition of the feedwater, and those differences vary with system operating conditions. Therefore, an accurate prediction of membrane performance would require concurrent consideration of ERD mixing. The relationship between SWRO system specific energy consumption, membrane recovery and membrane flux for a typical system is illustrated in Figure 15.

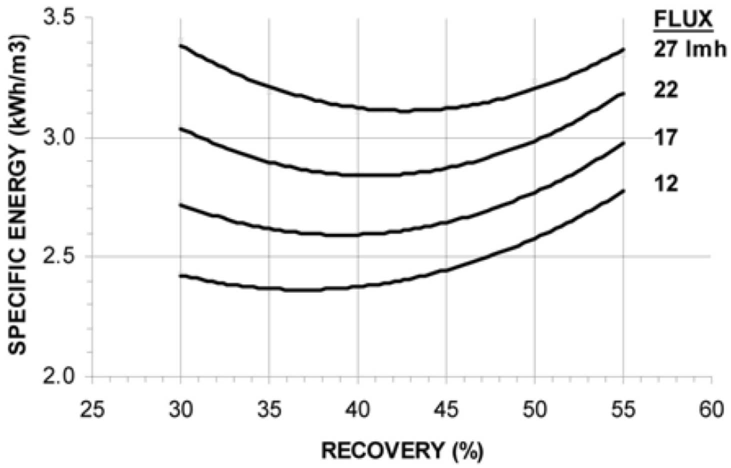

Figure 15. SWRO system specific energy vs. membrane variables for given design of membrane series

In Figure 15, specific energy is expressed in units of kilowatt hours per cubic meter of permeate (kWh/m3) and flux in units of liters of permeate per square meter of membrane surface per hour (lmh). The estimated specific energy data presented in Figure 15 were derived using a conventional membrane projection model, efficiency data from commercially available pumps, and published operating data for the PX-220 Pressure Exchanger device. These data indicate that lower flux rates and lower recovery rates generally result in lower system energy consumption and that an optimal minimum specific energy occurs between approximately 35% and 45% recovery (Richard, 2006).

9 WATER PRODUCTION COST

The SWRO system typically uses over 70% of the power required to operate the desalination plant. The rest of the power is consumed mainly by plant intake and pretreatment systems, and by the product water delivery pumps. An example of the power use of various facilities in a 200,000 m³/day seawater desalination plant treating source seawater with a total dissolved solids (TDS) concentration of 33,500 mg/L and average annual temperature of 23ºC is presented in Figure 16. This example includes the use of pressure exchangers for energy recovery.

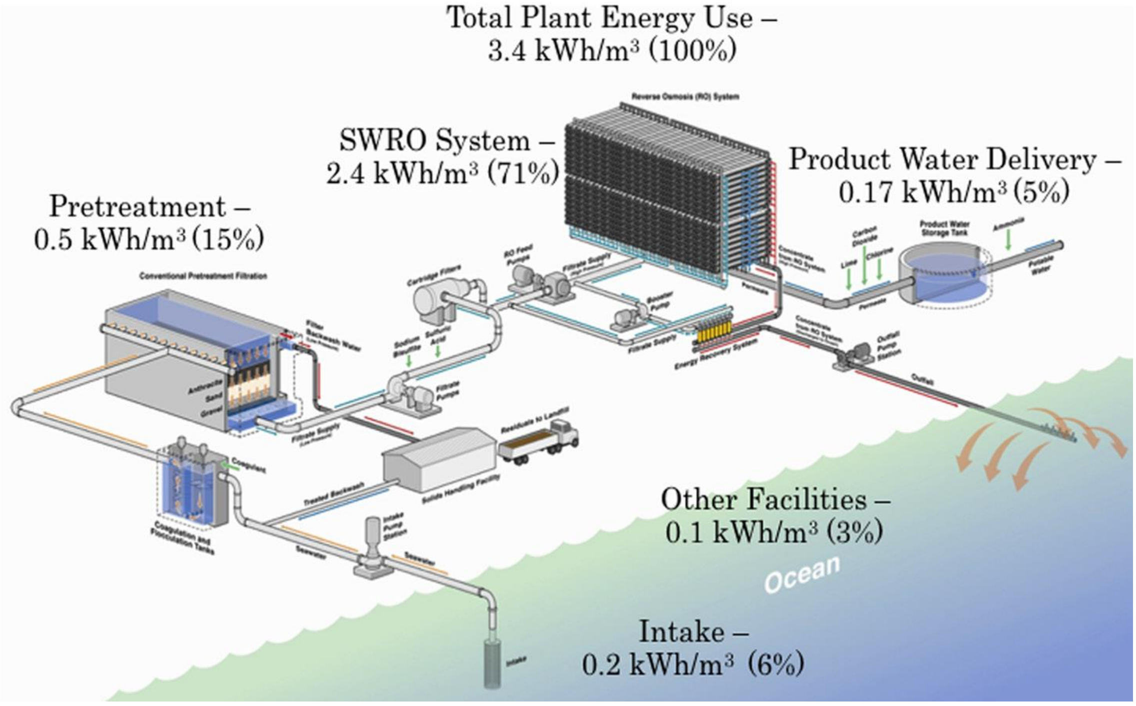

Figure 16. Breakdown of energy use of typical desalination plant

Power costs are directly related to the source water salinity and temperature, and to the associated osmotic pressure that has to be overcome in order to produce fresh water. Source seawater of lower salinity and higher temperature yields lower power use for production of the same volume of fresh water mainly due to the reduction of reverse osmosis (RO) feed water osmotic pressure.

Another key factor associated with overall energy use is the efficiency of the applied SWRO energy recovery system. A large portion of the energy applied for desalination is contained in the high-salinity product of desalination (i.e., the concentrate). Over 96% of this energy can be reused in the desalination process by installing recovery equipment that transfers it from the concentrate to new seawater fed to the SWRO system. The efficiency of energy transfer from concentrate to source seawater varies with the type of energy recovery technology (pressure exchanger, Pelton wheel, turbocharger, or reverse running pump) and with the overall water recovery and configuration of the SWRO system.

Table 3 provides typical ranges for energy use of reverse osmosis membrane systems of medium and large seawater desalination plants (i.e., plants with fresh water production capacity of 40,000 m3/day or more). This table is based on actual data from over 30 SWRO plants constructed between 2010 and 2017. As seen from Table 3, SWRO systems of best-in-class desalination plants use between 2.4 and 2.8 kWh of electricity in order to produce one cubic meter of fresh water, while the industry average energy use is approximately 3.1 kWh/m3. It should be pointed out that the energy use presented in Table 3 only encompasses SWRO system operations, rather than the energy consumption of the entire seawater desalination plant. Usually, SWRO systems contribute between 65% and 80% of total desalination plant energy demand (Voutchkov, 2019).

Table 3. Typical Energy Use for Medium and Large Size SWRO Systems

Classification	**SWRO System Energy Use (kWh/m3)**
Low-end bracket	2.4-2.8
Medium range	2.9-3.2
High-end bracket	3.3-4.0
Average	**3.1**

Current trends in the reduction of the cost of desalination, and the increasing costs of the alternatives, are likely to continue, and it is not unlikely that cost reductions of 20 percent within 5 years will be developed for SWRO and 60 percent in 20 years (see Table 4) (Voutchkov, 2019).

Table 4. Forecast of desalination Costs fot Medium- and Large-Size Seawater Osmosis Projects

Parameters	**Year 2016**	**Within 5 years**	**Within 20 years**
Cost of water (US$/m3)	0.8-1.2	0.6-1.0	0.3-0.5
Construction cost (US$/MLD)	1.2-2.2	1.0-1.8	0.5-0.9
Electrical energy use (kWh/m3)	3.5-4.0	2.8-3.2	2.1-2.4

Note : 1 MLD = 1000 m3/day

Source : Voutchkov 2016; World Bank 2017a

The lowest theoretical energy consumption for the desalination of 35,000 mg/L of seawater at a temperature of 25ºC (i.e., typical Pacific Ocean water) is 0.76 kWh/m3, which cannot be achieved in practical terms. For a more realistic 50% recovery, this minimum theoretical energy use would be 1.06 kWh/m3. However, this energy consumption assessment assumes that all desalination plant equipment has 100% energy efficiency and all energy contained in the desalination plant concentrate is recovered and reused in the desalination process. Therefore, this energy threshold is the ideal theoretical minimum for seawater desalination.

Based on the systematic long-term testing of a full-scale state-of-the-art desalination system by the Affordable Desalination Collaboration (ADC) in the United States, the lowest energy use that could be achieved with actual state-of-the-art highly efficient commercially available desalination equipement and RO membranes at the time of testing (years 2006-2007) was determined to be 1.58 kWh/m3. Such energy use was measured at RO system recovery of 42% and average SWRO membrane flux of 10.2 liters/m2.h (Lmh).

The ADC study concluded, however, that SWRO system operation at such low recovery and flux does not yield the lowest overall cost of water production at unit cost of energy of US$0.10/kWh used for life-cycle cost assessment.

Based on a detailed cost-benefit analysis, ADS researchers have determined that for the tested seawater quality (e.g., typical Pacific Ocean seawater) **the "Most Affordable Point" of SWRO system desing is at plant recovery of 48% and flux of 15.3 Lmh. At this operational condition the minimum energy use of the SWRO system was determined to be 2.0 kWh/m3.** However, the "Most Affordable Point" design would vary with unit cost of energy and the project-and location specific construction and engineering costs and source water quality (Voutchkov, 2019).

Historically, one of the key obstacles limiting the wider use of seawater desalination for the municipal water supply has been the high cost of water production.

Table 5 presents the range of water production costs of medium and large size seawater reverse osmosis desalination projects. Information for this table is compiled based on comparative review of over 50 desalination projects in the United States, Australia, Europe, the Middle East, the Caribbean, and other parts of the world. As seen in Table 5, in 2018 the average industry-wide cost of production of desalinated water by reverse osmosis is approximately US$1.1/m3. The table indicates that the cost of water varies significantly and overall could be divided into three brackets – low, medium, and high end.

Table 5. Water Production Costs of Medium and Large Size SWRO Desalination Plants

Classification	**Cost of Water (US$/m3)**
Low-end bracket	0.5-0.8
Medium range	0.9-1.5
High-end bracket	1.6-3.0
Average	**1.1**

Figure 17 shows the significant difference in the cost of production desalinated water in various regions of the world.

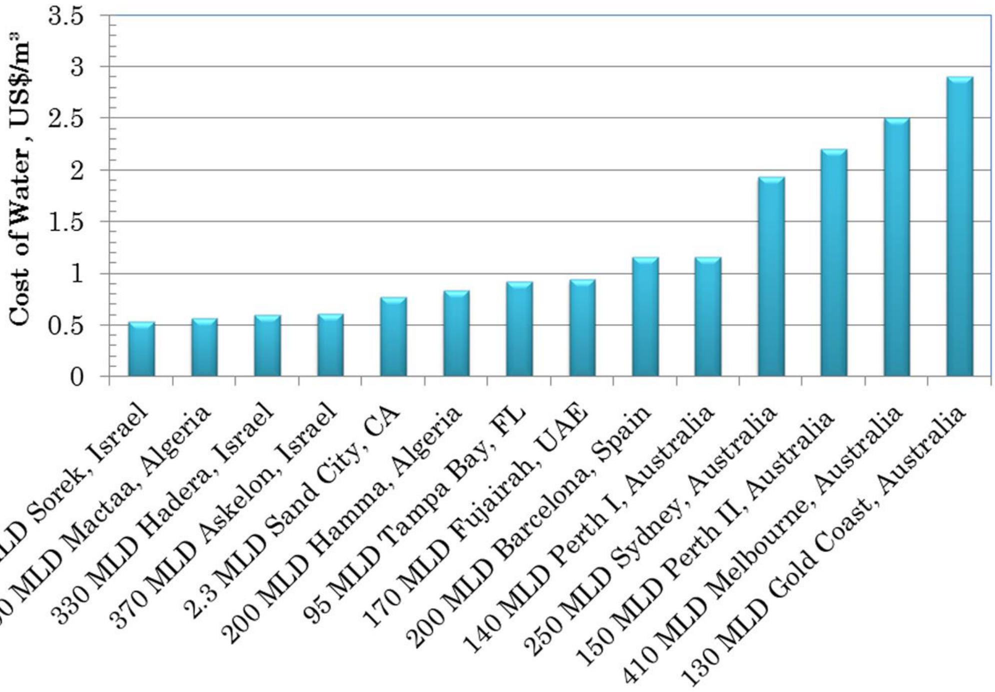

Figure 17. Cost of Water Production of Recent Seawater Desalination Projects

Cost of water production for seawater reverse osmosis (SWRO) desalination plants in Spain of plant capacity between 50,000 and 250,000 m3/day, built over the past 25 years, varies between US$0.74 to US$0.84/m3 (€0.63-0.72/m3) (Lapuente, 2012). Adjusted for inflation to year 2018 US$, this cost range is US$0.87 to US$0.98/m3. Such cost is determined for unit cost of power of US$0.0656/kWh (€0.0561/kWh). The Spanish desalination market is one of the most mature markets in the world and along with the Middle Eastern desalination market is indicative of the best-case realistic desalinated water production costs at present.

10 Software Description

Software used in this Master Thesis for simulation cases is Water Application Value Engine (WAVE), DuPont's Software which is in the public domain.

The Water Application Value Engine (WAVE) is a new modeling software program that integrates three of the leading technologies (ultrafiltration, reverse osmosis and ion exchange resin) into one comprehensive platform. The WAVE software is used to design and simulate the operation of water treatment systems using the UF, RO, and IER component technologies.

In this Master's Thesis, process described and simulations carried out are those related to reverse osmosis process.

Use of this software is described in the captures-Figures below:

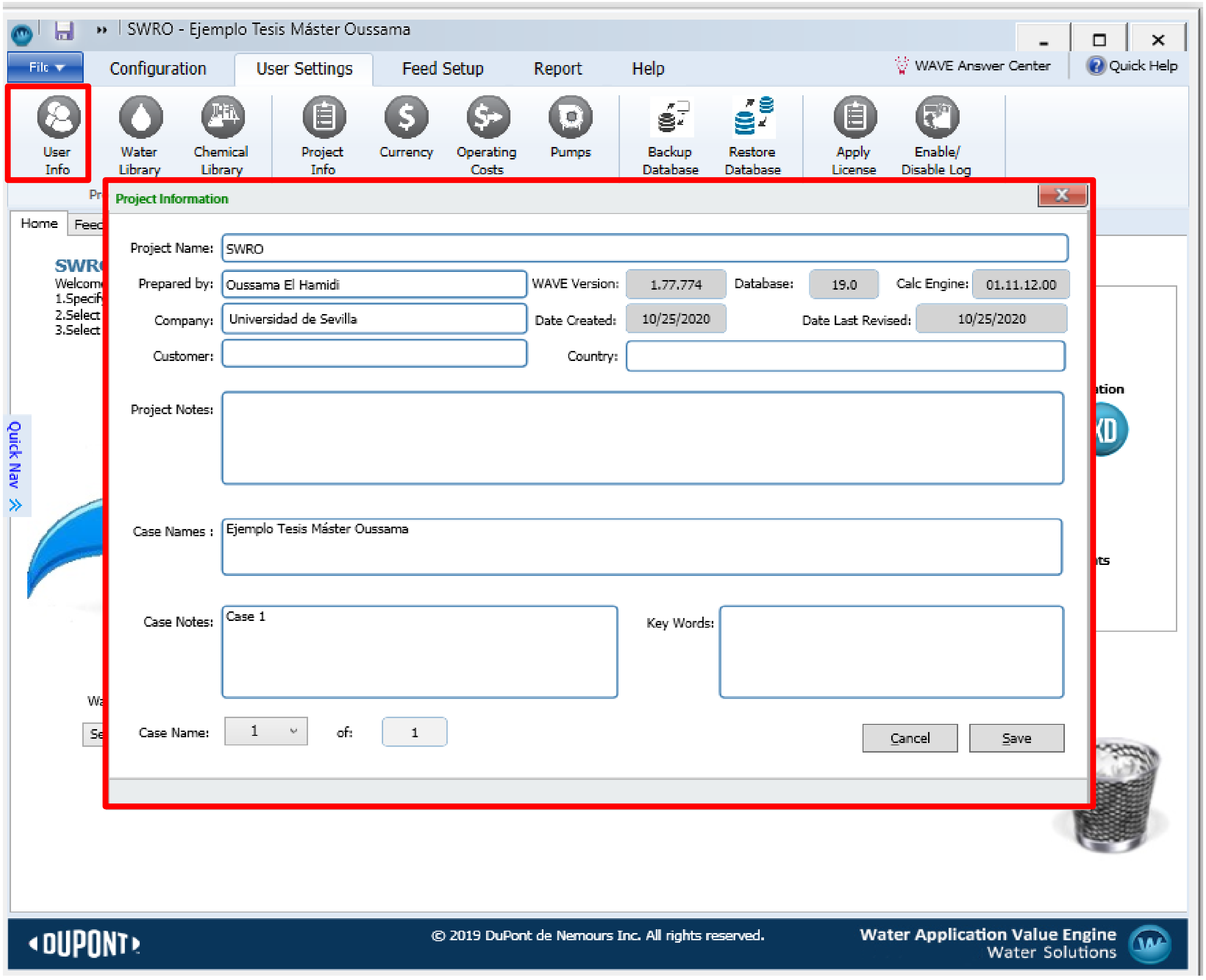

Figure 18. WAVE Software : Defining the Project Information

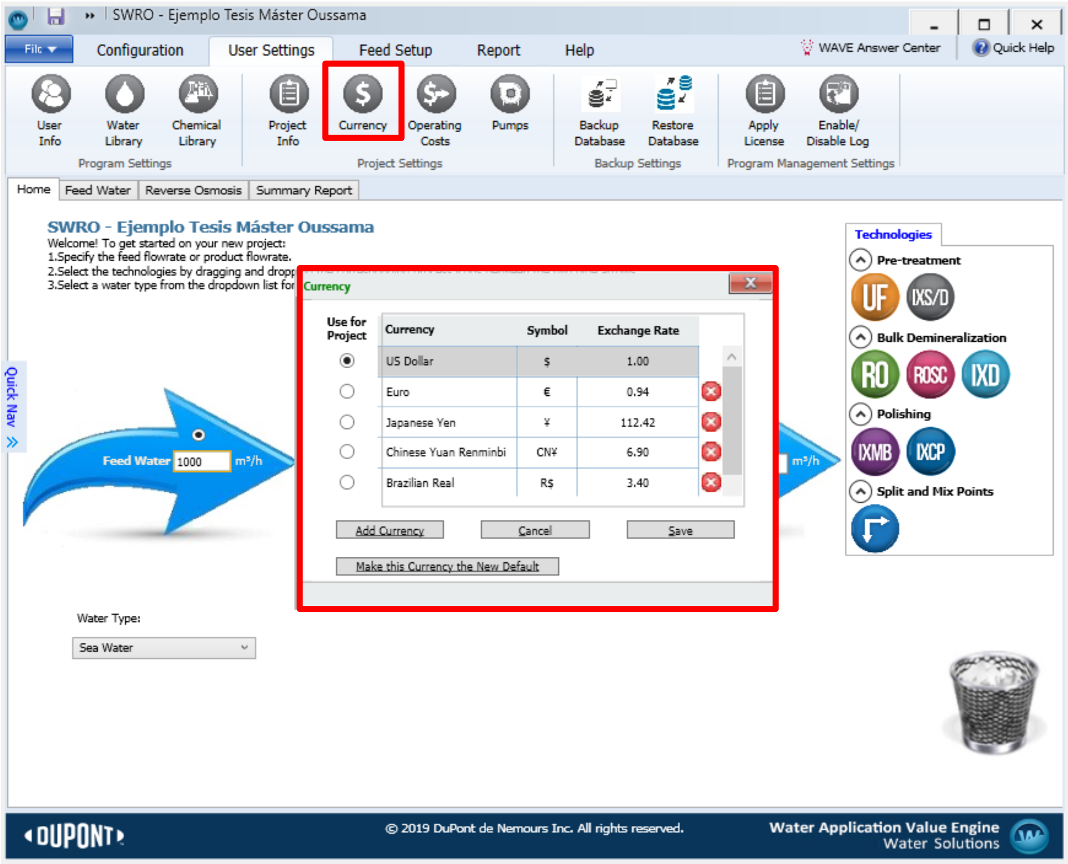

Figure 19. WAVE Software : Currencies and Exchange Rates

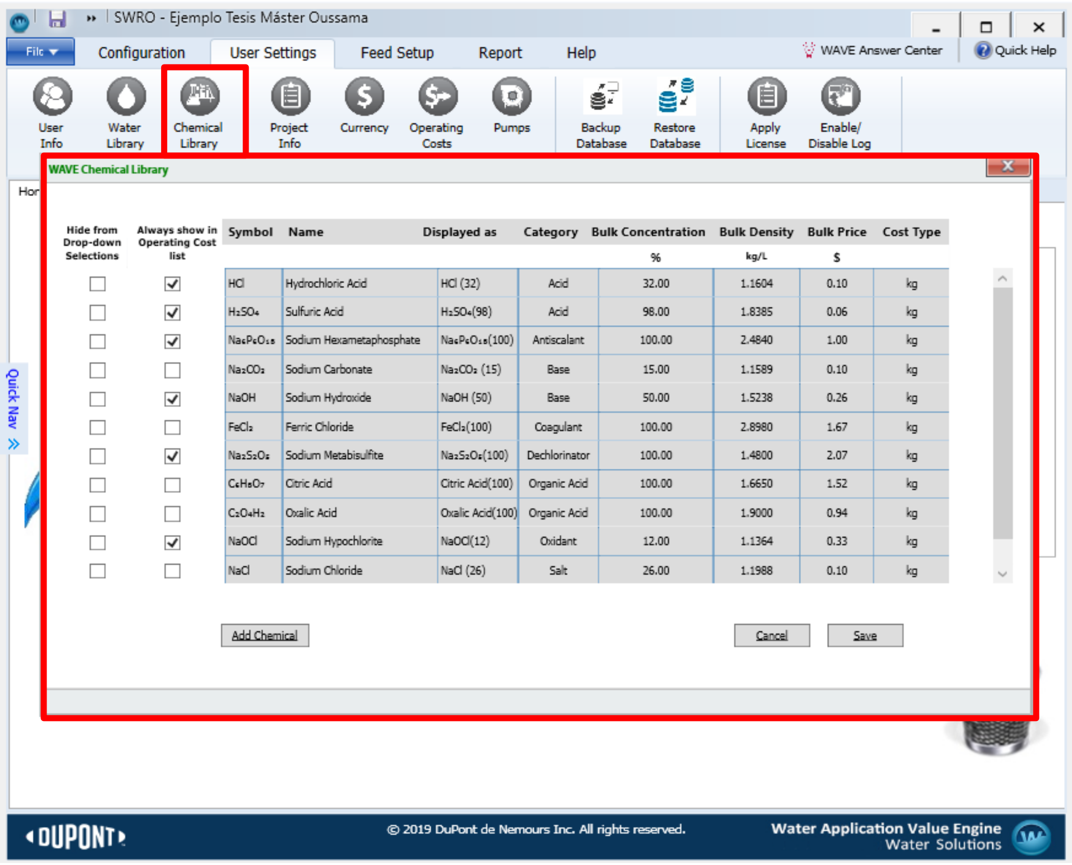

Figure 20. WAVE Software : Chemical Library

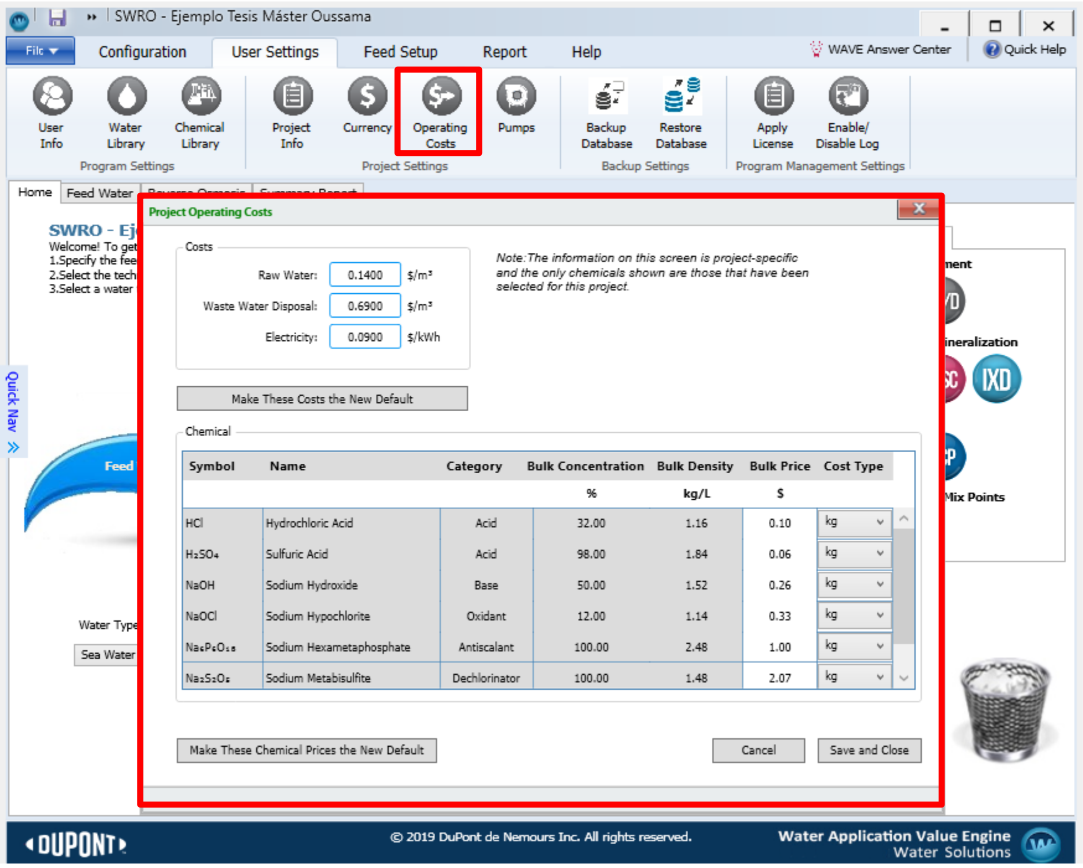

Figure 21. WAVE Software : Operating Costs

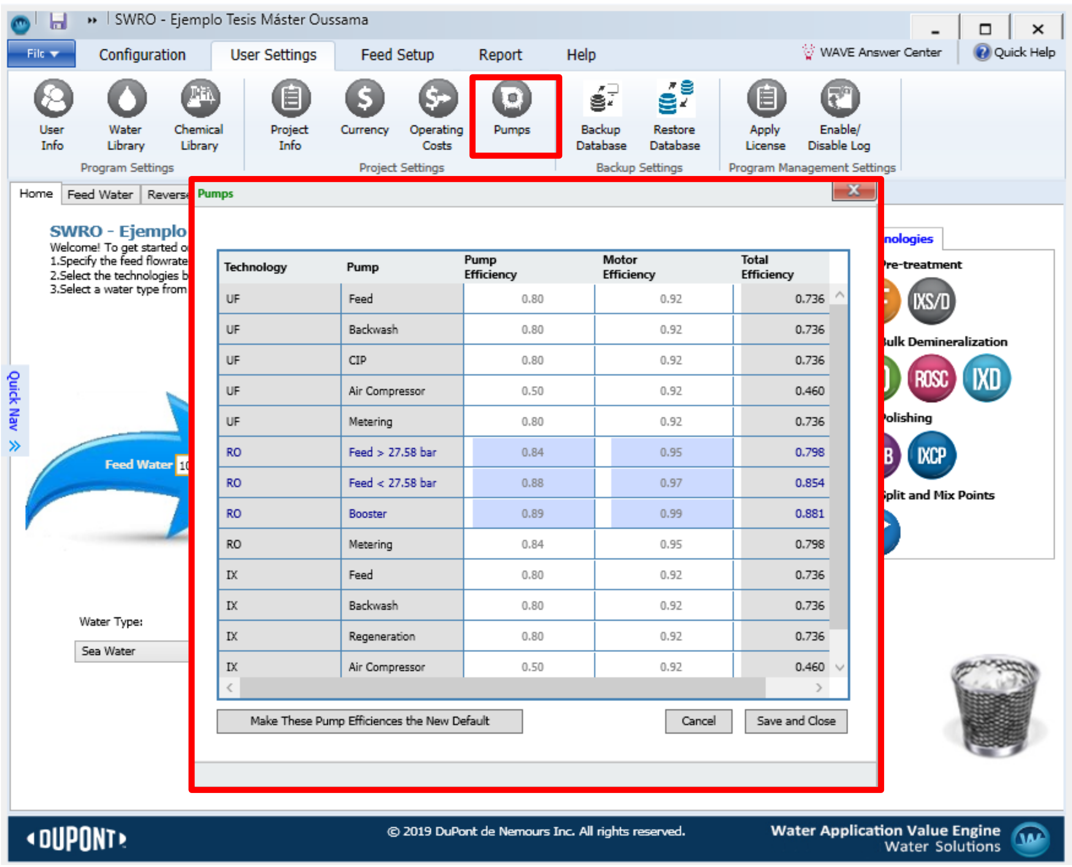

Figure 22. WAVE Software : Pump Efficiencies

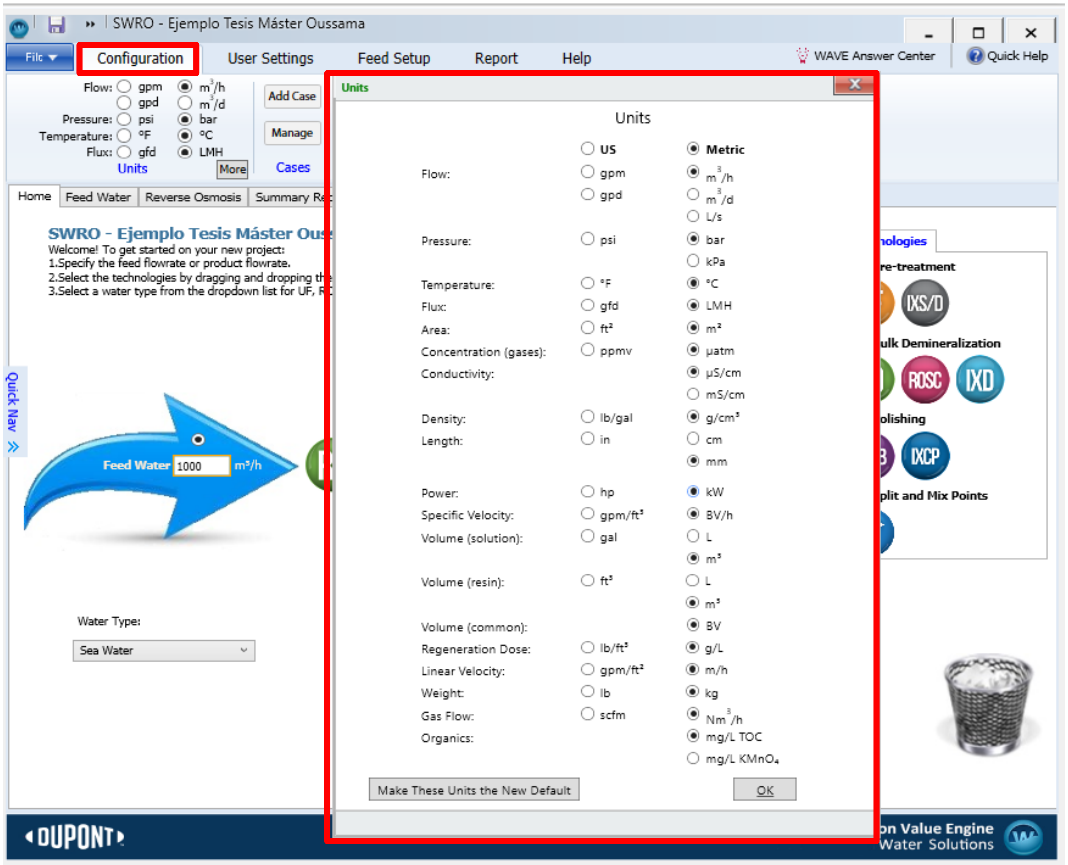

Figure 23. WAVE Software : Units of Measure

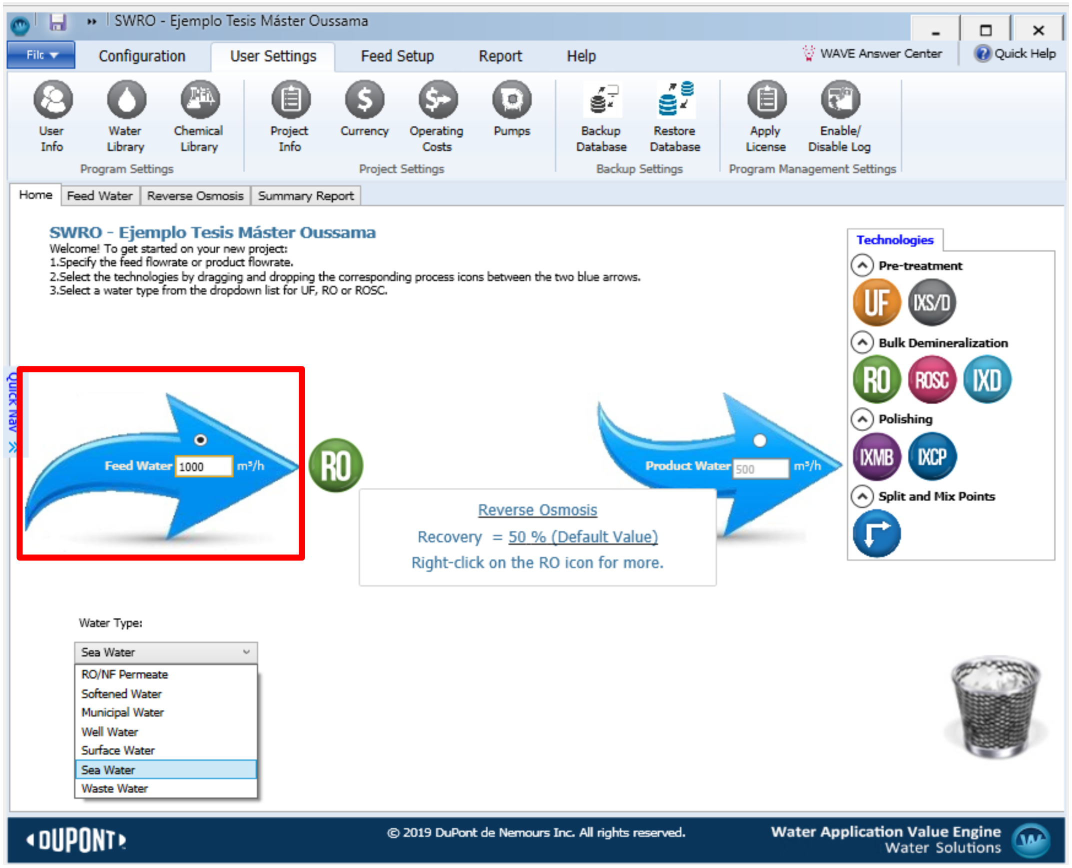

Figure 24. WAVE Software : Specifying the System Feed and Product Flows

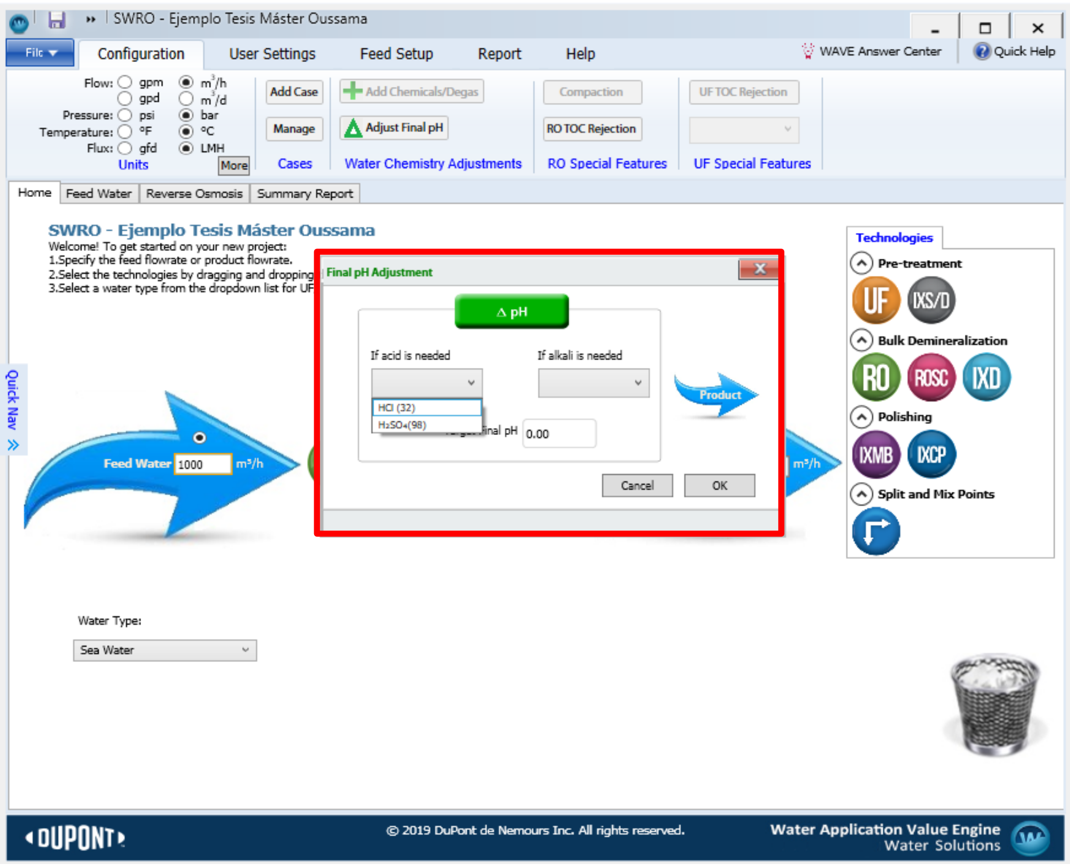

Figure 25. WAVE Software : pH Adjustment of the Final Product

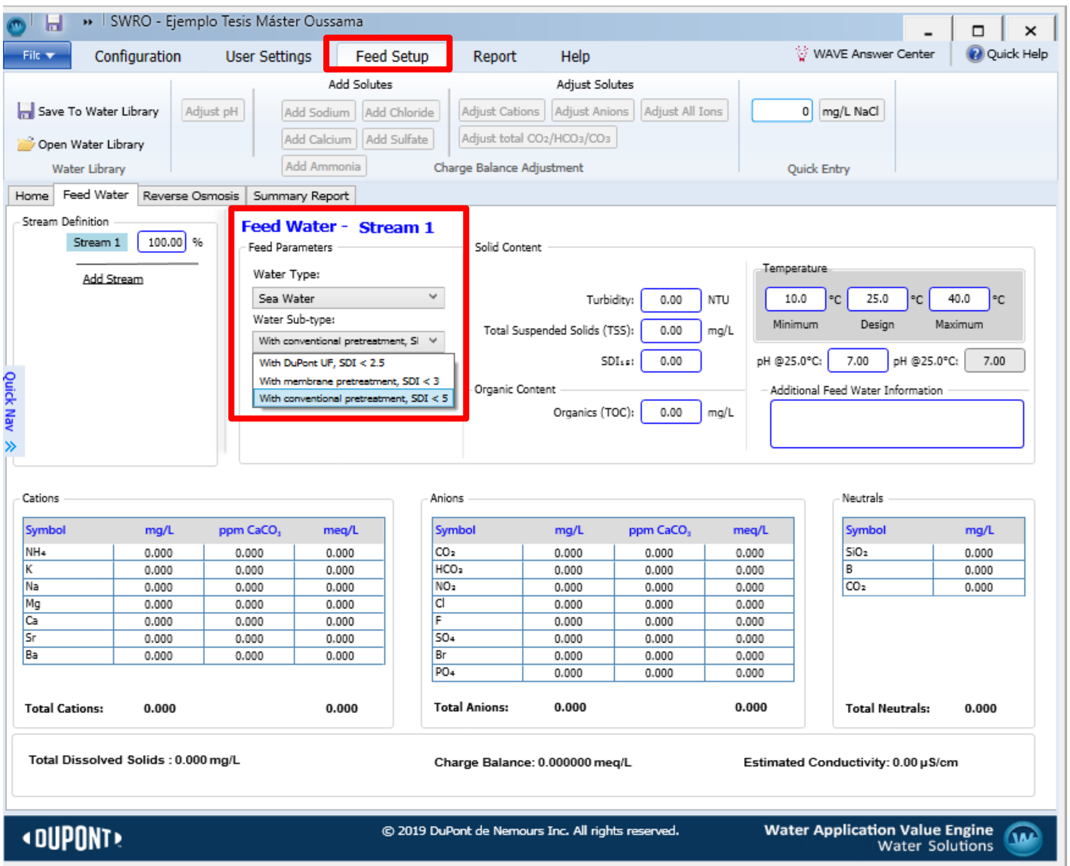

Figure 26. WAVE Software : Specifying the Water Type and Subtype in the Feed Water Tab

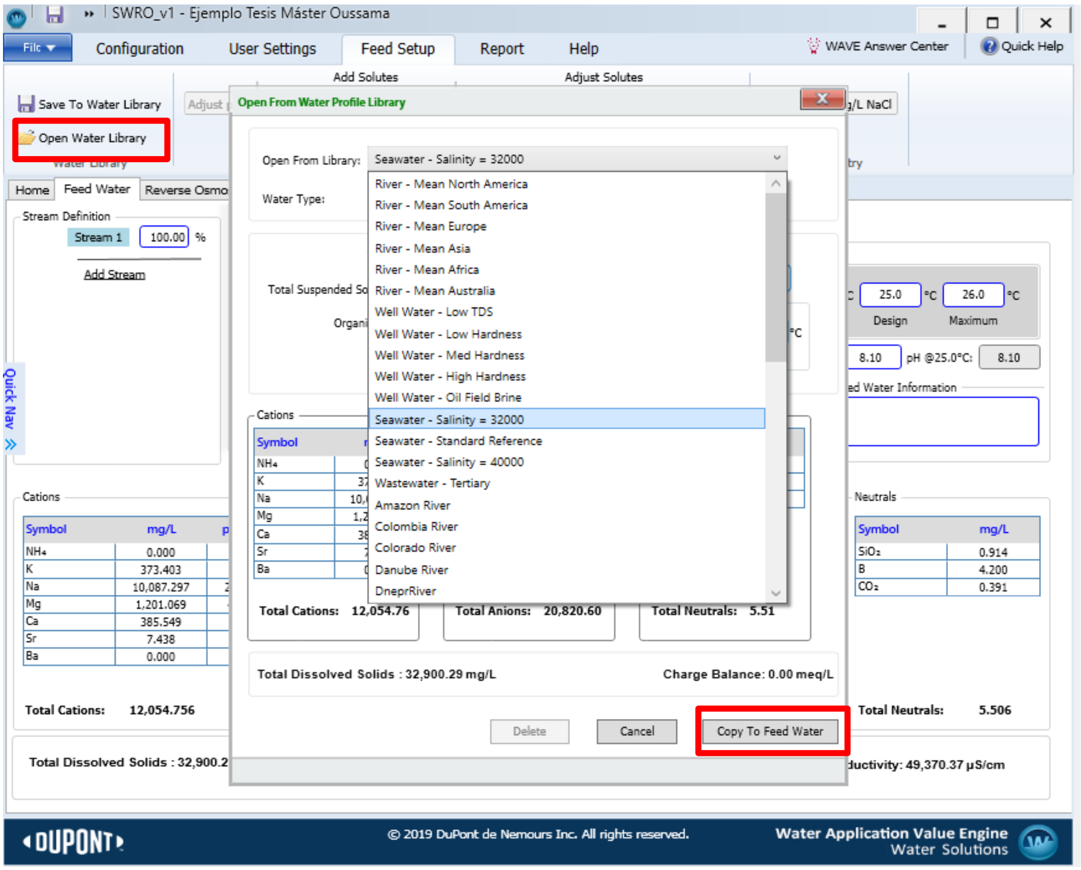

Figure 27. WAVE Software : Import from the Water Library

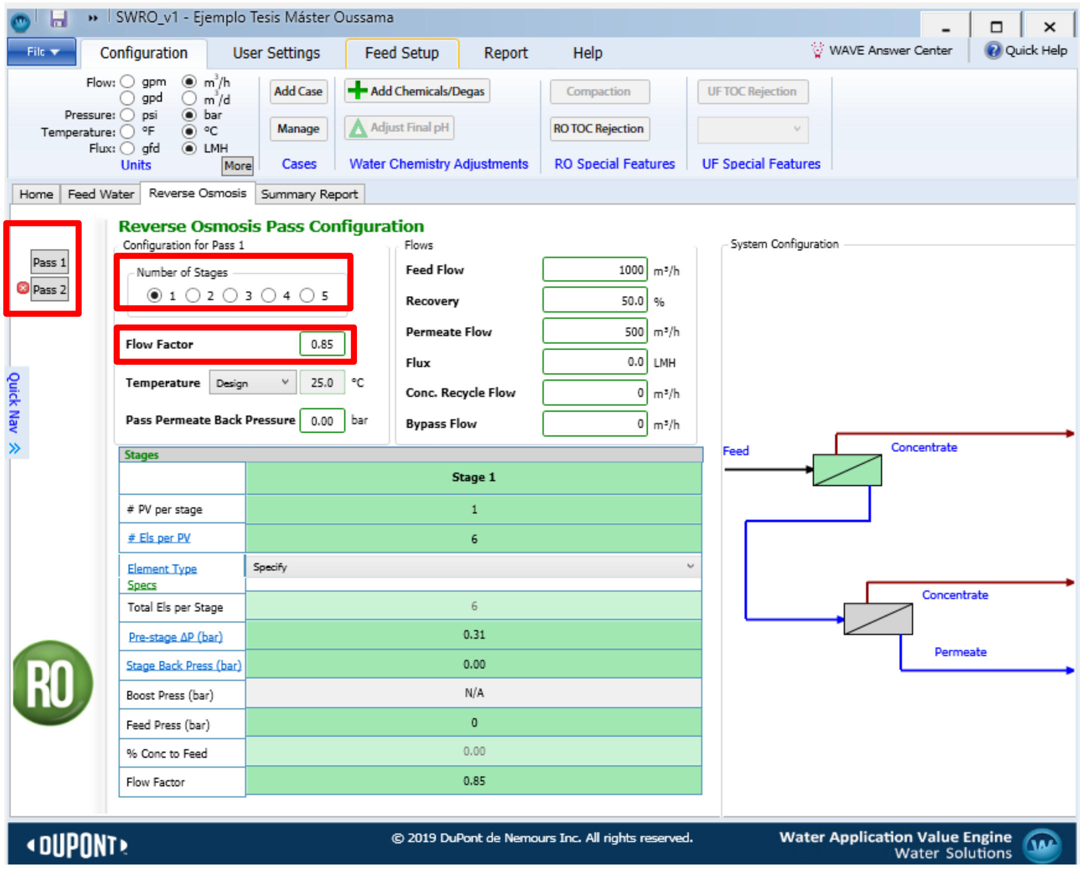

Figure 28. WAVE Software : Defining the RO System Configuration

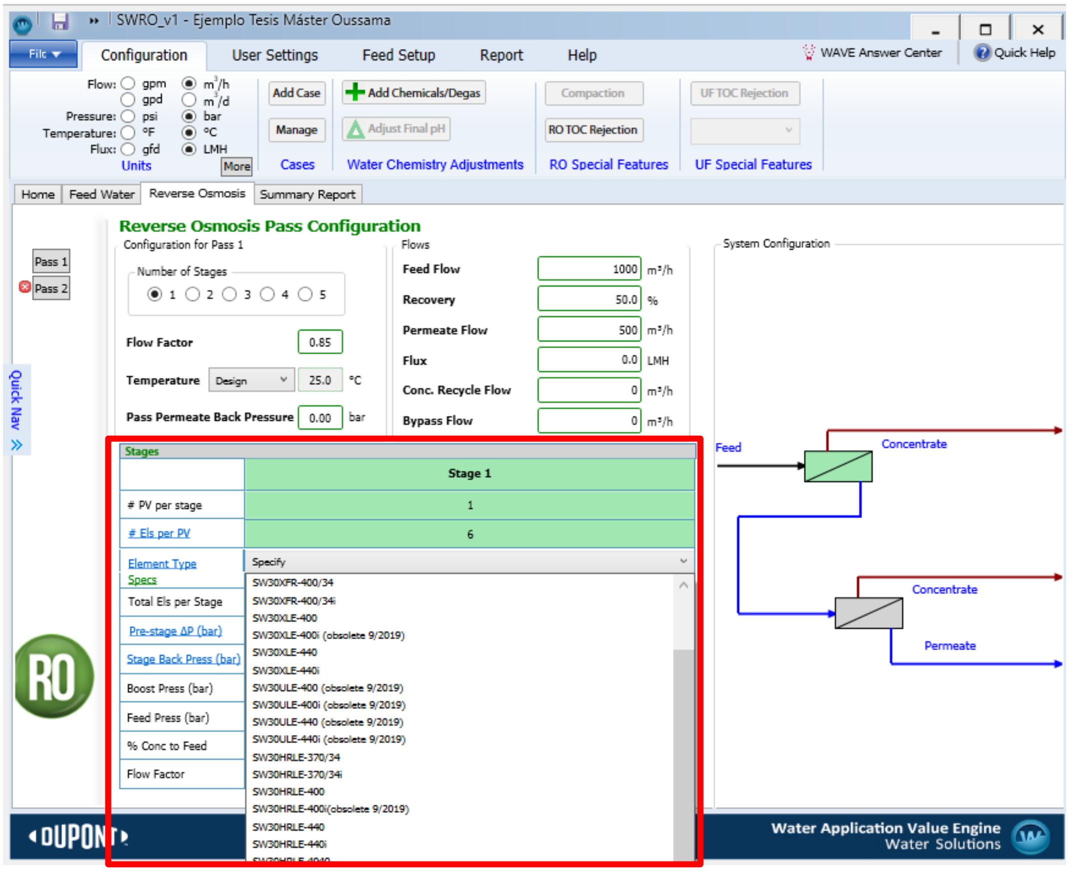

Figure 29. WAVE Software : Specifying Elements, Number of Pressure Vessels and Elements per Pressure Vessel

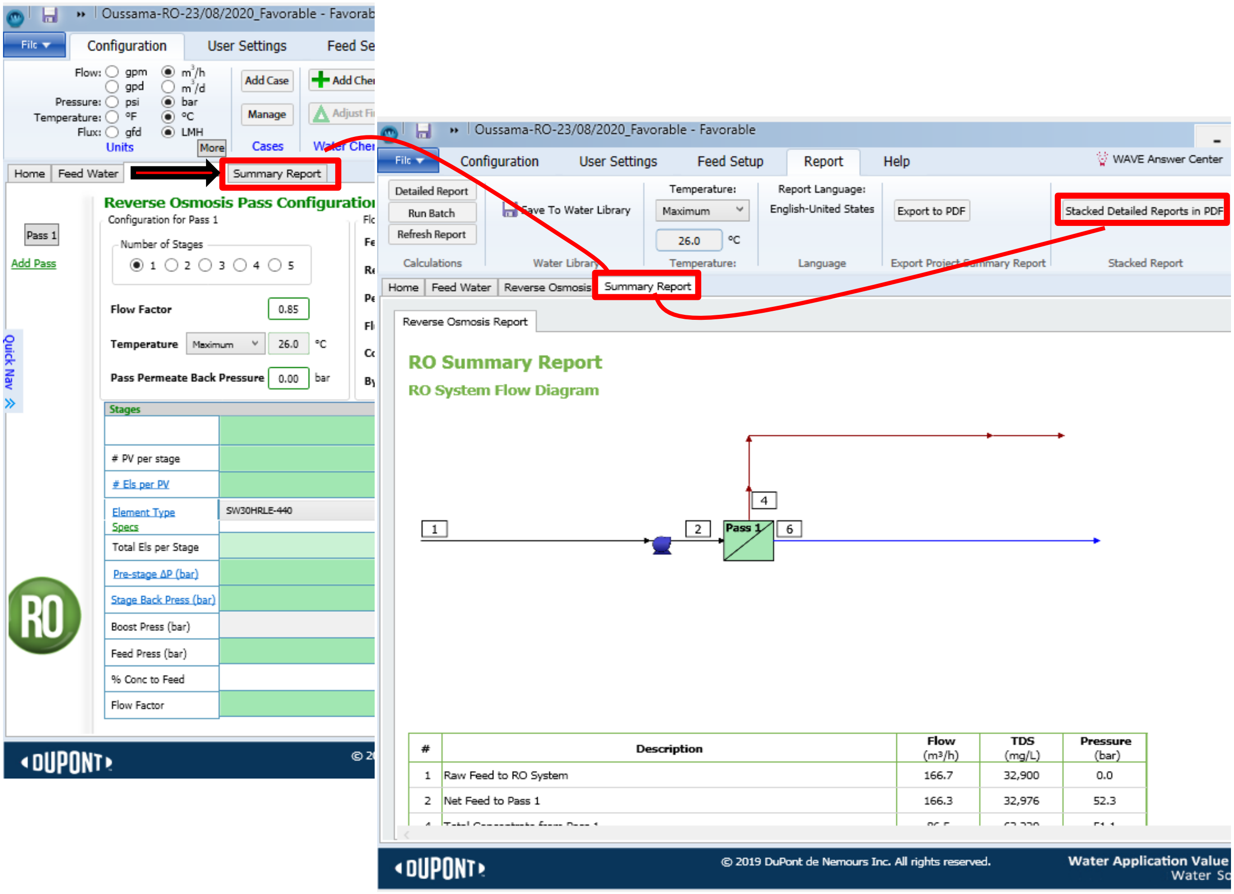

Figure 30. WAVE Software : Reverse Osmosis – Final Calculation

11 DESCRIPTION SIMULATION PROCESS

In this Master's Thesis, single-stage SWRO system is chosen to produce desalinated seawater (permeate) in one step using only a single set of RO trains operating in parallel. Under this typical single-pass SWRO system configuration, each RO train has a dedicated unit of a high-pressure RO feed pump. The high-pressure feed pump motor/operation is coupled with that of energy recovery equipment.

11.1. SWRO Plant Location

Location chosen for this SWRO desalination plant simulation is Morocco's Atlantic part. According to the National Office of Electricity and Drinking Water of Morocco (ONEE: Office National de l'Electricité et de l'Eau Potable), the characteristics of the seawater in this region of the Atlantic Ocean are the following (Table 6) :

Table 6. Atlantic Ocean's seawater characteristics

Parameter	Value
Total Dissolved Solids Concentration (g/L)	33-39
Temperature (ºC)	15-26
Boron (mg/L)	5
pH	8-8.2

Source : ONEE Morocco (ONEE, 2020)

The use for this SWRO plant will be to provide drinking water a small population of about 28.000 inhabitants, and the characteristics of the desalinated water required are the following (Table 7):

Table 7. Drinking water requirements

Parameter	Value
Total Dissolved Solids Concentration (mg/L)	≤ 500
Boron (mg/L)	≤ 1.0
Permeate flow desired (m3/h)	60

11.2. Objective

Objective of this Master's Thesis is determine in which scenario we can obtain the lowest SEC –specific energy consumption- in a Seawater Reverse Osmosis plant to meet with the drinking water requirements.

Simulation process in this work consists in two different parts as mentioned in the introduction. The first part, SWRO configuration which can obtain the lowest SEC without ERD -energy recovery device- varying quality parameters of feed water and efficiency of the devices. With this we will obtain 4 simulation cases using WAVE software. And the second part, we will calculate the SEC for the 4 cases above, but implementing the use of the energy recovery device. This second part will be obtained using my own Excel program based on energy's balance formulas.

At the end, we must have eight independent SEC calculations and four different energetic savings combinations.

Water Application Value Engine (WAVE) software environment is used to select the RO membrane and configuration (number of pressure vessels and elements) which best fit the conditions for the lowest SEC. For this purpose, principal variables will be fixed (mass flow rate and recovery) and the values of the other variables (temperature, concentration, energy efficiency's devices) will be modified for evaluate its impact in specific energy consumption.

Diagram presented in Figure 31 represents seawater reverse osmosis system without energy recovery device. The power required to drive the high-pressure pump(s) -HPP- is typically the largest component of the operating cost of SWRO systems. Most of the pressure energy in the feedwater flowing to the SWRO membranes leaves the membranes with the brine reject water.

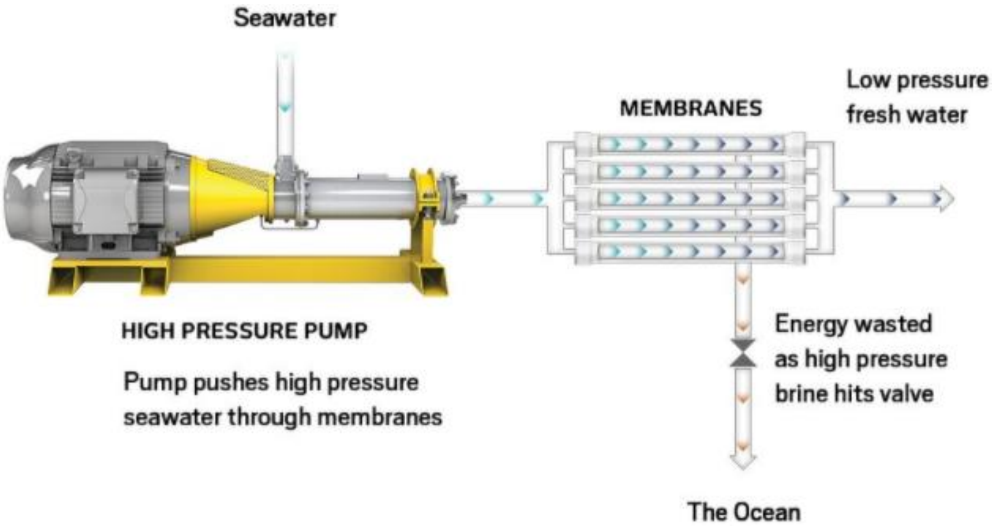

Figure 31. SWRO configuration without Energy Recovery Device (ERD)

The main function of an energy recovery device would be to improve energy efficiency by harnessing spent energy from the concentrate stream and delivering it back to the feed water, as represented in Figure 32.

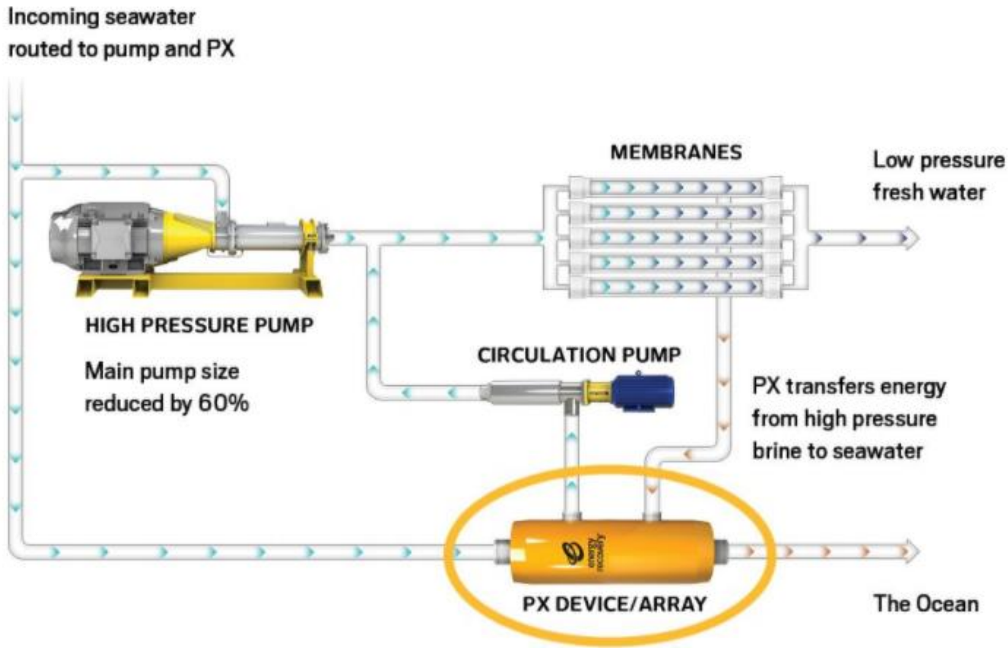

Figure 32. SWRO configuration with Energy Recovery Device (ERD)

11.3. Selection of equipements

11.3.1 High Pressure Pump

Next two high pressure pump manufacturers will be used in our simulations, as represented in Table 8.

Table 8. High Pressure Pump models

	Normal Energy Efficiency Device		**High Energy Efficiency Device**	
	Pump	Motor	Pump	Motor
Manufacturer	Flowserve	Siemens	Danfoss	Siemens
Model	MSM 065C	IE3	APP 86/1700	IE4
Speed (rpm)	3000	2 poles	1500	4 poles
Power (kW)	165	200	-	200
Maximum admissible flow (m3/h)	80	-	78	-
Efficiency	0,75	0,958	0,88	0,967
Global Efficiency	**0,719**		**0,851**	

11.3.2 Booster Pump

Next two booster pump models from same manufacturer will be used in our simulations, as represented in Table 9.

Table 9. Booster Pump models

	Normal Energy Efficiency Device		**High Energy Efficiency Device**	
	Pump	**Motor**	**Pump**	**Motor**
Manufacturer	ERI	Siemens	ERI	Siemens
Model	VP-4671	IE3	VP-XP 150x200	IE4
Speed (rpm)	3000	2 poles	3000	2 poles
Power (kW)	1,7	2,2	1,7	2,2
Maximum admissible flow (m3/h)	218	-	218	-
Efficiency	0,79	0,859	0,844	0,88
Global Efficiency	**0,679**		**0,743**	

11.3.3 Pressure Exchanger

Next two pressure exchanger models from same manufacturer wil be used in our simulations, as represented in Table 10.

Table 10. Pressure Exchanger models

	Normal Energy Efficiency Device	**High Energy Efficiency Device**
Manufacturer	Energy Recovery Inc.	
Model	PX-220	PX-Q300
Peak Efficiency	97,2	98
Flow range - brine flow m3/h	40-50	45-68

11.3.4 Seawater Membrane

Next two membrane models from same manufacturer will be used in our simulations, as represented in Table 11.

Table 11. Seawater Membrane models

	Normal Energy Efficiency Device	**High Energy Efficiency Device**
Manufacturer	Dupont (FilmTec)	
Model	SW30XHR-440	SW30HRLE-440i
Active Area (m2)	40,9	40,9
Pressure (bar)	55,2	55,2
Flow (m3/day)	25,0	30,2
Rejection (%)	99,82	99,8

It should be mentioned that I performed simulations firstly with SW30HRLE-440 and SEAMAXX-440. The specific energy consumption had coherent values, but the permeate's quality was very poor for SW30HRLE-440 membrane; and for SEAMAXX-440 membrane, the permeate quality did not meet with drinking water requirements (boron concentration was in the range of 1.04-1.42 mg/L, exceeding the maximum permisible).

It need to be appointed also that in terms of energy consumptions, SW30HRLE-440i has better performance (lower consumption) than SW30XHR-440. However, in terms of permeate quality, SW30XHR-440 has better results than SW30HRLE-440i (see Table 25). But I have chosen SW30HRLE-440i as a high energy efficiency device because the goal of this thesis is to obtain the lowest specific energy consumption.

11.4. Specific Energy Consumption (SEC) with ERD. Calculation method

The energy required to desalinate with an SWRO system can be expressed in terms of the specific energy consumption -the energy required per unit output of permeate- and calculated with the following equivalent equations:

$$SEC = (E_{HPP} + E_{BP})/Q_P \quad (1)$$

$$SEC = [Q_{HPP}\,(P_{HPP} - P_F)/\eta_{HPP} + Q_{BP}\,(P_{HPP} - P_{BPI})/\eta_{BP}]/Q_P \quad (2)$$

Where:

$SEC \equiv specific\ energy\ consumption\ system$

$E_{HPP} \equiv the\ high\ pressure\ pump\ energy\ consumed$

$E_{BP} \equiv the\ booster\ pump\ energy\ consumed$

$Q_P \equiv the\ permeate\ flow\ rate$

$Q_{HPP} \equiv the\ high\ pressure\ pump\ flow\ rate$

$P_{HPP} \equiv the\ high\ pressure\ pump\ outlet\ pressure$

$P_F \equiv the\ high\ pressure\ pump\ feedwater\ pressure$

$\eta_{HPP} \equiv the\ high\ pressure\ pump\ and\ motor\ efficiency$

$Q_{BP} \equiv the\ booster\ pump\ flow\ rate$

$P_{BPI} \equiv the\ booster\ pump\ intet\ pressure$

$\eta_{BP} \equiv the\ booster\ pump\ and\ motor\ efficiency$

In SWRO plant with energy recovery device configuration, next assumptions are made to calculate the specific energy consumption:

- Feedwater stream comes from a seawater supply pump, with certain pressure a little bit more than atmospheric pressure. We will consider 1.8 bar for this point, which is a realistic value done by ERI (Inc., Technical Dataseet, 2017).
- For the SEC calculation, we will not consider the energy consumed by the seawater supply pump.
- Low pressure concentrate stream, which is driven over the ocean, is at atmospheric pressure, which is 1 bar.
- Permeate stream leaves membrane without pressure. We will consider 0 bar, which is a realistic value done by ERI (Inc., Technical Dataseet, 2017).
- Equipment used are assumed without hydraulic energy loss, which means, the flow rate at device input is the same as that at device output.

In this configuration, all parameters are known except high pressure at the exit of the pressure exchanger. This pressure can be obtained using energy's balance for pressure exchanger device represented in Figure 33:

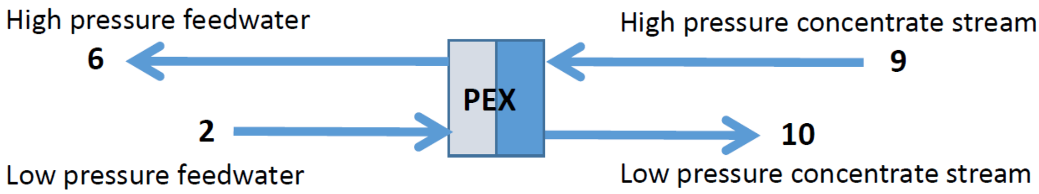

Figure 33. Energy balance for pressure exchanger

$$\eta_{PX} \cdot Q_{concentrate} \cdot (p_9 - p_{10}) = Q_{feed-PX} \cdot (p_6 - p_2) \qquad (3)$$

Where:

$\eta_{PX} \equiv pressure\ exchanger\ efficiency$

$Q_{feed-PX} \equiv feed\ stream\ towards\ PX$

$p_6 \equiv pressure\ at\ the\ exit\ of\ PX\ from\ feedwater\ side\_unknown\ factor$

$p_2 \equiv pressure\ at\ the\ entry\ of\ PX\ from\ feedwater\ side$

$Q_{concentrate} \equiv concentrate\ stream\ flow\ rate$

$p_9 \equiv pressure\ at\ the\ entry\ of\ PX\ from\ concentrate\ side$

$p_{10} \equiv pressure\ at\ the\ exit\ of\ PX\ from\ concentrate\ side$

Solving the unknown factor p_6 from Eq. (3) we can calculate the pressure at the exit of PX as follows :

$$p_6 = \frac{\eta_{PX} \cdot Q_{concentrate} \cdot (P_9 - P_{10})}{Q_{feed}} + p_2 \qquad (4)$$

Next step is to calculate the energy consumed by the high pressure and booster pumps.

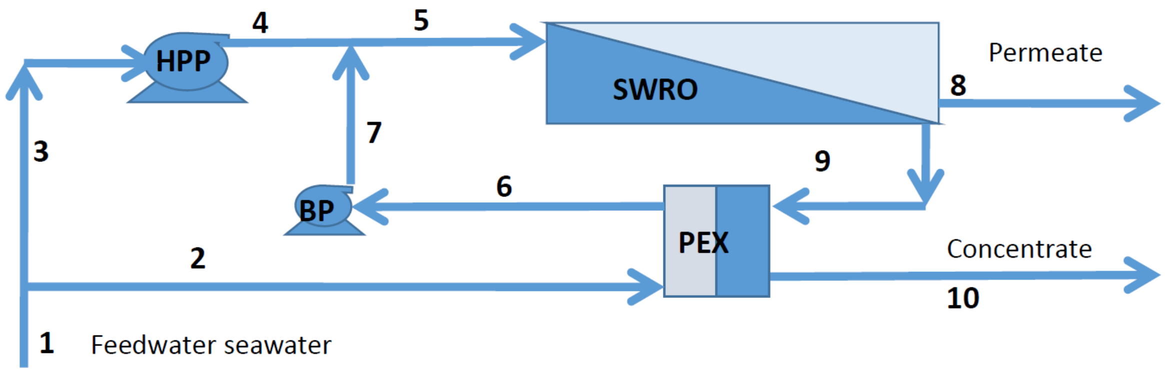

Figure 34. Single-stage SWRO system with PX energy recovery device

Energy consumed by HPP:

Implementing the energy balance around HPP in the system configuration represented in Figure 34 we obtain:

$$E_{HPP} = \frac{\left(Q_{feed-HPP}/3600 \right) \cdot (p_4 - p_3) \cdot 100000}{1000 \cdot \eta_{HPP}} \qquad (5)$$

Where:

$E_{HPP}[kW] \equiv energy\ consumed\ by\ HPP$

$Q_{feed-HPP}[m^3/h] \equiv feed\ stream\ towards\ HPP$

$p_4[bar] \equiv pressure\ at\ the\ outlet\ of\ HPP$

$p_3[bar] \equiv pressure\ at\ the\ inlet\ of\ HPP$

$\eta_{HPP} \equiv HPP\ efficiency$

Energy consumed by BP:

Implementing the energy balance around BP in the system configuration represented in Figure 34 we obtain:

$$E_{BP} = \frac{\left(Q_{feed-PX}/3600 \right) \cdot (p_7 - p_6) \cdot 100000}{1000 \cdot \eta_{BP}} \qquad (6)$$

Where:

$E_{BP}[kW] \equiv energy\ consumed\ by\ BP$

$Q_{feed-PX}[m^3/h] \equiv feed\ stream\ towards\ PX$

$p_7[bar] \equiv pressure\ at\ the\ outlet\ of\ BP$

$p_6[bar] \equiv pressure\ at\ the\ inlet\ of\ BP$

$\eta_{BP} \equiv BP\ efficiency$

12 Simulation Cases

12.1. SEC calculations without ERD

12.1.1 Case 1: unfavourable seawater conditions-normal efficiency devices

Parameters for this case 1 are from Table 6, Table 8, Table 9, Table 10 and Table 11 and outlined in Table 12:

Table 12. Case1 : Unfavourable seawater conditions-normal efficiency devices-without ERD

Parameters	Case 1	Units
Feed seawater characteristics		
TDS Concentration	38.000	mg/L
Temperature	15	°C
High Pressure Pump		
Manufacturer	Flowserve	
Global efficiency	0,719	%
Booster Pump		
Manufacturer	ERI	
Global efficiency	0,679	%
Membrane		
Manufacturer	Dupont	
Active area	40,9	m3
Feed seawater	25,0	m3/day

The estimated ionic composition is inserted in WAVE software as represented un Figure 35 (Dupont, 2020):

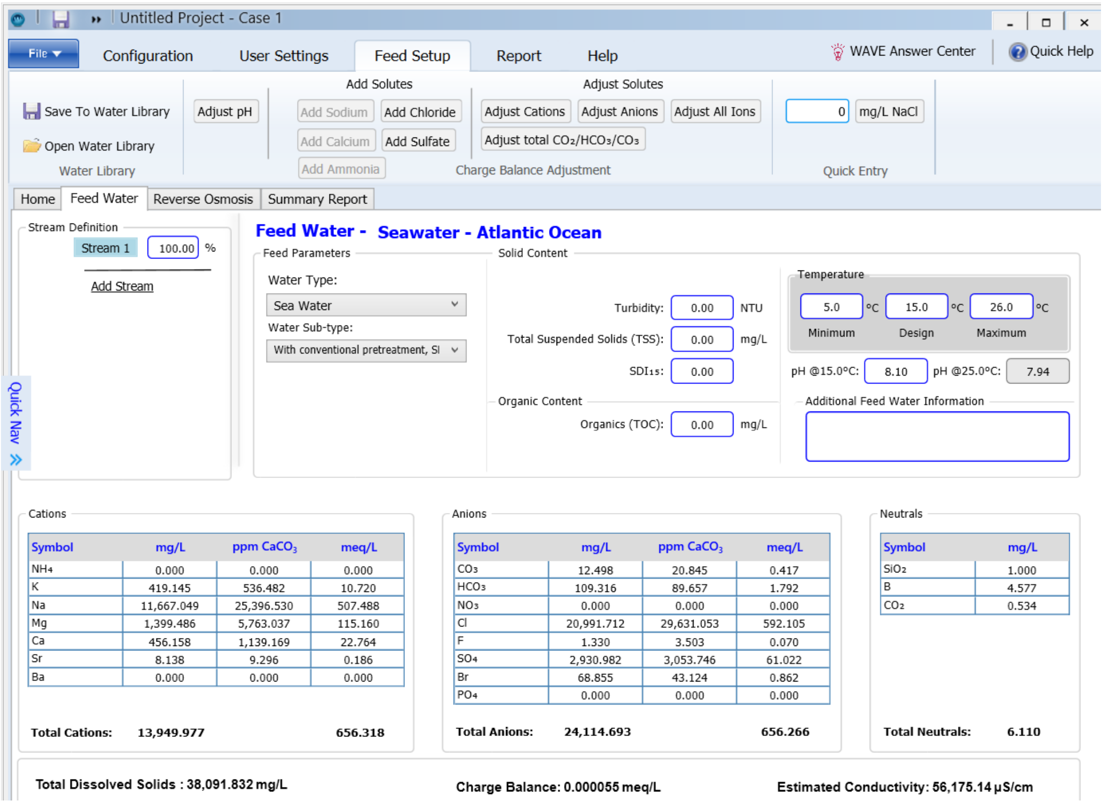

Figure 35. Ionic composition Atlantic Ocean seawater unfavourable conditions

Detailed results of this case 1 simulation are presented in Annex nº1. This results are summarized in Table 13:

Table 13. Case 1 simulation results-without ERD

Parameters	Membrane	Nº Elem.	Feed			Concentrate			Permeate				SEC (kWh/m3)
			Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Avg Flux (Lmh)	TDS (mg/L)	Boron (mg/L)	
Case 1	SW30XHR-440	105	125	68,9	38.192	65	67,6	73.350	60	14,0	84,09	0,39	5,57

12.1.2 Case 2: unfavourable seawater conditions-high efficiency devices

Parameters for this case 2 are from Table 6, Table 8, Table 9, Table 10 and Table 11 and outlined in Table 14:

Table 14. Case2 : Unfavourable seawater conditions-high efficiency devices-without ERD

Parameters	**Case 2**	**Units**
Feed seawater characteristics		
TDS Concentration	38.000	mg/L
Temperature	15	°C
High Pressure Pump		
Manufacturer	Danfoss	
Global efficiency	0,851	%
Booster Pump		
Manufacturer	ERI	
Global efficiency	0,743	%
Membrane		
Manufacturer	Dupont	
Active area	37,2	m3
Feed seawater	28,4	m3/day

Detailed results of this case 2 simulation are presented in Annex nº2. This results are summarized in Table 15:

Table 15. Case2 simulartion results-without ERD

Parameters	Membrane	Nº Elem.	Feed			Concentrate			Permeate				SEC (kWh/m3)
			Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Avg Flux (Lmh)	TDS (mg/L)	Boron (mg/L)	
Case 2	SW30HRLE-440i	105	125	63,9	38.190	65	62,6	73.347	60	14,0	113	0,53	4,36

We can see a significant improvement in SEC using high efficiency devices. There is also a little degradation in TDS and Boron permeate quality, but always we stay in the permitted levels described in Table 7.

12.1.3 Case 3: favourable seawater conditions-normal efficiency devices

Parameters for this case 3 are from Table 6, Table 8, Table 9, Table 10 and Table 11 and outlined in Table 16:

Table 16. Case3 : Favourable seawater conditions-normal efficiency devices-without ERD

Parameters	**Case 3**	**Units**
Feed seawater characteristics		
TDS Concentration	33.000	mg/L
Temperature	26	°C

High Pressure Pump		
Manufacturer	Flowserve	
Global efficiency	0,719	%
Booster Pump		
Manufacturer	ERI	
Global efficiency	0,679	%
Membrane		
Manufacturer	Dupont	
Active area	40,9	m3
Feed seawater	25,0	m3/day

The estimated ionic composition is done by WAVE software as represented un Figure 36:

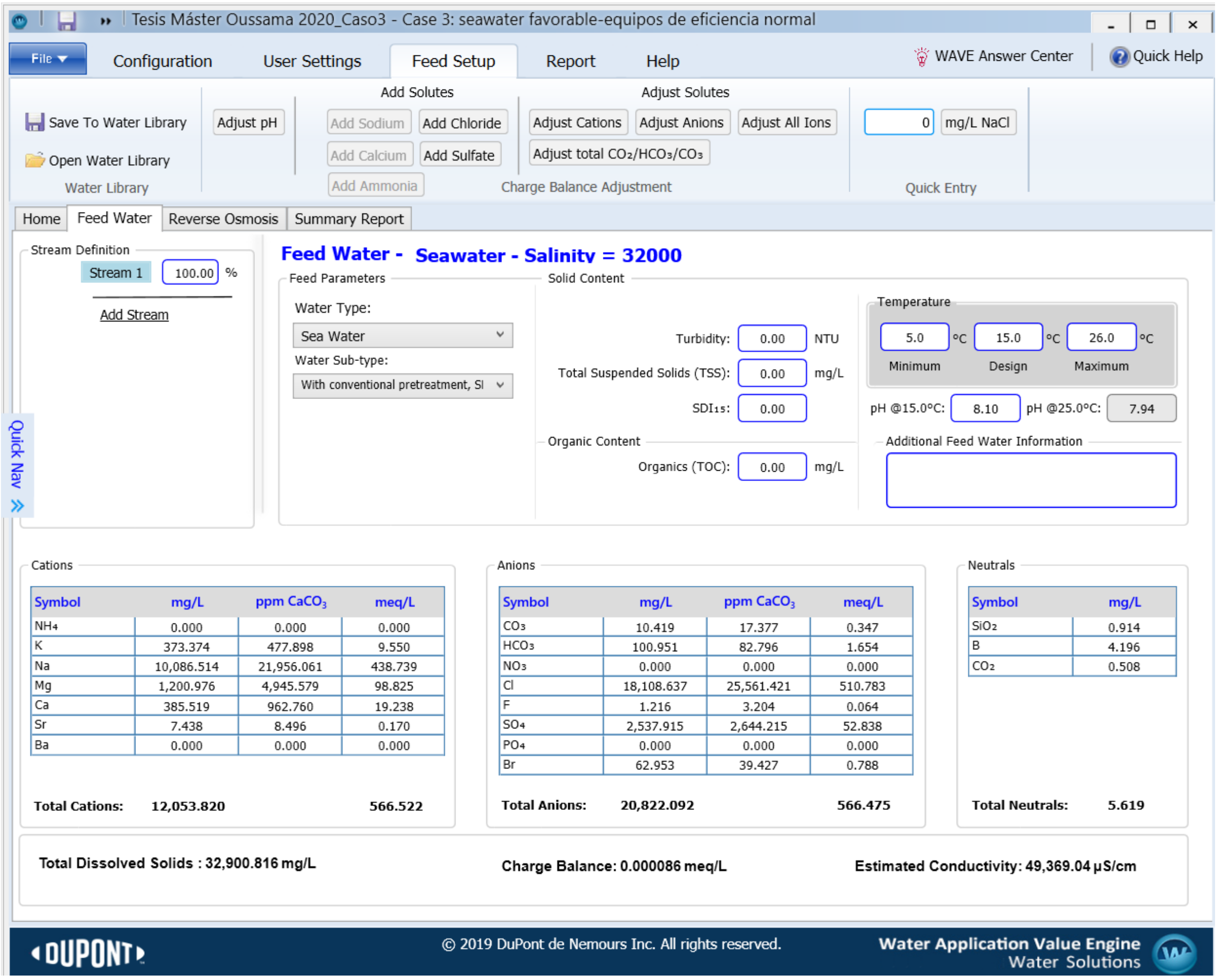

Figure 36. Ionic composition Atlantic Ocean seawater favourable conditions

Detailed results of this case 3 simulation are presented in Annex nº3. This results are summarized in Table 17:

Table 17. Case3 simulartion results-without ERD

Parameters	Membrane	Nº Elem.	Feed			Concentrate			Permeate				SEC (kWh/m3)
			Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Avg Flux (Lmh)	TDS (mg/L)	Boron (mg/L)	
Case 3	SW30XHR-440	105	125	61,1	32.975	65	59,8	63.330	60	14,0	72,33	0,36	4,95

12.1.4 Case 4: favourable seawater conditions-high efficiency devices

Parameters for this case 4 are from Table 6, Table 8, Table 9, Table 10 and Table 11 and outlined in Table 18:

Table 18. Case4 : Favourable seawater conditions-high efficiency devices-without ERD

Parameters	**Case 4**	**Units**
Feed seawater characteristics		
TDS Concentration	33.000	mg/L
Temperature	26	°C
High Pressure Pump		
Manufacturer	Danfoss	
Global efficiency	0,851	%
Booster Pump		
Manufacturer	ERI	
Global efficiency	0,743	%
Membrane		
Manufacturer	Dupont	
Active area	40,9	m3
Feed seawater	30,2	m3/day

Detailed results of this case 4 simulation are presented in Annex nº4. This results are summarized in Table 19:

Table 19. Case4 simulations results-without ERD

Parameters	Membrane	Nº Elem.	Feed			Concentrate			Permeate				SEC (kWh/m3)
			Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Avg Flux (Lmh)	TDS (mg/L)	Boron (mg/L)	
Case 4	SW30HRLE-440i	105	125	52,5	32.977	65	51,5	63.230	60	14,0	182,1	0,90	3,59

Below is a summary of the four cases studies until now, without ERD, as represented in Table 20:

Table 20. Summary results of cases 1, 2 3 and 4, without ERD

Parameters	Membrane	Nº Elem.	Feed			Concentrate			Permeate				SEC (kWh/m3)
			Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Pressure (bar)	TDS (mg/L)	Flow (m3/h)	Avg Flux (Lmh)	TDS (mg/L)	Boron (mg/L)	
Case 1	SW30XHR-440	105	125	68,9	38.192	65	67,6	73.350	60	14,0	84,09	0,39	5,57
Case 2	SW30HRLE-440i	105	125	63,9	38.190	65	62,6	73.347	60	14,0	113	0,53	4,36
Case 3	SW30XHR-440	105	125	61,1	32.975	65	59,8	63.330	60	14,0	72,33	0,36	4,95
Case 4	SW30HRLE-440i	105	125	52,5	32.977	65	51,5	63.230	60	14,0	182,1	0,90	3,59

12.2. SEC calculations with Energy Recovery Device

12.2.1 Case 1

Procedure to be followed in order to calculate the specific energy consumption associated with seawater reverse osmosis plant, is described in the preceding point 11.5.

Detailed calculations can be found in Annex nº5. But these results are outlined in next Table 21:

Table 21. Case1: Energy savings using ERD-PX

Energy consumed by HPP	Energy consumed by BP	Permeate m3/h)	SEC without ERD	**SEC with ERD**	**Energy savings**
155,54	6,29	60	5,57	**2,70**	**51,58%**

12.2.2 Case 2

Detailed calculations can be found in Annex nº6. But these results are outlined in next Table 22:

Table 22. Case2: Energy saving using ERD-PX

Energy consumed by HPP	Energy consumed by BP	Permeate m3/h)	SEC without ERD	**SEC with ERD**	**Energy savings**
121,62	4,21	60	4,36	**2,10**	**51,90%**

12.2.3 Case 3

Detailed calculations can be found in Annex nº7. But these results are outlined in next Table 23:

Table 23. Case3: Energy savings using ERD-PX

Energy consumed by HPP	Energy consumed by BP	Permeate m3/h)	SEC without ERD	**SEC with ERD**	**Energy savings**
137,46	5,71	60	4,95	**2,39**	**51,80%**

12.2.4 Case 4

Detailed calculations can be found in Annex nº8. But these results are outlined in next Table 24:

Table 24. Case4: Energy saving using ERD-PX

Energy consumed by HPP	Energy consumed by BP	Permeate m3/h)	SEC without ERD	**SEC with ERD**	**Energy savings**
99,29	2,94	60	3,59	**1,70**	**52,54%**

12.3. Results

For a better visualization of the initial requirements and results obtained, a summary can be consulted in next Table 25:

Table 25. Summary of simulations

	Case 1	Case 2	Case 3	Case 4
DRINKING WATER REQUIREMENTS				
TDS Concentration (mg/L)	≤ 500			
Boron (mg/L)	≤ 1.0			
FIXED VALUES				
Permeate (m3/h)	60,0			
Recovery	48%			
Average Flux (Lmh)	14,0			
FEED SEAWATER				
TDS Concentration (mg/L)	38000		33000	
Temperature (ºC)	15		26	
DEVICES				
High Pressure Pump				
Manufacturer	Flowserve	Danfoss	Flowserve	Danfoss
Global efficiency (pump-motor)	0,719	0,851	0,719	0,851
Booster Pump				
Manufacturer	ERI	ERI	ERI	ERI
Global efficiency (pump-motor)	0,679	0,743	0,679	0,743
Membrane				
Model FilmTec	SW30XHR-440	SW30HRLE-440i	SW30XHR-440	SW30HRLE-440i
Active area (m2)	40,9	40,9	40,9	40,9
Feed seawater (m3/h)	25,0	30,2	25,0	30,2
Pressure Exchanger				
Model ERI	PX-220	PX-Q300	PX-220	PX-Q300
Efficiency	0,972	0,980	0,972	0,980
RESULTS				
Feed				
Pressure (bar)	68,9	63,9	61,1	52,5
TDS Concentration (mg/L)	38192	38190	32975	32977
Concentrate-brine				
Pressure (bar)	67,6	62,6	59,7	51,5
TDS Concentration (mg/L)	73350	73347	63330	63230
Permeate				
TDS Concentration (mg/L)	84,09	113	72,33	182,1
Boron (mg/L)	0,39	0,53	0,36	0,90
ENERGY REQUIRED (kWh/m3)				
Without Energy Recovery Device	5,57	4,36	4,95	3,59
With Energy Recovery Device - PX	2,70	2,10	2,39	1,70
Energy savings	51,53%	51,83%	51,72%	52,65%

13 CONCLUSIONS

All cases studied in this simulation comply with drinking water requirements and with low energy consumption. However, if we do a careful analysis, we can highlight the following points:

- In any case, it is always recommended the use of energy recovery devices, because we can reduce energy consumption by more than 51%.
- If our SWRO plant will be located at a sea with high salinity concentration seawater, the use of devices with normal energy efficiency maybe it could be interesting if we do not have enought budget to deal with price of high efficiency devices, because the specific energy consumption 2,70 kWh/m3 remains low. However, we have to assume that the final costs along the plant cycle, will be more expensive.
- The results show that the use of high energy efficiency devices is more significant if the seawater concentration is minor. In our case, for the high salinity concentration feedwater, the energy savings achieved with high energy efficiency devices is 22,22%, while the use of these high efficiency devices in a low salinity concentration seawater, brings energy savings around 28,87%.
- It need to be appointed that in terms of energy consumptions, SW30HRLE-440i membrane has better performance (lower consumption) than SW30XHR-440 membrane. However, in terms of permeate quality, SW30XHR-440 has better results than SW30HRLE-440i (see Table 25). But I have chosen SW30HRLE-440i as a high energy efficiency device because the goal of this thesis is to obtain the lowest specific energy consumption.
- The lowest specific energy consumption obtained was 1.70 kWh/m3 of permeate water, at the expense of worst permeate quality of the four cases examined.

This work is intended for administrations (or private entities) who wish to built a SWRO plant, in a way that depending on the conditions of the future plant location and devices desired, they could be known in advance how much energy savings can be achieved and permeate quality can be obtained, and thus to define the most suitable location for the plant and the minimum conditions required in terms of equipements desired and drinking water requirements and in this way, they can put up for tender execution of the works with the correct requirements and budget.

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Annex nº1. Case 1 : Simulation results

Annex nº2. Case 2 : simulation results

Annex nº3. Case 3 : Simulation results

Annex nº4. Case 4 : Simulation results

Annex nº5. SEC calculations case 1

Annex nº6. SEC calculations case 2

Annex nº7. SEC calculations case 3

Annex nº8. SEC calculations case 4