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Energy Recovery Devices in Seawater Reverse Osmosis Desalination Plants with Emphasis on Efficiency and Economical Analysis of Isobaric versus Centrifugal Devices

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Energy Recovery Devices in Seawater Reverse Osmosis Desalination Plants with Emphasis on Efficiency and Economical Analysis of Isobaric versus Centrifugal Devices

by

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Abstract

With huge demands for potable water in regions lacking fresh water sources such as surface or ground water, various potential technologies have been explored for eliminating water shortage. Seawater emerged as a potential source and a major lifeline for such water-deprived areas. The development of seawater reverse osmosis (SWRO) technology proved to be a groundbreaking innovation, making it easier to extract pure water from seawater. Ever since its inception, SWRO technology has taken many leaps towards the development of energy efficient and high yielding systems. The reduction in energy consumption of desalination plants that were based on the SWRO technology emerged as a major driver of the technology revolution in this field. The improvement of membrane life and salt rejection, increase in recovery, and decrease in energy consumption has been the primary criteria for sifting through available technologies for incorporation in desalination plants. Many developments have, ever since, occurred in this direction. The membrane life has multiplied and the Total Dissolved Solids in the product are now as low as 100 mg/L. In addition, recoveries of 40-50% have been achieved. By recycling energy, many SWRO desalination plants have significantly lowered their total energy consumption. With the help of energy recovery devices (ERDs), it is now possible to decrease power consumption and increase efficiency of the seawater reverse osmosis desalination plant.

The first large-scale municipal SWRO plant was installed in 1980 in Jeddah, Saudi Arabia. This plant consumed 8 kilowatt-hours energy per cubic meter of water produced. This consumed energy was less than half of what was usually consumed by other

conventional distillation processes. However, the SWRO desalination technology has one disadvantage. The seawater, which is to be desalinated, is pressurized with the help of high-pressure pumps. A large amount of energy is consumed during this process. Once the desalination is complete, the remaining reject water has to be eliminated as waste. Since the brine reject produced in this process has a high pressure, simply dumping it back into the sea is a waste of energy. This pressure can be reused and thus, the energy could be recycled. This idea led to the innovation of energy recovery devices (ERDs) that prevent the wastage of energy in the SWRO process. The hydraulic energy in the highly pressurized reject brine can be re-used with the help of ERDs, and energy consumption can thus be reduced by significant high amounts. The development of ERDs helped in the set-up and operation of large-scale SWRO plants, and facilitated the economic viability of the desalination process. The energy requirements of conventional SWRO plants are presently as low as 1.6 kWh/m^3, making the process more cost effective and energy efficient than other technologies. About 80% of the total cost of desalinated water is due to energy consumption and capital amortization. The remaining costs are associated with other maintenance operations such as replacement of membranes and other components, labor associated costs etc.

Since energy consumption is the main determinant of final costs of the product, increasing energy efficiency of the plants is of primary concern. This paper deals with various energy recovery devices such as the Francis turbine, Pelton wheel, turbocharger, Recuperator, DWEER and Pressure Exchanger, used in SWRO desalination plants along with case studies associated with each of these. Special focus is given to the energy efficiency and costs associated with these devices. A brief discussion of the devices that are currently under investigation is also provided in the conclusion.

An analysis of isobaric versus centrifugal devices is also conducted in this work. A comparison between the energy recovery turbine (ERT) manufactured by Pump Engineering Inc. (PEI) and the pressure exchanger (PX) manufactured by Energy Recovery Inc. (ERI) energy recovery systems is performed using collected data from provided water analyses and respective manufacturers' device specifications. The different configurations used for this comparison were applied to the Jeddah SWRO desalination plant for a total productivity of 240,000 m³/day. As a result of this analysis, the specific energy consumption of the ERT and PX configurations were 2.66 kWh/m^3 and 2.50 kWh/m^3 respectively. Analysis shows however that although the PX configuration achieved the best specific energy consumption, the ERT was favored over it due to its lower capital and maintenance costs. Therefore, the final conclusion of this work, in this special case, is that the ERT configuration is more economical than the PX configuration.

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Chapter 1: Introduction

1.1 ERDs Operational Principles and Types

Areas with abundant seawater and scarcity of freshwater have turned towards desalination of seawater to meet their water requirements. The most widely used technology for this purpose is the Sea Water Reverse Osmosis (SWRO) process. SWRO possesses the capability of producing high quality potable water from a water source as unconventional as seawater. It is due to this fact that SWRO is gaining significance all over the world as a means of sustainable water supply. The process of reverse osmosis (RO) for desalination of seawater was introduced in the 1970s. Since then, alternatives have been sought for the reduction of operational costs associated with the process.

Following are some definitions and figures that will help us understand what a reverse osmosis process is and how it is.

- Osmosis: The tendency of water to flow through a semipermeable membrane into a more concentrated solution.
- Reverse Osmosis: The passage of water out of a solution when a pressure greater than the osmotic pressure is applied on the solution side of a semipermeable membrane.
- Semipermeable Membrane: A membrane that allows water to pass through but rejects most ions and molecules.
- Osmotic Pressure: The pressure needed to stop the flow of water through a semipermeable membrane.

- Reverse Osmosis Membrane (RO): RO membranes act as a barrier to all dissolved salts, inorganic molecules, and molecules with a molecular weight greater than approximately 100. Rejection of dissolved salts is typically 95-99 percent. Transmembrane pressures for RO typically range from 200 to 800 psi for seawater.

RO is a relatively new process compared to distillation and electrodialysis. As mentioned in the definitions, RO is semipermeable membrane separation process which separates the water from a high pressurized saline solution from the solutes or the dissolved salts and inorganic molecules by flowing through that membrane. The solution does not undergo any heating or phase change in this separation process. The major energy consumption phase in RO desalination technology is for applying enough pressure to the feed water to overcome the natural osmotic pressure.

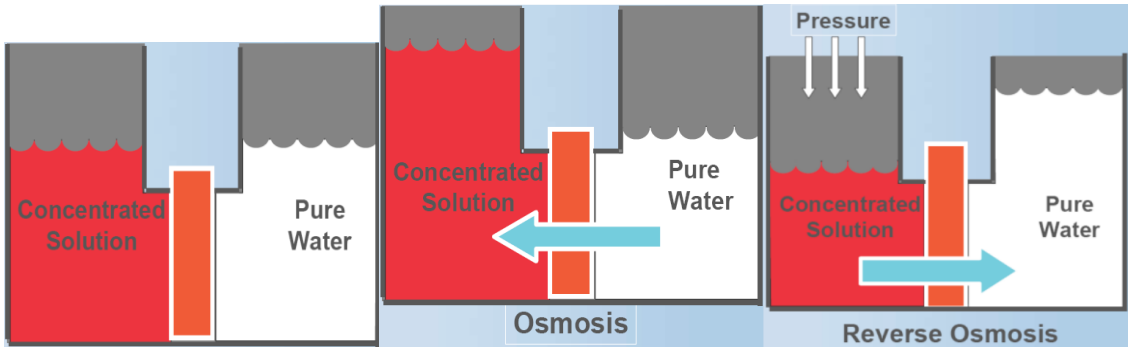

Figure 1-1: Reverse Osmosis Conceptual Illustration

The hope that the membrane technology used in this process would ultimately improve, later on, was just a part of the battle to "sell" the new technology. Yet, a search is on in full swing for the discovery of other ways and technologies that would make the new technology more cost effective.

RO desalination is an energy intensive process in which energy (electricity) consumption is one of the largest contributors towards the total costs of water supply.

The cost of the final product, i.e. water is increased due to an increase in energy consumption during the production process. In seawater RO desalination, a significantly large amount of energy is involved in pressurizing the seawater for driving it through the RO membrane. This pressurization is achieved with the help of a high-pressure pump, which is the most significant energy consumer in a SWRO plant. Desalination of brackish water of lower salinity requires lesser energy than that having higher salinity, at the same recovery. It is important to note, however, that brackish water desalination requires recoveries of 75% or above for optimal, economical and profitable operation. Another cause of concern is the difficulty involved in the handling and disposal of brine, which is a waste product of this process. Increase in required recovery beyond 75% in the desalination process of brackish water leads to a proportional increase in energy consumption. Higher recovery requires higher energy [1]. Thus, reduction in energy consumption is the most logical and effective way of making the RO desalination process of saline water more cost effective, thereby leading to a more sustainable water supply.

In the process of RO desalination, highly pressurized water is driven across the RO membrane. It works on the principle that when a net (positive) driving pressure is held at the feed side of the membrane, water passes through it, leaving the salts behind. Energy consumption occurs when water (raw feed) is driven through the membrane with the help of high-pressure pumps that supply the required pressure to attain a favorable flow rate. The salinity of feed water, the configuration of the process, the operating conditions such as recovery and driving pressure etc, directly affect the amount of energy required in the process. Several studies have investigated the amount of energy consumption during the cross flow processes. However, a specific assessment and delineation of the energy usage during RO desalination has not yet been done [1].

A huge amount of energy is expended to achieve the required pressure levels for the process, which is then rendered useless after the process ends. By this, it is implied that the energy used to raise the pressure of the seawater feed goes to waste when the remaining brine, which is also at high-pressure, has to be eliminated as a waste. A way had to be sought that would enable the reuse of the pressurized brine and would thus help in reuse of energy. The disposal of highly pressurized brine proved to be a major drawback of the system and led to an urgent need for the formulation of an efficient "energy recovery" process. This thesis is aimed at assessing the works on design and development of energy recovery devices, which aid in minimizing energy loss during seawater desalination. The advantages and disadvantages of most popular ERDs are discussed, along with case studies to exemplify the same. A thorough analysis of the cost and energy efficiency of each ERD is also done. Furthermore, a brief introduction on recent developments in ERDs is provided.

The main function of an energy recovery device would be to improve energy efficiency by harnessing spent energy from the reject and delivering it back to the feed. Several methods have been explored in this domain of energy recovery devices (ERDs), which are classified as follows:

- hydraulic to mechanical-assisted pumping
- hydraulically driven pumping in series
- hydraulically driven pumping in parallel

The hydraulic to mechanical-assisted pumping (see Figure 1-2) uses a turbine, which is attached to a shaft that is connected to a pump and a motor. The shaft operates on the main feed. The pump, to which the shaft is connected, may be of two types— a kinetic centrifugal type or a positive displacement type. Other devices used earlier include the Pelton wheel turbines and the Francis turbines, which are also referred to as reverse running pumps. The main shortcoming of the hydraulic to mechanical-assisted

pumping system is that it involves double energy conversion. The first conversion occurs when hydraulic energy of the brine is converted to mechanical energy of a rotating shaft. The second conversion occurs when the mechanical energy of the shaft is then converted to the hydraulic energy of feed [2].

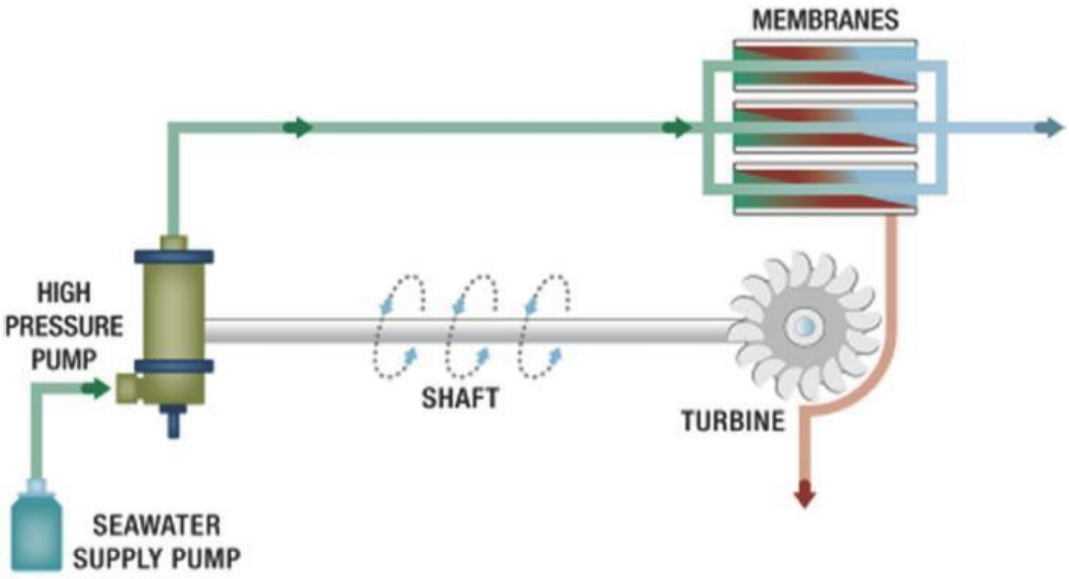

Figure 1-2: Hydraulic to Mechanical Assisted Pumping

This system of hydraulic to mechanical-assisted pumping is highly inefficient and does not significantly lower the costs associated with the process. Therefore, the search was still on for a more efficient ERD. Devices based on newer designs and technologies were then introduced. These devices drove a secondary assisting pump, thereby reducing the load on the main feed pump. In spite of its utility in reducing load and energy consumption, the reduction was not significant enough to make a considerable difference in the costs incurred during the process.

The hydraulically driven pumping in series belongs to the second class of ERDs. It has an impeller and a turbine, which are coupled to a shaft within the same casing. The main feed pump and the impeller and runner are placed in series. PEI's "hydraulic

turbocharger", Grundfos' "Pelton-drive pump" and FEDCO's "hydraulic pressure booster HPB" are examples of the second class of ERDs. These gained significant acceptance among consumers, especially in small and midsized desalination plants. Their full-fledged use in larger systems, like the plants in the Mediterranean and the Middle East for instance, was limited because of their size limitations. Moreover, these systems failed to address the problem of converting energy from hydraulic to mechanical and then back to hydraulic, thereby hindering the efficiency of operation. They were, however, an improvement over the first class of ERDs.

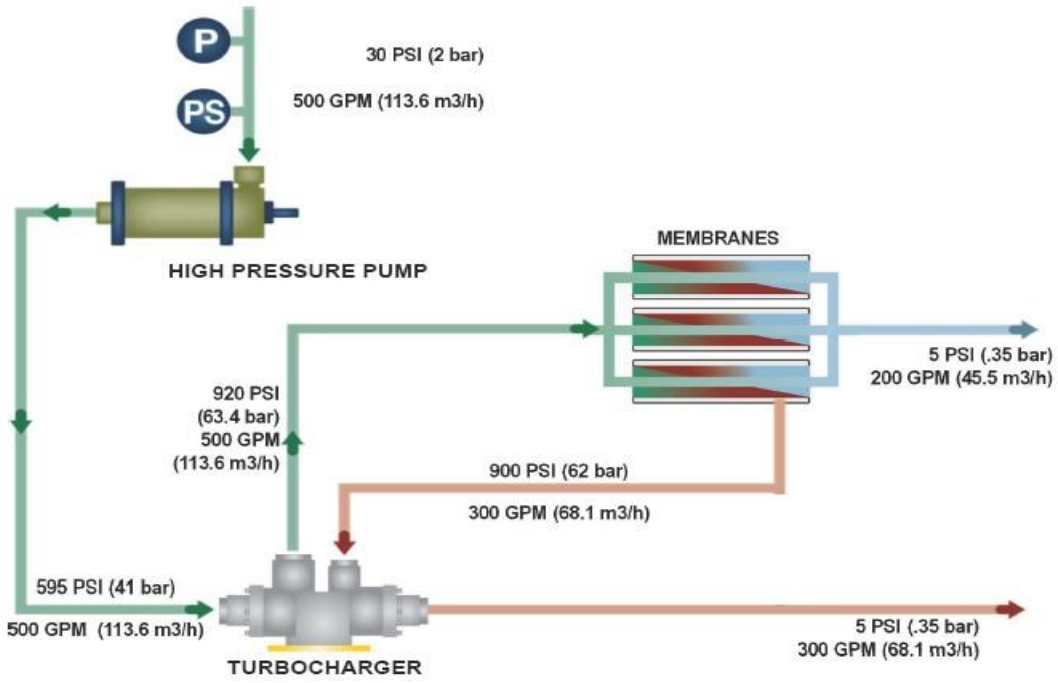

Figure 1-3: Hydraulically Driven Pumping in Series

The late 1980s saw the emergence of a new technology that functioned on the "theory of work exchange". It involved a direct transfer of hydraulic energy of brine to hydraulic energy of feed, lacking the "drag" that would have resulted from the passage of the water through the shaft. This brought the technology closer to 90% efficiency [3].

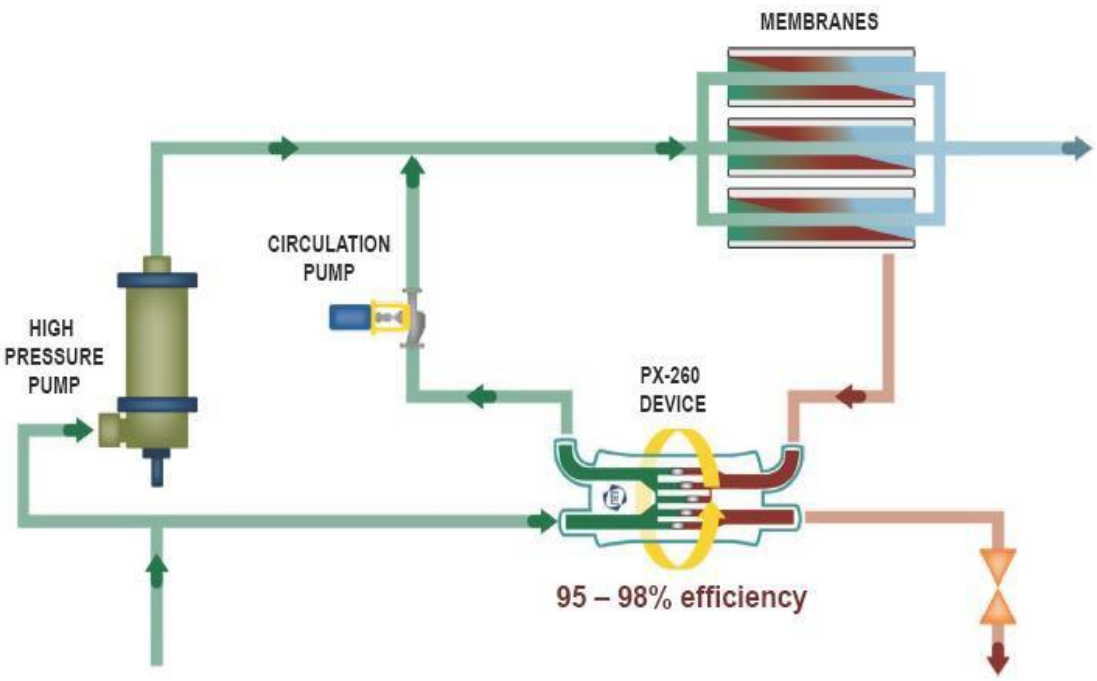

Figure 1-4: Hydraulically Driven Pumping in Parallel

This "theory of work exchange" led to the development of the third class of energy recovery devices, namely, hydraulically driven pumping in parallel. It employs the pumping of a 'buffer separating feed' or of freely reciprocating pistons. The main feed pump is placed in parallel to the device and operates on a portion of the feed, which is equal to the amount of the permeate. The device operates on the other portion of the feed whose amount is equal to the spent brine. This is based on the concept of "work exchange". In these ERDs, the hydraulic energy of brine is directly converted to hydraulic energy of feed, leading to over 90% energy efficiency. A new work exchanger device was developed based on a technology in which the number of stationary channels is fixed. A piston divides each of these channels into two working volumes, one of which is in association with brine and the other (opposing one) is in association with the feed. An exchange process ensues in these partitions, which is synchronized using

valves. A similar process is employed in other work exchangers wherein multiple channels are connected to a spinning rotor. The PX (pressure exchanger) is one such work exchanger. This device is also based on the same principle, in which, hydraulic energy of brine is directly converted to hydraulic energy of feed via direct contact between the two. This design disposes the requirement of valves, as there is no need for synchronizing the brine and the feed. The spinning rotor acquires a speed of 1500 rpm due to the angular momentum induced by the fluid. Because of the high speed, the fluid transit time is only $1/30^{th}$ of a second, which is much less, to allow the mixing of the feed and the brine. This is thus an advantageous process. The intermixing of the feed and brine is further eliminated with the help of feed buffer. Along with the rotor's rotation, the feed buffer in the channel also reciprocates. The mixing decreases with an increase in the size of the buffer. Furthermore, the cyclic amount of feed and brine flowing through the device also decreases. By increasing the speed of the rotor, the flow rates of the brine and the feed can be increased. This increase is dependent on the conditions of the system, apart from the design of the rotor. Thus, the device's performance is limited to a small capacity, with very narrow feed and brine conditions.

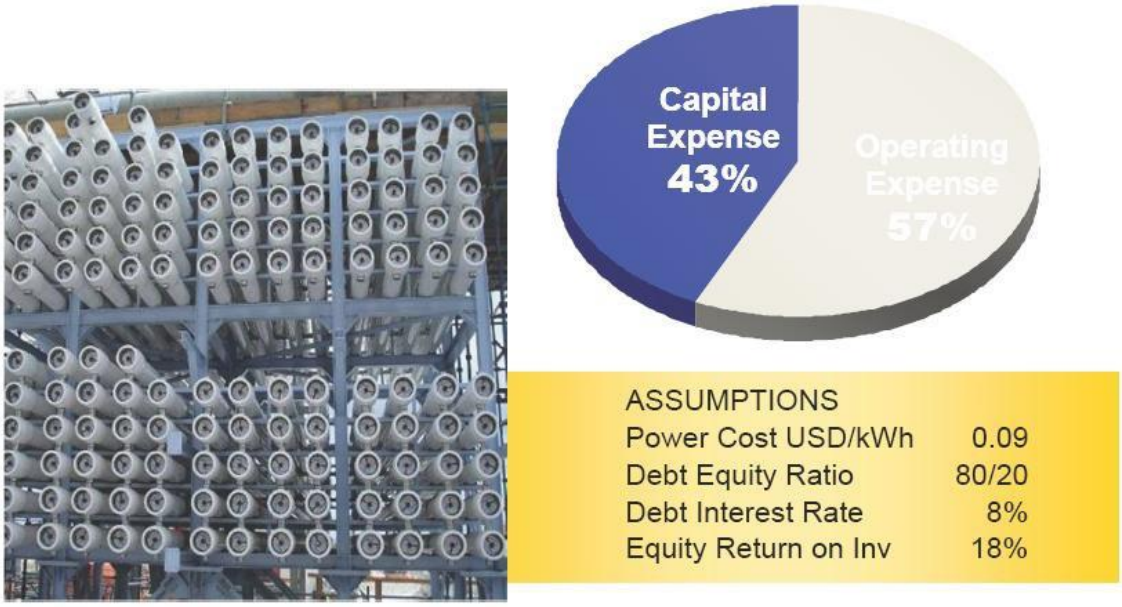

Figure 1-5: Desalination Plant Capital & Operating Costs

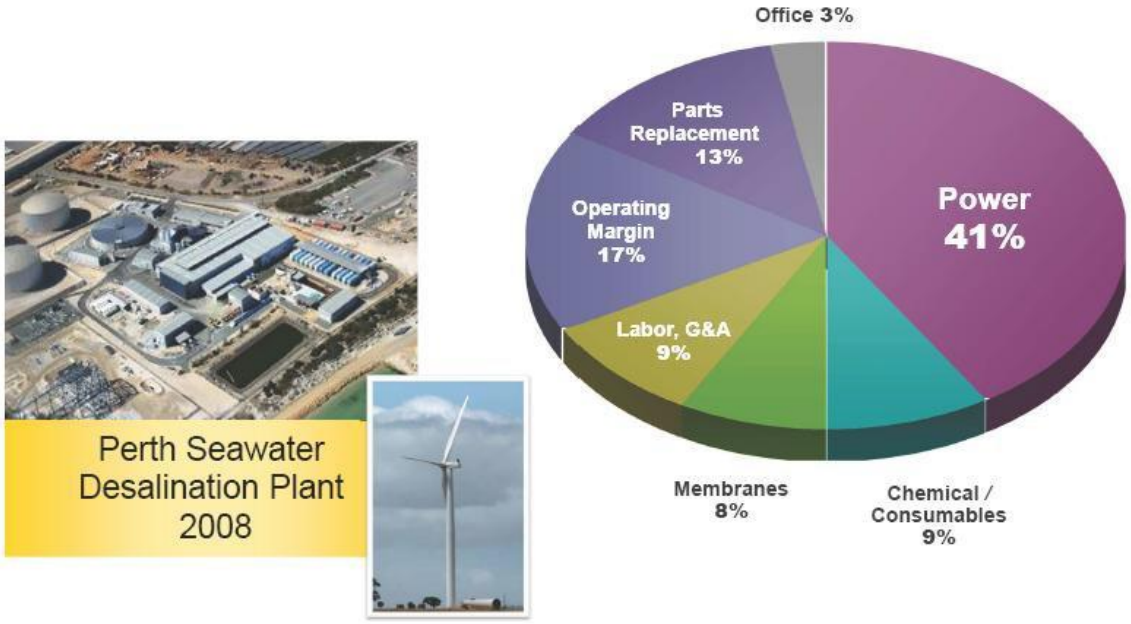

Figure 1-6: Operating Expenses—Breakdown

This limitation can be overcome by using an ERD, in which the rotor's speed is controlled externally, making it independent, to enable manual and calculated adjustments for the optimization of the performance. The performance optimization would be made possible by allowing an exchange of energy for a greater volumetric flow, along with the elimination of mixing between the feed and brine [2]. Two designs of work exchange dominated the ERD market. These were developed after many years of research and development. One of these designs employs pistons and valves for the exchange process and the other design employs a spinning cylindrical rotor. These designs have enabled the achievement of high efficiency and have thus reduced the total costs incurred during operation of desalination plants [3].

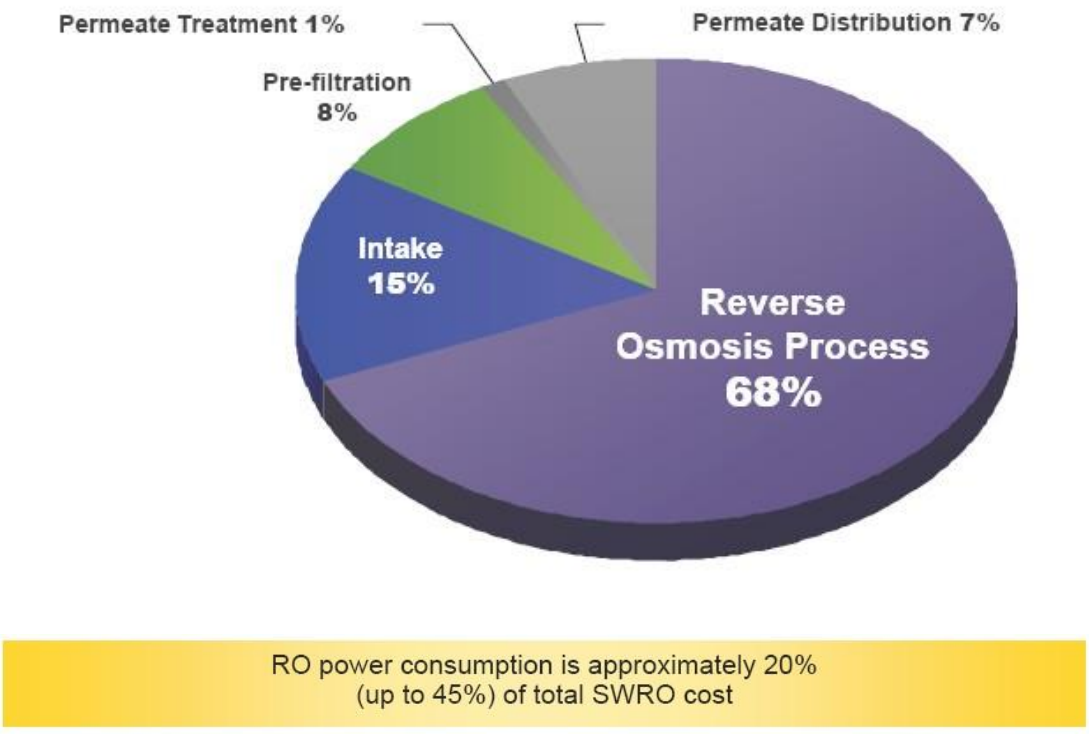

Figure 1-7: Power Use—Breakdown (Seawater RO)

Source: Affordable Desalination Collaboration, 2008

1.2 Literature Review

Farooque et al [4] have explicitly described the performance and efficiency of various ERDs used in several Saline Water Conversion Corporation (SWCC) SWRO desalination plants in Saudi Arabia. They compared the efficiencies of these ERD systems based on operating conditions for one year and also assessed their effect on the high-pressure pump's total energy consumption and savings, along with an assessment of the energy loss incurred during the process stream of the desalination plants. The mean efficiency of the assessed ERDs varied from 3.2% to 65%, enabling 1.5% to 27% savings on the high-pressure pump's total energy consumption [4]. The mean power consumption of the pump ranged from 5.56 to 7.93 kWh / m^3 [4]. A significant amount of energy was wasted due to throttling, which consumed about 6.4% - 21.8% of the total energy supplied to the high-pressure pump [4].

A brief description of the energy recovery technology used during the desalination process in large plants was provided by Peñate and Rodríguez [5]. They described the modifications needed for the replacement of Pelton turbines with isobaric chamber devices. An exhaustive examination of the achievable levels of energy efficiency of these systems was also done. An emerging technology based on the principle of pressure work exchange was put forth by Al-Hawaj [2]. The device employed a rotating member with multiple free-sliding double-sided ball pistons that functioned on pressure exchange between fluids that were pressurized at varying levels. He also discussed the technical aspects of the work exchanger apart from assessing the predicted efficiency based on qualitative comparisons with other ERDs [2].

Andrews and Laker [6] provided a historical overview of large scale ERDs that work on the principle of work exchange, beginning with the application of SWRO in 1975 to the present state of technology in desalination. As is evident from their work, technology

based on work exchange has evolved tremendously since the time of its inception. They also described twelve years of the application of this technology in desalination plants.

Furthermore, an important and original calculation model was developed by Migliorini and Luzzo [7] to account for the different conditions of sea water based on carbonate equilibrium. The use of this classical equilibrium system for calculations enabled the formulation of a complete mass and chemical balance of the system, along with the other characteristics of water. This model of calculation is not dependent on the characteristics of the membrane and so, can be used for a quick designing of the plant.

Farooque, Ali and Al-Reweli [8] have stated that Francis Turbines were popular in the early days of SWRO technology owing to their ease of use and simplicity. As briefly discussed in the previous section, FT uses kinetic energy derived from brine coupled with the pump motor of the main feed to minimize the loss of energy during transfer from one fluid to the other. Due to their limited efficiency, which was below 75%, they lost their popularity and have been replaced by more efficient devices.

Baig [9] has investigated the theory of energy double dipping in hydraulic to mechanical assisted pumping devices, Pelton wheels and Francis Turbines. He stated that the maximum efficiency of Pelton wheels ranges between 80 to 85%. He emphasized the fact that the Pelton wheel and the FT share a common feature of transferring the energy recovered from brine back to the high pressure pump by coupling them to a common shaft. Computing total loss of energy, the energy lost by the high pressure pump and the reduction in the wheel's energy efficiency were taken into account. This is what was referred to as "double-dipping" in energy efficiency.

Farooque [8] rendered the ERT turbocharger hydraulically driven pumping in series class of ERDs similar to the Pelton turbines only however lacking a motor. Nevertheless, unlike Francis turbines and Pelton wheels, the turbocharger has been specifically designed for RO systems. Pump Engineering Inc. (PEI) and the Fluid Equipment

Development Company (FEDCO) are examples of companies that currently manufacture turbochargers. The function of this device is the transmission of hydraulic energy from reject brine to the feed. These two fluids may be at a different pressure and flow rate. In this system, there is no need of electrical cooling and other such requirements.

Lechugal and de Tauro [10] presented Aqualyng as the only company that has its own patented ERD. The Recuperator ERD employs the pressure of the reject to pressurize the feed, and this process is maintained by the flow of brine from the membranes. Thus, the feed and the reject acquire the same pressure and flow, without intermixing with each other. Since this may induce a drop in pressure across the membranes and the Recuperator, another pump is required to boost the pressure. The HPP's capacity must be equal to the product flow from the system. In order to fulfill this requirement, only an HPP, which is smaller than the typical HPPs, is required. An HPP, which is 60% smaller would provide a 40% recovery. This process can save a significant amount of energy.

Andrews [6] described the DWEER^{TM} energy recovery device to have two pressure vessels arranged in parallel. To avoid interrupting the flow of the reject, while one vessel is under operation, the other vessel is stationary, and has fresh feed. The pressure from the reject stream is transferred to the feed stream through a piston and the intermixing between the feed and reject is kept at a bare minimum. As the piston is designed in such a way that it has the least drag, the energy transfer between the two fluids is theoretically 100%. Therefore, the direct exchange of energy between the two fluids, i.e. the reject and the feed is highly efficient when compared to ERDs that rely on the conversion of energy by shaft of the turbines based on the centrifugal principle. In the DWEER system, by the time the piston in the operating vessel completes its working stroke, the other vessel is completely filled with feed, and the functions are switched.

MacHarg [11] demonstrated how the PX device pressurizes the feed water directly. This is in contrast with the energy recovery turbine, where the energy of the concentrate is converted to mechanical energy by rotating the shaft and thus recovering energy. Because of the direct pressurization with PX device, there are no losses due to absence of the transformation process in this case. This results in extremely high energy efficiency achieved by the PX devices. This will considerably reduce the power consumption of the SWRO plant employing these PX devices.

1.3 Investigation Objectives

The objective of the present thesis is to evaluate and discuss the history and evolution of the different ERDs, apart from assessing the differences in their design and operation. The efficiencies of all the discussed devices are also presented. This investigation will largely focus on the energy efficiency and economy of use of isobaric devices in comparison with centrifugal devices.

There are eight main chapters in this thesis. Beginning with chapter-two to chapter-seven, the concept of ERDs along with their historical aspects is introduced. The devices are arranged in the order of their introduction in desalination technology, beginning with the Francis turbine, followed by the Pelton wheel, then the turbo charger, followed by the Recuperator, and finally, ERI's Pressure Exchanger, PX. The last chapter, i.e. chapter-eight emphasizes on the energy efficiency and cost effectiveness of isobaric devices versus centrifugal devices, in addition to an evaluation of other newly designed devices that have undergone intensive research and development.

Chapter 2: Francis Turbine / Reverse Running Pump

2.1 History and Design

Francis Turbines (FT), also known as reverse running pumps belong to the first class of ERDs, i.e. hydraulic to mechanical-assisted pumping, as discussed previously in the introduction [2]. These devices were the first to be employed in SWRO municipal scale desalination plants. Pelton wheels later replaced these in 1980s because of their higher efficiency [12].

Figure 2-1: Francis Turbine with Generator

From the English Wikipedia. Taken By 13:14, 28 Mär 2004 Stahlkocher

2.2 Disadvantages of the Francis Turbine

The earliest identified disadvantage of FT was that the flow range and pressure required for achieving maximum efficiency of operation was narrow and limited. In addition, these ERDs did not generate energy until the design condition reached about 40% [8]. In SWRO desalination plants, especially those in the Middle East and similar regions, variations in temperature of the place and changes in membrane permeability occurring due to fouling of the membrane or due to ageing, inversely affect the efficiency of these devices [8].They are also difficult to control and pose a significant challenge in maintenance. The hydraulic energy that is recovered by these devices is mechanically transferred to the driver, similar to the Pelton wheel. The assembly involves a clutch between the turbine and the pump. The FTs were inefficient and the amount of energy consumed increased with change in the operation conditions. They were also inefficient for a low range of flow. Because of the disadvantages of these devices, they were replaced with those that were more efficient [13].

Figure 2-2: The Trinidad SWRO Plant Implementing Francis Turbine

Other devices that replaced FTs were more efficient as they directly transferred the pressure to feed water from the reject pressure. The energy recovery achieved through these devices was higher than that of FTs, however, they were not yet used in large SWRO plants [14].

SWRO plants at the SWCC (Saline Water Conversion Corporation) at Al-Jubail and Yanbu in Saudi Arabia use FTs as ERDs [8]. Their performances are evaluated in the case studies that follow.

2.3 Case Studies

2.3.1 Al-Jubail SWCC SWRO Desalination Plant

The SWCC's SWRO desalination plant at Al Jubail, Saudi Arabia, has fifteen trains, four of which operate on "Toray spiral wound membranes". The other eleven operate on "DuPont B-10 twin hollow fine fiber membranes" [4]. The trains at this plant obtain a recovery of about 28.6–35%, with the feed flow remaining constant at 723 m^3/h [4]. The HPP's and ERD's specifications at the Al Jubail plant are given in Table 2-1. At this desalination plant, the temperature of the feed (seawater) varies from 17 to 35°C and the pressure of the feed lies in the 62.4–84.2 bar range [8].

Table 2-1: Specifications of HPP and ERDs Used at Al-Jubail SWRO Plant

High pressure pump details	Specification	Rated for 900 m^3/h 0.88 at 81 bar
	Power Factor	0.88
	Voltage (kV)	13.8
	Overall efficiency (%)	79.9
Energy recovery device details	Specification	Rated for 485 m^3/h at 71.5 bar
	Overall efficiency (%)	81.85

The Francis turbine or the reverse running pump was preferred instead of the Pelton wheel at the SWRO desalination plant at Al Jubail. This was because of

- The availability of standard pumps made of materials that were resistant to seawater.
- Lack of Pelton wheel turbines of suitable capacity for use in seawater desalination processes
- The operational experience associated with pumps and turbines similar to the FTs in the SWCC-SWRO plants.
- High costs of maintaining the Pelton wheel turbines, especially during replacement of the runner blades.

The use of a direct flange connection for connecting the ERT to the drive motor is preferred over the use of a clutch connection. Maintenance needs such as the replacement of the rollers call for frequent discontinuation of the ERTs in desalination plants [9]. The major characteristics of the design employed in these ERDs are described as follows:

- The ERD belongs to the first class and uses a Francis turbine, which is the reverse running pump type, manufactured by Ingersoll Dresser from UK
- The maximum recovery of power is 33%, which amounts to 760 kW and the capacity is 485 m^3 / h.
- The Total Dynamic Head is 71.5 bar

Prior to the evaluation of the efficiency and performance of the SWRO desalination plant at Al Jubail, the elementary principles and formulae that will be used throughout the case studies are recapitulated here:

a. Specific energy consumption (SEC):

The specific energy consumed (SEC) by HPPs is expressed in kWh/m^3. The SEC is calculated by dividing the total electricity input to the HPP (in kW) with the total product flow (m^3/h). The power input is calculated using a standard equation [4].

$$P_{ia} = 1.73 \times V \times I \times y \quad (1\text{-}1)$$

where,

P_{ia} = actual power input in kW

V = voltage in kV

I = current in A

y = power factor, decimal.

The power and voltage factor used for these calculations are given in Table 2-1 [4].

b. Percentage energy saving by ERD (ES):

Percentage energy saving by ERD is calculated using the formula:

$$ES_{erd}(\%) = (ES_{erd} / P_{ie}) \times 100 \quad (1\text{-}2)$$

where,

$$ES_{erd} = P_{ie} - P_{ia} \quad (1\text{-}3)$$

where the actual power input, P_{ia}, is obtained from the Eq. (1-1) and the expected power input, P_{ie}, is calculated using the equation given below [14]:

$$P_{ie} = WP_{on} / \eta_p \quad (1\text{-}4)$$

where,

η_p = overall efficiency of HPP

WP_{on} = net hydraulic power output

The WP_{on} is calculated using the following equation:

$$WP_{on} = WP_d - WP_s \quad (1\text{-}5)$$

The hydraulic power (WP) is calculated using the equation given below [8]

$$WP = (p \times Q) / 36 \quad (1\text{-}6)$$

where,

WP_d = hydraulic power at the discharge of HPP, kW

WP_s = hydraulic power at the suction of HPP, kW

p = pressure, bar

Q = flow rate, m^3/h [8].

c. Efficiency of ERD (η_{erd})

The overall efficiency of ERD includes the ERD's efficiency in addition to the loss in efficiency because of the flexible coupling that connects it to the HPP. The overall efficiency is thus calculated as follows [8]:

$$\eta_{erd} = (WP_{in} / P_{on}) \times 100 \quad (1\text{-}7)$$

where, net hydraulic power input, WP_{in} to ERD is calculated using the following equation:

$$WP_{in} = WP_r - WP_{fr} \quad (1\text{-}8)$$

where, WP_r represents the hydraulic power of the reject entering the ERD; and WP_{fr} represents the hydraulic power of the final reject exiting the ERD, which is calculated using the Eqns. (1-6). The net power output, P_{on}, from the ERD is nothing but the power saving achieved by the ERD, ES_{erd}, and is calculated using the Eqns. (1-3).

d. Percentage throttle loss (TL)

A percentage of energy is lost while throttling the discharge pressure with a valve. This throttle loss is calculated using the equation given below:

$$TL(\%) = [(WP_{ut} - WP_{dt}) / WP_{ut}] \times 100 \quad (1\text{-}9)$$

where,

WP_{ut} = hydraulic power upstream of throttle valve

WP_{dt} = hydraulic power downstream of throttle valve

The hydraulic power is calculated using the Eqns. (1-6) [8].

The minimum, maximum and the average values of all the above four parameters for the trains discussed in this case study are given in Table 2-2. As calculated, the average SEC of the plant is 7.42 kWh/ m^3 and the average SEC of each train varies from 6.64 kWh/ m^3 to 8.74 kWh/ m^3 as given in Figure 2-3 [4]. It is important to note here that the train, whose available data pertaining only to the winter months (Train B), was found to have the lowest SEC, while Train L, whose data was available only for the summer months, had the highest SEC. It is therefore inferred that at the Al Jubail plant, the performance efficiency of ERD differs with changing seasons, especially because of the variation in temperature. Such a temperature dependence was not observed in other plants [4]. Therefore, seasonal changes affect ERD performance as is reflected by the changes in SEC [8]. The dependence of the SEC and η_{erd} values on change in the temperature and pressure of the reject observed for the Train F, as shown in Figure 2-7 and Figure 2-8 indicate that ERD efficiency increases with increase in the pressure of the reject. Low feed temperatures result in higher pressure of the reject, which in turn reduce the SEC and increase ERD efficiency.

Table 2-2: Energy Consumption and ERD Efficiency at Al-Jubail Plant

	Energy consumption by HPP, kWh/m^3	Energy saving by ERD, %	ERD efficiency, %	Throttle loss, %
Minimum	6.38	11.93	33.48	13.37
Maximum	9.74	32.21	72.51	36.1
Average	**7.42**	**22.63**	**54.83**	**21.77**
Std. dev.	0.54	4.54	9.29	4.01

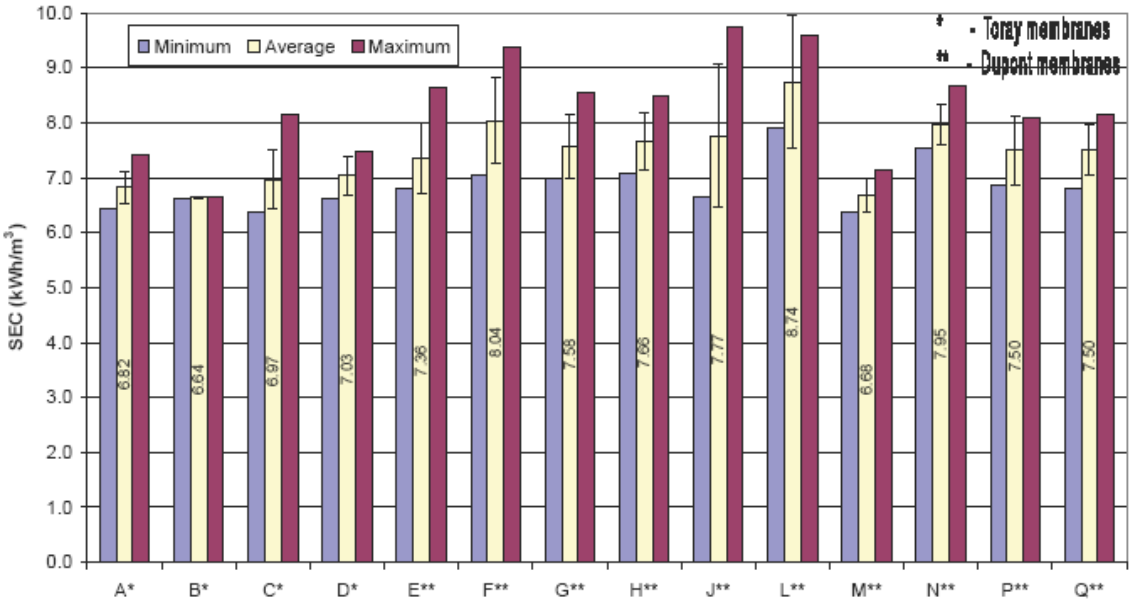

Figure 2-3: SEC by HPP of Al-Jubail SWRO Plant Trains

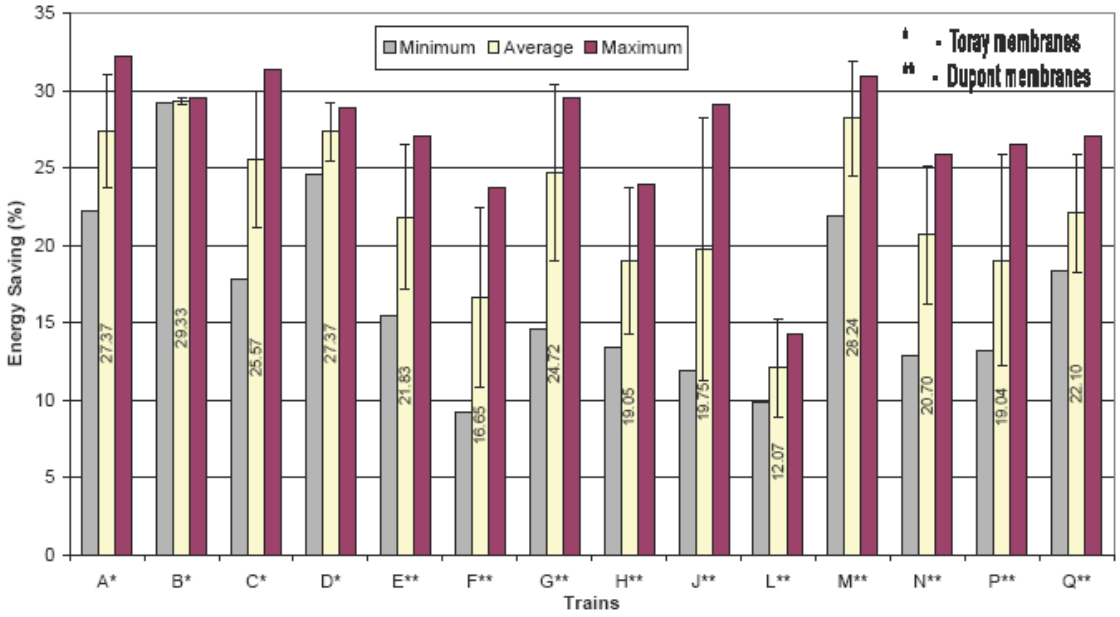

Figure 2-4: Energy Saving by ERDs of Al-Jubail SWRO Plant Trains

Another notable observation is that while the average SEC value is expected to be almost constant because of the maintenance of a constant feed flow and discharge pressure in the HPP, it is found that the average value varies widely. This may be due to the variation in ES values, with Train L having the least value of about 14.3% and the Train B having the highest value of about 29.3% (Figure 2-4) [4]. Furthermore, this variation in the ES value of ERD may be due to the differing η_{erd} value, with Train L having the least value of about 40.3% due to low reject pressure owing to the high temperature of the feed, and Train B having the highest value of about 72.3% due to high reject pressure owing to low temperature of the feed (Figure 2-5) [4]. The average ES value of the whole plant was 22.6%, ranging between a minimum of 11.9% and a maximum of 32.2%. The plant's average η_{erd} value was 54.8%, ranging between a minimum of 33.5% and a maximum of 72.5% (Table 2-2) [4].

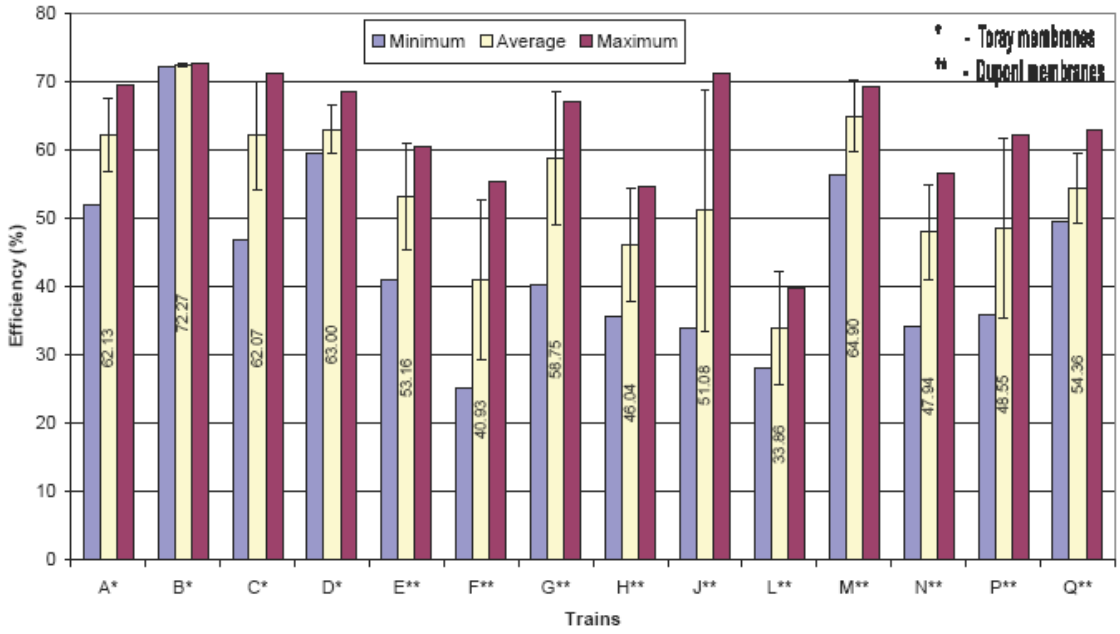

Figure 2-5: Efficiency of ERDs of Al-Jubail Plant Trains

As given in Figure 2-7 and Figure 2-8, the performance of ERD varies with the conditions of the system. The pressure of the reject, which varies from 56 to 82.1 bar, depends on the change in the temperature of the seawater, which varies from 17 to 35°C [4].

The TL value observed for all Trains vary significantly, with 15.6% being the lowest and 32.9% being the highest (Figure 2-6). The average TL of the whole plant was 21.8%, with 13.4% being the lowest and 36.1% being the highest (Table 2-2) [4]. It is evident that the performance of FTs is influenced by changes in the pressure and flow of the feed.

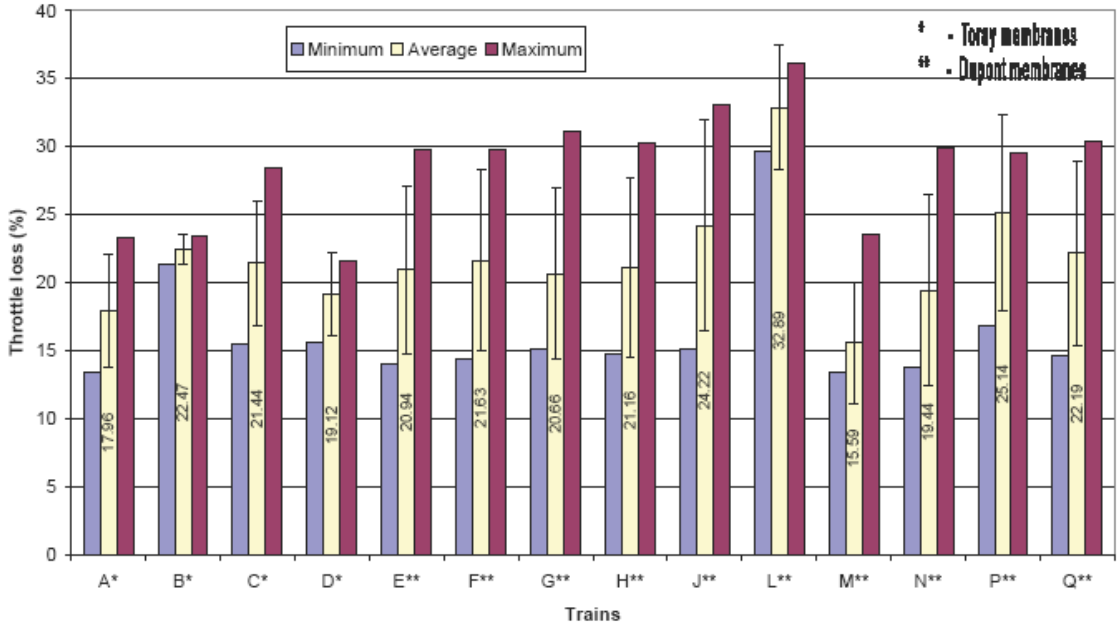

Figure 2-6: Energy Lost by Throttling in Al-Jubail SWRO Plant Trains

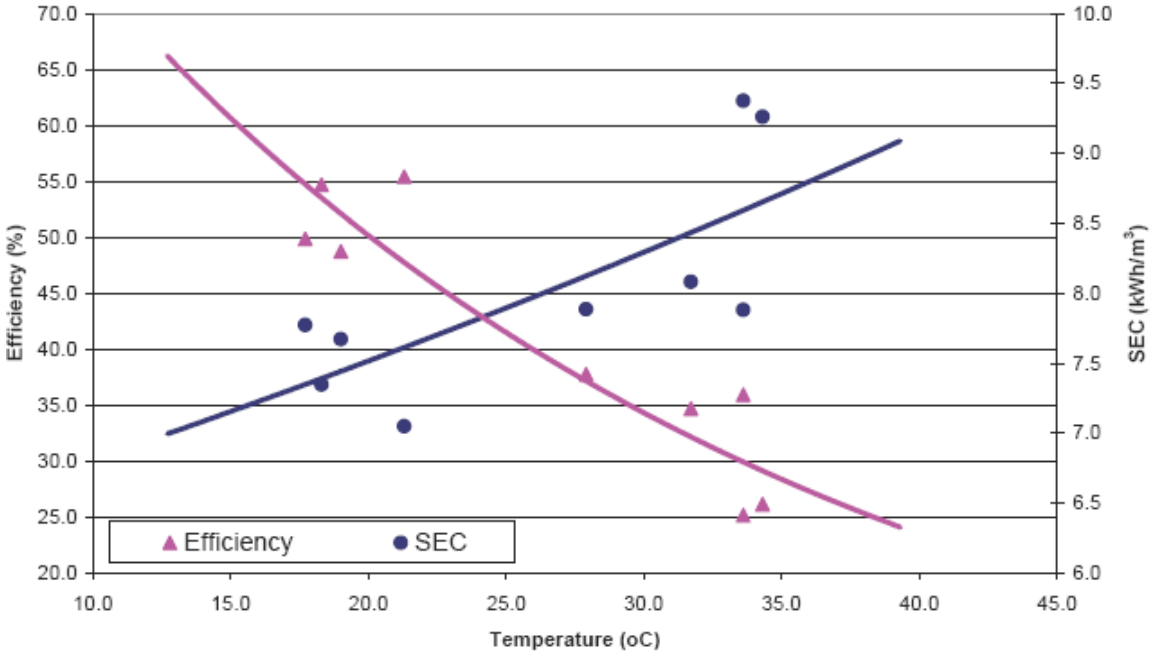

Figure 2-7: ERD Efficiency and SEC VS Feed Temperature at Al-Jubail Plant

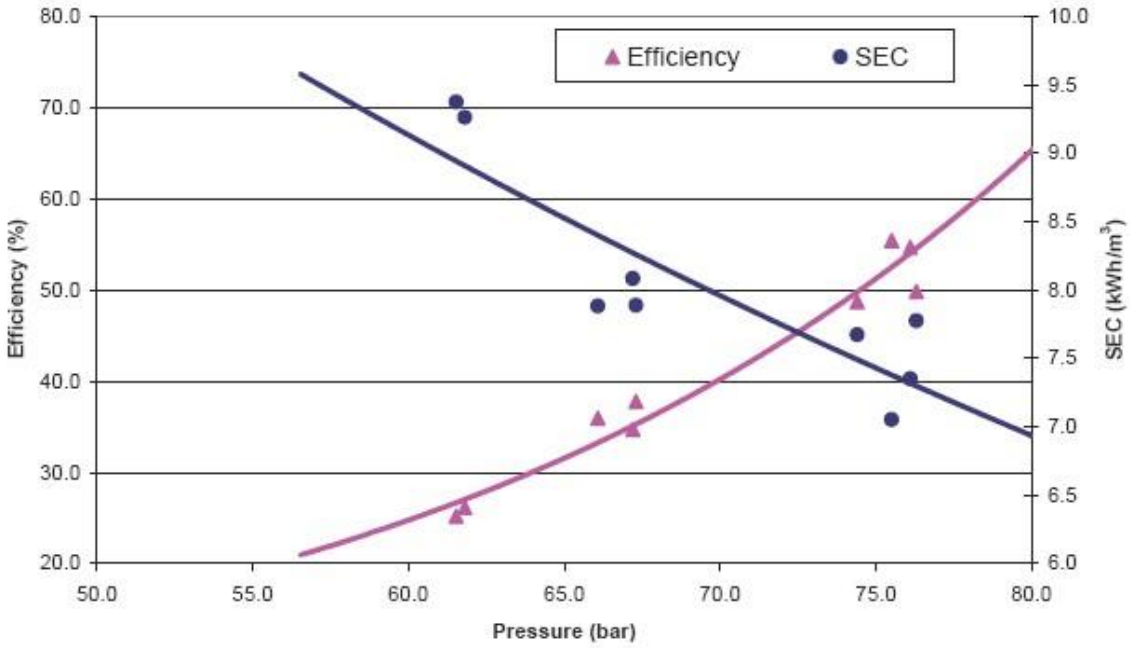

Figure 2-8: ERD Efficiency and SEC VS Reject Pressure at Al-Jubail Plant

The optimum performance of the ERD is affected when non-ideal conditions of operation are employed. Thus, it is ideal to consider the combined effect of interaction between the pump and the ERD that are operating in unusual conditions [8]. Therefore, the detailed analysis of the FT and pump system used in the SWRO desalination plant at Al Jubail was done. The efficiency of the plant influenced by the operating conditions was studied for one year. In addition, total energy consumption and saving by the HPP was also observed [4].

2.3.2 Yanbu SWRO Desalination Plant

The SWRO desalination plant at Madinat Yanbu Al-Sinaiyah, the Yanbu Industrial City in Saudi Arabia comprises 15 trains [4]. The HPP of each of these trains is coupled, via flexible coupling, with a Francis turbine [8]. Of the 15 trains at this plant, some operated at a 660 m^3/h reject flow while others operated at a 750 m^3/h reject flow. The

ones at a lower reject flow used new membranes while those at a higher reject flow used old membranes [8]. The remaining ones operated at a 750 m^3/h reject flow using old membranes initially, following which, they reached a lower reject flow of about 660 m^3/h due to replacement of the old membranes with new ones. Trains with higher reject flow had lower recovery rates (32%), while those with lower reject flow had higher recovery of about 35% [8]. In spite of this, the product flow for all the trains at the plant remained constant at 350 m^3 / h. Apart from lowering the reject flow, new membranes were also found to increase the pressure of the reject, with old membranes giving a reject of 6 bar compared to 13 bar by new membranes [8]. Many developments have taken place in the design and technology of the SWRO desalination plants [15]. At the Yanbu SWRO desalination plant, the salinity of saltwater ranges from 42,000 to 45,000 mg/L [4].

The mean SEC of the plant is 5.56 kWh/m3 [4] and the mean SEC of each train ranges from 5.31 to 5.77 kWh/m3. The average SEC for trains using new membranes was found to range from 5.66 to 5.77 kWh/m3 [8]. This value of SEC in trains using new membranes is higher than that of trains using old membranes, whose average SEC ranges from 5.31 to 5.6 kWh/m3 [8]. This may be due to the fact that ERDs of trains having old membranes save more energy (27.7 – 30.3%) in comparison with the 20.8-22.2% energy saving in trains having new membranes [8]. This difference in energy savings depends on the efficiencies of ERDs employed in the trains, apart from the reject pressure. The η_{erd} values of the ERDs in trains having old membranes, wherein the actual flow equals the ERD design flow, range from 63.12 to 71.2% [8], and the η_{erd} values of the ERDs in trains having new membranes range from 60.8 to 62.5%, since the flow is different from the ERD's design flow. The η_{erd} values for all trains ranged from the lowest value of 48.6% to the highest value of 79% [4].

Throttling leads to considerable energy loss. It is an indispensable requirement for the high-pressure pump as the seawater is delivered at a higher pressure than needed

by the membranes, which is reduced to optimum levels using the throttle valve. At the Yanbu desalination plant, the TL values do not depend on old and new membranes. The mean TL value for all trains at this plant ranges from the lowest value of 10.9% to the highest value of 22.7% [8]. As in the first case, the SEC value of this plant can also be decreased from the current 5.56 kWh/m^3 to 4.67 kWh/m^3 [4].

The average ES for the plant is 25.9%, with 17.2% being the lowest and 32.7% being the highest [8]. Since the η_{erd} value is 65%, it is expected that the ES value would be higher than the observed value of 25.9% [8]. Thus, the ES value is lower than expected. This may be attributed to the fact that the pressure of the reject, which is between 6 to 13 bar, is used to pump up the reject for "backwashing the pretreatment media filters" [8]. It is expected that by decreasing the final pressure of the reject to the lowest value that is sufficient enough for pumping, may also decrease the SEC from the current value of 5.56 kWh/m^3 [4].

At this plant, the temperature of the seawater (feed) ranges from 25 to 35°C [4]. This also affects the pressure of the feed, which ranges between 56.8 – 66.7 bar [8]. This variation in the pressure of the feed is not significantly large, and so, does not seem to affect the performance of the ERD. It is observed that the performance of ERDs at the Yanbu desalination plant is not affected by seasonal temperature variations [4].

Chapter 3: Pelton Wheel

3.1 History and Design

Pelton wheel was invented during the 1850s. Originating in San Francisco, it is a kind of water wheel. The Pelton wheel used in SWRO desalination plants is easy to operate. It has an input nozzle through which high-pressure feed is directed onto the buckets of the wheel. The nozzle is designed such that the entire kinetic energy of the pressurized feed is converted to mechanical energy manifested as rotation [16]. The buckets, also referred to as vanes, of the wheel are arranged in series around the shaft, which intercepts the feed stream [17]. As in the hydraulic turbocharger, the pump in the Pelton wheel is driven by a turbine. This pump enhances the pressure of the feed before it enters the HPP, thereby decreasing the energy consumption [18].

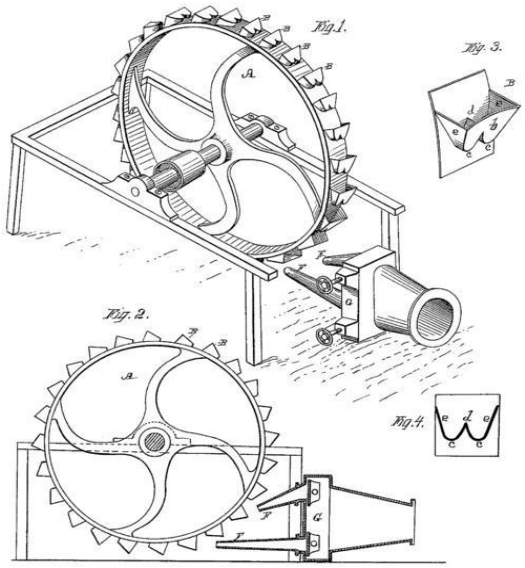

Figure 3-1: Pelton Wheel Drawing from Original Patent (October 1880)

The Pelton Wheel is popular worldwide and is more efficient than the FT [19]. The efficiency of the Pelton wheel remains constantly high even during variations in the pressure and flow of feed [8]. One significant challenge, however, is the design and maintenance of metal parts, as they are easily corroded when exposed to seawater [17].

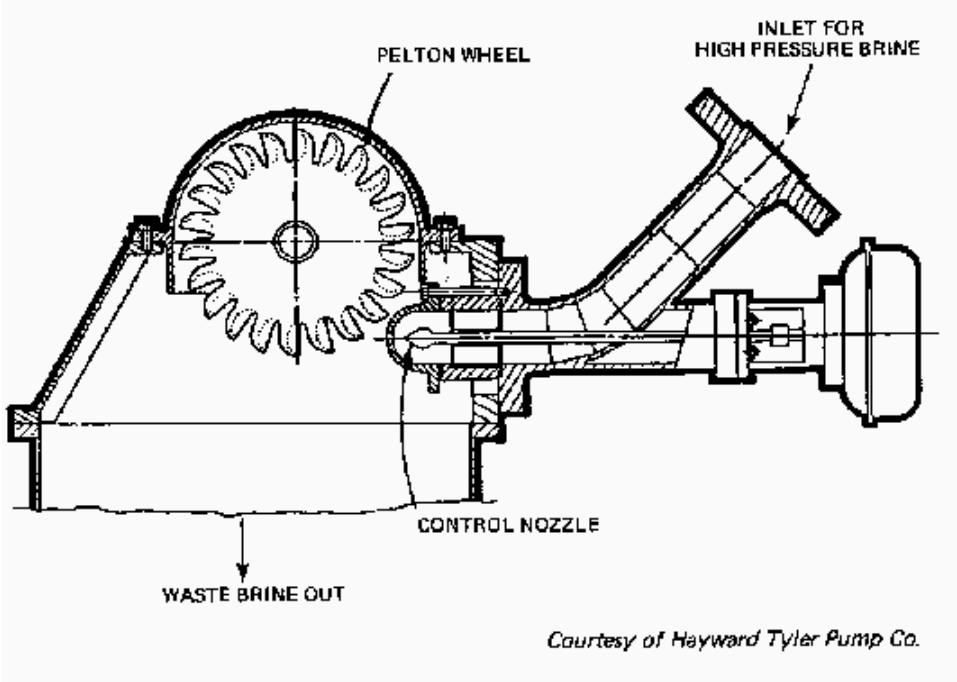

Figure 3-2: Sectional Arrangement of a Pelton Wheel

3.2 Efficiency Double Dip

The achievable efficiency of SWRO desalination plants using Pelton wheels is 80 to 85% [9]. A common characteristic of the Pelton wheel and the FT is that these transfer the energy recovered from brine back to the HPP via the shaft. While computing total loss of energy, the energy lost by the HPP and the reduction in the wheel's energy efficiency must also be taken into account [9]. This can also be referred to as "double-dipping" in energy efficiency [9]. Along with a reduction in the recovery, there is an increase in the amount of high-pressure feed entering the ERD, which decreases the

efficiency of energy recovery. Evidence suggests that the energy efficiency of a desalination plant using a centrifugal HPP, coupled with a Pelton wheel, increases with an increase in the percentage of recovery. Therefore, most SWRO desalination plants are designed to work at a higher recovery. In plain terms, it can be said that the ERD operating at a recovery of 45% has twice more efficiency than that operating at a recovery of 25%, and it is due to this fact that desalination plants are being designed to achieve a higher recovery [17].

3.3 Case Studies

3.3.1 Maspalomas II SWRO Plant

The Maspalomas II SWRO plant has a 20,400 m3/day production capacity. It also employs a 20,000 m3/day EDR (electrodialysis reversal) plant for desalination of brackish water and is located in Spain, Gran Canaria [14].

A typical SWRO Plant carries out its process as given: firstly, the raw seawater is acquired and filtered using anthracite and sand filters. This filtrate is then again filtered through cartridge filters. The Maspalomas II SWRO has five trains with a daily feed intake capacity of 41,000 m3 [14]. About 40% of the seawater is recovered and 60% of the reject is transferred back to the sea. The feed comprises of 35,000 mg/l TDS. Francis Turbines are the ERDs employed at this plant [14].

After its installation in 1987, the plant was expanded again in the 1990s [14]. The Brine Conversion System (BCS) was tested at this site. In this system, a 2nd stage SWRO plant was added for the recovery of brine from the reject [14]. A novel quality of this plant is that once seawater has been desalinated in the first stage, the reject water is desalinated again in the second stage. This use of second stage SWRO increased the

product recovery from 40% to 60% and therefore, led to reduction in energy consumption [14]. A Pelton wheel was used in the second stage SWRO at this plant.

A yet another system, the Full-scale Brine Conversion System, was then built after the initial BCS was pilot tested. The advantage of using such a system was that there was no need of expanding the facilities for intake of seawater and for its pretreatment. This plant is credited as the first one to use BCS. The system involves pressurization of brine to 90 bar [14]. The brine is then driven into concentrator membranes, where about 33% water is recovered from the reject. Furthermore, during this process, a Pelton wheel is used to recover the remaining energy from the reject. The process flow of a train at the plant is given in Figure 3-3 [14]. The total electricity consumed by the train is 3.77 kWh/m^3 and the total power consumption by the HPP is 445 kW [14].

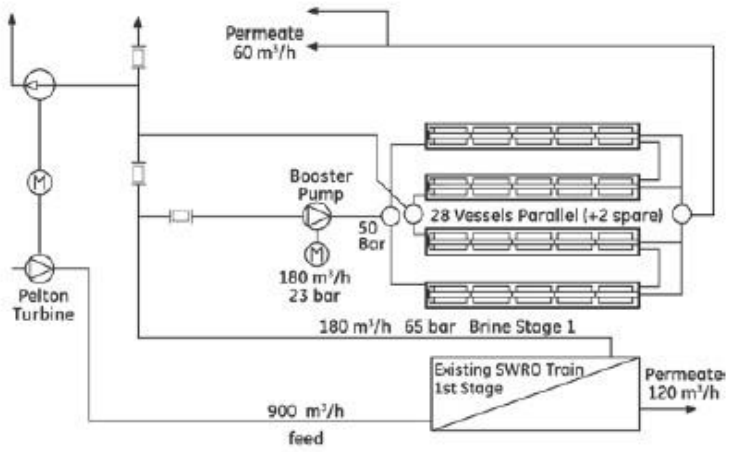

Figure 3-3: Process Flow Diagram for One BCS Unit at Maspalomas II

The product flow in trains with BCS is 118 m^3/h with a product flow of 41 m^3/h, making a total flow of 159 m^3/h [14]. The Pelton wheel's total power consumption is 533 kW, and so, the total electricity consumption is 3.35 kWh/m^3 [14]. The energy consumption for the production of water by SWRO with BCS unit is lower than the

energy consumed by conventional SWROs [14]. This is because instead of wasting the brine produced in first stage, it is reused for further desalination in the second stage. This saves a lot of energy that would have been spent for acquiring the water, pre-treating it and then pressurizing it. It is found that in typical SWRO desalination plants that are of a single stage, the energy consumption reduces as the water recovery increases because lesser water has to be pressurized for achieving a required quantity of product [8]. Because of the BCS system in two-stage plants, lesser amount of water has to be pressurized for achieving the same amount of product. This is the reason for the increasing popularity of the BCS, which increases recovery and decreases power consumption [8]. It should however be noted that at the second stage, the salinity of the feed is higher and so, the level of pressurization required for BCS is also higher when compared to the first stage. Therefore, with an increase in recovery, there is a decrease in energy savings.

In addition, the efficiency of HPPs and ERDs also affects the energy consumption and amount of recoverable energy [14]. When the power consumption by a single stage SWRO unit with a considerably low recovery is compared with that of a two stage SWRO with a high recovery, other factors such as the salinity of salt water, the kind of pumps used and the ERDs employed should also be taken into account. It is surprising to know that in a few cases, single stage SWROs are found to consume lesser energy than two-stage ones [14]. As for the two stage SWRO plant at Maspalomas II, the two stage units are more energy efficient than single stage units.

Different designs have been explored for the coupling of ERDs with BCS units for minimization of energy consumption [18]. The choice of design would depend on many characteristic plant features and operation parameters such as size, energy costs, capital required, maintenance and the kind of ERDs available. In the two stage plant at Maspalomas, a booster pump increases the pressure of the reject obtained at the end of

the first stage to be used as feed for the second stage [14]. Another proposed design for minimizing the consumption of energy is the use of BCS along with a turbocharger. In this design, an HPP will be used to pressurize the feed in the first stage. The turbocharger will then be used to pressurize the reject of the first stage to be used as feed by BCS in the second stage. The energy from the reject of the second stage is used by the turbocharger for energy recovery [14].

3.3.2 Ummlujj SWRO Desalination Plant

This plant, owned by the SWCC, has two trains named 100 and 200. Each of these trains has two HPPs that are coupled with a Pelton wheel. One set of HPP and its coupled ERD is kept on standby while the other one is running. Hardness of water is removed during pretreatment. The salinity of the seawater at this plant is between 41,000–43,000 mg/L. Table 3-1 shows the specifications of this plant [4].

It is apparent by now that the efficiency of an ERD unit affects the energy savings. SEC amounts to more than 80% of the total energy required [18] for the production of one unit of the permeate. The design of a plant is such that it is optimized for least SEC, which is the energy consumed by the HPP. However, the throttle valve challenges this objective. The throttle valve is used for the regulation of the pressure of the feed. The energy in the feed stream is reduced by the throttle valves before reaching the membrane, which makes it difficult to reduce SEC [8]. Therefore, attempts have been made for the evaluation of the efficiency of ERD and amount of energy lost due to throttle, so that the SEC can be reduced by designing appropriate technology. SWCC's SWRO plants employ both the FT and the Pelton wheels. The Ummlujj plant is the only SWCC plant that uses only the Pelton wheel, and so, it is our focus in this section while

some of the rest of the plants such as Yanbu, Jubail, Duba and Haql, which utilize reverse running pumps or Francis Turbines, were evaluated in the previous chapter [4].

Table 3-1: Ummlujj Plant Specifications

High pressure pump details	Specification	Rated for 400 m^3/h 0.86 at 65.8 bar
	Power Factor	0.86
	Voltage (kV)	4.16
	Overall efficiency (%)	70
Energy recovery device details	Specification	Rated for 251 m^3/h at 53 bar
	Overall efficiency (%)	85

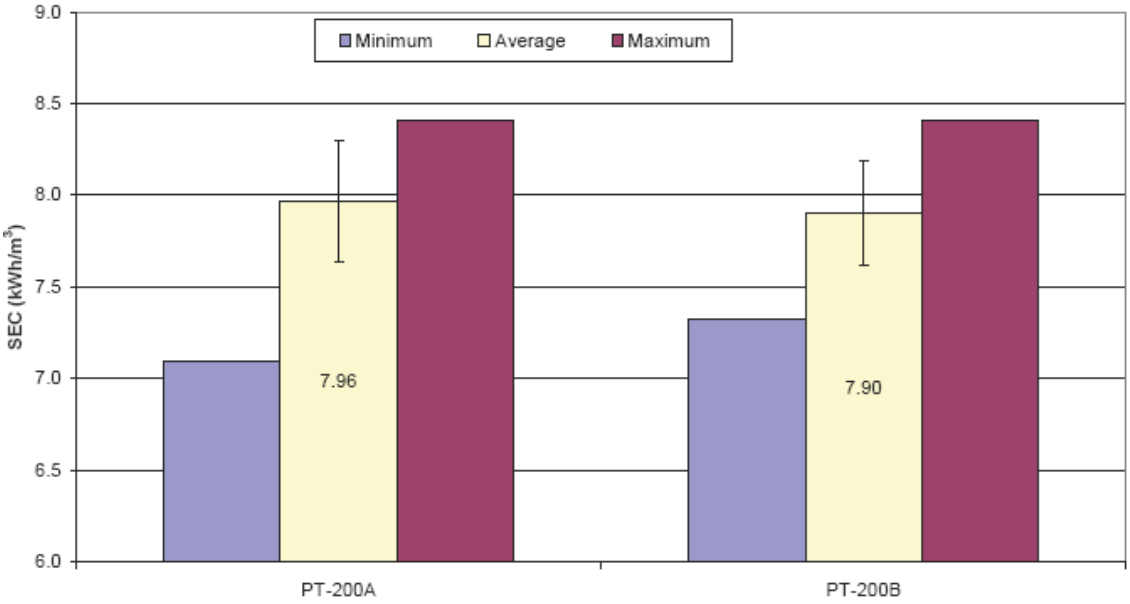

Figure 3-4: SEC by Different HPPs/ERDs at the Ummlujj Plant.

The SEC is affected by the difference in the transmembrane pressure, which is necessary for the achievement of the required flow rate under various conditions of operation. This is further influenced by the energy efficiency of the pump coupled with the ERD for the recovery of hydraulic energy from brine [8]. In addition, the performance of Pelton wheels is affected by differences in the pressure and flow. The performance of

the pump / Pelton Wheel system used in the Ummlujj SWRO plant are analyzed here [4]. The product recovery of this plant is 25% at a feed pressure of about 60-65 bar, which is influenced by seasonal changes in temperature that ranges from 23.1 to 34.6°C [4].

The fundamental equations for evaluating the system performance have been used as mentioned in the previous chapter, to display some values of operation for the Ummlujj SWRO plant.

Table 3-2: Energy Consumption and ERD Efficiency at Ummlujj Plant

	Energy consumption by HPP, kWh/m3	Energy saving by ERD, %	Overall ERD efficiency, %	Throttle loss, %
Minimum	7.09	23.61	53.89	6.16
Maximum	8.41	31.85	82.28	12.54
Average	**7.93**	**27.38**	**64.36**	**10.39**
Std. dev.	0.04	0.27	1.76	0.8

Table 3-2 shows the minimum, maximum and average value of all the four calculated parameters for both the HPP/ERDs of the plant. The mean SEC for Train 200 was 7.93 kWh/m^3 [8] and the mean SEC for each HPP coupled with ERDs was 7.96 kWh/m^3 for 200A and 7.9 kWh/m^3 for 200B (Figure 3-4) [4]. The SEC values ranged from the lowest 7.09 kWh/m3 to the highest 8.41 kWh/m3 (Table 3-2) [4].

The average ES was 27.4% with 23.6% being the minimum and 31.9% being the maximum (Table 3-2). The ES value was almost the same for both 200A and 200B as shown in (Figure 3-5). The high efficiency of the energy recovery devices leads to a high ES. The efficiency of one ERD was 63.1% and that of the other one was 65.6% (Figure 3-6). The average value of η_{erd} for the two ERDs was 64.4% with 53.9% being the lowest

and 82.3% being the highest [8](Table 3-2). It is important to note here that there was no relative difference in η_{erd} and SEC values in response to temperature of the feed and pressure of the reject. Only a minute variation of about 57.9–62.8 bar was observed. The TL of one unit was 9.8% and that of the other unit was 11% (Figure 3-7). The mean TL value for the Train named 200 was 10.4%, with 6.2% being the lowest and 12.5% being the highest (Table 3-2). As in the other case studies, it is expected that if a VFD is installed, the SEC value of the desalination plant can be decreased from the present 7.11 kWh/m^3 to 7.93 kWh/m^3 [4].

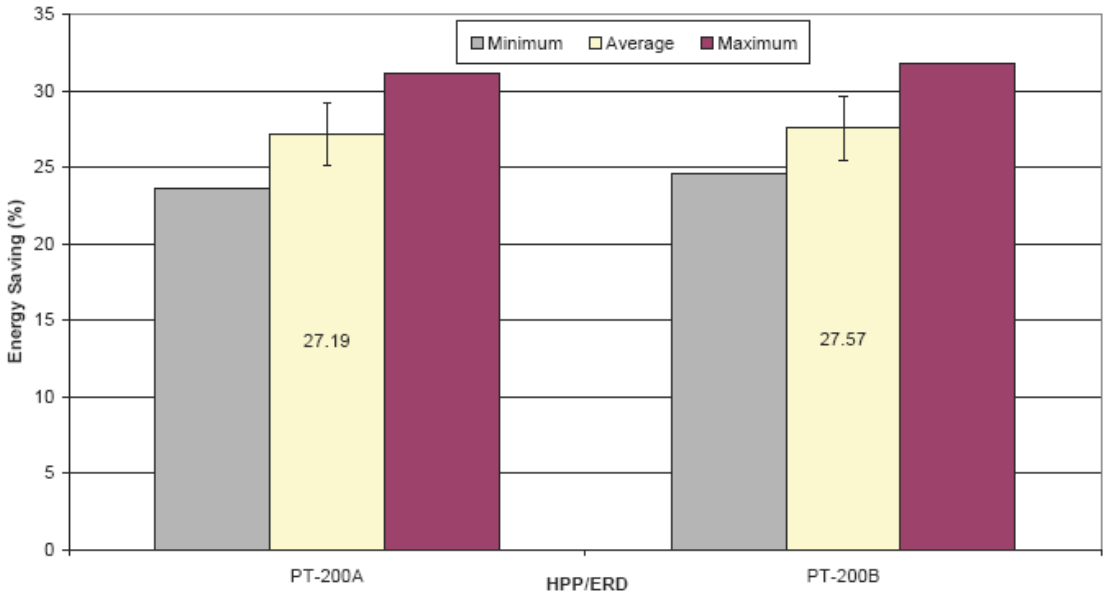

Figure 3-5: Energy Saving by Different ERDs at the Ummlujj Plant

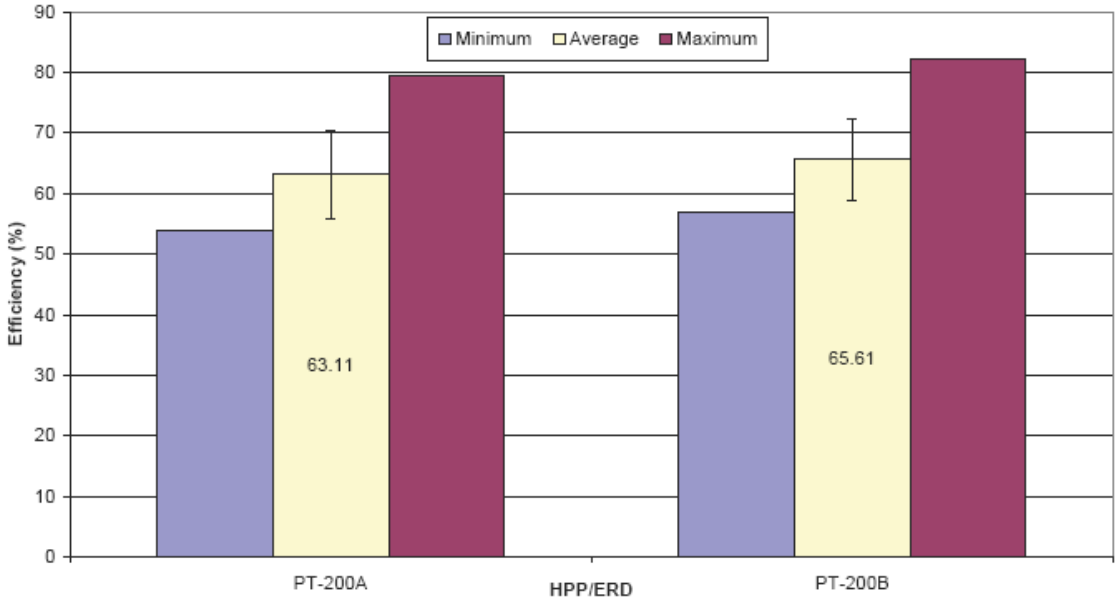

Figure 3-6: Efficiency of Different ERDs at the Ummlujj SWRO Plant

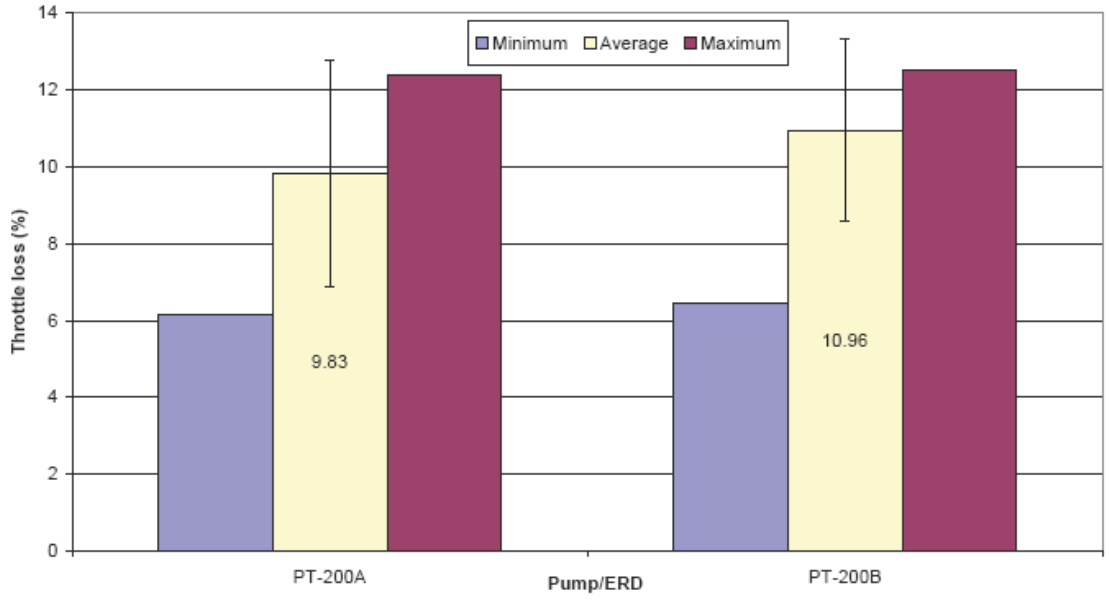

Figure 3-7: Energy Lost by Throttling in HPP Systems at the Ummlujj Plant

Chapter 4: Turbo Charger / Hydraulic Pressure Booster (HPB)

4.1 History and Design

The hydraulic turbocharger is of the centrifugal type and has been in use since 1990s [5]. It is a second generation ERD and employs alloys that are resistant to corrosion. Some of the alloys used include 2205 and other steels of Duplex grades [20].

A nozzle drives the reject onto a turbine, which is connected to a centrifugal spinning impeller [21]. The use of the turbocharger is to boost the pressure of the feed that has been pressurized by the HPP for reaching the required feed pressure [22].

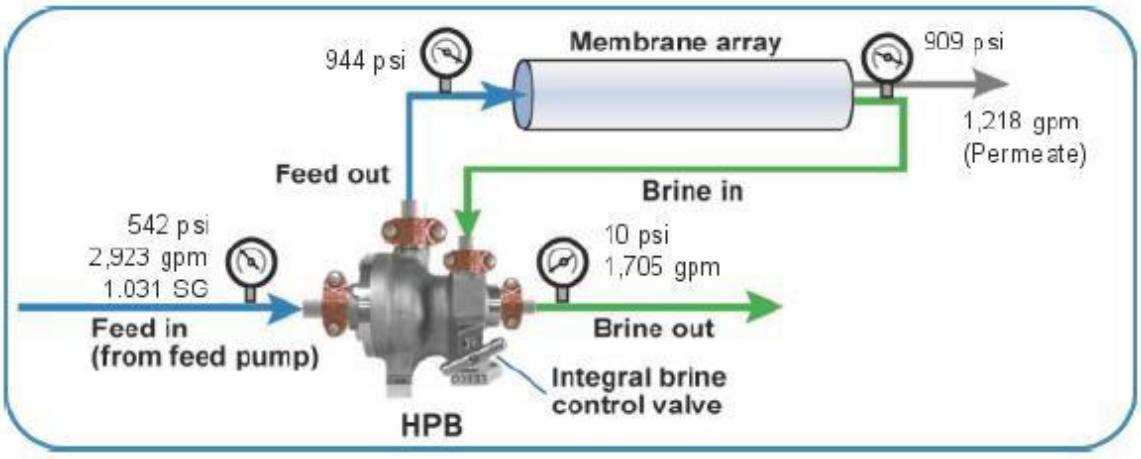

Figure 4-1: SWRO Process with FEDCO Turbocharger / HPB

A turbocharger unit consists of a hydraulic turbine and an HPP. The turbine is similar to a reverse running pump [8]. The HPP and turbocharger are not connected directly to overcome the disadvantages that are observed in FTs and Pelton wheels, thereby

allowing operation flexibility [21]. In addition, turbochargers are easy to install and are significantly energy efficient. An SWRO process employing a turbocharger is shown in the Figure 4-1.

The impeller of the HPP is made of the same material as the impeller of turbocharger. Both the impeller and the turbine of the turbocharger are centrifugal "close-coupled mixed-type" with both axial and radial flows [21]. The transfer of energy by the turbocharger increases the pressure of the feed, and the rotating element of the device is balanced. It has a by-pass that allows manual control of the flow [8]. This is required when the flow rate of brine at second stage is higher than needed [22]. This is required even more when the feed experiences large variations in temperature or when the membrane used is old. The energy recovery by the turbocharger is achieved when the discharge pressure required by the HPP is decreased.

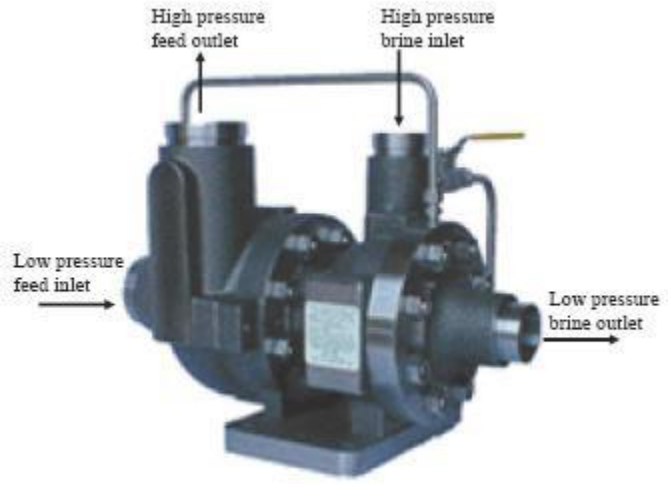

Figure 4-2: A Turbo Charger Unit

The maximum efficiency achieved by these devices is 89%-90% [5], which is slightly higher than the efficiency of the Pelton wheel as the HPP in the Pelton wheel runs at a

higher head, decreasing the efficiency. The highest transfer efficiency that can be achieved by hydraulic turbocharger is calculated by multiplying the efficiency of impellers, nozzles and turbine, as 90% x 90% x 99% = 80% [21]. Each of these three factors influences the efficiency of this device. As shown in the Figure 4-1, control valves and nozzles can help in adjusting the performance.

As discussed in the previous case study on the Maspalomas II SWRO plant, turbochargers are also used along with Pelton wheels. In this case, the turbocharger is used in Brine Conversion System (BCS) during the second stage recovery of water from reject obtained in the first stage. It thus increases the water recovery by 60% [5]. Plants with turbochargers are reported to have an efficiency of about 70%. Several smaller plants installed in the 1990s to 2000 with a capacity of 210 to 5,700 m^3/d have also employed turbochargers along with BCS [5]. Apart from these, large plants employing the BCS system have also been reported. For instance, the Caribbean Island and Mas Palomas have large plants employing the BCS system [23].

These devices, i.e. turbochargers, are more reliable compared to earlier ERDs. They also require low maintenance. However, one limitation of these devices is that they can recover only 50-80% energy [17].

4.2 Case Studies

4.2.1 Greek Islands Oia SWRO Desalination Plant

As already discussed, the performance of a turbocharger depends on flow and pressure of the feed. The performance of the turbocharger system in conjunction with the pump in the Oia SWRO desalination plant is analyzed further. This analysis is based on documented energy efficiency reports of one year of plant operation [4].

Hundreds of Greek islands in the Aegean Sea suffer from water shortage [16]. Increased tourism in the area has further aggravated the crisis. Thus, installation of desalination plants at each island seemed to be a good solution. However, the set-up of desalination plants was made difficult by widely varying water demands, higher costs associated with the product, and the dearth of qualified operators. Therefore, small scale SWRO plants were set-up [16]. One of the small plants is the SWRO desalination plant at Oia. This plant is further studied here. Table 4-1 details the specifications and characteristics of this plant. The data for evaluation was obtained from the Oia plant, which has two units using different ERDs. One used the turbocharger while the other used the Pelton wheel[16]. The present case study evaluates the unit employing the turbocharger.

Table 4-1: Characteristics of the Oia SWRO Plant

Location	**Number of units**	**Number of inhabitants** **Total production, m3/d**	**Total production, m3/d**
Island of Santorini, Community of Oia	2	600 permanent inhabitants 8,000 in tourist season	550

Since the area experiences heavy tourism, there is a huge demand for water. The desalination of water is not sufficient to meet the needs of the locals as well as the tourists. Therefore, private wells are also used in addition to the desalinated water. However, the water from the wells is of low quality. The local municipal water companies own the desalination plants and the price policy for the desalinated water is revised each

year. However, it is reported that this price policy is largely based on social policy rather than economy and investments [16].

The SWRO plant at Oia employs the HTC (Hydraulic TurboCharger^{TM}) manufactured by PEI. This turbocharger is designed in such a way that the pressure of the feed stream is boosted by utilizing the hydraulic energy of reject. As shown in Figure 4-3, the HTC boosts the pressure of the feed. The HPP provides a boost of about 660 psi to the pressure of the feed [23]. This is then further enhanced by the HTC, making the final pressure 880 psi, which is the optimum pressure for operation. The HTC recovers the energy from pressure of the reject brine which is at high pressure [16].

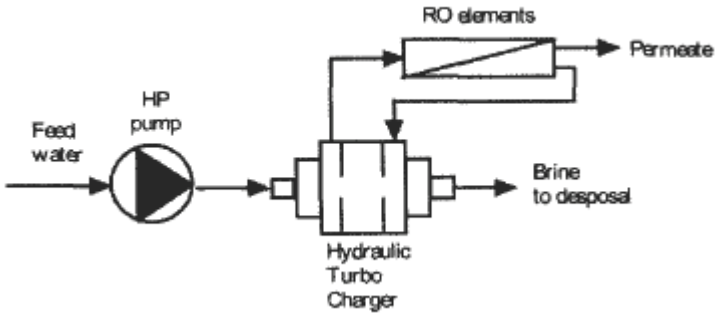

Figure 4-3: HTC as a Feed Pressure Booster in an RO System

Data for this case study was obtained from reports on energy consumption for three months, during which, all parameters were measured and recorded. The total energy consumption includes the energy consumed by pumps, lights etc. Table 4-2 enlists the recorded data [16].

As is evident from the data in Table 4-2, the SEC is not influenced by the size of the plant in spite of the expectation that SEC would be inversely proportional to the size of the plant [5]. An analysis of this data reveals that the efficiency of a turbocharger is

higher than the efficiency of Pelton wheels. Owing to their small size and low costs, turbochargers are more popular than the Pelton wheel in SWRO desalination plants [16].

Table 4-2: Data for the Energy Recovery System

Operating and consumption data for the Hydraulic TurboCharger™. Capacity 160 m3/d						
Working time, h	Energy consu-mption, kWh	Prod-uction, m^3	Tempe-rature, °C	Permeate condu-ctivity, µS/cm	Operating pressure, psi	Specific consu-mption, kWh/m^3
48.5	1,515	308	19	740	880	4.91
110.2	3,451	739	21	740	880	4.66
524.5	16,516	3,572	24	820	880	4.62
497.7	15,516	3,389	25	850	880	4.66

4.2.2 Atlantic Ocean Plant

The Atlantic Ocean SWRO plant has four trains, each of which is of 2,500 m^3/d capacity. The seawater has total dissolved solids of about 36,000 mg/l [5]. The recovery rate of the plant is 40%. The total consumption of energy is lowered to 4.18 kWh/m^3 using an ERD [5]. The ERD uses a turbine attached to the HPP. The feed flow in each

train is 3,785 m^3/d and the feed pressure is 67 bar [5]. As the seasonal temperature varies, the quality of seawater also changes, with total dissolved solids changing from 56,600-68,000 mg/l from summer to winter. The final product will have to have just 400 mg/l TDS [5]. This plant uses a turbocharger as an ERD. The make and model of the turbocharger is TURBO^{TM}, HTC-900HR. This turbocharger boosts the pressure of the feed to 82.76 bar [20]. Its flexible auxiliary turbine allows variations in the flow and pressure of the feed as per the seasonal change in temperature and the subsequent change in the conditions of the feed. This plant uses fifty trains in summer months. A total recovery of about 26.4% is achieved during this period, and the product flow increases by 37%, and amounts to 925 m^3/d. During the winter months, a total of 38 trains are used. As compared to the summer months, the recovery rate is higher (31%) during winter. The total product flow is also higher, at 1,150 m^3/d, with a 47% increase in capacity, which is also higher than that during summer months [20]. The flow of the feed through the 38 trains in winter is in excess. It is more than what is needed to charge the turbocharger, and the excess high-pressure feed stream is thus split into two. One stream drives the turbocharger and the second is used for energy recovery by driving the other energy recovery turbines, which are actually made of modified impellers [20]. The total energy consumption by the HPP is 3.83 kWh/m^3 [5], and saves 8% energy.

The currently used reverse running pump energy recovery turbine at this facility is used under low-volume and high-pressure feed conditions with minor alterations in the impeller. The production at this plant has increased from 37 to 47% due to the application of BCS [20]. This increase, however, varies with the season. The application of BCS has also reduced the total energy consumption by 5% to 10%. This reduction in energy consumption is also dependant on the seasonal temperature. As is apparent from this case study, the use of BCS along with energy recovery turbines helps in achieving a good operating efficiency [20].

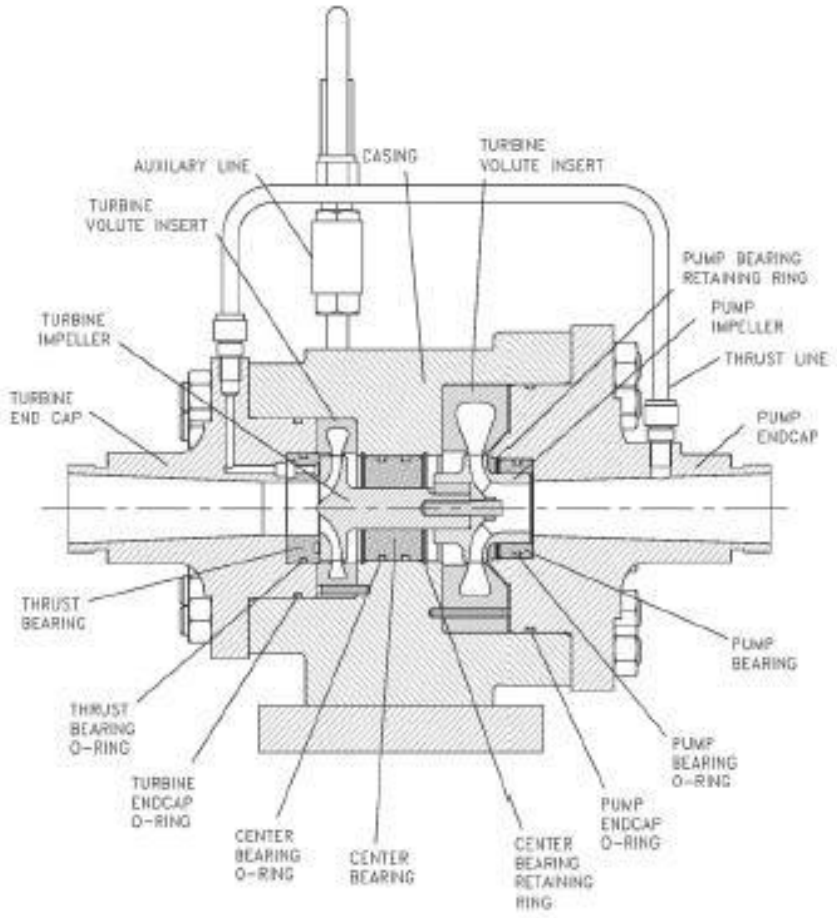

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Figure 4-4: Turbocharger / Hydraulic Pressure Booster Construction

Chapter 5: Recuperator

5.1 History and Design

The Recuperator ERD by Aqualyng™ belongs to the third class of ERDs – namely, the hydraulically driven pumping in parallel, discussed in the introduction chapter. The Recuperator works on the principle of work exchange. It transfers the hydraulic energy of the brine directly to the hydraulic energy of the feed, with minimal "drag" associated with the shaft [3]. It is also an Isobaric Energy Recovery Device, especially belonging to the "piston-type" of work exchangers [24]. This device, which belongs to the class of hydraulically driven pumping- in parallel, utilizes buffer separating feed or reciprocating pistons.

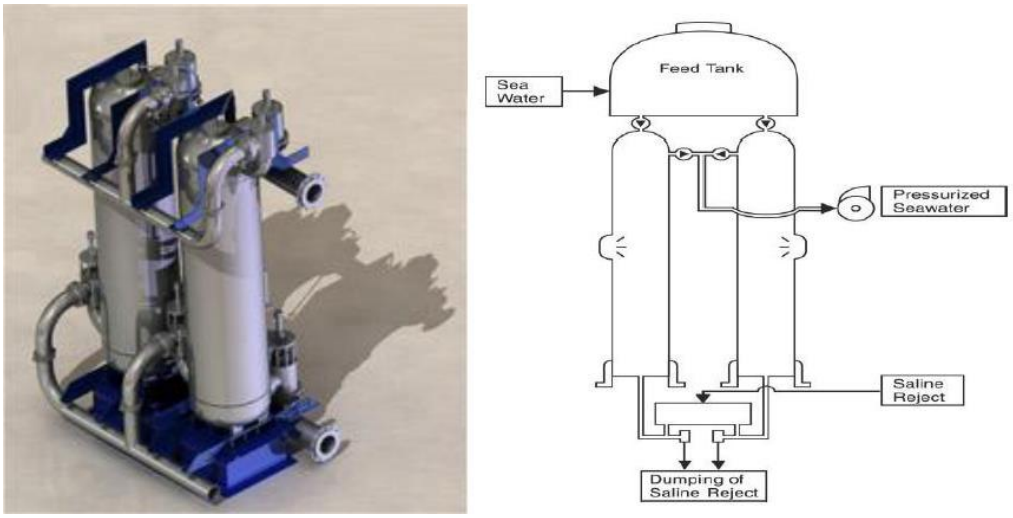

Figure 5-1: Aqualyng™ Pressure Recuperator

The construction of the Recuperator is such that it has vertical stainless steel chambers operating alternatively. They function in a compression-transfer and decompression-discharge sequence. The feed is pre-treated and is pressurized up to a constantly maintained pressure. The flow rate of the feed is also maintained at a constant value. The energy from the pressurized brine is recycled [24]. The device has three-way valves that are specially used to control the flow [10]. All these valves are necessary for the maintenance of the flow to the booster pump [25].

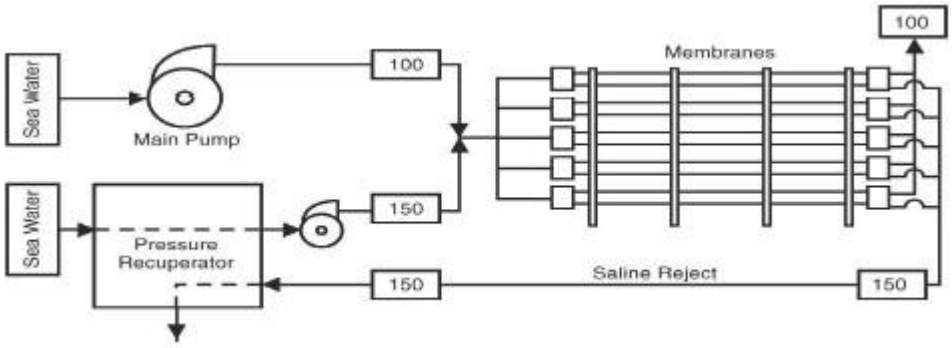

Figure 5-2: The Aqualyng System

The Recuperator™ has reduced the energy consumption up to 2-2.5 kWh/m^3 in this desalination plant [25].

5.2 Case Studies

5.2.1 The Tauro Plant

The capacity of this plant is 2000m^3/d. The membranes used for desalination at this plant are made of 180 polyamide membrane units. These units have a very high salt rejection capacity. The HPP is a quintoplex plunger pump, with a 2000 m^3/d capacity and 320 rev/min speed [10]. The HPP has 83-85% efficiency (Figure 5-3). As is apparent from the figure, the recovery is 1.93 kWh/m^3 with a 37% recovery rate.

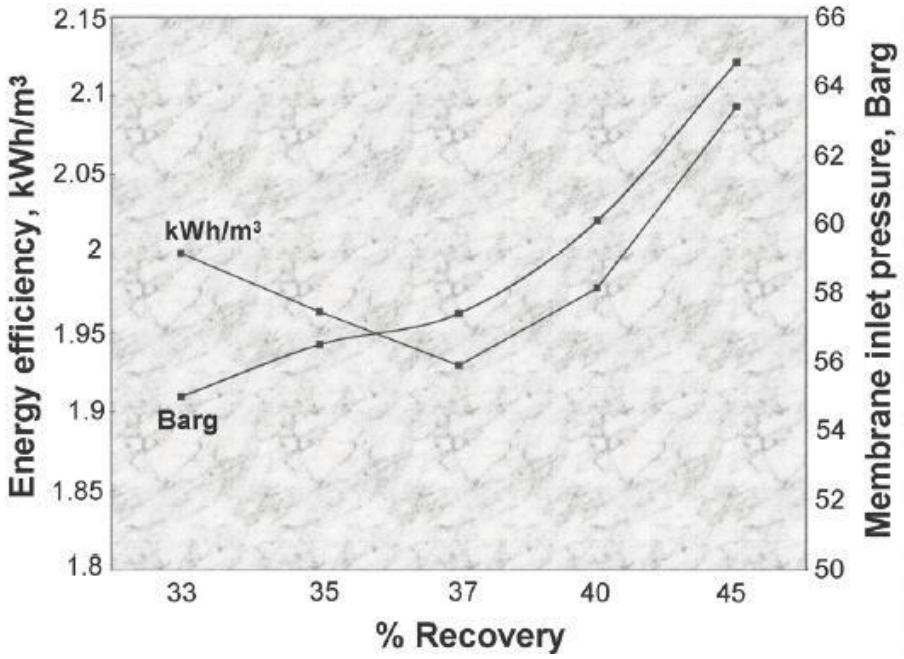

Figure 5-3: Tauro SWRO Plant Energy Efficiency

As the average salt content of the feed water decreases, the pressure on the membrane reduces, and the flow of the water across the membranes rises. At such a stage, the SEC is very less as the energy consumed by the HPP decreases. As the flow increases, the pressure across the Recuperator™ and the membranes decreases, by which the recovery is lowered. In such a case, the energy utilized by HPP is lower and that utilized by the booster pump is higher. This increase in the energy consumption by the booster pump is more than that utilized by the HPP. Each plant has a minimum point according to the number of membranes and the efficiencies of other components. The Figure 5-4 illustrates the flow and pressure at minimum point.

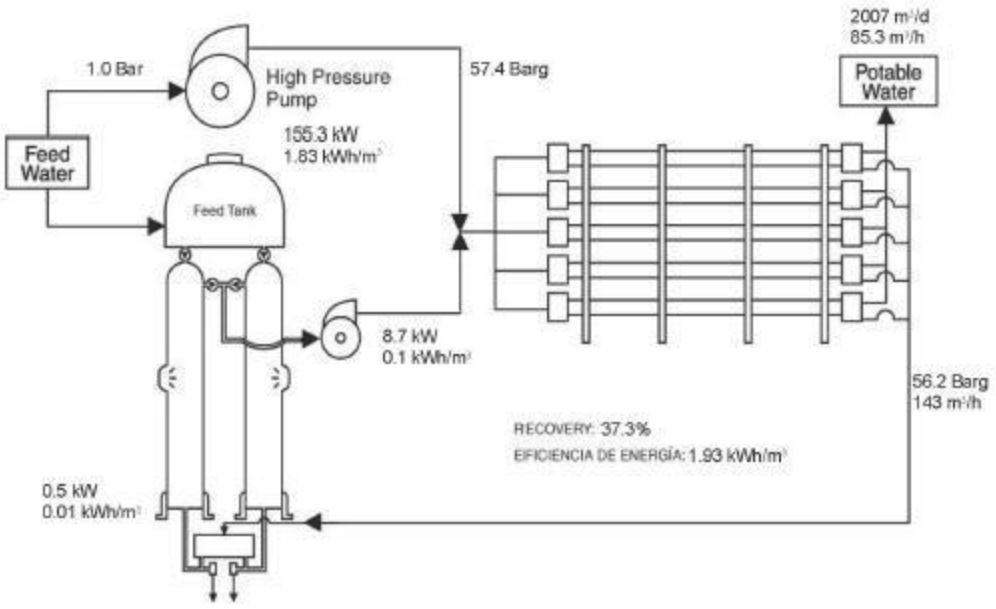

Figure 5-4: Some Operational Results of the Tauro SWRO Plant

Chapter 6: DWEER

6.1 History and Design

ERDs such as turbochargers, FTs and Pelton wheels convert the hydraulic energy of brine to mechanical energy and then back to hydraulic energy. This principle of energy recovery has drawbacks as it is less efficient than the energy recovery that can be achieved by direct transfer of energy from hydraulic to hydraulic, i.e. from reject to feed [26]. As the Recuperator (previous chapter), the DWEER™ also belongs to the third class of ERDs which are hydraulically driven pumps in parallel. These are designed to separate the reject and the feed by a piston for diminished intermixing between the two (Figure 6-1) [6]. By separating the feed and the reject, it can be ensured that that the increase in salinity and pressure of the feed is always the least [27].

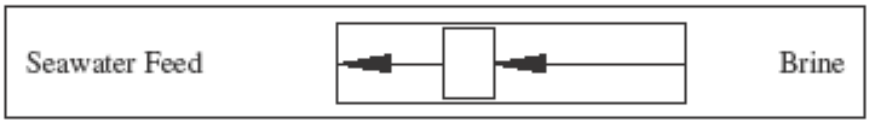

Figure 6-1: Piston to Ensure Minimum Mixing of Brine and Seawater Feed

The DWEER™ has three main subassemblies: LinX™ valve [6], the pressure vessels and the check valve nest (Figure 6-2) [27]. A booster pump is also required to boost the feed pressure to make it equal to the pressure of the feed pump [8].

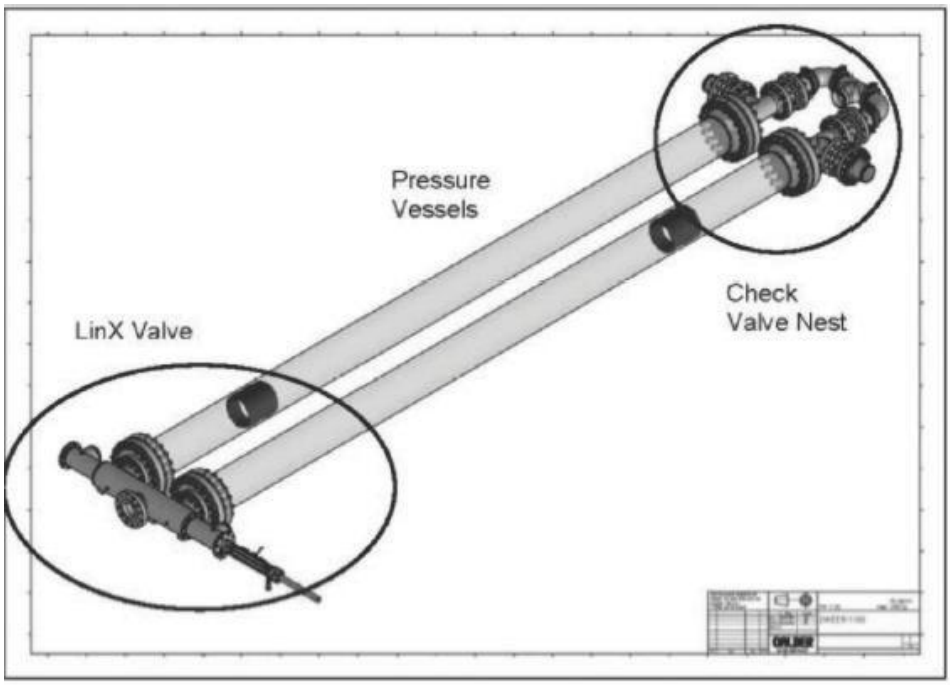

Figure 6-2: The DWEER^{TM} Work Exchange

Figure 6-3 illustrates the integration of a work exchanger into the plant. In contrast to the conventional integration with a Pelton wheel, the feed stream is split into two, one of which is driven into the HPP and the other to the ERD. Since the HPP can handle a flow, which is equal to or just a little higher than the product flow, its size has to be reduced. Therefore, a recovery of 40% is achieved with an HPP, which is reduced to 40% [6]. A booster is added to compensate for the dip in pressure, however, this pump consumes lesser energy [27].

In an RO, there is a sharp decrease in pressure between the feed and the reject, which is entering the DWEER^{TM}. Since the piston and the membrane are at a similar pressure, it is placed in a pressure vessel. Owing to the limited volume of this vessel, a valve is used to enable the vessels in exchanging their functions. A booster pump enables the flow pressure in the effluent exiting from the DWEER^{TM} to equal the discharge pressure of the high pressure pump, thereby making the system to function in

a loop [26]. The rate of flow from booster pump is equal to the flow rate from membrane, unless a leakage is present in the membrane.

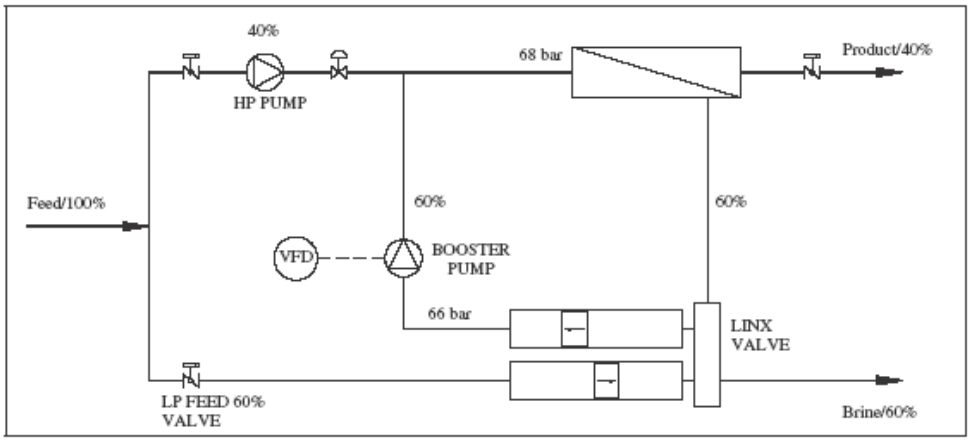

Figure 6-3: Integration of the Work Exchanger into an RO Desalination System

The largest capacity attained currently is 500 m³/h. These can be placed in parallel for increasing the capacity. For instance, a plant in Grand Cayman, Spain with a Total Dissolved Salts value of 37,000 mg/L [28], and a capacity of 1,071 m3/d with SEC of 3.00 kWh/m^3 was upgraded by installing the DWEER^{TM} system that increased its capacity to 1,699 m3/d with an SEC of 2.22 kWh/m^3 [8].

6.2 Losses of a Work Exchanger (Efficiency)

In case of a work exchanger, losses are more worth considering than efficiency [29]. In contrast to ERDs such as Pelton wheels or FTs, it is not possible to assess the shaft power in the DWEER^{TM}, while the evaluation of only hydraulic power is also not enough. For this reason, other possible causes of losses are to be considered, which include "Mixing, leakage, overflush, high pressure differential, low pressure differential, noise" [27].

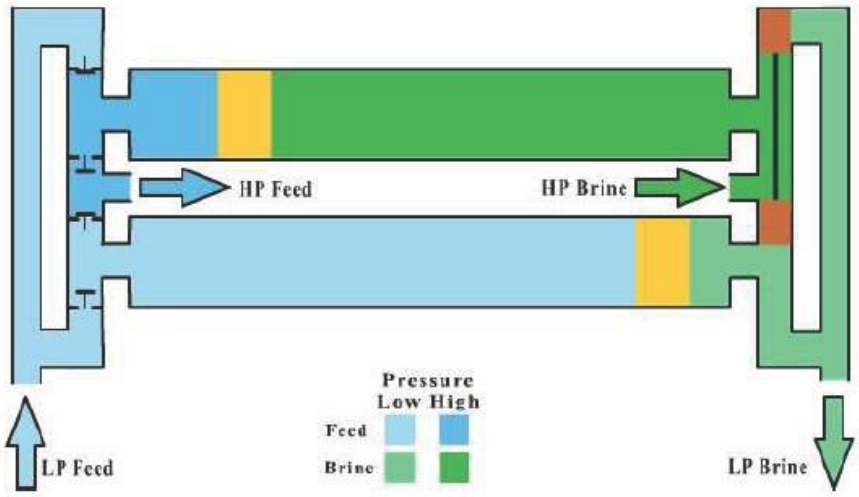

Figure 6-4: Schematic Diagram of Dual Work Exchanger DWEER System

Mixing: This increases the total dissolved solids in feed water, and thereby, result in an increase in the required pressure of the feed. Because of the increase in pressure requirement, the HPP has to work more to achieve the desired pressure. Therefore, it consumes more energy, leading to a lower efficiency and higher power consumption. Therefore, it is important to keep the mixing value in check to avoid unnecessary and excess consumption of energy. Any increase in the required pressure of the feed entering the membrane will have to be compensated by the HPP, which then consumes higher energy. For prevention of mixing, the DWEER^{TM} employs a piston that prevents intermixing of the feed and the brine. In other such devices, the flow as well salinity is also kept in check [27].

Leakage: This is also called "lubrication flow" and occurs when reject that is at high-pressure leaks to the feed that is at low pressure. To compensate for this, the HPP will have to work harder to provide more flow and so, will consume larger amounts of energy, resulting in decreased efficiency of the plant [27].

- Overflush: The water from feed that is directly drained is called overflush. This is needed to remove the remaining brine from the vessel before the vessel is filled with feed. Because of this, the HPP will have to supply more feed. This again leads to increase in power consumption, which subsequently decreases efficiency. Because of this overflush, a lot of feed water that has been pre-treated is wasted. This further adds to the costs of pre-treatment of feed water. Another important aspect to be considered is that both overflush and mixing are interrelated. Lack of proper flushing of brine would increase the total dissolved solids of the feed. Again, an increase in TDS leads to a higher working of the HPP to achieve the desired pressure, resulting in an increase in the energy consumed by the pump [27].
- High-pressure differential: High-pressure differential results from the pressure drop between the reject from HPP and the feed outlet. Because of the difference in pressure, the booster pump will have to supply higher pressure for which it consumes more energy [27].
- Low-pressure differential: This pressure differential occurs when there is a high difference in pressure between the feed inlet and the brine outlet, because of which, the feed pump consumes more energy to supply higher pressure [27].

6.3 Case Studies

6.3.1 Tuas SWRO Plant in Singapore

This plant is a private BOO (Build, Own, Operate) contract. The contract was awarded to Hyflux Ltd. The plant has a production capacity of 136,000 m^3/day [27]. The plant is directly connected to the water distribution network of the country. The objective of the plant was constant supply of water along with increasing in plant capacity from the initial 20% to about 100%, rising in small magnitudes [27]. The train design of the plant

was chosen after serious consideration. It has a two-pass design with a recovery of about 45% in the first pass, with a capacity of 150,000 m^3/day [27]. The plant employs DWEER™ 1100. Each device attains an optimum flow of 250 m^3/h. Therefore, about 30 DWEER™ 1100 units are required to achieve the required flow at the plant [27].

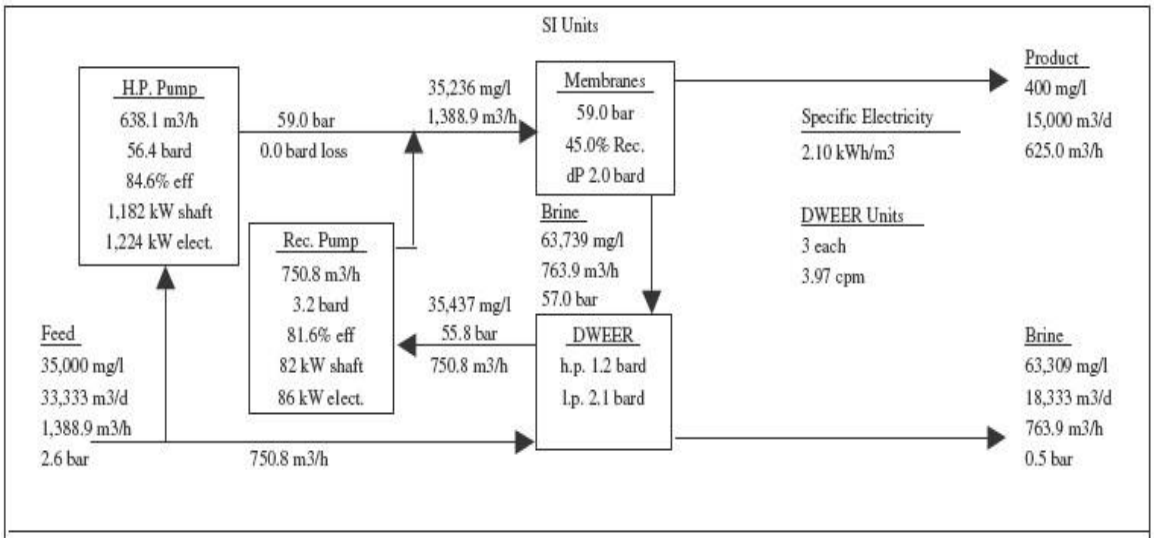

Figure 6-5: Train Process Flow, Tuas, Singapore, 10 Trains

It was initially intended that the plant should operate with great flexibility. Therefore, Hyflux used 10 trains in the plant with each train's capacity amounting to 15,000 m^3/day with three DWEER™ 1100 units per train. The train layout at this plant at Singapore is shown in Figure 6-5 [27].

As the plant is built using a main central design, it appears to have a central train. As shown in the Figure 6-6, the use of DWEER™ 2200 increased the flow to 500 m^3/h. This value is double of what is achieved by the DWEER™ 1100. The use of three HPPs would enable the plant to run at a capacity of 33, 66 and 100 percent [27]. It is also proposed that 16 DWEER™ units can be used in one rack and can be split into four DWEER™ units. This way, during operation at 66% capacity, one set of four DWEER™

units can be switched off and during operation at 33%, two sets of four DWEER^{TM} units can be switched off [27].

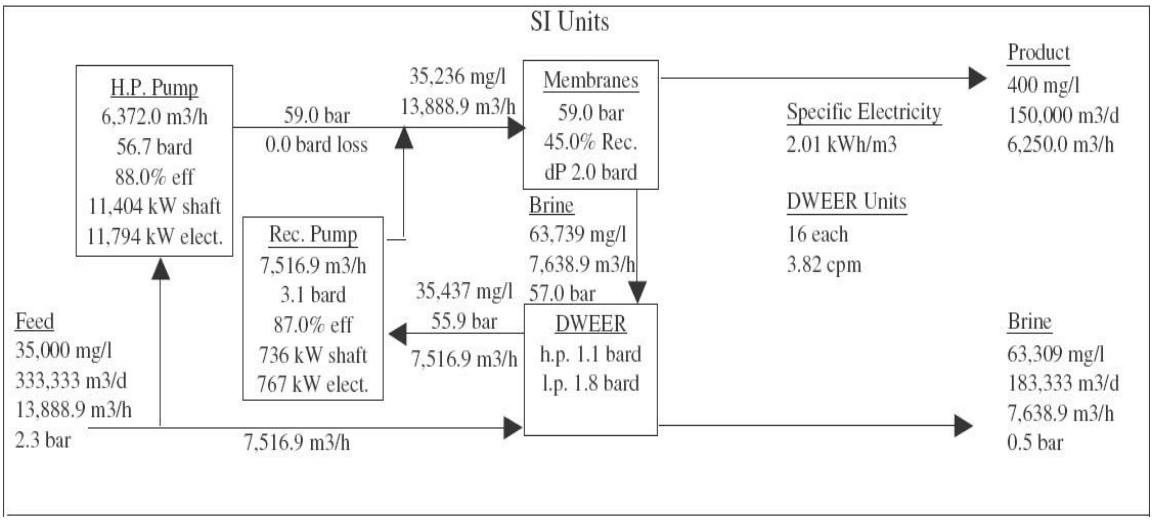

Figure 6-6: Train Process Flow Tuas, Singapore Centre Design

Using these two settings, the energy consumption by the plant decreased from 2.1 to 2.01 kWh/m^3 [27]. This may be because of the following:

- Increase in the efficiency of both HPP and motor.
- Increase in efficiency of the motor and recirculation pump.
- Decrease in loss by the DWEER^{TM} units.

In addition to these, the capital costs involved in the operation of the plant can be reduced by the following measures:

- By reducing the HPPs and booster pumps from 10 to 3. The capital costs can be reduced by selecting the best suited pumps.
- Using lesser implements and instruments
- Reducing the number of DWEER^{TM} units used.

The three control loops of a work exchanger are shown in Figure 6-7. A Variable Frequency Drive (VFD) can be used in conjunction with the booster pump for controlling the brine flow.

The VFD of the HPP can also be used to control flow rate and pressure of the feed across the membrane. As an alternative to this, a flow meter may also be used for adjusting the valve that controls the discharge from HPP.

- The VFD can also be controlled to adjust the flow rate to the work exchanger.

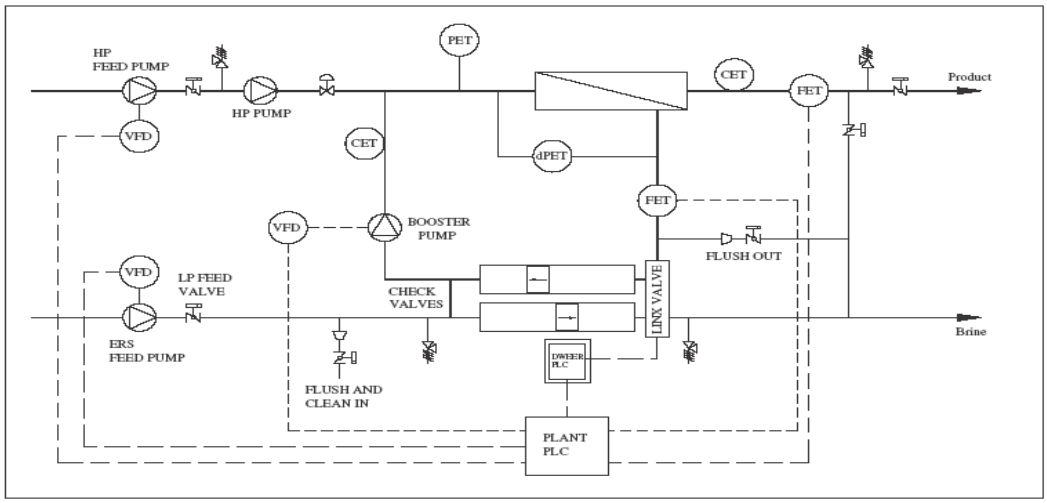

Figure 6-7: Three Main Control Loops for the Work Exchanger

The DWEER^{TM} units are supplied with Programmable Logic Controllers in which a timer signals when the valve has to start its cycle. At normal conditions of operation, there is no variation in the cycling time. Each DWEER^{TM} unit is designed such that there is utilization of 90% of the vessel so that about 10% addition in brine flow will not cause much difference in the functioning [27].

The DWEER^{TM} units are also supplied with special sensors that detect overflush as well as underflush. If any of these is detected, the information is sent to the Programmable Logic Controllers (PLC) of the plant, which directs it on how the flush can

be controlled and minimized. As is understood, it is not possible to control overflush without a PLC at the plant. The PLC is also important at large plants for the diagnosis and control of other equipment [27].

Figure 6-8: Wearing Parts Which are to be Changed

In addition to the listed functions, the PLC of DWEER^{TM} carries out tests that are helpful during maintenance.

- Maintenance: The DWEER^{TM} device is designed such that it works for a lifetime. The materials used are standard, Super Duplex or non-metallic. For this reason, the important parts of the device do not have to be replaced throughout the lifetime. The other parts that are prone to wear or corrosion can be easily acquired and replaced. Some of the components, which are prone to corrosion are given in Figure 6-8 [27].

DWEER™ is known for its basic high energy efficiency of operation. Another important advantage is that the energy consumption remains almost constant over a wide range of operating conditions.

- In case of Constant Flow: DWEER™ will not be affected considerably by a varying system pressure, if the flow is constant. However, there will be an increased leakage through the LinX™ valve as the operating pressure increases. The Singapore example depicted in the Figure 6-5 shows that the leakage increase will be from 1.5% to 1.9% for the increase in the operating pressure [27].

The HP pump is required to deliver more flow at higher operating pressure but at the same time booster pump will deliver lesser flow. When the results of the Singapore example are extrapolated, the leakage rates are expected to increase from 13.1 m^3/hr at design value to 14.6 m^3/hr at 69 barg. This amounts to an additional leakage flow up to 1.5 m^3/hr [27]. The increased power consumption of HP pump accommodating the leakage values can be calculated as follows;

$P_{hppumpdelta}$= 1.5m^3 / h * (6.9 – 2:6) barg /36 /0.846 =3.2kW

Corresponding decrease in the power consumption at Booster Pump is given by

$P_{booster\ pump\ delta}$= 1.5m^3/h * 3.2barg /36 /0.816 = 0.16kW

The increase in overall power consumption is

$P = P_{hp\ pump\_delta} – P_{booster\ pump\_delta}$= 3.04 kW

Considering this additional power consumption in the value for the total power absorbed by both high pressure and booster pump totaling 1264 KW, this additional power consumption amounts to a negligible value of 0.2% [27]. It can be inferred from these calculations that the DWEER ™ efficiency is not affected by the changing pressure as long as a constant flow is maintained. The Figure 6-9 shows that the overall power consumption increases mainly due to an increase in membrane feed pressure, which will exert a higher differential pressure on the HP pump.

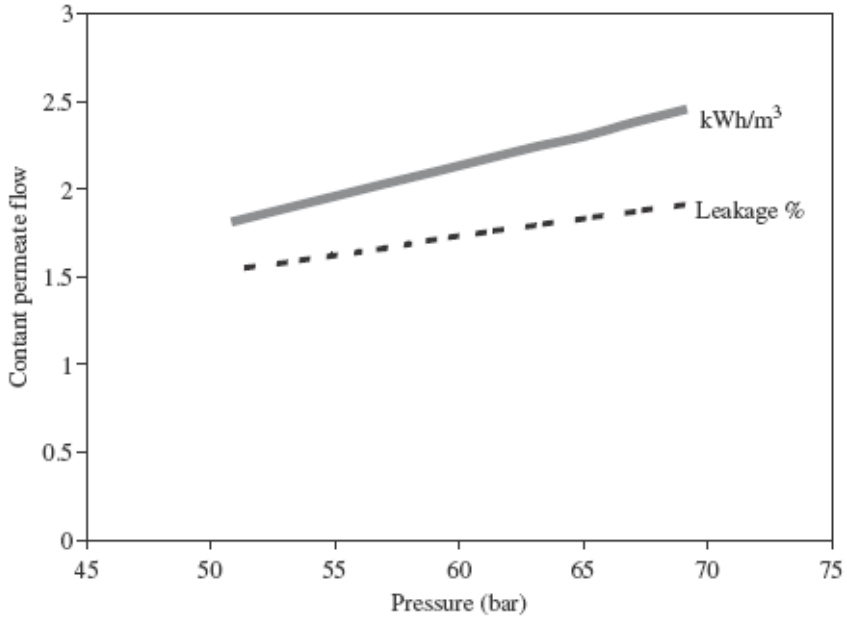

Figure 6-9: Overall Power Consumption

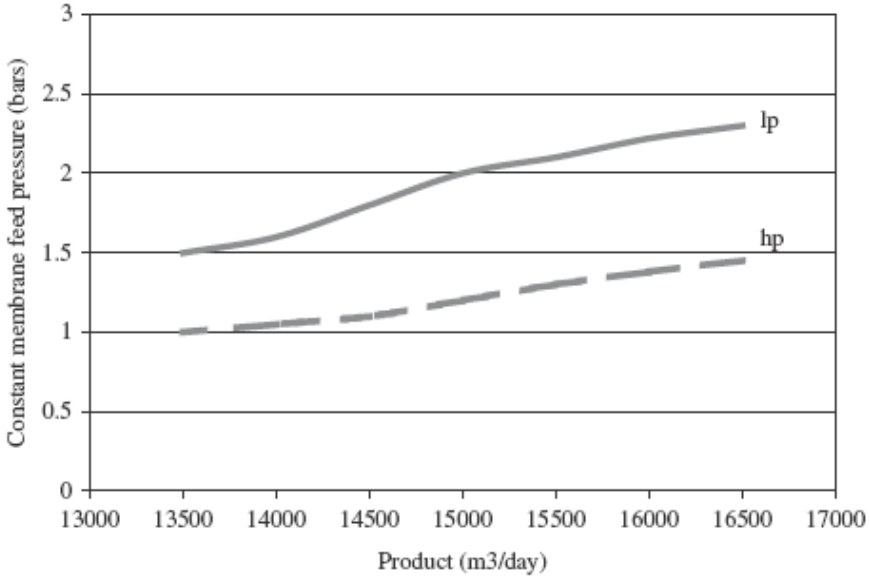

Figure 6-10: Constant Differential Pressure

In case of constant membrane feed pressure: Figure 6-10 depicts the calculated differential pressures across the LinX^{TM} valve, check valve nest and pressure vessel at

constant brine solution pressure but with variable brine flow rates. In this case, DWEER^{TM} leakage will not change at all. Now, the booster pump has to overcome the increased high-pressure differential head and the feed pumps need to supply low-pressure differential heads which are having decreased value. The Singapore example (Figure 6-5) shows an increase of high pressure differential pressure from 1.2 barg of design value to 1.4 barg of higher production value that amounts to an increase of 10%. This results in increased power demanded by booster pump and is given by:

$P_{booster\ delta}$ = 763.9m^3 = h*1:1*(1:4 – 1:2)/36/0:816 = 5.76kW

In addition, the low-pressure differential pressure will be increased from 2.1 to 2.3 barg. This results in the additional power absorbed b the feed pump as given by:

$P_{feed\ delta}$ = 750.8m3/h*1:1*(2.3 – 2.1)/36/0.8 = 5.74kW

Thus, the total additional power absorbed by booster pump and the feed pump is 11.5 kW. Now, putting this value in the value of total absorbed power of the HP pump and the booster pump having 1264 kW, it is found that the increase is just in the range of 1% for an increase of the production of 10%.

Chapter 7: Pressure Exchanger (PX)

7.1 History and Design

The ERI PX® - Energy Recovery Inc., Pressure Exchanger system comes under the classification of third class of ERDs, these are hydraulic driven pumping operating in parallel.

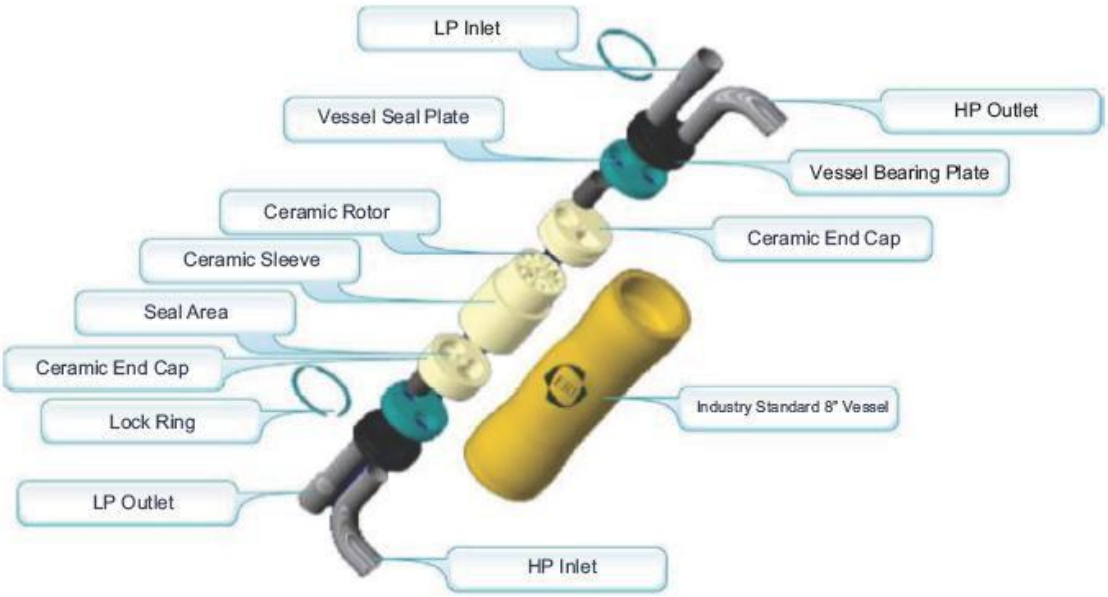

Figure 7-1: ERI Pressure Exchanger Exploded View

Rotor Pressure Exchange is built by Energy Recovery Inc.'s, a firm that has put an effort of over 100 years in its technology and development. The Work exchanger devices that are built for seawater RO plants are treated as the most noteworthy technological breakthrough in desalination techniques achieved in the last 15 years. The PX® is the

device that transfers the pressure of the high pressure fluid stream to a low pressure fluid stream working on the principle of positive displacement [30]. These devices are not as similar devices used in lesser demanding environments; PX is able to meet the tough requirement as it is specially built for SWRO systems. This was introduced as a commercial product in the year 1997 [31]. Subsequently, PX design has seen many improvements, which have resulted in higher capacity of the single rotor to a very high value of 50 m^3/ hr. But, its fundamental technological frame on which it is built has not changed at all [11]. The technology employed involves SWRO scale energy recovery by undergoing many small pressure increments in a ceramic rotary device [32].

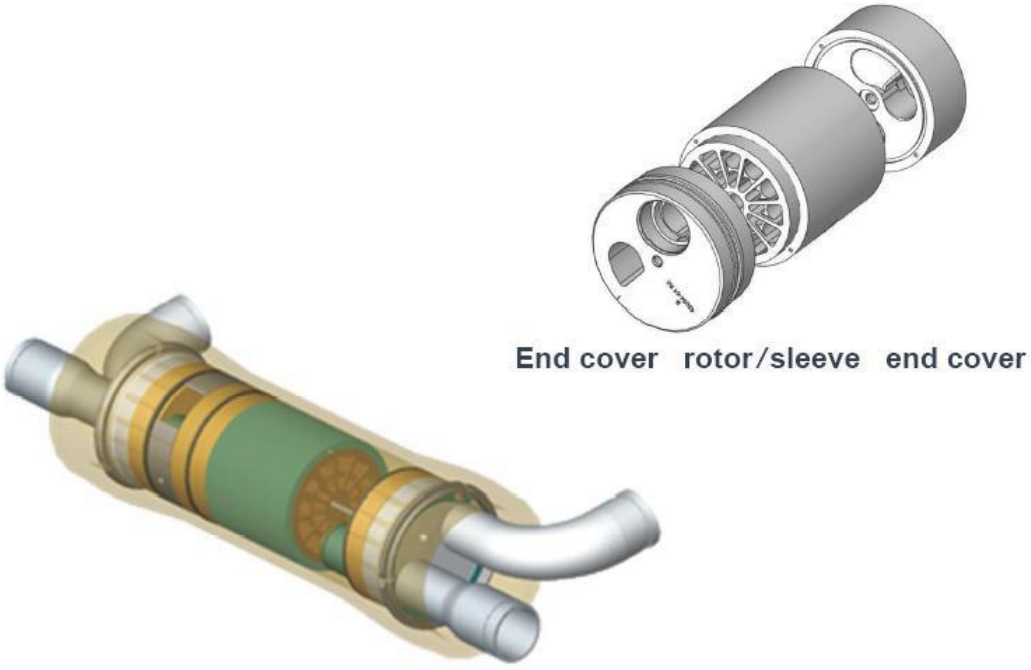

Figure 7-2: The PX Device

More than 400 seawater reverse osmosis (SWRO) units all over the world have employed ERI's PX Pressure Exchanger® ERDs. Just in the year 2006, more than 2500 units were supplied which are having a combined capacity of 1.8 million m^3/ day of the

permeate fluid [33]. Many of these plants have a capacity of 100,000 m^3/ day and there many bigger plants too. For example Perth, Australia has a unit of 160,000 m^3/ day [34], Hamma in Algeria has installed a unit of 200,000 m^3/ day, Hadera in Israel has installed a plant of 274000 m^3/ day [35]. Other units of high throughput are installed at Benisaf at Algeria with 200000 m^3/ day unit and Skikda at Algeria with 100000 m^3/ day unit. Many of these projects have incorporated 20 years maintenance and operating contract. So the suppliers must consider the reliability and service life, an important part of the design of these equipments [36]. 65 Series PX Pressure exchangers are most preferred devices for these equipments, and especially the models PX 180 and PX 220, are commonly used [34]. These models are available in the market since 2003 and more than 1400 units are in use until date. In 2006, ERI arranged with their clients to temporarily retrieve several long running PX units and, in the factory's test facility, they were evaluated for their performance [11].

PX device works on positive displacement and is an isobaric energy recovery device. It contains a ceramic cartridge which is the heart of the device [30]. The cartridge has a feed water end cover, rotor, sleeve and concentrate end cover as shown in (Figure 7-1 & Figure 7-2). The design of the rotor consists of axial ducts, which are arranged circularly around a centre tension rod. It rotates in the sleeve and both the end covers enclose the rotor. Sealing and bearing surfaces are also made of ceramic and the lubrication of the brushing surface is accomplished by the high pressure feed water. The end cover at the concentrate end consists of High Pressure HP Concentrate port for allowing in the HP IN (HP concentrate) and also a low pressure concentrate port for out flowing concentrate (LP OUT). At the feed water end cover side, there are two feed water ports termed LP IN and HP OUT. For the design of this element, ceramic is the natural choice because of its toughness, corrosion resisting property and its dimensional stability [33].

The high-pressure concentrate is used to direct pressurization of the feed water in the PX device. In order to lubricate the rotor, flow rate of concentrate is set at somewhat higher flow than the feed water so that small amount of feed water helps the lubrication of the rotor [30]. So, the PX device supplies the membranes a portion of feed flow (portion of concentrate) and the high pressure pump supplies permeate portion of feed water flow and also accommodates a small flow for the lubrication [11].

Figure 7-3 shows the operating cycle of the device. As explained above, a rotor duct is exposed on to LP IN and LP out end cover ports. As shown in the Step 1, the LP feed water the rotor duct. The positioning and the placement of the rotor ports is such that it provides tangential flow which exerts turning force on the rotor. The rotor ducts terminate in a Seal Zone where the flow is stopped and duct is sealed from HP and LP flow circuit as seen in step No 2. The duct rotates further to expose the incoming HP concentrate that pressurizes the feed water and further pushes it toward the membranes as shown in Step 3. The rotor continues to advance till the duct is sealed as seen in step 4 and the whole cycle begins again [36].

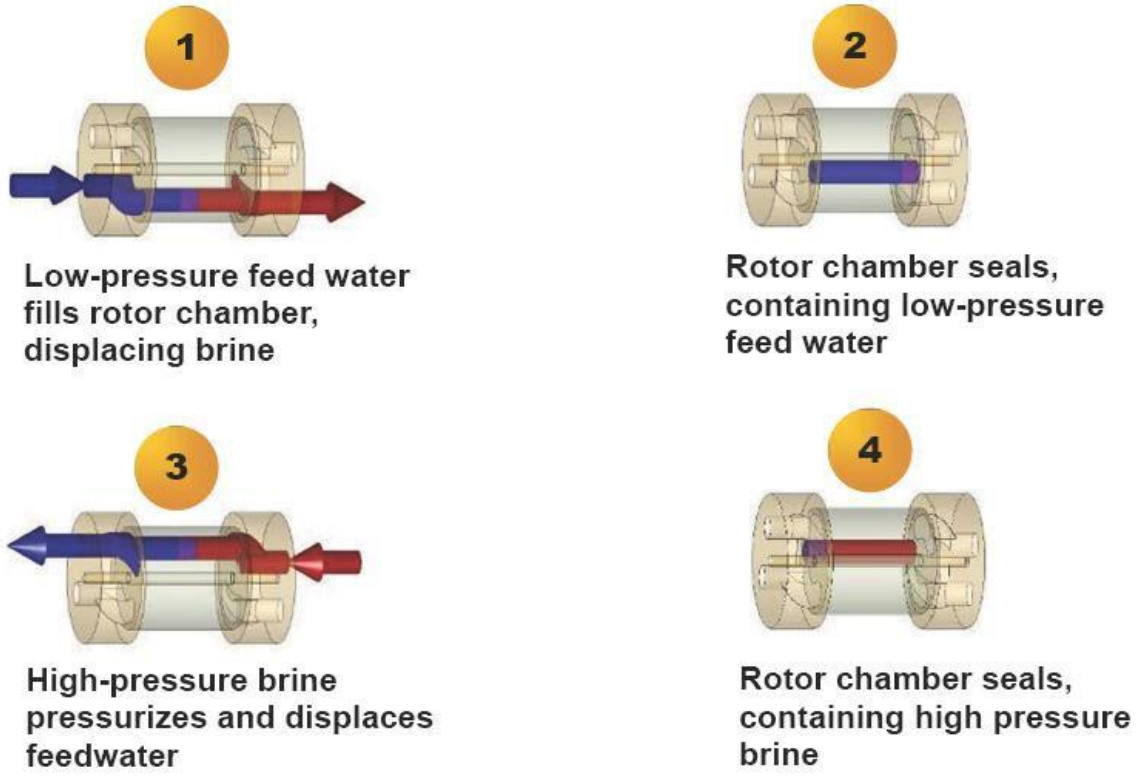

Figure 7-3: The PX Device at Work

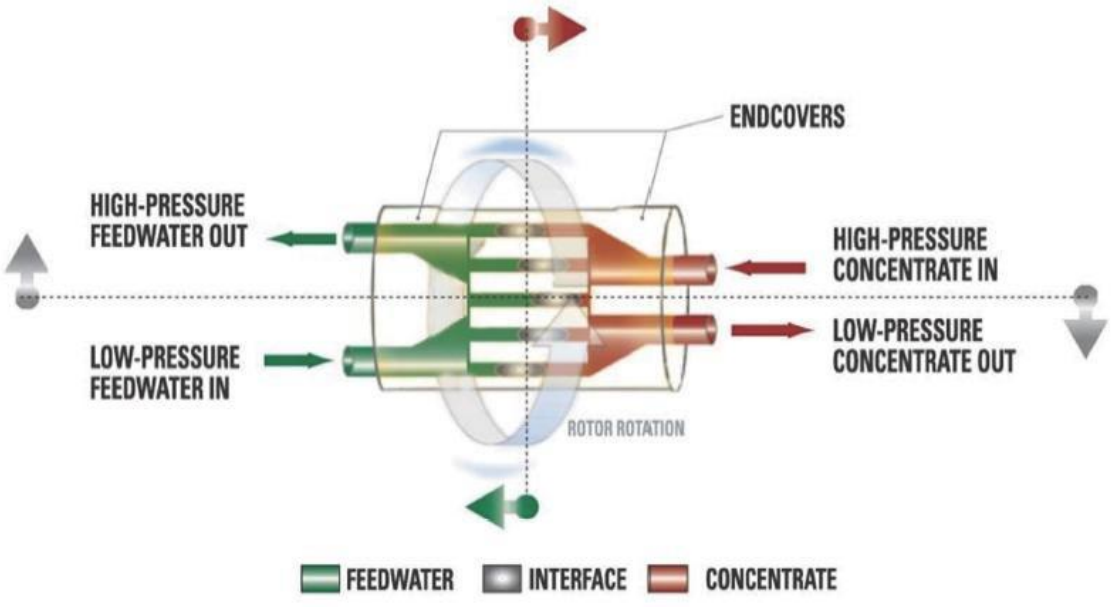

Figure 7-4: PX Device Operation Cycle

Though the feed water and the concentrate come in direct contact in the rotor, due to the water barrier that exists in the duct, there will be limited mixing between the feed water and the concentrate [36].

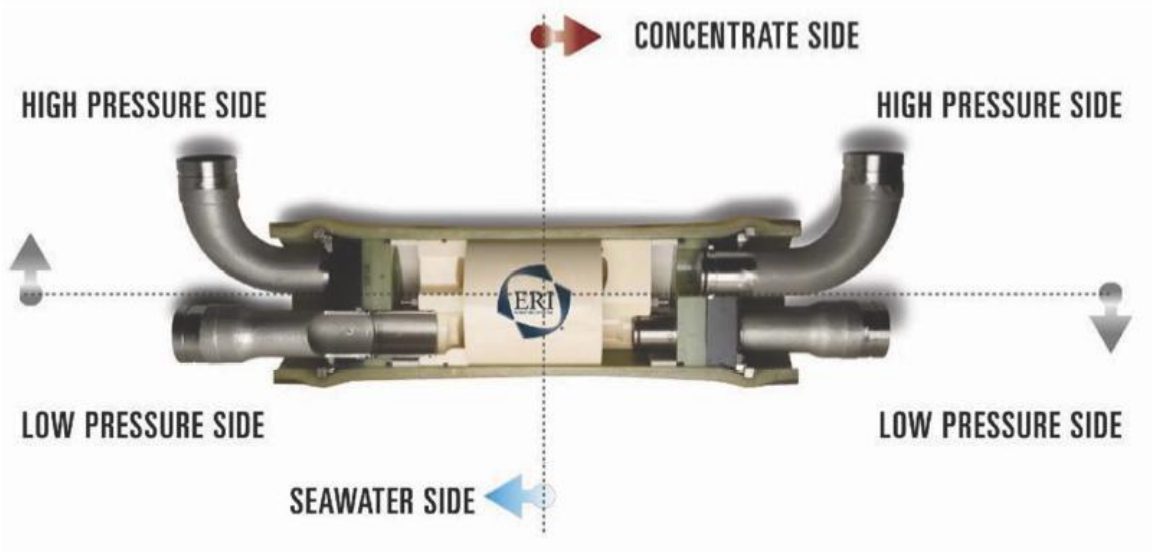

Figure 7-5: View from Inside Pressure Vessel

The design of the ceramic components is such that the interfacing feed water and concentrate does not reach the end of the duct before it is sealed and thus retaining the separation. If there is any water remaining from the previous cycles, it acts as a barrier against the mixing of these flows. Further, the ducts are designed with aspect ratio to be long and narrow so that the flow is stabilized and there is no breakup of the barrier due to turbulence [33].

7.2 Efficiency and Mixing

PX device performance can be quantified by its energy transfer efficiency and also the degree of mixing. Efficiency of the PX device is the ratio of total energy output by the

PX device to the total energy input to the unit expressed as percentage. In this case the total energy is obtained as the product of flow and pressure which is given in Eq 7-1[7].

PX efficiency = [**Σ** (Pressure x Flow Pressure)$_{out}$ / **Σ** (Pressure x Flow Pressure)$_{IN}$] x 100% (7-1)

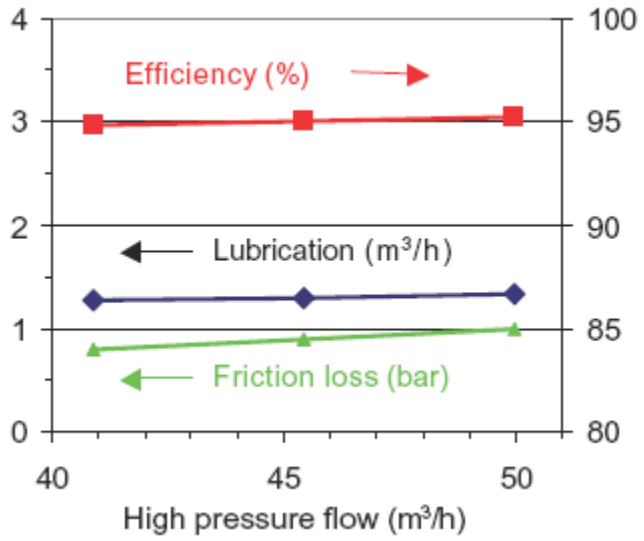

Figure 7-6: PX Efficiency

The relation shown here considers the flow and pressure losses in the PX unit. As Flow is lost in lubrication, the HP IN flow rate is greater than HP OUT flow rate and LP OUT flow rate is greater than LP IN flow rate. However, it is to be remembered that the loss due to lubrication is very small. It is just 1% of the concentrate feed flow. The losses due to pressure drops occur as the flow encounters friction from the internal passages in the PX assembly [33].

In SWRO operations using PX device, there is an increased salinity in the high pressure due to mixing in the PX causes increase in the osmotic pressure. If a balanced flow is maintained, i.e. high and low pressure flow rates are equal, then the PX 220 mixing is calculated by using the following equation and is approximately put at 6% [7]:

Volumetric mixing = (HP_{OUT} salinity – LP_{IN} salinity) / (HP_{IN} salinity – LP_{IN} salinity) x 100% (7-2)

The high-pressure flow that comes from booster or the PX pump mixes with the feed water from high-pressure pump before sending to membranes. Normally, salinity increases at the membrane regions, for the plant operating at 40% recovery is approximately 2.5% and is given by the equation:

Salinity increase = [(Membrane feed salinity – Seawater salinity) / Seawater salinity] x 100% (7-3)

This 2.5 % increase in the salinity at the membrane region results in increase of operating pressure by 1.3 bar, approximately [33]. If the PX performance is used to express the efficiency, decrease caused by mixing PX 220 with balanced flow is calculated to be 1%. Most plant operators and the engineers prefer to increase the membrane pressure without any changes in the other process settings or equipments. In fact, there is an increase of the salinity due to increase of temperature of just 2ºC that is equivalent of the same effect as seen by mixing in the PX. However, if the engineer or the plant operator chooses to compensate for PX, salinity increases to get the same permeate flow but without making any changes in the membrane pressure, then it can be accomplished by one of these three options [33]:

- By decreasing the recovery by 2%, which results in increase of 5 % of seawater feed flow by 5%.
- Increasing the membrane surface area by 6%
- Increasing the low pressure supply to PX by 5%

The data presented in Figure 7-7 shows the advantage of choosing the first option. The data relates to a plant that is supplied with 36000 TDS water at 25^0 C. If the recovery is decreased by 2 %, (from 40% to 38%), it results in net decrease in plant's operating cost by 0.02 KWH / m^3. This is acceptable for the reduction of recovery at just 2% [36].

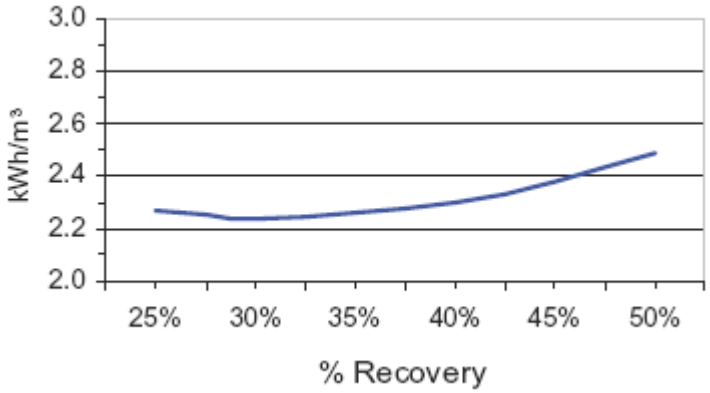

Figure 7-7: Plant Energy Consumption as a Function of Recovery

7.3 Case Studies

7.3.1 Perth SWRO Desalination Plant (PSDP)

Perth Sea Water Desalination PSDP plant is located at Kwinana beach, which is 25 miles south of Perth in Western Australia. Since November 2006, it has been supplying municipal drinking water to Perth city. It has a capacity of 143,000 m^3/day (or 38 MGD) and it is able to cater to 2% of the drinking water requirement of Perth [37]. This plant is the third largest SWRO in the world (as recorded in 2008 March), and is the largest SWRO desalination plant in the Southern Hemisphere. This was jointly built and commissioned by Suez Degremont and Multiplex Engineering Pvt Ltd. The unit is operated by Australian Water services which is a subsidiary of Degremont in Australia [38].

While designing this plant, it was planned to achieve maximum operating energy efficiency and also minimum green house gas emissions. There are 12 SWRO trains present in the first pass and each has production capacity of 13,350 m^3/d or 3.5 MGD [39]. The production of water from the plant varies depending on seawater salinity, temperature and the membrane aging. It achieves the production values of 150 to 300 mg/L, which works out to be 45% recovery efficiency. Six Weir split case centrifugal pumps (HP) feed the RO trains. Each of these pumps has the capacity of 1,144 m^3/hr at 620 meters of differential head. These are driven by Siemens made induction motors of 2600 kW each [40].

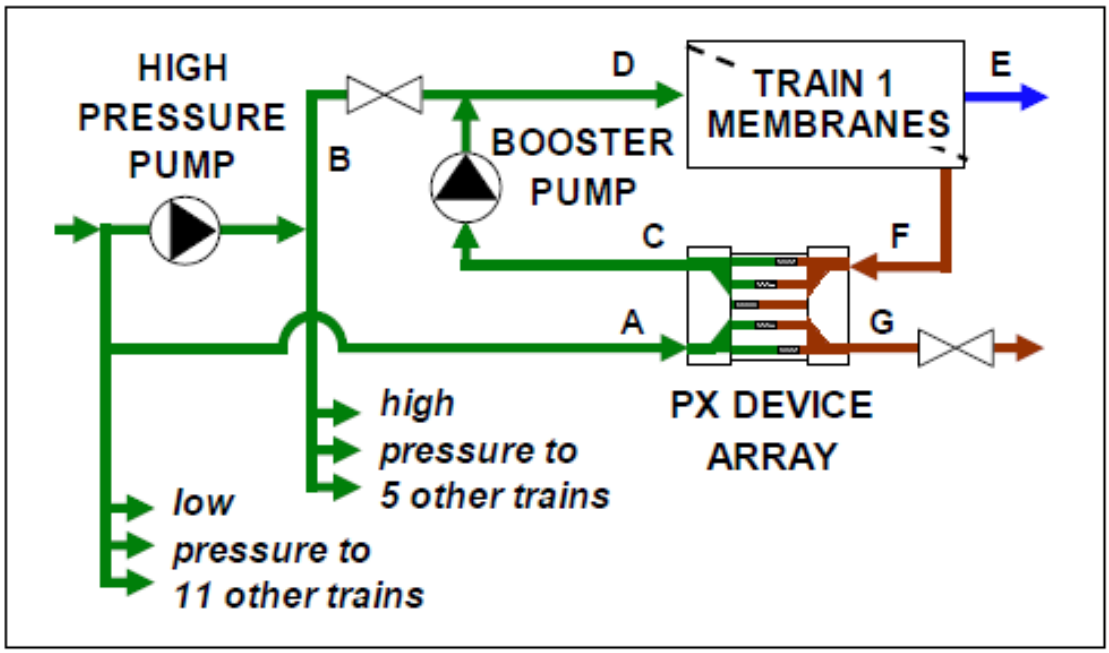

Figure 7-8: Conceptual Diagram of Pressure Center Configuration

The maximum efficiency of these pumps is 86%. The reject stream from Reverse Osmosis modules is made to pass through the 12 arrays of sixteen ERI models PX 220 energy recovery devices [38]. Each of these modules has a capacity of 800 m^3/ hr and

the pressure is transferred to the equal volume of incoming seawater. This pressure is boosted by RO modules with the help of 12 Union vertical booster pumps. These pumps have a capacity of 611 m^3/hr at 39 meters of differential pressure head and these are driven by 112 KW motors that are controlled and run on Variable Frequency Drives(VFD) [39]. The plant is built with six numbers of SWRO trains on each side of central pump aisle. As shown in Figure 7-8, the three numbers of HP pumps feed the high-pressure manifold as shown in the schematic that shows the arrangement for one train, which feeds the group of six racks. There is a high-pressure control valve that goes from the manifold to each train that allows the fine adjustment of feed pressure from the membrane. In addition, each of the rack has its own dedicated PX device array with the booster pump. These PX device arrays are located between the membrane vessel racks. ERI PX 220 energy recovery devices help to supply remainder of high pressure seawater [39].

Figure 7-9: SWRO Trains 4A, 5A and 6A

The hydraulic design of the plant provides a great flexibility of operating over wide range of flow and pressure conditions and yet achieves cost effective operation [37]. The plant is operated entirely from the electricity generated from wind-powered generator and thus meets its requirement of zero emission of green house gases. Figure 7-9 shows a photograph of a portion of the SWRO process [40].

Operating for a year, it was found that the plant exceeded the expectations of the designers. The first pass of SWRO train consumes 2.2 kW hours of energy per cubic meter of water (KWH/m^3) approximately [38]. The total energy requirement of the plant is around 3.2 to 3.5 kWh/m^3 that includes the energy required for intake, pre treatment, RO passes, post treatment and pumping the potable water to the reservoir which is 12 kilometers away from the plant [39].

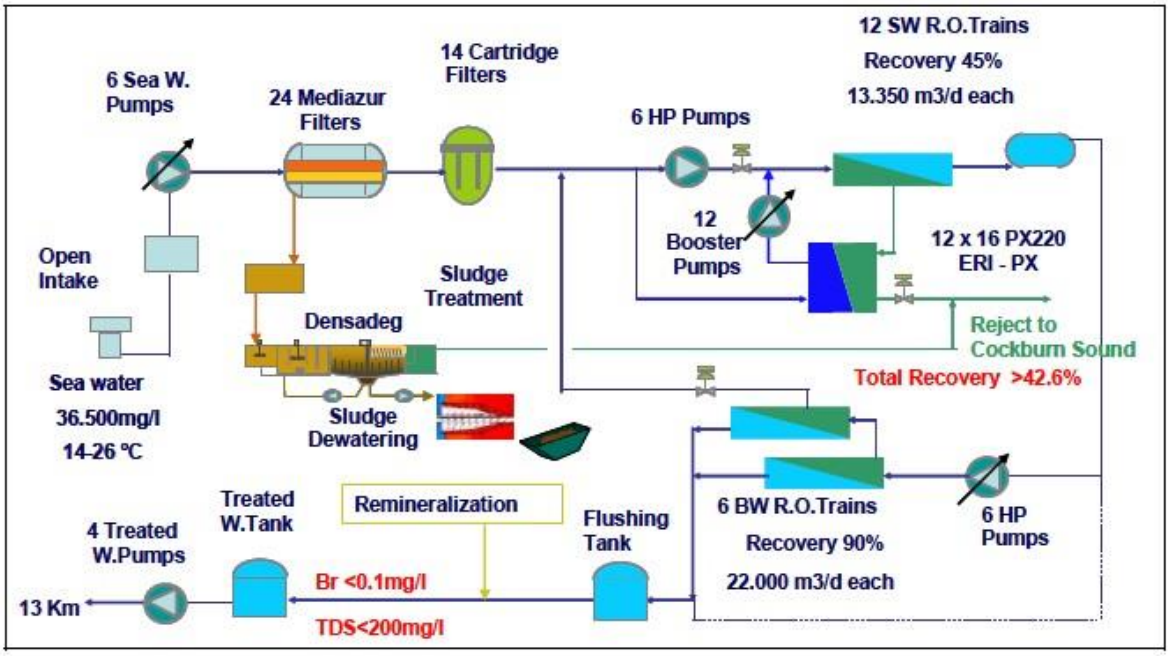

Figure 7-10: Perth Seawater Desalination Plant Process Diagram

Figure 7-10 shows the process diagram of PSDP. The feed water is drawn from and open intake at Cockburn Sound, which is quite nearby. There are six numbers of supply pumps that draw screens and output this to 24 dual media filter vessels and these in turn discharge to the cartridge filters, which let the fluid to RO process. The Variable frequency drive VFD motor pumps supply the seawater to the HP pumps and this arrangement saves energy and supplies to HP pump and energy recovery device at constant pressure [38].

With the help of a single pile, the treated water is conveyed to HP pumps and energy recovery devices. The sizing of the high pressure pumps is selected to achieve maximum efficiency and is also operated to achieve the same [37]. ERDs are used in arrays dedicated for each membrane train. The high pressure feed water from ERDs and HP pumps to the state of art first pass membranes that are built for low energy consumption [40]. When the permeate goes to the next pass it will achieve further reduction in the total dissolved solids (TDS) and also reduction in bromide concentration. The purified potable water is collected at the 4-hour buffer tank and then it is pumped to fresh water reservoir that is located at 13 kilometers away [40]. From there it is supplied to city of Perth as drinking water [40]. The rejected brine is used for backwashing dual media filters and then pumped to diffuse fields locate half a kilometer away to Cockburn Sound [38].

The PDSP is the largest facility of its kind in the world and it is built to realize the commitment of Western Australia to promote energy efficiency and decrease the green house gas emissions [40]. It is a carbon neutral plant and for its energy needs, it utilizes the renewable energy source of wind power that causes zero pollution. The electrical energy required for the plant is bought from the Emu Downs Wind Farm which is located 200 km north of Perth city [38]. The wind farm has plant capacity of 83 mega watts consisting of 48 wind turbines and the annual production is over 272 Giga Watt hours

pumped to the grid. This quantum of energy is sufficient for running the SWRO plant at Perth, which needs only 180 Giga Watt Hours a year [39].

Global Water Intelligence has recognized PDSP plant as the Desalination plant of the year in 2007 due to the innovative design backed by the successful performance [40]. This plant has been acclaimed as the landmark development in Australian water management industry. It is also regarded as the model plant for the whole world for development of sustainable seawater desalination plants all over the world [37].

Figure 7-11 shows the photograph of one of the twelve PX device arrays of the Perth plant [37] . The picture shows that the upper low-pressure manifold is supplying the seawater to the PX device from the left side. On the lower right, the low pressure outlet can be seen. This type of flow pattern is termed as Z Flow as the flow is from manifolds and PX devices. Similarly, the high pressure flow also has the Z Flow form with the inlet at lower side on the left [38]. If the bulk flow is made to enter and exit the array from the same end, it can be termed as C Flow and this would result in more even flow distribution. However, in the Perth design, manifolds are used with liberal dimension for diameters, which limits the flow variation through PX devices along with array. The variation is limited to 10% approximately [39].

Figure 7-11: PX Device Array Serving SWRO Train 6A

Table 7-1 gives the performance data for SWRO train 1A. Refer to Figure 7-8 as the process locations are indexed as shown in the figure. The measured data is seen in bold letters and calculated data in plain fonts [40].

Table 7-1: Train 1A Performance Data

TRAIN 1A		A	B	C	D	E	F	G
FLOW	m^3/hr	**674**	559	**666**	1225	**552**	673	**681**
PRESSURE	**bar**	**2.6**	**63.8**	**57.2**	**58.9**	-	58.2	**1.7**
SALINITY	**g/l TDS**	**34.0**	**34.0**	**35.6**	34.9	**0.435**	**63.5**	**61.1**

MEMBRANES		
Membrane Differential	bar	**0.70**
Water Recovery	%	45.0

HIGH PRESSURE PUMP		
Voltage	V	**11,000**
Line Current	A	**142**
Power Consumption	kW	2,705
Total Flow	m^3/hr	1,127
Specific Energy Consumption	kWh/m^3	2.40

SWRO SPECIFIC ENERGY	kWh/m^3	2.47

PX DEVICES		
PX Array Lubrication Flow	m^3/hr	7
Volumetric Mixing		5.1%
Mixing at Membranes		2.4%
Nominal PX Efficiency		95.7%
PX Efficiency at PX Array		96.7%

BOOSTER PUMP		
Power Consumption	kW	**45**
Specific Energy Consumption	kWh/m^3	0.07

Table 7-1 also shows that the lubrication flow through the PX devices is approximately 1% of the brine solution flow in to the array. The data is calculated for the train carrying 1.2% more seawater fed to PX device array at the process location “C” [40]. Under these conditions, the increase in the salinity at the membranes was at 2.4 %. If the flow rates were adjusted to be equal by setting the VFDs, the mixing increases slightly to 2.5% approximately [40].

The pressures at the both high-pressure and low-pressure streams to PX device array (the locations B and G) were measured at the upstream end of the array. Based on these pressure measurements, the efficiency of the PX device calculated was 95.7%. But by measuring the pressures at the inlets and outlets of the PX device manifolds, the calculated transfer efficiency was 96.7 % [37].

Figure 7-12: Perth SWRO Desalination Plant

While the data for the Table 7-1 was collected, the Trains 1A and 2A were being supplied with one HP pump. The specific energy consumed for each HP pump and the

booster pumps was 2.47 KWH/m^3 [40]. The high-pressure control valve was used to control the high-pressure flow rate. No data pertaining to supply pump performance was collected, and however, the design energy consumption of these pumps used for the conditions shown in the table gave a value of 0.3 KWH/m^3 [40]. Similarly, the energy consumption data for the second RO pass, post treatment pumping requirements, product water pumping are not collected but it is given that the design energy consumption was 1.4 kWh/m^3 for all these processes [38]. The total energy consumption of the plant, including these design figures is 4.2 KWh/m^3 [37].

The data shown in the Table 7-1 illustrates data from one train for one day. Additional data acquired on the same day and five other days are shown. As is apparent, their performances are similar [40]. Moreover, the trends of main parameters were also consistent, shown in Table 7-1.

The SWRO plant at Perth is a good example of how desalination can be done on a large scale without incurring high costs and damaging the environment. The plant was able to achieve low consumption of energy because of the use of isobaric ERDs, along with the use of renewable energy, thus minimizing damage to the environment [37]. This plant is thus a suitable model for the entire world for the sustainable desalination of water. This plant is a significant milestone in the area of large-scale SWRO technology as it operates on renewable energy, thereby reducing energy consumption to a very significant level [39].

Chapter 8: Conclusion and Recommendations for Future Research

8.1 Overview and Comparison

ERDs vary widely and as some were displayed in the previous chapters, each of these has its own advantages. This chapter explains how the optimization of an Energy Recovery Device can be done along with the criteria that are needed to be followed for the selection of the most suitable, efficient and cost effective device in Sea Water Reverse Osmosis desalination plants.

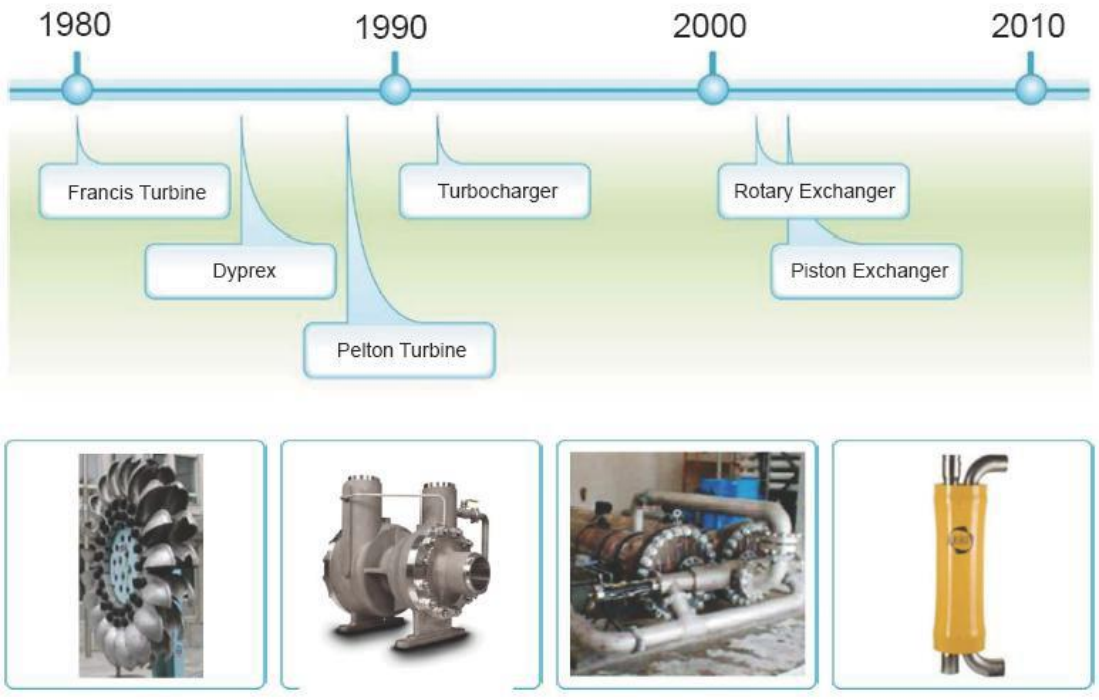

Figure 8-1: ERD Development History

As far as an assessment of ERDs is concerned, there is always a debate on whether work exchangers are more efficient than the turbochargers or the energy recovery turbines. As each has its own merits, it is often difficult to ascertain which one is better than the other. For instance, the Pelton wheel has a high efficiency and low cost motors can be used along with it. This would not only reduce energy consumption but would also save costs of the equipment and motors required. Therefore, Pelton wheels are extremely useful for reducing energy consumption as well as costs incurred for operating the HP feed pump [41]. According to Calder, far from being obsolete, these energy recovery turbines are great competitors against Isobaric chamber devices [42]. Apart from supplying Pelton wheels to smaller plants in 2005 and 2006, Calder has also provided energy recovery turbines for three large plants– the Cartagena II, whose capacity is 65,000m³/day; the Palmachim, whose capacity is 85,000m³/day; and the Rabigh, whose capacity is 200,000m³/day [43].

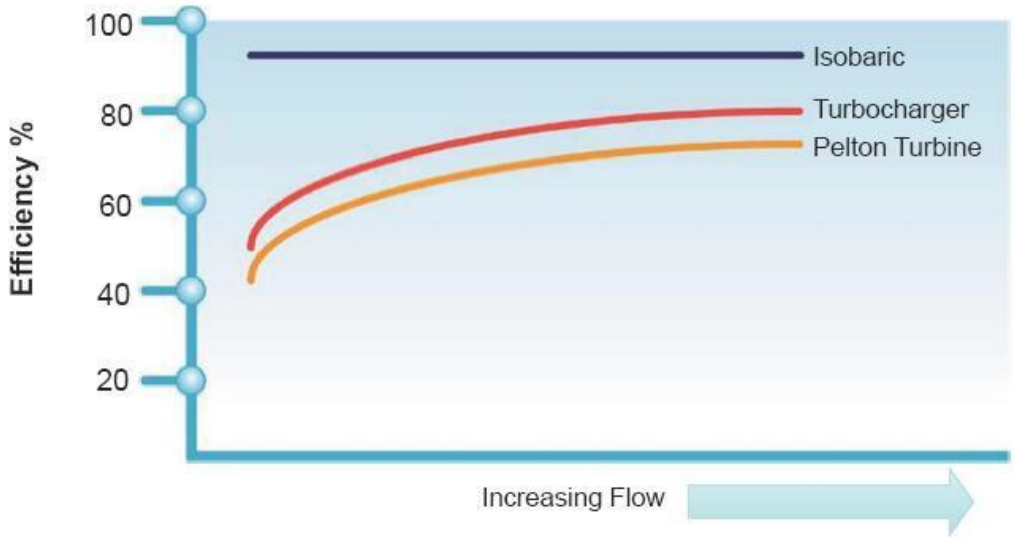

Figure 8-2: ERDs History

According to Energy Recovery Inc, the ERD with the highest energy recovery is the PX (as illustrated in Figure 8-2). The ERI demonstrated its effectiveness in July 2006 in trials held in Port Hueneme, California. These trials were conducted at the Seawater Desalination Test Facility of the US Navy [42]. As per the data available from these trials, the actual energy consumption was 40% lower than what was expected. According to the reports from ERI, these trials tested PX coupled with low-energy membranes and HPP, resulting in the least energy consumption achieved by RO desalination plant until that time. The energy consumption was less than 1.58 kWh/m^3 in these trials [43].

Eli Oklejas, president of FEDCO, argues that efficiency can be a "very misleading parameter" and that instead of considering which ERD is more efficient, it is more important to consider which ERD gives the least cost per unit permeate throughout its lifetime [43] . As he puts it, “Lifecycle cost is the key figure of merit in selecting pumps and ERDs and at the end of each day, it is the cost of the permeate that matters most [43].”

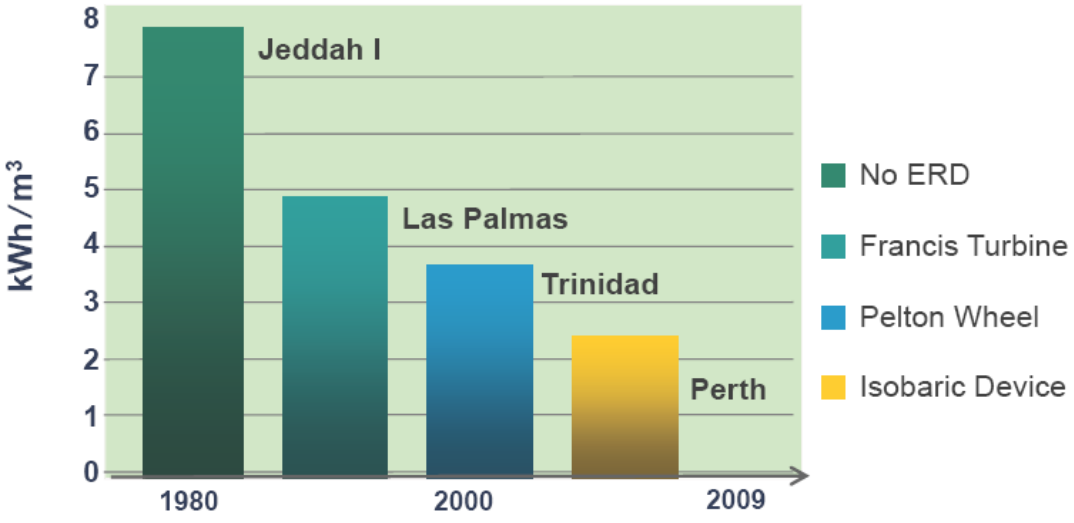

Figure 8-3: Improvements of SEC in SWRO Plants with Variable ERDs

8.2 Data Analysis

8.2.1 350 m^3/d ERT VS PX

For this research, a comparative analysis ERTs and PX is performed. The comparative analysis of the costs of both these systems is shown in the Table 8–1. This analysis is based on a production unit of 350 m^3/d capacity that uses both positive displacement as well as centrifugal pump designs [44]. As is apparent from the table, the PX requires larger investment and capital costs for its installation and implementation. This cost is 17% higher for pumps with centrifugal design when compared to those with the positive displacement designs [44]. The high capital costs are compensated within 2 months because of the low consumption of energy and low costs of operation and maintenance of the system, especially those employing the positive displacement pump design [3]. The device efficiency of both the types of ERDs is also dissimilar. While the efficiency of the energy recovery turbines varies vastly, with a maximum efficiency of about 80% [44]. The PX, on the other hand, has a constant energy efficiency of 90%, with a maximum value of 98% [3].

Figure 8-4 shows the energy consumption by devices with different designs, such as the ERT and the PX. The data also reflects the wide-ranging differences in the recovery rates. As is observed, all the designs except the PX have similar variations in the energy recovery and production rate values. There is a rise in energy consumption at lower recovery rates, which is different from the PX. This enables the operation of the system at low recoveries, thereby leading to an increase in the membrane life and hence lower the total costs [3].

Finally, when the construction and long-term maintenance of the system is considered, it is observed that the PX is constructed from ceramic and has a single rotating element without the conventional bearings. Therefore, the PX has low

maintenance costs because of its simple design. It also withstands corrosion due to high salinity and other marine related dissolved solids. On the other hand, almost all other ERDs are constructed from alloys and have bearings, seals, pistons etc that raise both the cost of maintenance and operation [3].

Table 8-1: Cost Data for a 350 m^3/d SWRO Desalination Plant

Feed Pressure – 60 bar				
Recovery – 40%				
Availability – 90%				
	Centrifugal		PD	
Capital Cost:	ERT	PE	ERT	PE
Pumping System	$31,000	$28,000	$40,000	$30,000
Energy Recovery System	$18,500	$30,000	$18,500	$30,000
Total Capital Cost	$49,500	$58,000	$58,500	$60,000
Capital cost per m^3/d	$141	$166	$167	$171
Energy used, kWh/m^3	4.4	3.2	3.8	2.5
Annual operational cost:				
Depreciation of capital 8% – 10yr	$7,377	$8,644	$8,644	$8,942
Maintenance				
Positive displacement – 10%			$4,000	$1,600
Energy recovery systems – 10%	$1,850	$3,000	$1,850	$3,000
Energy – $0.10/kWh	$50,589	$36,792	$43,691	$28,744
Total Operational Cost	$59,816	$48,436	$58,185	$42,286
Payback – months		9		2
Water cost reduction – $/$m^3$		$0.10		$0.14

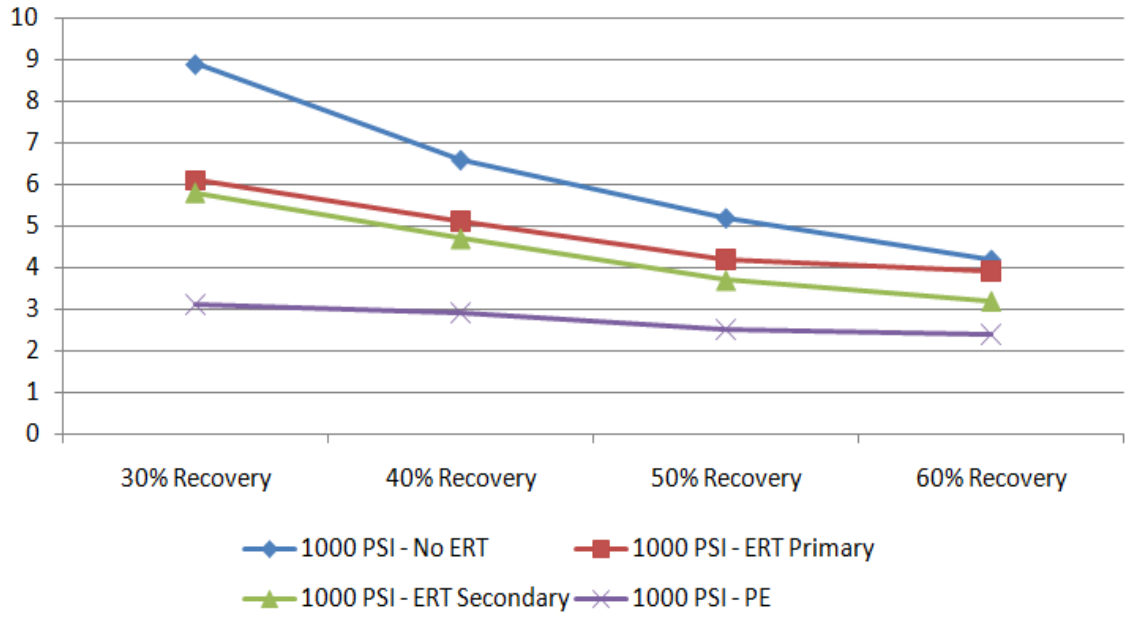

Figure 8-4: Energy Consumption vs. Recovery

8.2.2 Energy Optimization of Existing SWRO

This section deals with the comparison of SEC of various retrofits in an SWRO desalination plant. The methods of optimizing the design are also discussed.

For plants using the Pelton turbines, the biggest challenge is reducing the costs associated with energy consumption [41]. Isobaric ERDs with the highest efficiencies are used for attaining the highest savings in energy costs in SWRO desalination plants. Thus, deciding whether or not to retrofit ERTs in such plants is a difficult decision to make [5].

Different designs for the optimization of desalination plants using ERTs have been analyzed. Because of their high energy efficiency, they can be employed in various retrofit designs for either decreasing energy consumption or increasing the production capacity [41]. Five retrofits are discussed as follows:

- Retrofit No.1: In this design, the same high-pressure pump is used and an isobaric ERD is supplied in each train.

- Retrofit No.2: This is similar to the retrofit no. 1. It however requires a pump to increase the pressure of the feed.
- Retrofit No.3: It requires an isobaric ERD in each train.
- Retrofit No.4: This is built on a new train that is run at the second stage of the pre-existing train, which is running on the same HPP. An isobaric ERD is also installed.
- Retrofit No.5: This is identical to the previous retrofit. The only difference is that the brine from second stage passes through a pre-existing Pelton turbine [5].

For the optimum reduction in energy consumption, the retrofit No. 1 and 2 are suggested, while on the other hand, retrofit No. 3, 4 and 5 can be used to increase the plant's capacity. A comparison of the outcomes of these retrofits is summarized in Table 8–2. The data used belongs to an SWRO plant of 10,000 m^3/d capacity. The findings of these comparisons are summarized below.

Table 8-2: Comparison of ERDs with Different Configurations

Criteria	SWRO w/ ERT (Pelton)	Rtr. No.1 HPP + isobaric ERD	Rtr. No.2 BOP + HPP + isobaric ERD	Rtr. No.3 RO train + isobaric ERD	Rtr. No.4 ERD used as a BOP
Total capacity (m^3/h)	2 x 5,000	10,000	10,000	2 x 7,200	2 x 5,000 + 2 x 2,693
No. vessels / No. Elements	104 / 728	104 / 728	104 / 728	150 / 1050	104 / 728 - 62 / 434
Total feed flow (m^3/h)	926	926	926	1334	1436
No. of HPPs required	2	1	1	2	2
No. of BOPs required	0	1	2	1	0
Energy (kW)	1363.6	1014.2	1029.2	1424.08	1933.2
SEC (kWh/m^3)	3.27	2.43	2.47	2.39	3.02
Capacity increase	n/a	0%	0%	44.20%	53.80%
Energy savings range	n/a	25.60%	24.50%	0%	0%

The performance and efficiency of the plant can be increased by installing an isobaric ERD. The costs associated with energy consumption are also reduced.

- The 2nd and 3rd retrofits are more advantageous than the 1st and 4th retrofit.

The product costs of the fourth retrofit are 17% higher than the third one. The third retrofit is more preferable as it has lower costs of running and maintenance.
There is no much difference between the costs associated with energy consumption for the third and second retrofits. Owing to their larger size, the third retrofit requires a larger space. It should be preferred over the second one if there are no space limitations [5].

8.2.3 Energy Consumption for Several SWRO Desalination Plants

The ERDs employed at different SWRO plants at the Greek islands are compared in the Table 8–3. The data pertaining to the energy consumption and efficiency is collected and summarized [45]. It should be noted that at the time of collection of data, the recovery, temperature and other parameters were constant. Their efficiency is compared based on their SEC [45].

Table 8-3: Specific Energy Consumption for SWRO Plants

Location	Oia	Oia	Oia	Ios	Ithaki	Syros	Mykonos
Production (m^3)	12,000	5,400	9,000	14,880	9,275	17,856	15,000
HPP Power (kW)	110	75	75	75	200	110	160
ERD	Pelton wheel	Turbo charger	Pelton wheel, Grundfos	PX-60	Pelton wheel	Pelton wheel	Pelton wheel
Energy consumption (kWh)	55,200	25,110	47,563	45,073	87,000	109,992	125,350
SEC (kWh/m^3)	4.6	4.65	5.28	3.02	9.38	6.16	8.36
Recovered energy (kWh/m^3)	13.93	11.62	18.85	7.55	37.12	16.21	36.33

As is evident from the data, it can be seen that the PX is the most effective ERD [46]. When the SEC is divided by production capacity, the amount of energy consumption per unit volume is lower for PX and the turbocharger ERDs. In case of the Ithaki plant, higher SEC was observed on using Pelton wheels [45].

8.3 ERDs in Future Research

8.3.1 Fluid Switcher (FS)

The Fluid Switcher (FS)-ERD is an ERD of the positive displacement type. It is still under research. Designs that explore its stand-alone as well as parallel operations have also been under examination.

As the Reverse Osmosis technology is developing larger and larger plants are being set up all over the world with each train ranging between 10,000–15,000 m^3/d capacities [47]. As the need for increasing capacities of these plants grows, many designs have been tested to achieve the objective. Tests have been done to evaluate if increase in size of ERDs would increase performance efficiency [47]. Trials have also been done to assess whether parallel set-up of ERDs can prove beneficial in decreasing energy consumption. As proven by trials and pilot tests, parallel operation of ERDs is advantageous and the most effective way to reduce power consumption and increase efficiency. Parallel set-up increases the capacity of the device and also diminishes fluctuations in the working streams [47].

The FS-ERD has three components, namely, the rotary fluid switcher, check valve nest along with two pressure cylinders. The rotary fluid switcher is the main component. The working principle of this device is shown in Figure 8-5. In the working phase 1, the cylinder 1 receives high-pressure brine and at the same time, pre-filled LP feed is pressurized and then pumped out. This is the pressurizing stroke. At the same time, the

high-pressure brine in the second cylinder is depressurized and drained out by the incoming low-pressure feed. This is the depressurizing stroke [47]. Once the FS-ERD completes both the strokes, the switcher rotates and the second working phase begins wherein a motor drives it at 7.5 rpm. Thus, alternative stroke modes are achieved in the cylinders. The feed and brine are isolated from each other using a piston. Therefore, no intermixing occurs between the two fluids [47].

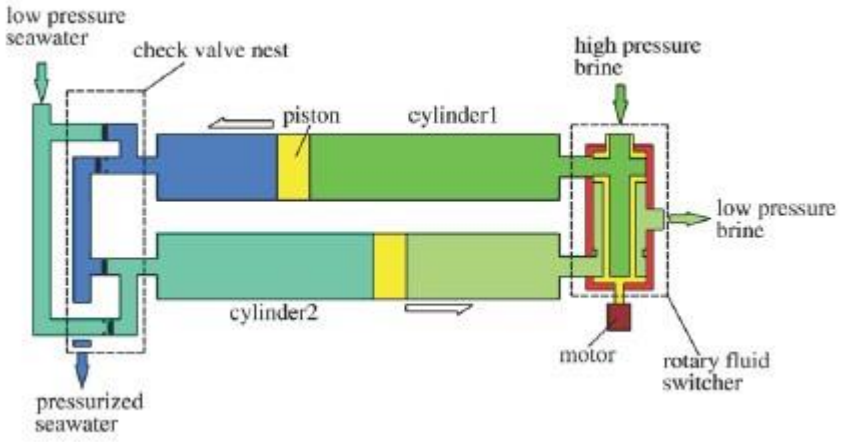

Figure 8-5: Working Principle of FS-ERD at Phase I

8.3.2 Isobarix

The Isobarix® device has been launched in competition with ERI's PX. This device is similar to the PX except for some alterations that allow lesser energy consumption and higher flow [48]. This device was developed by Leif Hauge. Its novelty lies in the fact that it lacks the mechanical complexity associated with other ERDs. This device functions in the following way- It has a rotor with six columns arranged as in a bullet chamber. High-pressure reject enters these columns and collides with low pressure water that is entering the columns at the other end at the same time [48]. The momentum of the high pressure reject is transferred to the low pressure water, which

then gets pressurized and turns back. The entry and exit of water spins the rotor very quickly, as the process repeats at a rate of thousand times per second. There is a very minute amount of intermixing between the brine and the feed [48].

As in Pressure Exchangers, the Isobarix® is also constructed using ceramics. To be specific, the Isobarix® is made of corundum. Since this is only second to diamond in hardness, it is resistant to wear and corrosion. Although these devices do not achieve a higher efficiency than pressure exchanger, they are however 20% cheaper and run more quietly [48].

Isobarix® devices can't possibly get more efficient than PXs, but it is claimed it could be 20% cheaper to build and much quieter.

Figure 8-6: Model XPR-512S

This device has been named the "Axle Positioned Rotor XPR" and the XPR-512S is the biggest Isobarix® device having a capacity of 114 m^3/h. This device has an 8" rotor that fits inside a pressure vessel. In comparison, the PX has a double row duct rotor. Only a 6.5" rotor can fit inside the pressure vessel. The flow of the XPR-512S is 500gpm while that of PX is 300 gpm [48].

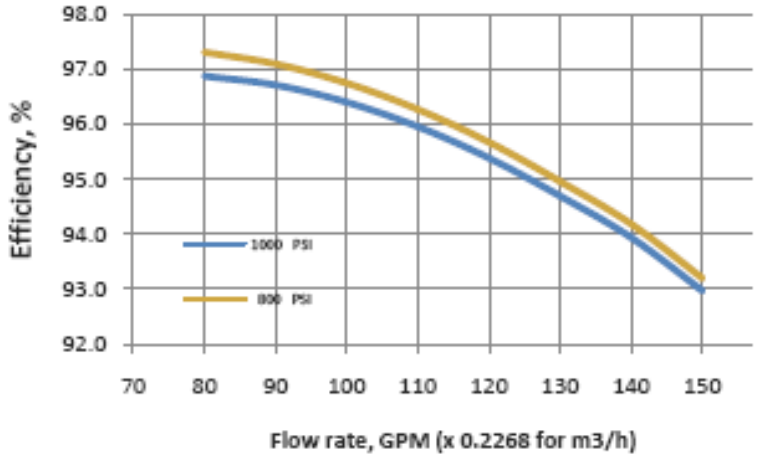

Figure 8-7: Efficiency at 800-1000 PSI

8.3.3 Desalitech's Closed Circuit Desalination (CCD™)

Desalitech's Closed Circuit Desalination (CCD™) technology provides an energy saving solution by reducing the cost of desalination by 20% and consuming minimal energy, only about 1.7 kWh/m^3. The device achieves a maximum recovery of 65%. This technology is used for a variety of applications as listed below:

- It is used for desalination of seawater
- It is used for desalination of brackish water
- It is used for the treatment of surface and ground water
- Treatment of municipal and industrial water
- Cooling towers, boilers & turbines makeup water

The present focus of Desalitech is on standalone plants. The technology is also applicable for large desalination plants of very high capacities. A pilot plant of capacity of 240 m^3/d capacity is currently under use and it utilizes the CCD™ technology. This technology is a good alternative to ERDs as relies only on the circulation of high-

pressure reject. The basic operation of the Desalitech's CCD^{TM} technology is summarized as follows:

Figure 8-8: Desalitech CCD^{TM} Unit

- System is filled at atmospheric pressure.
- Circulation pump started to enable cross flow.
- Desalination at constant flow with increasing pressure
- Desired recovery is achieved.
- The pump is stopped.
- The system is decompressed with a few drops (water is incompressible).
- The brine is flushed out with fresh feed water at low pressure.
- 99.7% of all high-pressure water becomes permeate.

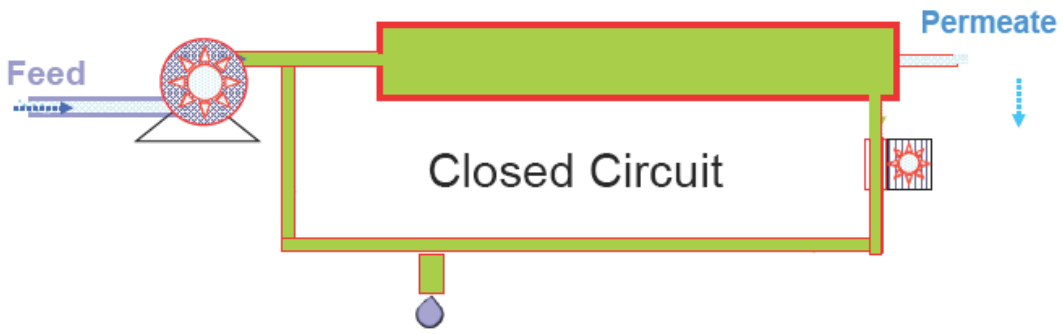

Figure 8-9: Hydrostatic Membrane Process

8.4 Conclusion and Merits of ERT versus PX in Jeddah SWRO Plant

In this section of the thesis a comparison is emphasized between ERTs and PXs for the Jeddah SWRO plant located on the Red Sea of the western coast of Saudi Arabia. The plant is designed to efficiently and economically provide 10,000 m^3/h (240,000 m^3/day) of high quality potable water using seawater as the feedwater source with quality shown in Table 8-4 and utilizing an existing open intake. The pretreatment available for the SWRO is coagulation and flocculation (when needed) followed by gravity filtration and cartridge filtration. The plant product water quality is to meet the requirement per Jeddah RO Phase-3 specifications of 40% overall recovery and the chloride limits of 40 – 60 mg/l. The plant consists of a two pass SWRO system described as follows:

- 24 1st Pass RO trains of average production 453 m^3/h (10,872 m^3/day) per train
- 24 2nd Pass RO trains of average production 417 m^3/h (10,000 m^3/day) per train

Each 1st pass SWRO train consists of 108 pressure vessels holding 8 seawater membranes each for a total of 864 membranes at a conservative flux rate of 14.1 LMH (liter/m^2/hr). The membrane used for this analysis is Toray TM820-400 rated at 25

Table 8-4: Jeddah SWRO Feed Water Analysis

Parameter	mg/L as ion	mg/L as $CaCO_3$
Calcium	450	1,125
Magnesium	1,550	6,107
Hardness		7,232
Copper	0.005	
Iron	0.03	
Boron	5.2	
Sodium	13,866	
Barium	0.37	
Strontium	9.5	
Potassium	N/A	
Bicarbonate	146.4	120
Chlorides	24,290	
Sulfates	2,992	
Nitrate	N/A	
Fluoride	N/A	
Silica	0.06	
pH	8.1	
TDS	43,300	

m^3/day when tested under conditions of 80% recovery using 32,000 ppm NaCl water at 5.52 MPa and 25 °C. The use of ERT turbocharger as the ERD is evaluated against ERIs pressure exchangers PXs taking into account economical and efficiency aspects. The following is to be noted for below data in Table 8-5:

- “Eff. “is abbreviation for efficiency
- Booster pump is only used with ERI’s PX design
- Power required is calculated at the maximum pressure where temperature is 21°C and membranes are 5 years old as per Toray’s membrane projections.

Table 8-5: Jeddah SWRO Feed Water Analysis

ERD	RO HP Pump Eff.	Booster Pump Eff.	Power Required (kW)	kWh/m³	RO HP Motor kW[5]	PX Booster kW[5]
Turbine	86% [1]	NR	1193-1463	2.66-3.29	1390	
Pelton Wheel	86% [2]	NR	1278-1304	2.82-2.88	1650	
ERI	81-82% [3]	82%	1065-1175	2.35-2.59	1400	75
Calder [4]		NR				

Notes:

a. Based on Torishima axially split case pump

b. Based on split ring pump

c. Based on API Split Case pump

d. The Calder/Dweer was not a competitive option since the brine flowrate is slightly higher than the maximum recommended flow required for (2) parallel units which put Calder to use three units/train.

e. Motor kW is based on 15% safety where the motor is sized to accommodate additional 15% of flow at the same TDH.

It is observed from above data that the use of ERI will only slightly decrease the operating cost in comparison with the turbocharger. The table also shows that the Pelton wheel is less efficient than the turbocharger at moderately high and temperatures.

The pump / ERD design pressure is based on the 21°C, 5-years projections (worst case) and the flowrate requirement mentioned earlier. Figure 8-10 below shows a basic design of this unit using the turbocharger.

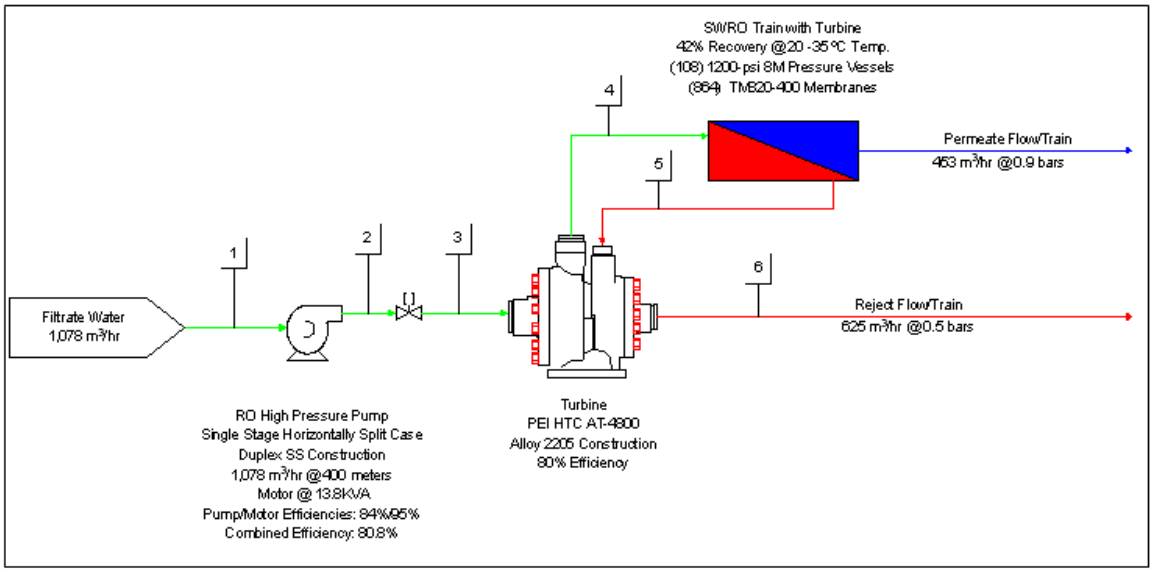

Figure 8-10: Jeddah Train Design with ERT

The turbocharger proposed is manufactured by Pump Engineering Inc. (PEI), model HTC AT-4800. This turbine was used in Jebel Ali desalination plant for DEWA – a 4,700 m^3/h (113,500 m^3/day) plant and has been in operation since April of 2007. The ERT option advantages over the PX will be mainly the low capital cost, simplicity in operation, and low cost of maintenance. The maximum boost pressure of the turbocharger is rated at 30.8 barg at 78.9% maximum efficiency.

Table 8-6, Table 8-7, and associated figures below present specific energy consumption and general operating data for a single train using turbocharger throughout 5 years at an operating temperature of 21°C and 36°C. The pump selected shall be designed based on required feed pressure at 21°C at year 5 less the boost pressure from the turbine plus the additional pressure required for the pressure drop across the throttling valve, plus the headloss due to friction in pipelines and the pressure required for the permeate stream. The available pressure for the throttling valve is the difference between NPSHa (Net Positive Suction Head available) and NPSHr (Net Positive Suction

Head required) across the pump plus any additional pressure above the minimum pressure required for reverse osmosis.

Table 8-6: Jeddah SWRO ERT Analysis 21°C

Year	0	1	2	3	4	5
Temp.(°C)	21.0	21.0	21.0	21.0	21.0	21.0
Permeate Flowrate (m^3/hr)	445.4	442.5	443.6	444.3	449.4	445.7
Brine Flowrate (m^3/hr)	635.0	631.0	632.5	633.5	640.6	635.5
Feed Flowrate (m^3/hr)	1,080	1,074	1,076	1,078	1,090	1,081
Required Feed Pressure (bar.g)	64.0	65.6	66.5	67.1	69.3	68.4
Brine Pressure (bar.g)	62.5	64.1	65.0	65.7	67.8	66.9
Required Pump (kW)	1,262	1,287	1,308	1,390	1,382	1,352
Power required (motor 95% eff.) (kW)	1328.4	1354.7	1376.8	1462.9	1454.3	1423.7
SEC (kWh/m^3)	2.98	3.06	3.10	3.29	3.24	3.19
ERT Efficiency (%)	78.9%	78.8%	78.5%	78.5%	78.9%	78.5%
ERT Boost Pressure (bar.g)	28.4	29.1	29.5	29.8	30.8	30.4
Actual RO HP Pump Pressure (bar.g)	35.6	36.5	37.0	37.3	38.5	38.0

Table 8-7: Jeddah SWRO ERT Analysis 36°C

Year	0	1	2	3	4	5
Temp.(°C)	36.0	36.0	36.0	36.0	36.0	36.0
Permeate Flowrate (m^3/hr)	448.3	449.0	450.1	450.1	450.8	451.5
Brine Flowrate (m^3/hr)	639.0	640.1	641.6	641.6	642.6	643.6
Feed Flowrate (m^3/hr)	1,087	1,089	1,092	1,092	1,093	1,095
Required Feed Pressure (bar.g)	59.7	61.2	61.8	62.1	62.5	62.7
Brine Pressure (bar.g)	58.3	59.8	60.3	60.7	61.0	61.3
Required Pump (kW)	1,133	1,213	1,224	1,234	1,246	1,250
Power required (motor 95% eff.) (kW)	1192.6	1276.4	1362.3	1298.8	1311.2	1315.8
SEC (kWh/m^3)	2.66	2.84	3.03	2.89	2.91	2.91
ERT Efficiency (%)	78.9%	78.9%	78.9%	78.9%	78.9%	78.9%
ERT Boost Pressure (bar.g)	26.4	27.1	27.4	27.6	27.6	27.8
Actual RO HP Pump Pressure (bar.g)	33.3	34.1	34.4	34.5	34.8	34.9

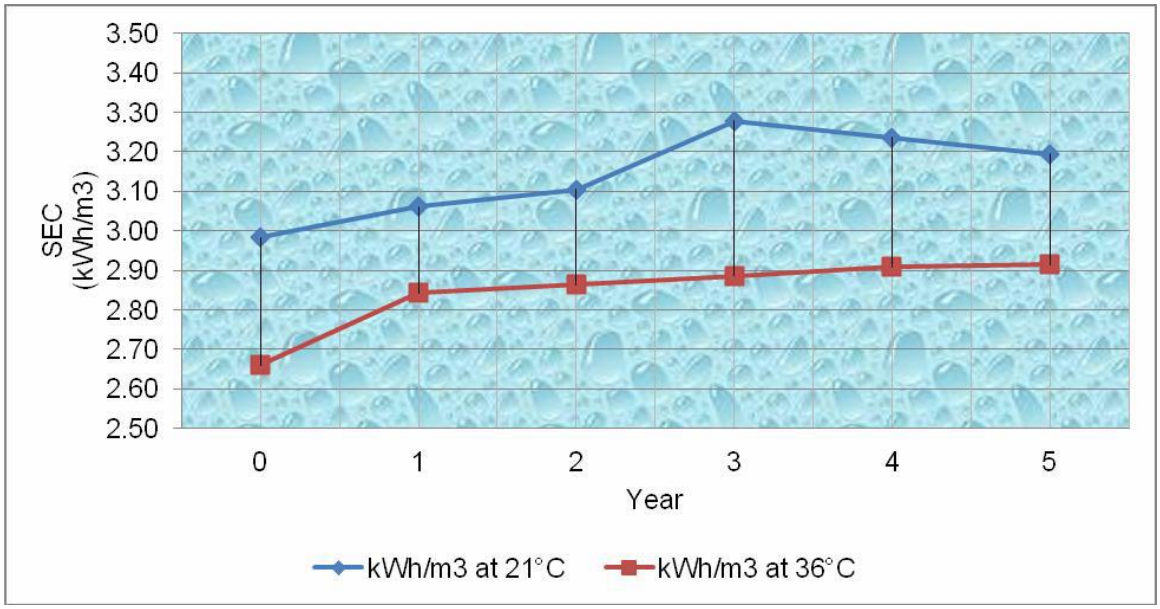

Figure 8-11: SEC versus No. of Years for ERT Design

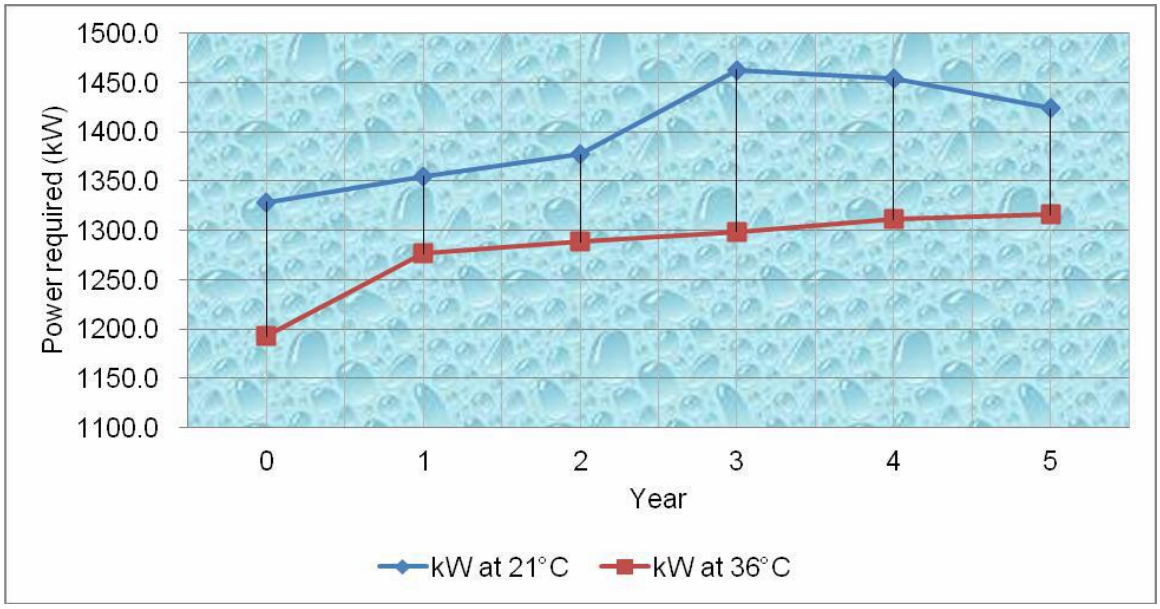

Figure 8-12: Energy Required versus No. of Years for ERT Design

As displayed above we can observe the lowest SEC and lowest total power required for the ERT option was at year 0 and 36°C at a value of 2.66 kWh/m^3 and 1192 kW

respectively, and the highest SEC and highest total power required was at year 3 and 21°C at a value of 3.29 kWh/m^3 and 1462.9 kW respectively.

Figure 8-13 below shows a basic design of this unit using the ERI PX.

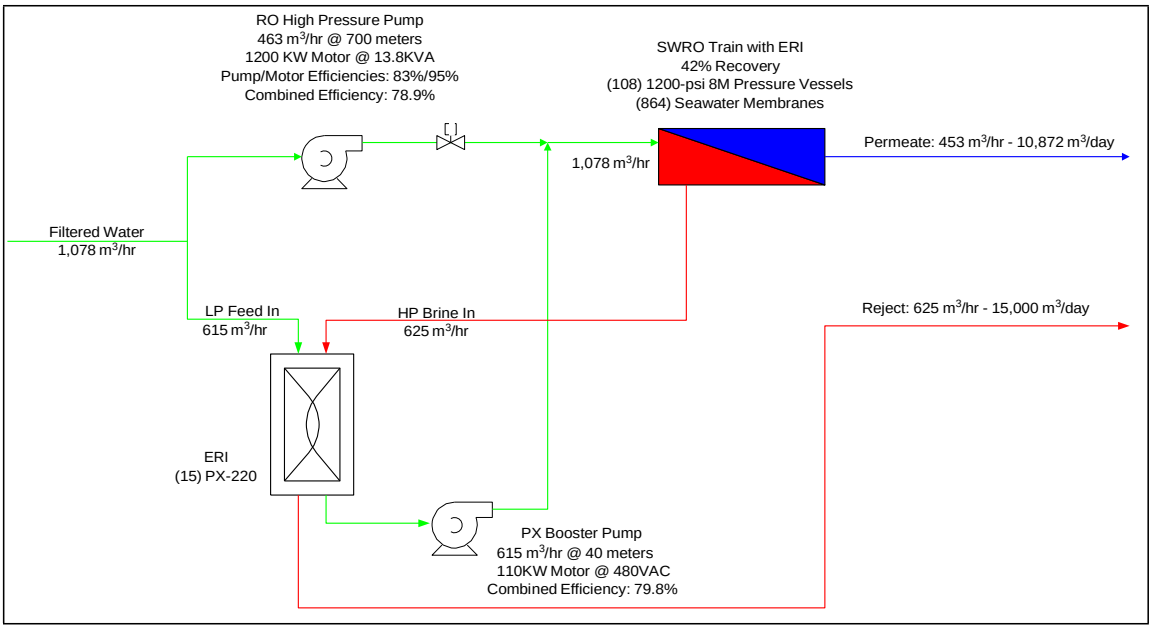

Figure 8-13: Jeddah Train Design with PX

Each SWRO train uses a dedicated rack of 16 ERI PX-220s (15 on duty & one standby). The design flowrate for the RO HP pump is 463 m³/hr at 69.5 bars (688 meters) TDH. At 15% additional load the motor selected should be based on 533 m³/hr. The available options for this pump are detailed in the table below.

Table 8-8: Available HP Pump Options for PX Design

Manufacturer	Type	Efficiency	Model	Motor KW
Sulzer [1]	API 610 Split Case	82%	6x8x12 ½B MSD – 4 Stages	1300
Torishima	Non-API Split Case		MHH200/3	

Notes:

1. The rated impeller diameter of the Sulzer pump is 254 mm and the maximum impeller diameter is 318 mm, which implies that pump capacity can increase by at least 20% over the design point. To account for the 15% additional flow, the motor selected for the RO HP pump shall be rated at 1300 kW and designed to operate at 13.8 kVAC/3ph/60Hz power supply.

The design flowrate for the PX booster pump is 615 m^3/hr at a maximum of 40 meters TDH (Total Dynamic Head). At 15% additional load, the motor will be selected to handle 707 m^3/hr at 40 meters. The available options for this pump are detailed below.

Table 8-9: Available Booster Pump Options for PX Design

Manufacturer	Type	Model	Pump Eff.	Motor HP/KW
KSB	API, Horizontal radially split volute casing, RPH Series	RPH-RO 250-401		
Flowserve	API, Horizontal axially split casing pump	8HHPX15C	85.5%	
David Brown/Union	API, In-line vertical pumps, VHK Series	10x10x15A1 VHK		

The pressure exchangers ERI's PX-220s are designed to be assembled on site with all the required high pressure and low pressure manifolds. The rack will have a space for 16 units.

Table 8-10, Table 8-11 and associated figures below present specific energy consumption and general operating data for a single train using PX units throughout 5 years at an operating temperature of 21°C and 36°C.

Table 8-10: Jeddah SWRO PX Analysis 21°C

Year	0	1	2	3	4	5
Temp.(°C)	21.0	21.0	21.0	21.0	21.0	21.0
Permeate Flowrate (m3/hr)	445.4	442.5	443.6	446.3	449.4	445.7
Brine Flowrate (m3/hr)	635.0	631.0	632.5	633.5	640.6	635.5
Feed Flowrate (m3/hr)	1080	1074	1076	1078	1090	1081
Required Feed Pressure (bar.g)	64.0	65.6	66.5	67.1	69.3	68.4
Brine Pressure (bar.g)	62.5	64.1	65.0	65.7	67.8	66.9
Diff. Press. (bar.g)	1.50	1.50	1.50	1.40	1.50	1.50
RO HP Pump Flowrate (m^3/hr)	455.0	452.0	453.0	454.0	460.0	456.0
PX Booster Pump Flowrate (m^3/hr)	631.0	627.0	628.0	629.0	636.0	631.0
Required Pumps (kW)	1,115	1,134	1,153	1,165	1,218	1,192
Power required (motor 95% eff.) (kW)	1,174	1,194	1,214	1,226	1,282	1,255
SEC (kWh/m^3)	2.50	2.56	2.60	2.62	2.71	2.67
PX Net Transfer Efficiency (%)	95.8	95.8	95.8	95.8	95.8	95.8

Table 8-11: Jeddah SWRO PX Analysis 36°C

Year	0	1	2	3	4	5
Temp.(°C)	36.0	36.0	36.0	36.0	36.0	36.0
Permeate Flowrate (m3/hr)	448.3	449.0	450.1	450.1	450.8	451.5
Brine Flowrate (m3/hr)	639.0	640.1	641.6	641.6	642.6	643.6
Feed Flowrate (m3/hr)	1087	1089	1092	1092	1093	1095
Required Feed Pressure (bar.g)	59.7	61.2	61.8	62.1	62.5	62.7
Brine Pressure (bar.g)	58.3	59.8	60.3	60.7	61.0	61.3
Diff. Press. (bar.g)	1.40	1.40	1.50	1.40	1.50	1.40
RO HP Pump Flowrate (m^3/hr)	457.0	458.0	459.0	459.0	454.0	455.0
PX Booster Pump Flowrate (m^3/hr)	636.0	637.0	638.0	638.0	625.0	626.0
Required Pumps (kW)	1,047	1,075	1,088	1,069	1,096	1,093
Power required (motor 95% eff.) (kW)	1,102	1,132	1,145	1,125	1,154	1,151
SEC (kWh/m^3)	2.34	2.39	2.42	2.38	2.43	2.42
PX Net Transfer Efficiency (%)	95.8	95.8	95.8	95.8	95.8	95.8

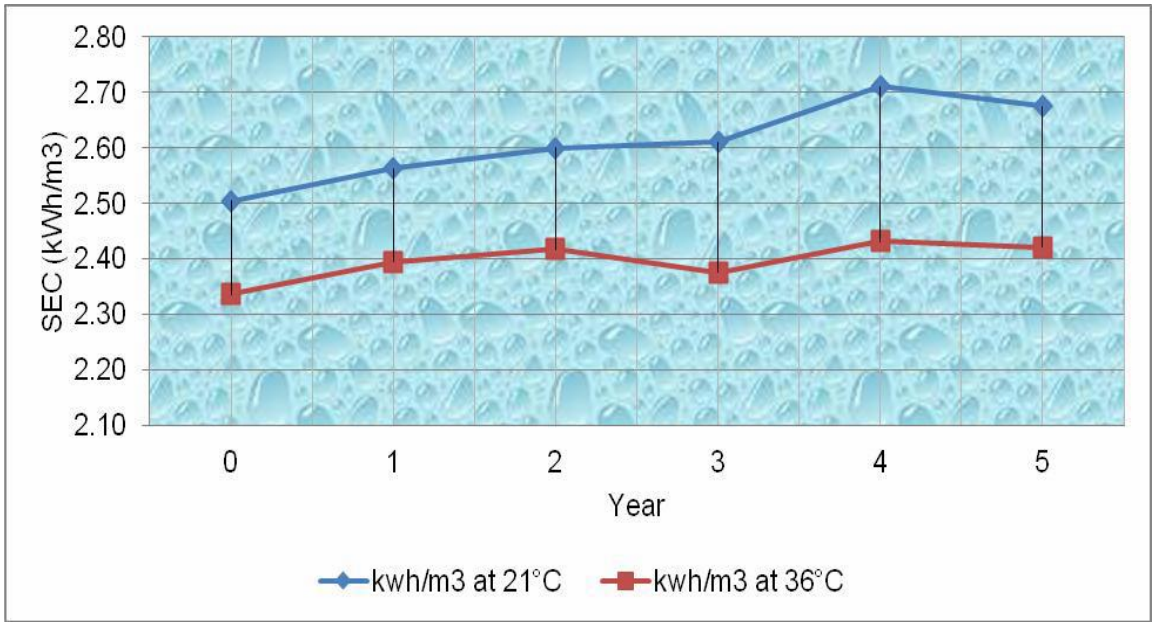

Figure 8-14: SEC versus No. of Years for PX Design

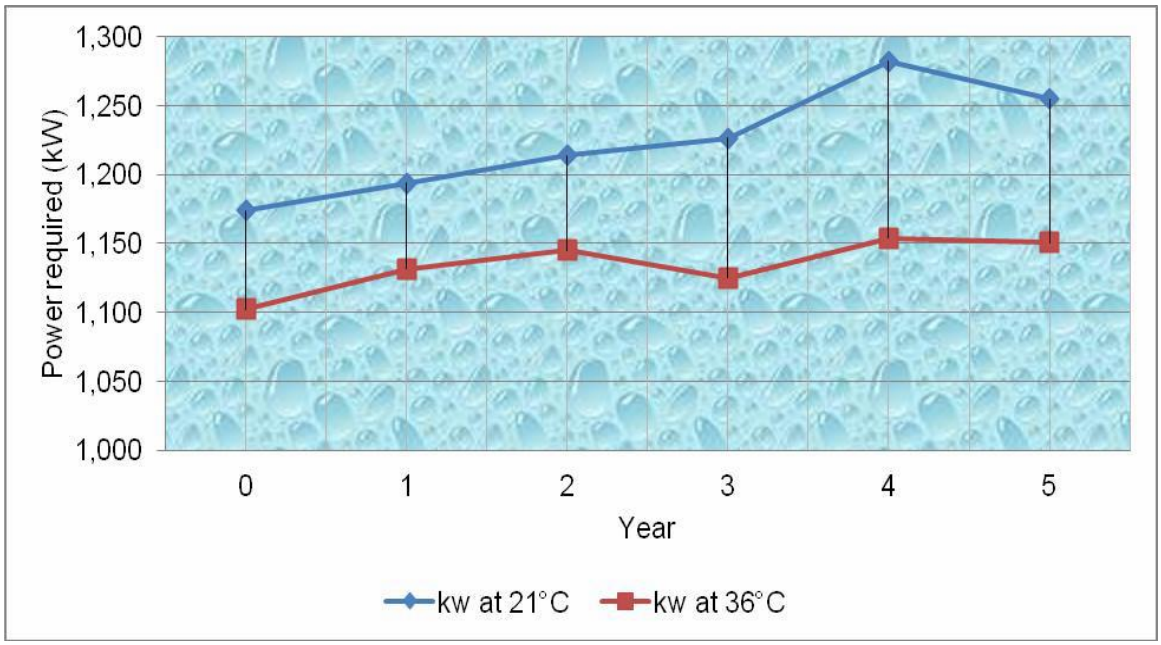

Figure 8-15: Energy Required versus No. of Years for PX Design

As displayed above we can observe the lowest SEC and lowest total power required for the PX option was at year 0 and 36°C at a value of 2.34 kWh/m^3 and 1102 kW respectively, and the highest SEC and highest total power required was at year 3 and

21°C at a value of 2.71 kWh/m^3 and 1226 kW respectively. These values although lower than the ERT's for the Jeddah plant were not sufficient enough to compensate for difference in capital cost, maintenance cost and difficulty of operation. This takes into account of considering the relatively low cost of energy in the Middle East region as well.

As inferred from the case studies on SWRO plants across the world, it is concluded that compared to centrifugal devices, isobaric devices are more energy efficient. However it is concluded as follows that many variables play different roles as contributing factors to selecting the most adequate ERD system in SWRO plants:

a. Total specific energy consumption of SWRO train (HPP, BP, ERD)
b. Total capital cost (HPP, BP, ERD)
c. Cost of energy (classified by region)
d. Maintenance cost
e. Operational cost
f. Total plant production and recovery required
g. Pumping system selected (centrifugal / PD)
h. Variable efficiencies of selected pumps and ERDs and their optimum duty points
i. Depreciation of capital costs and periods considered
j. Payback months cycle
k. Worst case scenario conditions (membrane life and lowest operating temperatures)
l. Cost of pretreatment system specific energy consumption
m. Footprint and noise requirements limitations
n. Environmental aspects considered and greenhouse gas emissions limitations

This thesis covers the most prominent and widely used energy recovery devices in seawater desalination plants. The advantages and disadvantages of each one are discussed and a comparative analysis has thus been made. As is evident, in the course of time, one ERD was followed by another that had better efficiency and energy

recovery. Pelton wheels, turbochargers and pressure exchangers followed the initial Francis Turbines. Below is a comparison table which summarizes the merits of the different ERDs that were investigated in this study.

Table 8-12: Different ERDs Conclusive Comparison

Type	Class	Maxiumum Efficiency	Advantages	Disadvantages
Francis Turbine	Hydraulic to mechanical assisted pumping	75% - 80%	• Low capital cost • Direct flange connection to be preferred over clutch	• Efficiency "Double Dip" • Narrow operating pressure and flow range • Lower efficiencies in regions with variable temperature ranges • Difficult to maintain and control due to clutch assembly • Not suitable for low flow ranges due to poor efficiency
Pelton Wheel	Hydraulic to mechanical assisted pumping	80% - 85%	• Low capital cost Easy in operation • Optimization of Pelton wheel and nozzle design for efficient kinetic to mechanical energy transformation • High efficiency maintained over the full operation range	• Efficiency "Double Dip" • Distributor geometry induces dissymmetry and secondary flows at the inlet of the nozzle

Table 8-12 (Continued)

Type	Class	Maxiumum Efficiency	Advantages	Disadvantages
ERT	Hydraulically driven pumping in series	90%	• Relatively low capital cost • Specifically designed for RO Relatively small footprint and easy to install, operate and maintain • Used duplex grades of stainless steel corrosion resistant alloy parts • No electrical cooling or pneumatic requirements • Turbocharger and HPP are not directly connected providing a degree of flexibility	• Limitation of only being able to recover 50-80% energy • Efficiency decline in accordance with the efficiencies of impeller, nozzle and turbine • Efficiency decline as the flow rate or pressure of the reject stream strays from optimal
Recuperator	Hydraulically driven pumping in parallel	92% - 97%	• Directly transfer of brine hydraulic energy to feed hydraulic energy without going through shaft work • Seawater of the same flow and pressure as the saline reject with no mixing • HPP required is about 60% smaller than that of the traditional technology	• High capital cost • To compensate for the pressure drop across the membranes (0.5-1.5bar) and in the Recuperator system (0.2- 0.6 bar) a booster pump that can take high suction pressure is needed • Mixing, lubrication, overflush, high pressure differential, low pressure differential

Table 8-12 (Continued)

Type	Class	Maxiumum Efficiency	Advantages	Disadvantages
DWEER	Hydraulically driven pumping in parallel	98%	• Brine and feed are separated by a piston to ensure minimum mixing • For a piston designed for minimum drag the transfer of energy is essentially 100%	• High capital cost • Booster pump is needed • Mixing, lubrication, overflush, high pressure differential, low pressure differential
PX	Hydraulically driven pumping in parallel	98%	• Core built of ceramic selected to be the ideal material for its toughness, corrosion resistance and dimensional stability withstanding the harshest saline environments Unlike turbines no transformational losses occur in a PX device • Stable efficiency over wide range of recoveries • Lack of traditional seals and bearings	• High capital cost • Booster pump is needed • Complexity of design, operation and maintenance • Mixing, lubrication, overflush, high pressure differential, low pressure differential

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