COMPARATIVE STUDY OF VARIOUS ENERGY RECOVERY DEVICES USED IN SWRO PROCESS[1]

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SUMMARY

In SWRO desalination process industries, the reduction of energy consumption constitutes one of the major thrust areas of research. The cost of energy in SWRO process is usually about 30 to 50% of the total production cost of water and can be as much as 75 % of the operating cost, depending on the cost of electricity. Excepting Jeddah and Al-Birk, all the SWCC SWRO plants are equipped with one or other type of energy recovery devices, which are utilized to recover an otherwise wasted energy in the reject. These energy recovery devices (ERD) are of varying efficiencies and their ability to recover the wasted energy is different in each case. ERD performance is very much dependant on the operating parameters such as flow as well as pressure, which of course is influenced by the feed water temperature. This report describes in detail the performance of several ERD systems used in various SWCC SWRO plants and compares their efficiencies with regard to the operation conditions for a period of one year and its effect on total energy saving and total power consumption by the high pressure pump in addition to the energy loss occurring in the process stream of SWRO plants. The average overall efficiency of ERD ranged from 3.2% for Haql to a maximum of 65% for Yanbu plant. Whereas the energy saving made of total energy consumed by the high pressure pump by ERD ranged from a meager 1.5% at Haql to a maximum value of 27.4% observed at Ummlujj. The average power consumed by the high pressure pump was in the range of lowest for Yanbu at 5.56 kWh/m^3 and highest was observed for Ummlujj plant of 7.93 kWh/m^3. However, it was observed that a substantial amount of energy is lost by throttling that ranged from 6.4% the lowest

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observed at Haql and highest was at Jubail of 21.8% of the total energy input to the high pressure pump. It was found that only at Al-Jubail plant, the performance of ERD was affected by the seasonal variation in operation parameters and for the rest of the plants the variation was not large enough to cause any significant change in the ERD performance. The detailed literature study revealed that reverse running pumps are no more considered to be applied in new plants mainly due to their low efficiency. Pressure exchangers are found to be the most efficient (≈ 94%) ERD which can result in lowest specific energy consumption (SEC). Turbo charger is found to be simple and low cost but with lower efficiency (≈ 70%). However, it has the ability of adding second stage SWRO and its operation on recovered energy with a potential increase in plant yield and product recovery ratio. Pelton Wheels are found to be widely used with proven track record with medium efficiency (80% to 90%). Since a substantial amount of energy is lost in throttling at Al-Jubail and Yanbu plants, installation of variable frequency drive (VFD) may be explored at these plants, if proven to be economically beneficial. Also, retrofitting of ERDs with better performing ERDs at Duba and Haql plants may be considered while giving due consideration to the age of the plants as well as economics. The study also recommends that the selection of ERD for a specific application be made only after thoroughly analyzing different aspect such as capital cost, installation cost, maintenance cost, ease of operation, reliability, availability and long term source of supply of spare parts of both ERD as well as high pressure pump (HPP) in addition to SEC. Finally, it should be possible to significantly expand existing plant capacity, such as Jeddah plants, by using existing HPPs with pressure exchangers, the latter as energy recovery and transfer system as source of energy without having to add HPPs. It is recommended that this topic is further investigated by SWCC RDC jointly with other SWCC departments.

1. INTRODUCTION

Producing potable water of acceptable quality with minimum cost is the major goal of everyone in the water industry. Fresh water production by desalination of seawater is known to be an expensive affair due to its high energy demand. Since the advent of RO in 1970's need for finding a way to reduce associated operating costs was paramount. Recent advances in seawater reverse osmosis that have allowed this reduction in the cost of desalinated water include the application of energy recovery devices (ERDs) and the utilization of ultra high pressure RO membrane in a system to recover brine from the first stage RO system. It is a fact that due to the low recovery (about 35%) of seawater reverse osmosis (SWRO) process, a lot of water had to be pretreated, then pumped to high pressure before dumping about 65% of this pressurized water to the sea as reject. Limitations in the membrane module design, however, prevented SWRO system from operating at higher water recoveries. The cost of energy in SWRO process is usually about 30 to 50% of the total production cost of water and can be as much as 75 % of the operating cost, depending on the cost of electricity [1, 2]. It is also reported that 75 to 85% of total cost of water production is energy use and capital amortization [3]. In a recent study conducted here and else where, it was found that energy constituted the largest share of the total unit water cost for all studied RO systems followed by cost of machinery. Moreover, energy consumption by the high-pressure feed pump accounts for at least 35% of operating costs [4]. All these described cases are for the SWRO plants, which operate without any energy recovery devices. Thus it can be summarized that the energy contributes to major cost factor for the production of drinking water. Hence reducing the energy cost, which is mainly due to wastage of energy in high-pressure brine, should be the major goal of desalination industries.

By means of several ERDs, which are available in the market, it is possible to reduce the energy consumption and eventually the water cost. It was in 1980’s SWRO plants started using ERDs to recover energy from high-pressure brine and at present a vast majority of seawater desalination facilities do use some form of ERD to lower power consumption. Indeed, energy recovery has become one of the hottest topics in SWRO desalination and several new devices are being developed in the market, which claim superiority over others. Many of these ERDs work on different principles and the major players among them are described below.

1.1 Francis Turbine (Reverse Running Pump)

Francis Turbine (FT) or the reverse running pump is one of the foremost ERDs used in this field and was widely used by SWRO industries because of its simplicity and ease of operation. This was one of the old systems, which utilizes the kinetic energy from the brine to run and is coupled to the main feed pump motor so that little energy is lost in the transfer. The FTs are not very popular mainly because of the perception that its efficiency is lower than competitive devices, i.e., a maximum efficiency around 75%.

FTs are sized to specific characteristics and the flow or pressure changes need to be by-passed, with resulting losses in its efficiency, i.e., the pressure and flow range at which the system will run with maximum efficiency is very narrow. Moreover, FTs generally do not generate power until 40% of the design condition is achieved [3]. In reality in a SWRO plant like one situated in the Middle East, the operating pressure could vastly vary due to change in seasonal temperature as well as change in membrane transport property due to ageing of membrane or fouling etc, which might render FTs less efficient. SWCC SWRO plants at Al-Jubail as well as at Yanbu employ FTs for recovering energy from the brine [5, 6].

1.2 Pelton Wheel

Another popular system utilized, is the Pelton Wheel (see Figure 1), which also works on the similar principle as of Francis Turbine but with improved efficiency. This is one of the old system claims to be highly efficient depending on plant capacity as well as water recovery. The Pelton Wheel takes advantage of the high-pressure energy, which remains in the reject (brine), from the reverse osmosis process. The high-pressure concentrate is fed into the Pelton wheel hydraulic impulse turbine, which then produces rotating power output, which is used to assist the main electric motor in driving the high-pressure pump. This concept allows a smaller, less costly motor to be utilized and saves a very considerable proportion of the power and, therefore, cost necessary to drive the pump. The system is very easy to operate with only one control and consists of an adjustable input nozzle to convert water pressure into kinetic energy contained in a high velocity jet. This is directed to a series of buckets- or metal vanes in the modern sense- around a rotating shaft that intercepted the jet stream and converted the kinetic energy into rotational energy to turn a shaft and then finally discharges the water at atmospheric pressure.

Pelton Wheel is in significant use throughout the world and claims to be more efficient as well as more economic than reverse running pump as proved at Galdar-Agaete, Canary Islands [7] and at Sureste desalination plant, Gran Canaria [8]. It is also claimed that its efficiency stays relatively high over the full operation range and the changes in flow and pressure, basically, do have only a small effect on operation of the turbine [9]. However, in reality this unit also suffers from loss of efficiency as in the case of Francis Turbine, but to a lesser extent, especially when operating in the off duty range. Moreover, if the unit is not properly positioned and designed in an RO plant, which is the normal practice, the system could suffer from loss of efficiency [10]. Here also, energy recovery starts at about 40% of system pressure and the inlet nozzle acts as a brine control valve and no further pressure control is used on the RO system.

1.3 Hydraulic Turbo Charger

The Turbo charger has been specifically designed for RO systems (see Figure 2). This device transfers hydraulic energy from one liquid stream, the RO brine, to a second fluid stream, the feed. The two flows may be at different pressures and rates. The system is entirely powered by the brine; it has no electrical cooling or pneumatic requirements. Turbo charger consists of a hydraulic turbine and a pump, thus it is an integral turbine driven centrifugal pump. The turbine section is a single stage radial inflow type (similar to a reverse running pump). The pump portion is a single stage centrifugal with its impeller mounted on the turbine shaft. The energy transfer results in a feed pressure increase. The entire rotating element is dynamically balanced as a unit. The device has a by-pass around it that enables the operator to control and balance the flow. This by-pass is needed when second stage brine flow is more than that is required for the boost pressure, especially when the feed is subjected to large temperature variations as are usually seen in surface intake plants and/or for membrane ageing, this arrangement becomes important. Here the energy saving is achieved because the main high-pressure pump’s required discharge pressure is reduced.

Turbo chargers are mainly used in conjunction with ultra high pressure RO membrane - Toray’s Brine Conversion System (BCS)- in the second stage to recover brine from the first stage RO system thus increasing overall water recovery up to 60% for ocean seawater (TDS ≈ 35,000 ppm). The unit has a claimed efficiency up to 70% depending on their capacity. There are several small plants built during 1996 –2000 capacity ranging from 210 to 5,700 m^3/d utilizing Turbo Charger with BCS system [3]. Larger BCS system plants are also being successfully operated at Caribbean Island (14,800 m^3/d) and Mas Palomas, Gran Canaria, Spain (20,400 m^3/d) [11].

1.4 Pressure Exchangers

Devices using the principle of positive displacement are commonly referred to as pressure exchangers. The two basic designs dominating the market are; one which use valves and pistons to effect its exchange, and another which only uses a single spinning cylindrical rotor to achieve its purposes. Desalco’s Work Exchanger Energy Recovery (DWEER) represents former, and Energy Recovery Inc.’s Pressure exchanger (PX), represents latter. They claim to have a flat performance curve but tend to be less effective at higher water recovery. Here energy saving is achieved by reducing the volumetric output required by the main high-pressure pump and claim to have 91 –96% efficiency [12, 13].

The PX (see Figure 3) claims to be of 95% efficiency in recovering the energy with small leakage (mixing of feed and reject) occurring. It works well with lower recovery systems, as the main feed pump should be equal to permeate quantity. The PX technology is different from conventional ERD design, where the brine is passed through the PX unit and its pressure energy is transferred directly to a portion of the incoming seawater feed. This seawater stream, nearly equal in volume to the reject stream, then passes through a small booster pump, which makes up for the hydraulic losses through the SWRO system. This seawater stream then joins the seawater stream from the main high pressure pump (HPP) without passing through the HPP. Thus, the HPP is sized to match the permeate flow, not the full flow. The HPP also makes up the small volume of brine lost through the PX hydrostatic bearing. The PX’s one moving part, a shaft-less ceramic rotor with multiple ducts, is hydrostatically suspended within a ceramic sleeve. The rotor effects an exchange of pressure from brine to feed through direct contact displacement. High flow capacities are obtained by arranging multiple units in parallel. Since the main high-pressure pump flow equal the product water flow, the energy savings is actually achieved at lower conversion rates. Overall energy consumption of an SWRO plant using PX device has a low point at conversion rates of typically between 30-40%. Outside these conversion points the plant will start to consume slightly higher amount of power. The system claims to have easy start and stop procedure and requires high pressure by-pass valve to control the pressure initially [2]. PX’s are used at Lanzarote, Spain [14] and in Canary Island, Spain [15] both at capacity of 5000 m^3/d.

DWEER (see Figure 4) works similar to PX, however, here instead of a rotor, positive displacement pistons are used. A booster pump to boost the required feed pressure equal to the feed pump pressure is also needed. DWEER transfers the fluid pressure in the brine stream to fluid pressure in the feed across a piston, where it reduces mixing of the brine and feed. For a piston designed for minimum drag, the transfer of energy in this scheme is essentially 100%. For this reason, the fundamental exchange of energy between the brine and seawater feed is more efficient than centrifugal devices relying on shaft conversion of power. However, in an actual RO system, there is a pressure drop between the feed entering the RO module and the brine exiting from it and entering the DWEER. Because of this loss, it is not possible for the effluent from the DWEER to flow back into the feed. Also, because the piston is at the pressure of the membrane array, it must be housed within a pressure vessel. The pressure vessel has a limited volume, so a valve causes the two vessels to exchange functions before the piston in that volume completes its stroke. By installing a booster pump, the flow exiting the DWEER is now able to match the discharge pressure of the HPP, allowing the system to operate in a loop. The flow rate of this booster pump is equal to the membrane brine flow rate less some small leakage. The HPP, therefore, pumps only the permeate flow. The largest current device has a capacity of 500 m^3/h, which can be installed in parallel for higher capacity. A SWRO plant in Grand Cayman, Spain with feed TDS of 37,000 mg/L, capacity 1,071 m^3/d with specific energy consumption (SEC) of 3.00 kWh/m^3 was upgraded by introducing DWEER, which resulted in increased capacity of 1,699 m^3/d with SEC of only 2.22 kWh/m^3 [16]. Another study [17] shows details of the application of DWEER in Caribbean Islands at different location from plant capacity ranging from 3,200 to 10,300 m^3/d with train capacity of 1,600 m^3/d to 2,500 m^3/d and it also describes about a proposed 20,000 m^3/d with 4 DWEER in a single train.

The Aqualyng is another type of pressure exchanger process, which uses the saline reject in a sequential process to directly pressurize seawater [18]. The process achieves to obtain seawater, in principle of the same flow and pressure as the saline reject with no mixing of their fluids. To compensate for the pressure drop across the membranes (0.5 – 1.5 bar) and in the recuperator system (0.2 – 0.6 bar) a booster pump that can take high suction pressure is needed. A control system takes care of automatic control of the system, so there are no interruptions in flow of high pressure seawater to the membranes. It claims no mixing of fluids in the recuperator, however, the instruments required should be of very high quality.

Vari – RO direct drive engine is another energy recovery device, which is under development and testing stage only [19]. It claims to have optimum efficiency, simple mechanical design and high potential for operational reliability.

1.5 ERDs used in SWCC SWRO Plants

Out of many ERDs described in the above sections, SWCC SWRO Plants utilize mainly reverse running pump and Pelton Wheel for recovering energy available in the reject. The newer ERDs such as PX have not been utilized because many of SWCC SWRO plants were constructed early. The only plant, which employs Pelton Wheel is Ummlujj SWRO plant and rest of the plants utilize reverse running pump, viz., Jubail, Yanbu, Duba and Haql. However, Jeddah and Al-Birk plants do not have any energy recovery system at present. Also, a Pressure exchanger of PX type was evaluated (2 years ago) in a separate project at RDC pilot plant [20].

1.6 Comparative Studies

As there are many different kinds of ERDs available in the market and each claims to be superior to the other, the problem faced by the end user is to decide which of energy recovery device (ERD) technologies are best suited for the plants, for the new as well as the existing plants. In order to make a practical comparison of energy recovery technologies, one should mainly look to the overall energy consumption of the entire process of the RO system being considered. Specific energy consumption is largely dominated by two factors; the amount of trans-membrane pressure difference required to achieve the necessary permeate flow rate at various mass transfer conditions as well as the design and efficiency of the feed water pump in combination with the respective energy recovery system installed to recover the available hydraulic energy in the discharge brine [10]. However, hydraulic devices, i.e. feed pump (typically centrifugal) and energy recovery device (typically turbine), do have a very specific duty point in terms of flow rate and pressure, at which they will perform with optimum energetic efficiency. It is reported that performance of Pelton wheel, Francis Turbine as well as Turbo charger are affected by variation in flow and pressure [21]. Since non-ideal operating parameters cause deviation from optimum component performance, the combined interaction effects of two energy conversion devices (pump and ERD) operating under non-ideal, yet realistic, conditions are to be considered. Thus the aim should be to obtain minimum average SEC throughout the year. Moreover, the ease of operation as well as maintenance requirement of ERDs also need to be addressed in order to choose the right ERD for any plant. There were also some attempts to combine different ERDs to take best advantage of the situations, like combining Turbo charger with Pelton Wheel [22].

Even though vast majority of the literature on ERDs originate from the ERD manufacturer, there are some independent studies done recently and are available. In one such study [1] the author evaluated 6 typical cases of ERDs, where he compared only specific energy consumption of train with capacities 300, 1000 and 6000 m^3/d at different recovery ratio of 35 and 45% as well as different feed TDS of 37000 and 45000 mg/L. The study was conducted at specific operation condition, which did not take into consideration of non-ideal situation and the results showed that the pressure exchangers, PX and DWEER are the formidable competitors, in terms of energy savings. However, their longevity and maintenance costs have yet to be fully demonstrated as well as capital cost, which seems to be higher at present. The study also revealed that Francis turbine was the poorest in performance among all the ERDs evaluated.

In another study [10] the impact of various energy recovery strategies for single-stage RO system was evaluated and compared in terms of energetic efficiency. Study was undertaken with the view that for a given recovery rate, the required feed pressure varies based on temperature and salinity. The study was based on Arabian seawater conditions, for an SWRO plant with capacity of 950 m^3/d and showed that Turbo charger with Pelton helper turbine combination resulted in best average SEC consumption. The worst efficiency configuration was found to be also perhaps the most widely used; the Pelton Turbine with feed throttling.

There is a lack of serious independent study with regards to comparison of various ERDs in terms of real time operation conditions of a SWRO plant, especially with respect to variation in pressure and flow. Hence, there is an urgent need to study all these ERDs available in the market with respect to operation condition variation in SWRO plants, especially in SWCC SWRO plants. This will help in identifying best ERD suitable for an existing plant as well as for future SWRO plants to be built. This study evaluated various energy recovery devices available in the market through literature survey as well as one used in SWCC SWRO plants and compare their efficiencies in terms of energy saving, ease of operation as well as maintenance requirements. As the ultimate aim is to produce the product water at least possible SEC, all the efforts in designing and operating SWRO plants are directed to achieve the same. However, the feed throttling valve used to regulate the feed pressure to membrane counteracts the efforts made by ERD by destroying energy available in the feed stream by throttling. Hence, in this report efforts have been made to analyze the SEC, percentage power saving by ERD (ES), efficiency of ERD and percentage throttling loss of each train as well as total plant in order to assess the energetic efficiency of the SWRO section of different SWCC plants where ERDs are utilized.

2. RESEARCH OBJECTIVES

1. To evaluate existing devices already in use at SWCC SWRO plants and to recommend ways to improve their performance.

2. To evaluate various energy recovery devices available in the market in terms of their efficiency in energy saving including various advantages and disadvantages associated with each of these energy recovery devices and finally to identify the most suitable energy recovery device for specific application and requirements.

3. EXPERIMENTAL

3.1. Plants Description

A total of 5 SWRO plants namely, Yanbu, Al-Jubail, Duba, Haql and Ummlujj are covered in this study. Yanbu SWRO plant consists of 15 trains and is designated in the alphabetical order from A to O. Each train is equipped with a HPP coupled with an energy recovery device (reaction type Francis turbine) using a flexible coupling. Al-Jubail SWRO plant consists of 15 trains and is designated in the alphabetical order from A to Q excepting I and O. Each train is equipped with a HPP coupled with an energy recovery device (reaction type Francis turbine) using a direct flange. Duba

SWRO plant consists of two trains, namely 311 and 312 and each train is divided into two banks, i.e. A and B. Each train is equipped with a total of 3 HPP coupled using a direct flange with an energy recovery device (reverse running pump) of which each bank utilizes one HPP at a time and one remain always standby. The HPP/ERDs which are designated as PM303A, PM303B and PM303C belongs to Train 311 (both A and B banks) and HPP/ERDs which are designated as PM303D, PM303E and PM303F belongs to Train 312 (both A and B banks). Haql SWRO plant is similar to Duba SWRO plant and consists of two trains, namely T1 and T2 and each train is divided into two banks, i.e. A and B. Each train is equipped with a total of 3 HPP coupled using a direct flange with an energy recovery device (reverse running pump) of which each bank utilizes one HPP at a time and one remain always standby. The HPP/ERDs which are designated as PT-203A, PT-203B and PT-203C belongs to Train T1 (both A and B banks) and HPP/ERDs which are designated as PT-203D, PT-203E and PT-203F belongs to Train T2 (both A and B banks). Ummlujj SWRO plant consists of two trains, namely 100 and 200 and each train is equipped with two HPPs coupled with an energy recovery device (Pelton Wheel) of which one HPP/ERD is used at a time and other remain standby. During the data collection period Train 100 was operating with nanofiltration (NF) product, which resulted in isolation of ERD from the HPP because of low feed flow operation and was not included in this study. The HPP/ERDs of Train 200 are designated as PT-200A and PT-200B and only their performance are discussed in this report. The detail specifications of HPP and ERD of all the plants are given in Table 1. Data were obtained regularly for a period of about 1 year during October 2002 to October 2003 for all the HPP/ERDs except for train K of Al-Jubail plant as well as Train 100 of Ummlujj plant and were analyzed using computer program developed in excel spreadsheet.

3.2. Data Treatment

Data obtained from the plant includes current consumed by HPP, flow rates (feed, product and reject), pressures (suction of HPP, discharge of HPP, feed, product, reject before ERD and reject after ERD) and feed temperature. From the data obtained, SEC, percentage saving by ERD, efficiency of ERD and percentage throttling loss were calculated.

3.2.1 Specific Energy Consumption (SEC)

Specific energy consumption by the individual HPP which is expressed in kWh/m^3 is calculated by dividing actual electrical power input to HPP (in kW) by total product flow (m^3/h) from the respective train and the actual power input is calculated using the standard equation [23].

$$P_{ia} = 1.73 \times V \times I \times y \qquad (1)$$

where

P_{ia} = Actual electrical power input, kW
V = Voltage, kV
I = Current, A
y = Power factor, decimal

The values of voltage and the power factor used in the calculation were provided by the respective plants and are given in Table 1.

3.2.2 Percentage energy saving by ERD (ES)

Percentage energy saving by ERD is calculated by the following formula

$$ES_{erd}(\%) = \frac{ES_{erd}}{P_{ie}} \times 100 \qquad (2)$$

where

$$ES_{erd} = P_{ie} - P_{ia} \qquad (3)$$

where actual electrical power input, P_{ia} is obtained from eq.1 and the expected electrical power input, P_{ie} is obtained from the following equation

$$P_{ie} = \frac{WP_{on}}{\eta_p} \qquad (4)$$

where

η_p = Overall efficiency of HPP
WP_{on} = Net hydraulic power output, which is obtained from the following equation

$$WP_{on} = WP_d - WP_s \qquad (5)$$

where hydraulic power (WP) is calculated from the following standard equation [23]

$$WP = \frac{p \times Q}{36} \tag{6}$$

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

3.2.3 *Efficiency of ERD (η_{erd})*

Here, the overall efficiency of ERD is calculated, i.e., it includes the component efficiency of ERD and also any loss in efficiency due to flexible coupling through which it is connected to HPP and the overall efficiency is calculated as follows

$$\eta_{erd} = \frac{WP_{in}}{P_{on}} \times 100 \tag{7}$$

where net hydraulic power input, WP_{in} to ERD is obtained

$$WP_{in} = WP_r - WP_{fr} \tag{8}$$

where WP_r is the hydraulic power in the reject which enter the ERD and WP_{fr} is the hydraulic power of the final reject exiting from the ERD and are calculated using eq. 6. The net electrical power output from the ERD, P_{on} is nothing but the electrical power saving made by the ERD, ES_{erd} and is obtained by eq. 3.

3.2.4 *Percentage throttling loss (TL)*

The loss of energy due to throttling of discharge pressure using throttle valve at the discharge of HPP prior to membrane is calculated from the following equation

$$TL(\%) = \frac{WP_{ut} - WP_{dt}}{WP_{ut}} \times 100 \tag{9}$$

where

WP_{ut} = Hydraulic power upstream of throttle valve

WP_{dt} = Hydraulic power downstream of throttle valve

and the hydraulic power is calculated using eq. 6

4. RESULTS AND DISCUSSION

4.1 Performance Evaluation of ERDs Installed at SWCC SWRO Plants

4.1.1 Yanbu SWRO plant

Out of the 15 trains, some (trains A, C, H, I, J and L) were operating at reject flow of 660 m^3/h where new membranes are utilized and some, namely, B, D, E, F, G, M, and O trains at reject flow of about 750 m^3/h utilizing old membranes. The remaining two trains K and N were initially operated with old membranes with reject flow of about 750 m^3/h and later during the data collection period membrane replacement were made and rest of the period they were operating with new membranes at low reject flow of 660 m^3/h. The trains operating at higher feed/reject flow (utilizing old membranes) were having lower recovery of about 32% compared to 35% recovery of trains operating at lower feed/reject flow (utilizing new membranes). However, the product flow remained same at about 350 m^3/h for all the 15 trains regardless of the variation in product recovery. Moreover, the reject pressure after ERD was always higher at about 13 bar for trains utilizing new membranes compared to about 6 bar for trains employing old membranes.

Table 2 shows the observed minimum, maximum and average value of all the four calculated parameters, namely, SEC, ES, η_{erd} and TL for entire 15 trains of the plant. The average SEC value for the entire plant was found to be 5.56 kWh/m^3 and the average SEC for the individual train varied from 5.31 to 5.77 kWh/m^3 (Figure 5). It is interesting to note that the average SEC for the trains, which employ old membranes, were in the range of 5.31 – 5.6 kWh/m^3, which is lower than those trains that employ new membranes in the range of 5.66 – 5.77 kWh/m^3. One of the reasons is that the energy saving by ERDs of trains utilizing old membranes are higher in the range of 27.7 – 30.3% compared to trains utilizing new membranes of ES in the range of 20.8 – 22.2% (Figure 6). The higher ES is of course due to the higher efficiency of ERDs of trains employing old membranes as well as the lower pressure of the reject exiting from the ERDs. η_{erd} of ERDs of trains utilizing old membranes are in the range of 63.12 – 71.2%, where the flow is equivalent to design flow of ERD compared to 60.8 – 62.5% of ERDs of trains utilizing new membranes, where flow deviate from design flow of ERD as shown in Figure 7. Moreover, the discharge pressure of reject exiting from the trains of new membranes are about 13 bar compared to lower value of about 6 bar in case of trains employing old membranes. The average overall η_{erd} of ERDs for all the trains is about 65% which closely matches with claimed value of about 67% by the ERD manufacturer. The minimum value of η_{erd} observed among all the trains was 48.6% and maximum observed value was 79% (Figure 7).

The average ES by ERD for the entire plant was found to be 25.9% with minimum and maximum value of 17.2% and 32.7%, respectively (Table 2). As the η_{erd} is about 65%, the ES value is expected to be higher than the obtained value of 25.9%. The reason for the lower ES is that the reject from the ERD is exiting with a pressure in the range of 6 -13 bar which is utilized to pump up the reject for the purpose of backwashing media filters. Probably reducing and maintaining this final reject pressure at a minimum value which is adequate for pumping could further reduce the SEC from the present value of 5.56 kWh/m^3.

Although the SEC is minimized by utilizing ERD, there is still some energy wasted in the feed stream by throttling and the percentage throttling loss (TL) calculated for each train. Throttling is inevitable as the HPP is designed to deliver feed water at pressure more than required by the membrane and the required feed pressure is achieved by dissipating down the excess pressure utilizing a throttle valve. The TL values are not found to vary much with old and new membranes and the average value for each train ranged from a minimum of 10.9% to a maximum of 22.7% (Figure 7). The average TL value for the entire plant was found to be 16% with a minimum and maximum value of 9.9% and 27.72%, respectively (Table 2). Hence, if a variable frequency drive (VFD) is installed, the average SEC of the plant can be further reduced to 4.67 kWh/m^3 from the present value of 5.56 kWh/m^3.

During the data collection period the feed temperature varied from 25 to 35^{o}C and corresponding feed pressure variation, which was from 56.8 to 66.7 bar. However, this variation in the feed pressure did not reflect on the performance of the ERDs contrary to what was stated by Manth et al [24-26]. Probably this variation in the feed pressure is not large enough to cause a marked effect on the ERD performance. Hence, it can be stated that seasonal changes at the Yanbu plant did not affect the performance of ERD as well as energy consumption.

4.1.2 Al-Jubail SWRO plant

Out of the 15 trains, 4 trains, namely A, B, C and D were operating with Toray spiral wound membranes. The remaining 11 trains, namely E, F, G, H, J, K, L, M, N, P and Q were operating with DuPont B-10 Twin hollow fine fiber membranes. However, no data was received for the Train K during the study period and hence the present study is confined to 14 trains only. During the study period the seawater feed temperature was in the range of 17 – 35^{o}C and the feed pressure was in the range of 62.4 – 84.2 bar. The trains were operating at product recovery in the range of 28.6 - 35% with an almost constant feed flow of about 723 m^3/h. Also, for the Train B, only data during winter months is available and for Train L, only data during summer months is available and for the rest of the trains, data for all the seasons are available.

Table 3 shows the minimum, maximum and average value of all the four calculated parameters for entire 14 trains of the plant. The average SEC value for the entire plant is found to be 7.45 kWh/m^3 and the average SEC for the individual train varied widely from a minimum of 6.64 kWh/m^3 (Train B) to a maximum value of 8.74 kWh/m^3 (Train L) as shown in Figure 7. It is worth mentioning that lowest value of SEC was obtained for the train for which only winter months data available, i.e., Train B and highest SEC was obtained for the train for which only summer months data is available, i.e., Train L. Hence, it can be inferred that the seasonal change does affect the performance of ERD and reflects in the SEC value as stated by Manth et al [24-26]. Figures 13 & 14, which show variation of SEC and η_{erd} with temperature and reject pressure for one of the train (Train F), clearly indicate the trend that higher the reject pressure due mainly to lower feed temperature results in higher efficiency of ERD and ultimately lower SEC.

It is expected that the variation in average SEC be small since the HPP is operated at constant discharge pressure and feed flow. However, a large variation in average was observed, which can be attributed to the ES made by ERD, where a wide variation is observed with lowest ES value of 12% was obtained for the Train L and highest ES value of 29% was obtained for Train B (Figure 10). This in turn was due to low η_{erd} value of Train L of 33.9% which was operated at lower reject pressure due mainly to high feed temperature compared to high efficiency of 72.3% of the Train B which was operated at high reject pressure due mainly to low feed temperature (Figure 11). The average ES for entire plant was found to be 22.4% with minimum and maximum observed values of 9.3% and 32.2% 25.2%, respectively. The average η_{erd} value for entire plant was found to be 54.2% with minimum and maximum observed values of 25.2% and 72.5%, respectively (Table 3). Hence, it is very clear from the data (Figures 13 & 14) that the ERD performance is very much dependent on the operation conditions (reject pressure in the range of 56 – 82.1) which was influenced mainly by the seasonal change in seawater feed temperature (17 – 35^{o}C).

The average TL value for the each train ranged from a minimum of 15.6% to a maximum of 32.9%, and the highest was obtained for Train L (Figure 12). The average TL value for the entire plant was found to be 21.8% with a minimum and maximum value of 13.4% and 36.1%, respectively (Table 3). It is expected that installation of VFD, shall reduce further the average SEC of the plant to a value of 5.83 kWh/m^3 from the present value of 7.45 kWh/m^3.

4.1.3 Duba SWRO Plant

During the study period the banks belonging to Train 311, i.e., 311A and 311B were operating with 108 membrane elements each and hence they were operating at about 155 m^3/h of feed flow rate. Whereas, the banks belonging to Train 312, i.e., 312A and 312B were operating at a feed flow rate of about 166 m^3/h because they were operating with 120 membrane elements each. The product recovery was about 35% for all the banks with a feed pressure in the range of 54 – 58 bar which was mainly governed by the seasonal change in feed temperature in the range of 24.5 – 30^{o}C.

Table 4 shows the minimum, maximum and average value of all the four calculated parameters for all the 6 HPP/ERDs of the plant. The average SEC value for the entire plant was found to be 6.11 kWh/m^3 and the average SEC for the individual HPP/ERDs varied widely from a minimum of 5.85 kWh/m^3 (PM303D and PM303F both belong to Train 312) to a maximum value of 6.6 kWh/m^3 (PM303C, belong to Train 311) as shown in Figure 15. It is interesting that the average SEC for the HPP/ERD belong to Train 312, which have more number of membranes (higher feed flow), were in the range of 5.85 – 5.89 kWh/m^3, which is lower than Train 311 that have less membranes (lower feed flow) in the range of 6.17 – 6.6 kWh/m^3. The minimum and maximum value of SEC for individual case was 5.78 kWh/m^3 and 6.75 kWh/m^3, respectively.

The average ES by ERD for the entire plant was found to be 5.5% with minimum and maximum value of 0% and 12.71%, respectively (Table 4). The average minimum and maximum value of ES obtained for HPP/ERD was for PM303C (0%) and PM303B (10%), respectively as shown in Figure 16, which correspondingly matches with η_{erd} of 0% and 26.45%, respectively (Figure 17). The average η_{erd} for all the ERDs was found to be 13.3% with observed minimum and maximum value for the individual case of 0% and 31.72%, respectively.

The average TL values were found to be lower for the Train 312 in the range of 4.26% - 7.78 compared to 7.44% - 13.36% for the Train 311 (Figure 18). The average TL value for the entire plant was found to be 8.09% with a observed minimum and maximum value of 0% and 14.22%, respectively (Table 4). Hence, if a VFD is installed, the average SEC of the plant can be further reduced to 5.62 kWh/m^3 from the present value of 6.11 kWh/m^3.

During the data collection period the feed temperature varied from 24.5 to 30^{o}C and corresponding reject pressure variation was from 50 to 56.9 bar. However, this variation in the feed pressure did not reflect on the performance of the ERDs similar to the case of Yanbu plant. Hence, it can be stated that seasonal changes at the Duba plant did not affect the performance of ERD as well as energy consumption.

4.1.4 Haql SWRO Plant

During the study period the banks belonging to Train T1, i.e., T1A and T1B were operating at about 171 m^3/h of feed flow rate. Whereas, the banks belonging to Train T2, i.e., T2A and T2B were operating at a feed flow rate of about 155 m^3/h. The product recovery was about 35% for all the banks with a feed pressure in the range of 54 – 60 bar which was mainly governed by the seasonal change in feed temperature in the range of 21.6 – 29.4 ^{o}C.

Table 5 shows the minimum, maximum and average value of all the four calculated parameters for all the 6 HPP/ERDs of the plant. The average SEC value for the entire plant was found to be 6.47 kWh/m^3 and the average SEC for the individual HPP/ERDs varied widely from a minimum of 5.79 kWh/m^3 (PT-203C which belong to Train T1) to a maximum value of 6.93 kWh/m^3 (PT-203F, belong to Train T2). It is interesting that the average SEC for the HPP/ERD belong to Train T1, which were operating at higher feed flow rate, were in the range of 5.79 – 6.39 kWh/m^3, which is lower than Train T2 that was operating at lower feed flow and were in the range of 6.67 – 6.93 kWh/m^3 (Figure 19). The minimum and maximum values of SEC for individual case were 5.6 kWh/m^3 and 7.23 kWh/m^3, respectively.

The average ES by ERD for the entire plant was found to be 1.49% only with minimum and maximum value of 0% and 12.68%, respectively for the individual case (Table 5). The average minimum and maximum ES value obtained for HPP/ERD was 0% (for PT-203A and PT-203D) and 9.94% for PT-203C (Figure 20), respectively, which correspondingly matches with η_{erd} of 0% and 21.56%, respectively (Figure 21). The average η_{erd} for all the ERDs was found to be 13.3% with observed minimum and maximum value for the individual case of 0% and 28.47%, respectively.

The average TL values are found to be lower for the Train T1 in the range of 1.43% - 3.03% compared to 6.95.44% - 13.23% for the Train T2 (Figure 22). The average TL value for the entire plant was found to be 6.35% with a observed minimum and maximum value for the individual case of 0% and 15.02%, respectively (Table 5). Hence, if a VFD is installed, the average SEC of the plant can be further reduced to 6.06 kWh/m^3 from the present value of 6.47 kWh/m^3.

During the data collection period the feed temperature varied from 21.6 to 29.4^{o}C and corresponding reject pressure variation was from 52.8 to 58.3 bar. However, similar to Yanbu and Duba plants, this variation in the feed pressure did not reflect on the performance of the ERDs. Hence, it can be stated that seasonal changes at the Haql plant did not affect the performance of ERD as well as energy consumption.

4.1.5 Ummlujj SWRO Plant

During the initial period of the study the train was operating with the entire reject from train going to ERD at rate of about 264 m^3/h and later after about 6 months, the train was modified to include some experiment to study different SWRO membranes in parallel. As a result of this modification only part (about 240 m^3/h) of the reject was going thorough the ERD during rest of the period. The product recovery was about 25% with a feed pressure in the range of 60 – 64 bar which was mainly governed by the seasonal change in feed temperature in the range of 23.1 – 34.6^{o}C.

Table 6 shows the minimum, maximum and average value of all the four calculated parameters for both the HPP/ERDs of the plant. The average SEC value for the Train 200 was found to be 7.93 kWh/m^3 and the average SEC for the individual HPP/ERDs was almost same for both HPP/ERDs, with 7.96 kWh/m^3 for PT-200A and 7.9 kWh/m^3 for PT-200A (Figure 23). The minimum and maximum values of SEC for individual case were 7.09 kWh/m^3 and 8.41 kWh/m^3, respectively (Table 6).

The average ES by ERD for the entire plant was found to be 27.4% with minimum and maximum value of 23.6% and 31.9%, respectively for the individual case (Table 4). Almost same average values of ES were obtained for both PT-200A (27.2%) and PT-200B (27.6%0 as shown in Figure 24. This high value resulted from the high efficiency of ERD, of 63.1% and 65.6%, respectively (Figure 25). The average η_{erd} for both the ERDs was found to be 64.4% with observed minimum and maximum value for the individual case of 53.9% and 82.3%, respectively (Table 6). It is also observed that the η_{erd} values are higher during later part of the data collection when part of the reject was not flowing through the ERD. No significant change in observed η_{erd} or SEC was also observed in relation to feed temperature and reject pressure, where the variation was very small, in the range of 57.9 – 62.8 bar only. Although the values of average η_{erd} as well as ES are found to be comparable to that of Yanbu plant, the obtained average SEC was highest for Ummlujj mainly due to low recovery operation of the plant at about 25% compared to about 35% for the rest of the plants.

The average TL values are found to be 9.8% for PT-200A compared to and 11% for PT-200B (Figure 26). The average TL value for the Train 200 was found to be 10.4%

with an observed minimum and maximum value of 6.2% and 12.5%, respectively (Table 6). Hence, if a VFD is installed, the average SEC of the plant can be further reduced to 7.11 kWh/m^3 from the present value of 7.93 kWh/m^3.

4.2 Summary of Analyses

The performance evaluation carried out show that presently used ERDs at SWCC SWRO plants are with average overall efficiencies in the range of 3.2% to 65%. Lower values of η_{erd} was obtained for both Duba and Haql plants where the ERD of 100 m^3/h capacity is used, especially at Haql plant the benefit derived from the ERD is very limited. The low value of η_{erd} of Duba and Haql ERD may have resulted from wear and tear accrued during more than 14 years of operation as well as may be due to small size of the ERD unit itself as the larger units are reported to be more efficient than smaller ones [9]. Due to the low values η_{erd} of Duba and Haql plants, the energy saving in both the plants are only 5.5% and 1.5%, respectively. Hence, there is a scope of replacing the present ERD with much higher efficiency ERD like Pelton Wheel which can be carried out with minimum re-engineering and alterations to the existing set-up as done at Malta [27] where the investment was recovered in 1.1 years from the savings in electric energy (cost of electricity in Malta is 2.8 US cents per kWh). Also, in Canary Islands about 15% reduction in SEC was achieved in one of the plants [8] and in another case 86% efficiency was obtained by retrofitting with Pelton Wheel compared to only 66% achieved using reverse running pump thus reducing SEC from 5.02 kWh/m^3 to 4.12 kWh/m^3 [7]. The latest Pelton Wheel of claimed efficiency of 90% [28] can be considered for such retrofitting at Duba and Haql plants, if found economically viable, where a reduction of SEC by about 2 kWh/m^3 is expected if such an arrangement is made. This will lead to about SR 500,000 saving at each plant at the local electricity cost of SR 0.15 kWh. However, due consideration is to be given to the age of the plant as the plants are already 15 years old.

The throttling loss for both Duba and Haql plants are found to be very low and if VFDs are installed to these plants of which the cost is approximately US$ 120 per each kW [29], then it might take about 9 years for the Duba plant and more than 10 years for the Haql plant to recover the money at the local electricity cost. Thus, the option of application of the VFD to Duba and Haql plants does not look attractive. The average

SEC obtained for both Duba and Haql plants were found to be quite higher compared to theoretical value of 2.07 kWh/m^3 where the 100% efficiency are assumed for HPP, ERD and VFD for typical Gulf seawater condition and also higher than 3.26 kWh/m^3 obtained for the same situation where efficiency of ERD with 89%, HPP with 85% and VFD with 97% are considered [25, 26]. The reason for high SEC at Duba and Haql are due to both lower efficiency of HPPs of 70% as well as very low overall efficiency of the ERDs. Hence, the aim should be to obtain a reasonably good value of SEC of about 4 kWh/m^3 by retrofitting with new ERD systems at Duba and Haql.

The Ummlujj plant is the only plant which utilizes Pelton Wheel and is the oldest among the all SWCC plants evaluated in this study, where an average η_{erd} of about 64% was obtained which substantiated the claims made in the literature that Pelton Wheels are more efficient than reverse running pumps and accordingly a large energy saving is made by the system. However, the large energy saving of about 27% which is the highest among all SWCC plants does not reflect on the average SEC value obtained which is the highest among all the plants evaluated. This is mainly due to lower water recovery of 25% compared to 35% recovery at the rest of the SWCC plants as well as due to lower efficiency of HPPs of 70%. Moreover, slightly larger throttling loss of about 10% at Ummlujj also adds up to the SEC value to make Ummlujj with highest SEC among all the plants. If VFDs are to be installed, in order to eliminate the throttling loss, it may take about 7 years at the cost of electricity and VFD assumed to recover back the invested amount. As the performance of ERD is relatively good, going for change in ERD does not look very attractive as the plant is already about 18 years old.

The average SEC obtained for Al-Jubail plant is also high because of lower η_{erd} of ERD which is influenced by the seasonal change in operation condition as well as due to very high throttling loss of about 22%, the highest among all the plants. As the throttling loss high, installation of VFD may be seriously considered at Jubail plant which might cost about 14 million Saudi riyal and can be recovered within 2 years period based on present cost of local electricity of 0.15 SR kWh and VFDs. However, it is reported that VDFs are very expensive for the capacity more than 1000 kW range [30] and can sometimes be even higher than the costs for motor and the pump itself

[25]. Moreover, VFDs are considered to be problematic by some users when environmental conditions such as high temperatures and high humidity exists [24]. Al-Jubail plant is the only plant where the ERD performance was affected by the change operation condition especially the pressure due to the large seasonal variation in temperature. If retrofitting using latest Pelton Wheel which requires only minor modification of the plant is considered at Al-Jubail then it could save about 6 million Saudi riyal per annum.

Similar to Al-Jubail plant, Yanbu plant does also have substantial amount of throttling loss which could also be recovered by applying VFD in those plant at expense similar to that of Al-Jubail and the investment can be recovered just over 2 years period at the price local electricity charge and VFD cost. As far as ERD is concerned they are in good shape with overall average η_{erd} of 65% which is the highest among all the ERDs of SWCC and may continue with the same foe some time. However, the SEC can be lowered further, if there exists any possibility of reducing the pressure in reject exiting from the ERD from the present value of 5 -15 bar. Although Yanbu plant does have the best and lowest SEC among all the ERDs analyzed, it could further lowered by retrofitting with better performing ERDs ($\eta_{erd} \approx 85\%$) which could save about 4 million Saudi riyal per annum at the present cost of electricity of 0.15 SR/kWh.

4.3 *Selection of the Right ERD*

As we understood from the literature the reverse running pumps which are mainly utilized by the SWCC plants except Ummlujj are no more considered to be applied to news plants as it represents the most ineffective technology [1, 25]. This is mainly due to its low η_{erd} which was also observed with ERDs of SWCC plants. The Pelton Wheel is the most widely used ERD which in combination with VFD driven HPP was found to give one of the lowest SEC compared other ERDs [25, 26]. The Pelton Wheel, which has come into forefront after several years in use are recently available with 80 – 90% efficiency and reported to have achieved efficiency of 87.18% in Spain [21, 28]. The turbo charger is another centrifugal device known for its simplicity and low cost, however, it is used in specific application where pressure boosting is required and hence are mainly used in conjunction with BCS systems [3, 11, 31]. The system can be also be used in single stage RO where it can reduce the discharge pressure of HPP (reduces pump and motor size) as well as reduce throttling loss by about 30 – 40% [30]. However, the maximum efficiency possible with turbo charger is only 70%.

Although the centrifugal devices occupy over 98% of ERDs worldwide in SWRO plants, the most efficient ERDs available in the market are those work on the positive displacement principle known as pressure exchangers such as PX and DWEER [1, 25]. DWEER is in operation since 1990 years in small plant of capacity 950 m^3/d and one of the largest plant of capacity 10,500 m^3/d is in service at Bahamas since 1997 [16, 17]. Moreover, DWEER has been selected in one of the largest SWRO plant to be built in Ashkelon, Israel of capacity 100 million m^3/y [32] as well as in Singapore plant of capacity 30 MGD [33]. The PX is relatively new and its largest unit is installed in Dekhelia, Greece in 3 units of capacity 10,000 m^3/d and the details of retrofitting using PX can be obtained elsewhere [34].

The comparative analyses done elsewhere concludes that the PX and DWEER are with efficiencies of about 94% which is highest among the different ERDs tested and the application of the same resulted in lowest possible SEC [30]. This was also experimentally proven at RDC, where a small unit of PX evaluated and an efficiency of 93% was obtained which resulted in a energy saving of about 58% with a remarkable reduction in SEC to 2.37 kWh/m^3 compared to 6.2 kWh/m^3 without using PX [20]. Also, an independent study on different commercial plants using different ERDs at Greece revealed that the PX is the most energy efficient one among other ERDs such as Pelton wheel and Turbo charger [35]. Application of PX and DWEER not only reduces the SEC but also drastically reduces the HPP size.

If one considers ease of operation and simplicity among the modern ERDs, the Turbo charger ranks first followed by Pelton Wheel and the pressure exchangers are slightly complicated. Capital cost wise Turbo charger stands lowest followed by Pelton Wheel and pressure exchangers are considered expensive [1, 17, 21]. However, while deciding the capital cost, the cost of HPP also should be considered as the pressure exchangers reduce the size of HPP, which shall also reflect on the total capital cost. Hence, prior to selecting a ERD for specific application, one has to look into all these aspects such as capital cost, installation cost, maintenance cost, ease of operation, reliability, availability and long term source of supply of spare parts in addition to SEC.

5. CONCLUSIONS

The detailed analyses of about one year performance data of various ERDs used in different SWCC SWRO plants revealed that the highest average ERD efficiency of 65% was obtained for Yanbu SWRO plant which also have lowest average SEC of 5.56 kWh/m^3. Although, average ES of Ummlujj plant was the highest at about 27.4%, the obtained average SEC was also highest mainly due to low recovery operation of the plant. The maximum energy wasted by throttling of about 21.8% was obtained for Al-Jubail plant and least for Duba and Haql plants. Moreover, only at Al-Jubail SWRO plant, ERD performance was affected by the seasonal variation in operating parameters and rest of the plants there was no significant effect was observed.

The detailed literature study revealed that reverse running pumps are no more considered to be applied in new plants mainly due to its low efficiency. Pressure exchangers are found to be the most efficient (≈ 94%) ERD which can result in lowest SEC. Turbo charger is found to be simple and low cost but with lower efficiency (≈ 70%). However, it has the ability of adding second stage SWRO and its operation on recovered energy with a potential increase in plant yield and product recovery ratio. Pelton Wheels are found to be widely used with proven track record with medium efficiency (80% to 90%).

6. RECOMMENDATIONS

Installation of VFD may be seriously considered to eliminate throttling loss in Al-Jubail and Yanbu plants, the cost of which is expected to be recovered within a period of 2 years.

Retrofitting of ERDs with better performing ERDs may be explored at Duba and Haql plants while giving due consideration to the age of the plants as well as economics.

While selecting ERD for a specific application, it is required to look into all the aspects such as capital cost, installation cost, maintenance cost, ease of operation, reliability, availability and long term source of supply of spare parts of both ERD as well as high pressure pump (HPP) in addition to SEC.

Application of pressure exchanger may be considered at least in one of new plants or in the existing SWCC plants, especially at Jeddah plant as it is proved to be the most efficient ERD which can result lowest SEC value.

Finally, it should be possible to significantly expand existing plant capacity, such as Jeddah plants, by using existing HPPs with pressure exchangers, the latter as energy recovery and transfer system as source of energy without having to add HPPs. It is recommended that this topic is further investigated by SWCC RDC jointly with other SWCC departments.

Table 1. Specifications of HPP and ERDs Used at SWCC SWRO Plants

Plant	High Pressure Pump Details				Energy Recovery Device Details	
	Specification	Power Factor	Voltage (kV)	Overall Efficiency (%)	Specification	Overall Efficiency (%)
Yanbu	Rated for 1170 m^3/h at 70.1 bar	0.91	13.8	81	Rated for 760 m^3/h at 52 bar	67
Al-Jubail	Rated for 900 m^3/h at 81 bar	0.88	13.8	79.9	Rated for 485 m^3/h at 71.5 bar	81.85***
Duba	Rated for 156 m^3/h at 62 bar	0.9	4.16	70	*Rated for 100 m^3/h at 47.7 bar	67
Haql	Rated for 156 m^3/h at 62 bar	0.9	4.16	70	*Rated for 100 m^3/h at 47.7 bar	67
Ummlujj	Rated for 400 m^3/h at 65.8 bar	0.86	4.16	70	**Rated for 251 m^3/h at 53 bar	85***

*	Reverse running pump
**	Pelton Wheel
***	Stand alone efficiency

Table 2. Energy Consumption Details and ERD Efficiency at Yanbu SWRO Plant

	Energy Consumption by HPP kWh/m^3	**Energy Saving by ERD %**	**ERD Efficiency %**	**Throttling Loss %**
Minimum	5.18	17.18	48.55	9.86
Maximum	6.17	32.65	79.03	27.72
Average	**5.56**	**25.85**	**64.99**	**16.03**
Std. Dev. (n = 217)	0.17	3.92	3.86	3.16

Table 3. Energy Consumption Details and ERD Efficiency at Al-Jubail SWRO Plant

	Energy Consumption by HPP kWh/m^3	**Energy Saving by ERD %**	**ERD Efficiency %**	**Throttling Loss %**
Minimum	6.38	9.26	25.18	13.37
Maximum	9.74	32.21	72.51	36.1
Average	**7.45**	**22.41**	**54.22**	**21.77**
Std. Dev. (n = 82)	0.59	4.96	10.38	4.01

Table 4. Energy Consumption Details and ERD Efficiency at Duba SWRO Plant

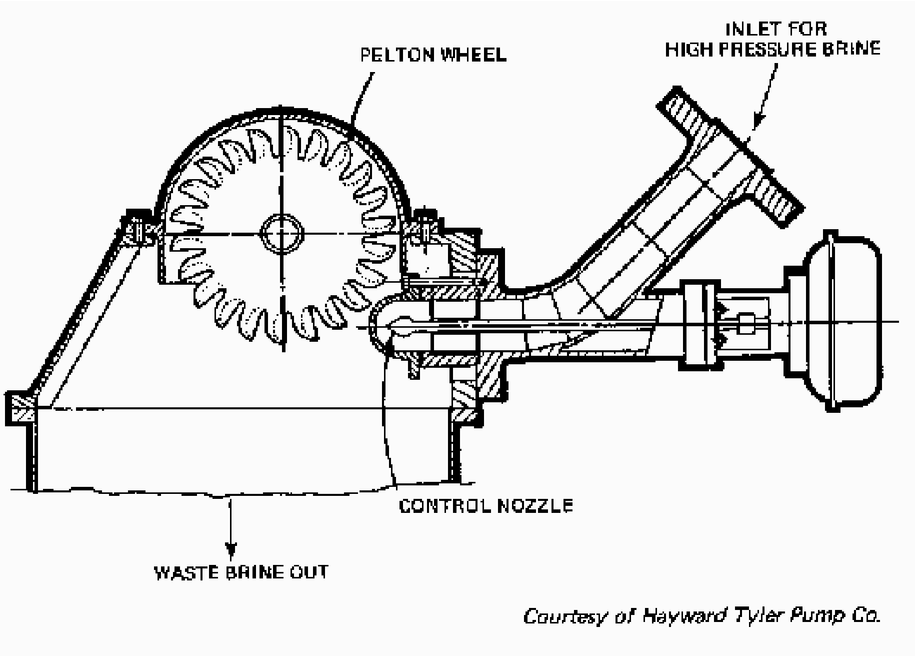
	Energy Consumption by HPP kWh/m^3	**Energy Saving by ERD %**	**Overall ERD Efficiency %**	**Throttling Loss %**
Minimum	5.78	0	0	0
Maximum	6.75	12.71	31.72	14.22
Average	**6.11**	**5.51**	**13.3**	**8.09**
Std. Dev. (n = 41)	0.31	3.9	9.68	3.44

Table 5. Energy Consumption Details and ERD Efficiency at Haql SWRO Plant

	Energy Consumption by HPP kWh/m^3	**Energy Saving by ERD %**	**Overall ERD Efficiency %**	**Throttling Loss %**
Minimum	5.6	0	0	0
Maximum	7.23	12.68	28.47	15.02
Average	**6.47**	**1.49**	**3.23**	**6.35**
Std. Dev. (n = 81)	0.41	4.33	9.45	4.98

Table 6. Energy Consumption Details and ERD Efficiency at Ummlujj SWRO Plant

	Energy Consumption by HPP kWh/m^3	**Energy Saving by ERD %**	**Overall ERD Efficiency %**	**Throttling 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. (n = 39)	0.04	0.27	1.76	0.8



Courtesy of Hayward Tyler Pump Co.

Figure 1. Sectional Arrangement of a Pelton Wheel

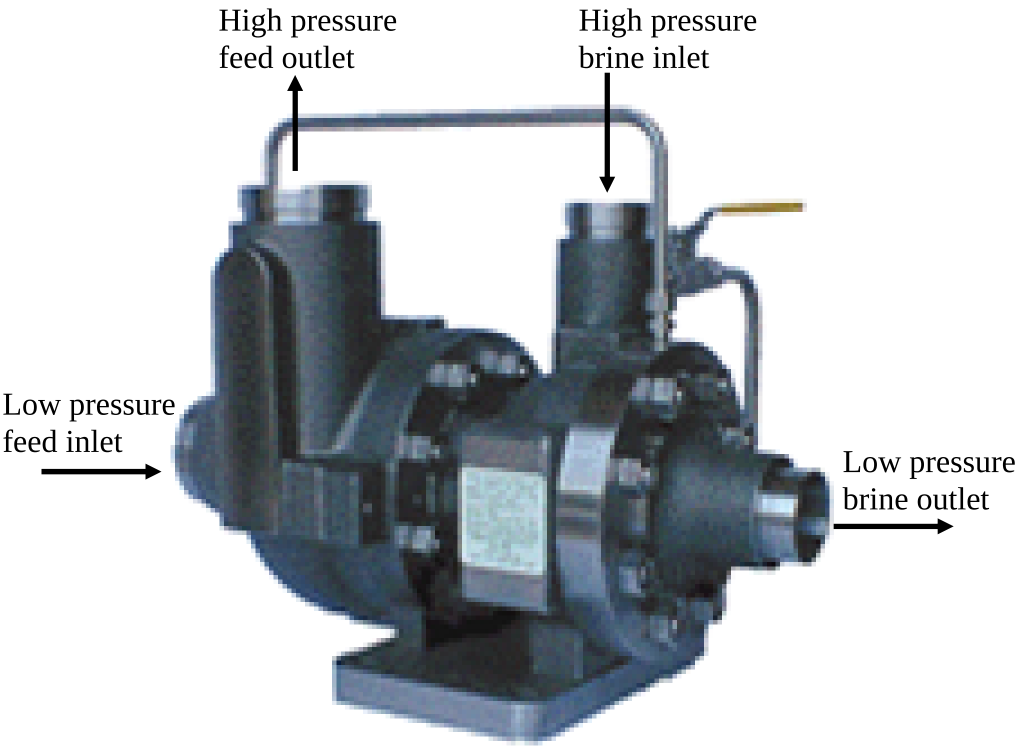


Figure 2. A Turbo Charger Unit

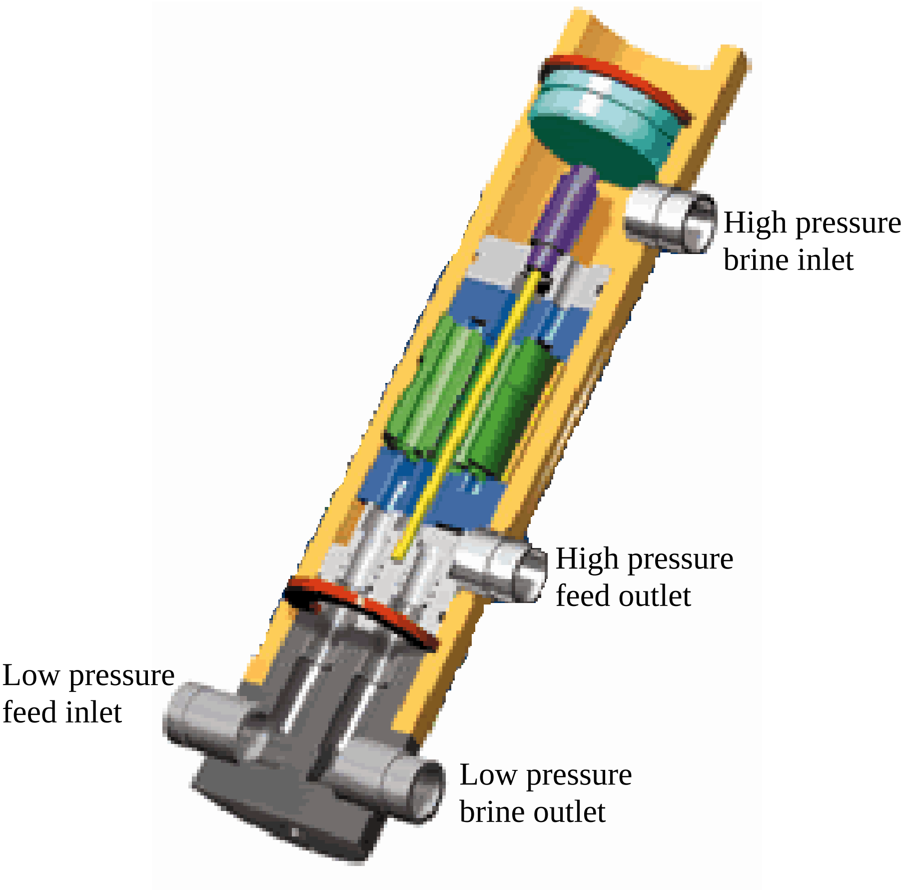


Figure 3. An Exploded View of a Pressure Exchanger

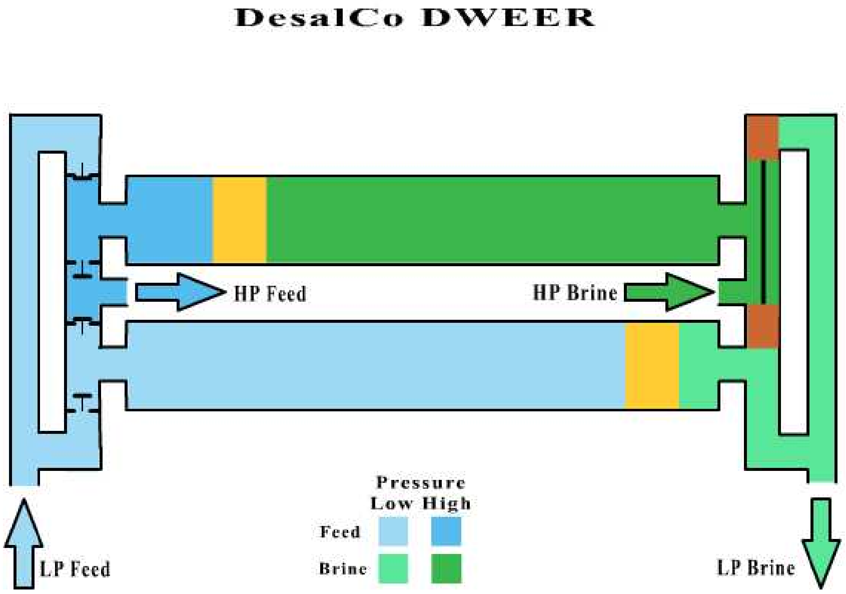


Figure 4. A Schematic Diagram of Dual Work Exchanger Energy Recovery (DWEER) System

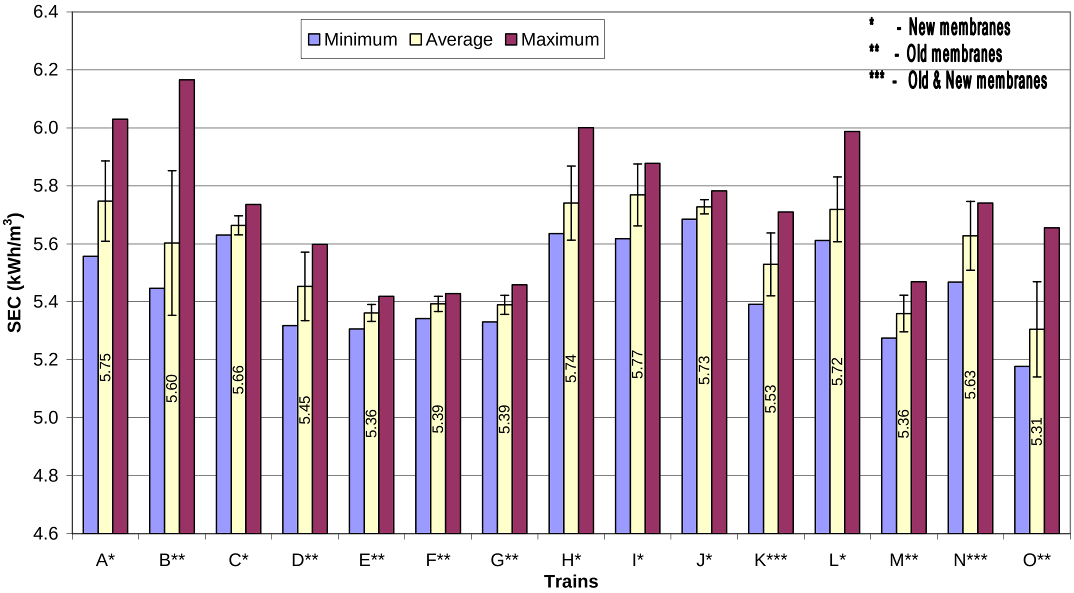


Figure 5 : Specific Energy Consumption (SEC) by High Pressure Pump of Different Trains of Yanbu SWRO Plant

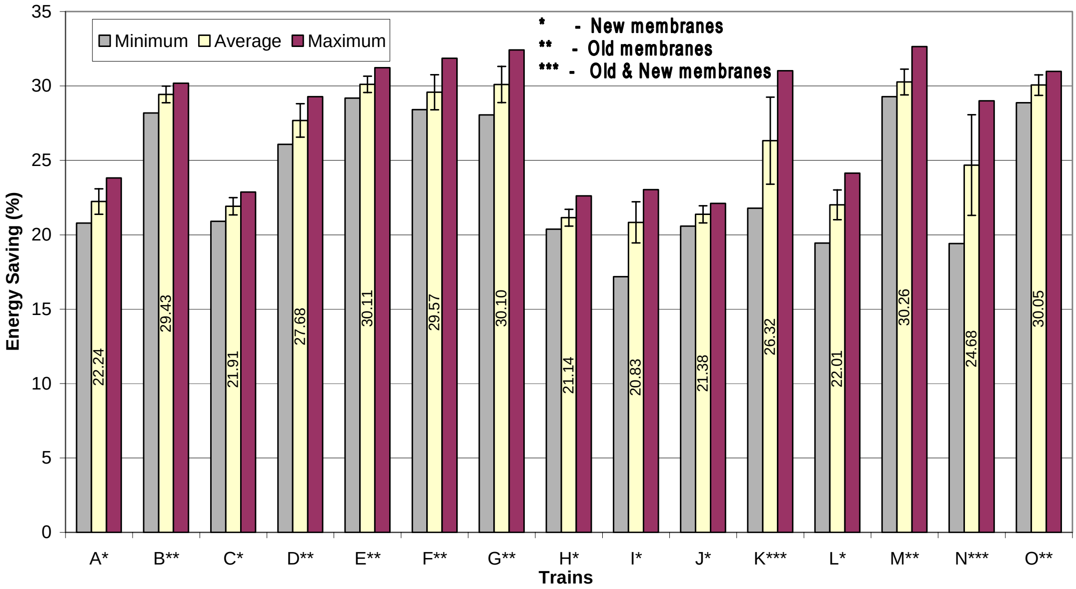


Figure 6 : Energy Saving by Energy Recovery Devices of Different Trains of Yanbu SWRO Plant

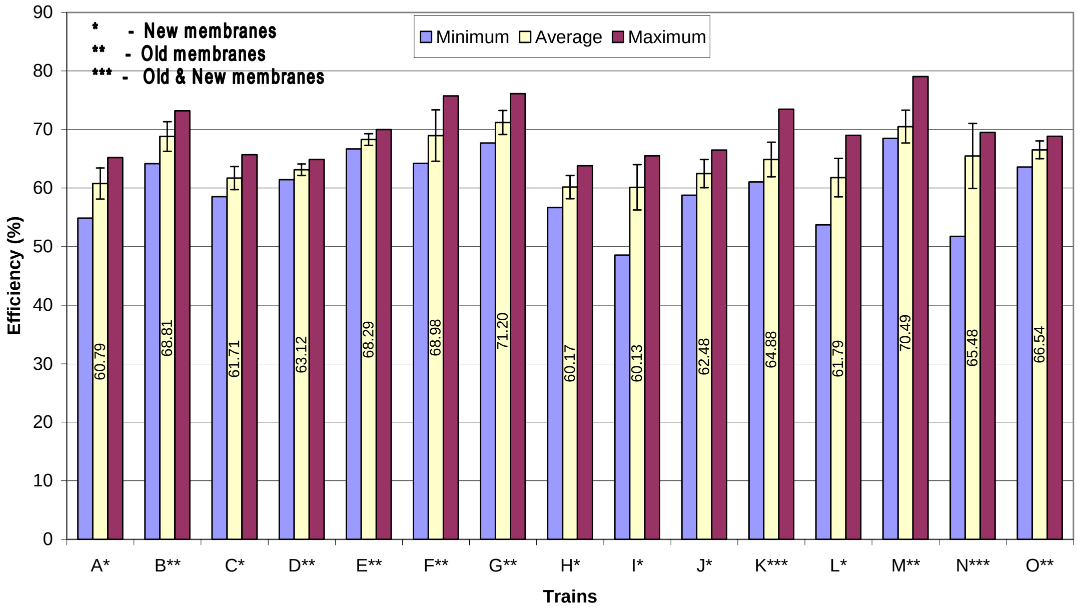


Figure 7 : Efficiency of Energy Recovery Devices of Different Trains of Yanbu SWRO Plant

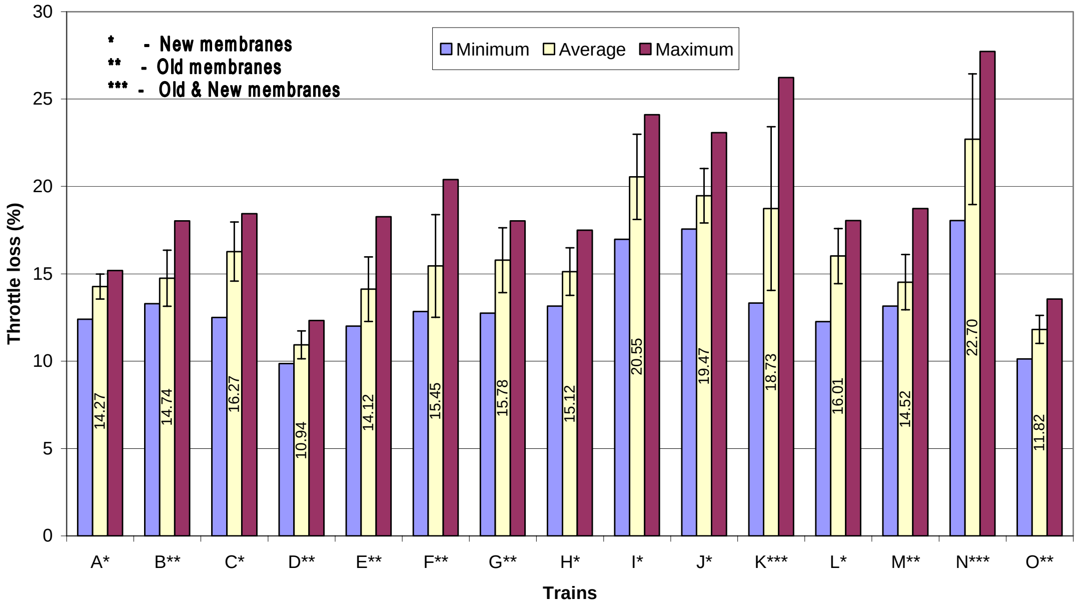


Figure 8 : Energy Lost by Throttling in Different Trains of Yanbu SWRO Plant

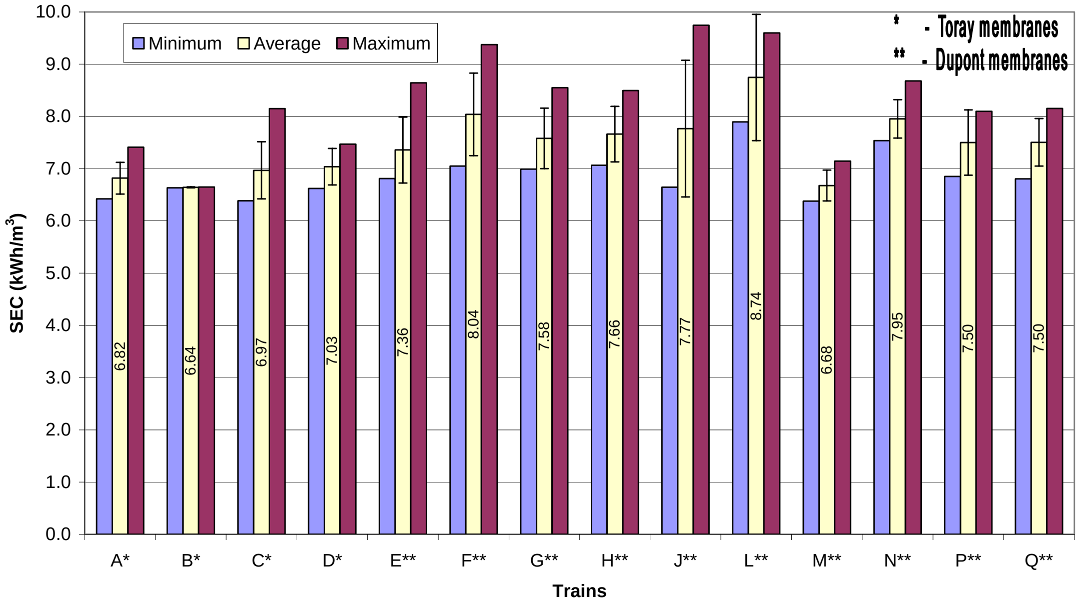


Figure 9 : Specific Energy Consumption by High Pressure Pump of Different Trains of Al-Jubail SWRO Plant

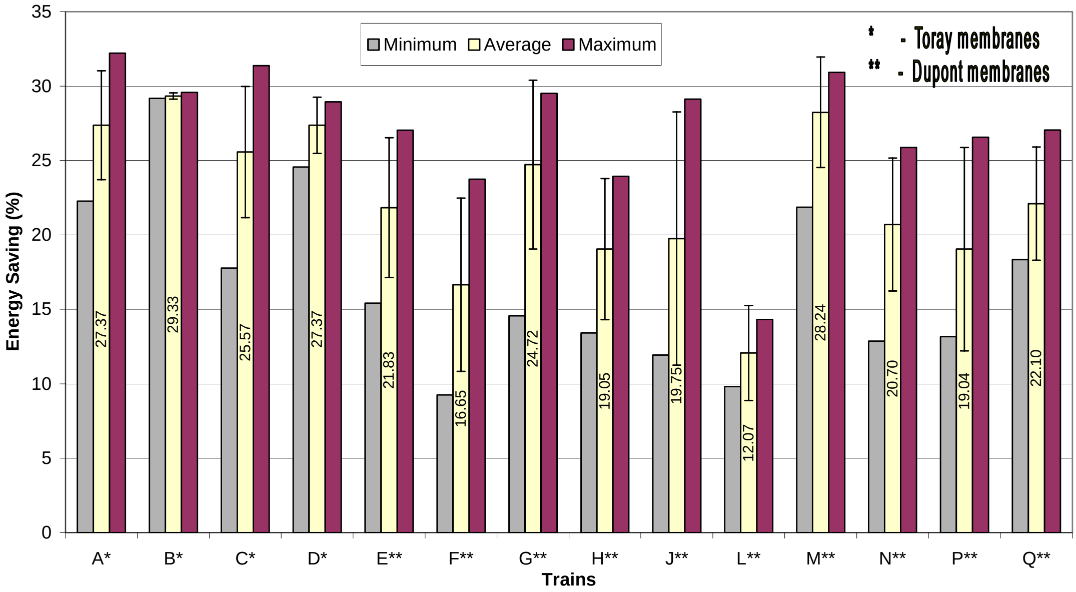


Figure 10 : Energy Saving by Energy Recovery Devices of Different Trains of Al-Jubail SWRO Plant

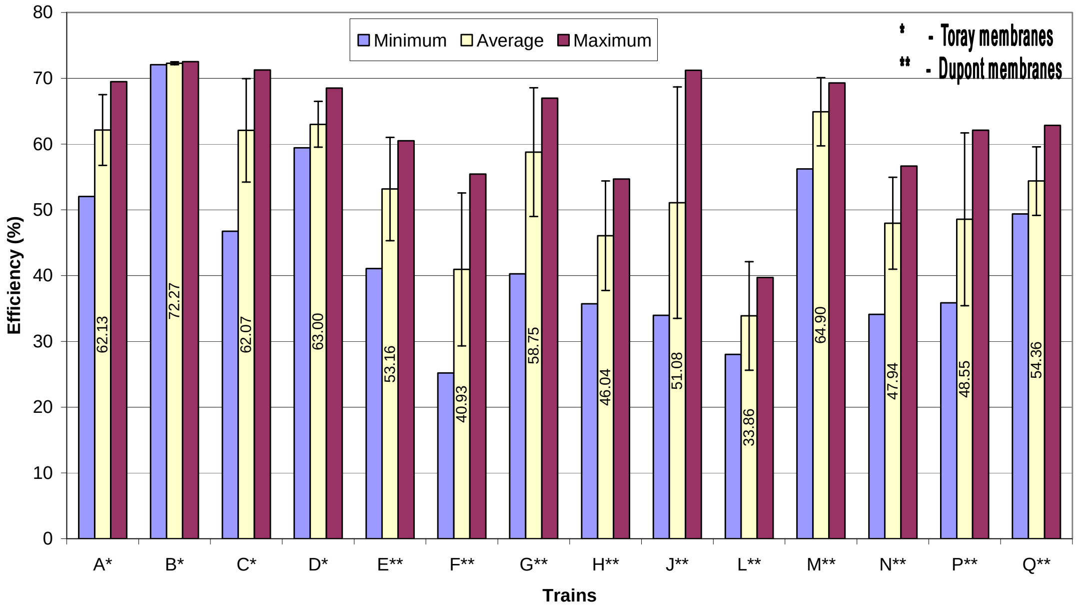


Figure 11 : Efficiency of Energy Recovery Devices of Different Trains of Al-Jubail SWRO Plant

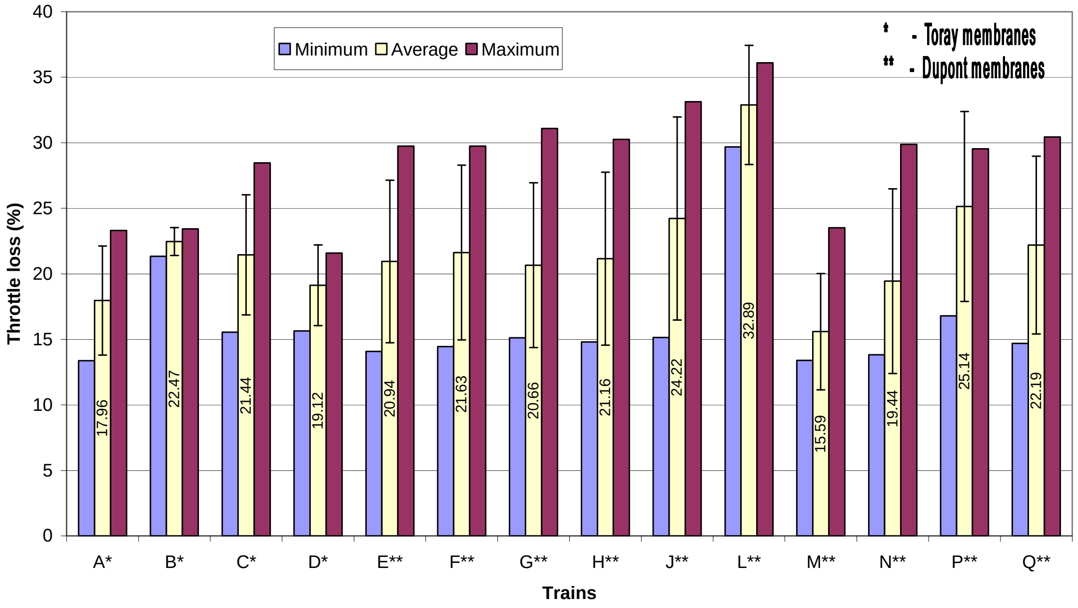


Figure 12 : Energy Lost by Throttling in Different Trains of Al-Jubail SWRO Plant

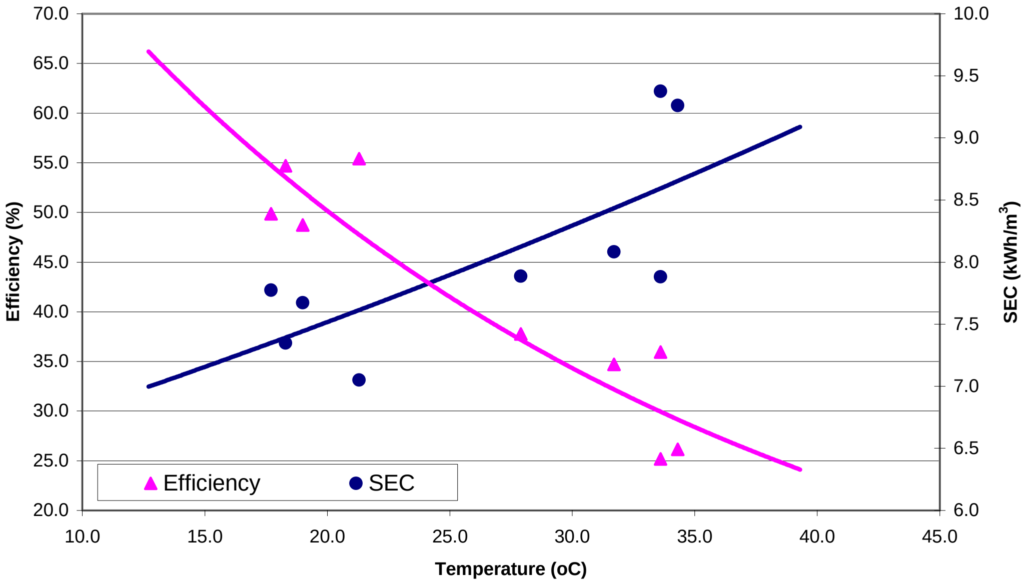


Figure 13 : Variation in ERD efficiency and SEC with change in feed temperature in one of the trains of Al-Jubail SWRO plant

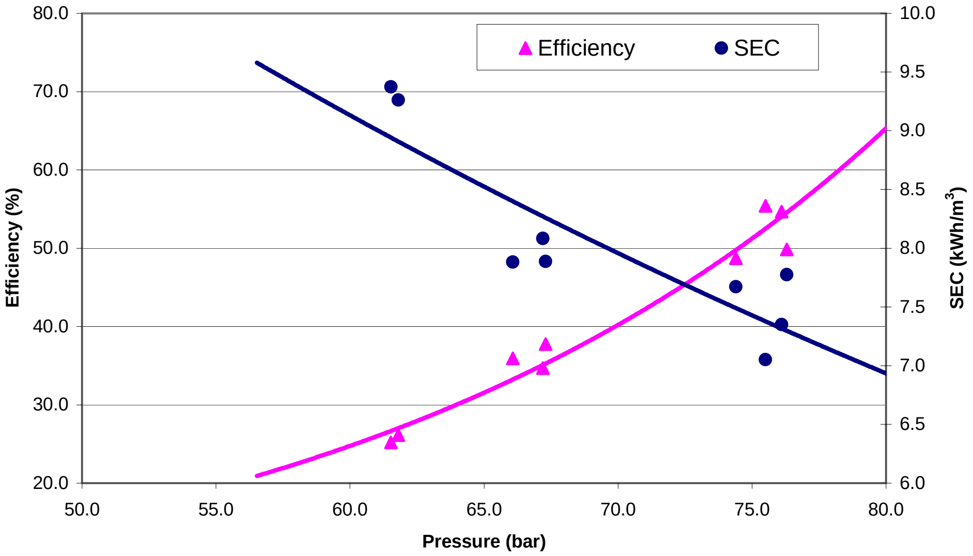


Figure 14 : Variation in ERD efficiency and SEC with change in reject pressure resulting from the variation of feed temperature in one of the trains of Al-Jubail SWRO plant

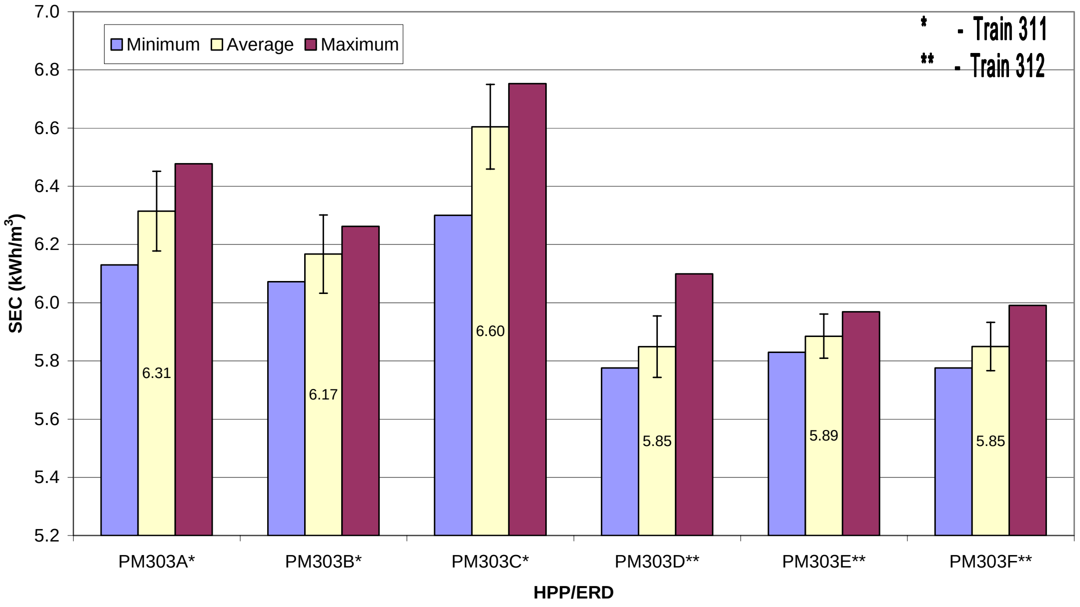


Figure 15 : Specific Energy Consumption by Different HPP/ERDs of Duba SWRO Plant

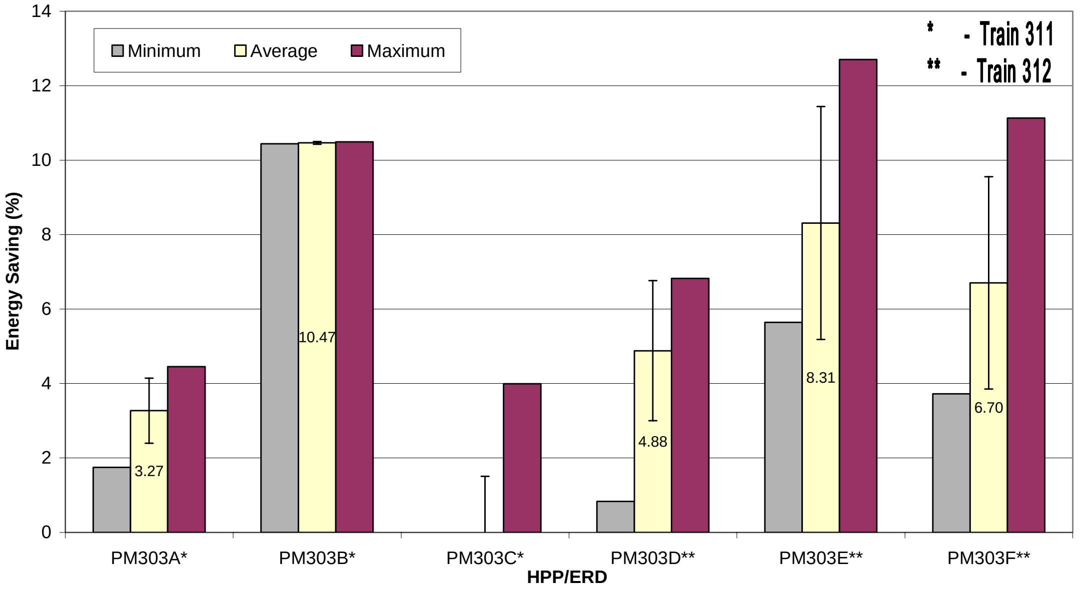


Figure 16 : Energy Saving by Different Energy Recovery Devices of Duba SWRO Plant

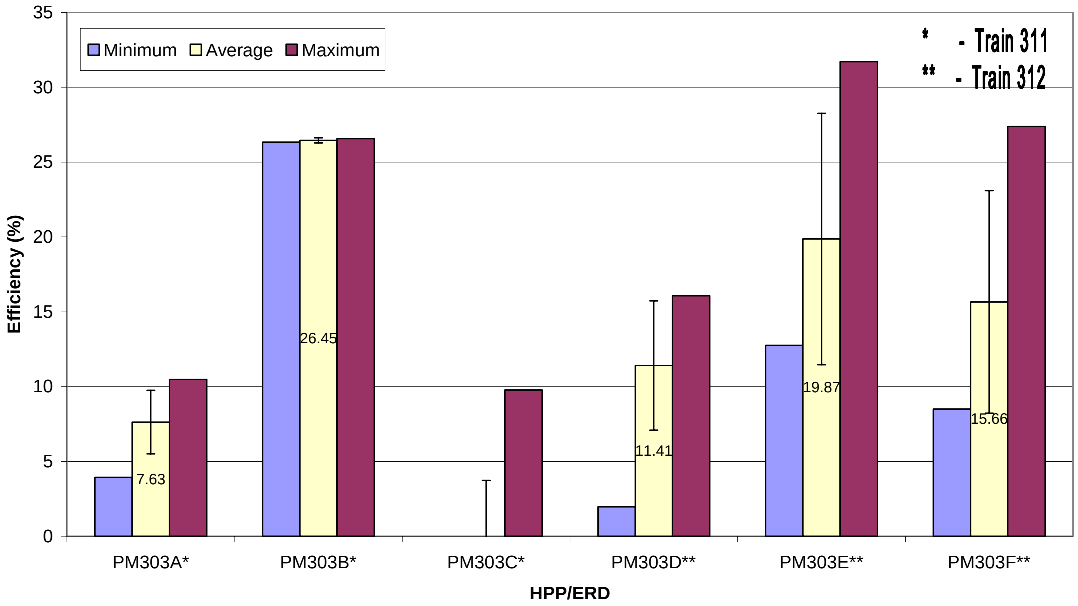


Figure 17 : Efficiency of Different Energy Recovery Devices of Duba SWRO Plant

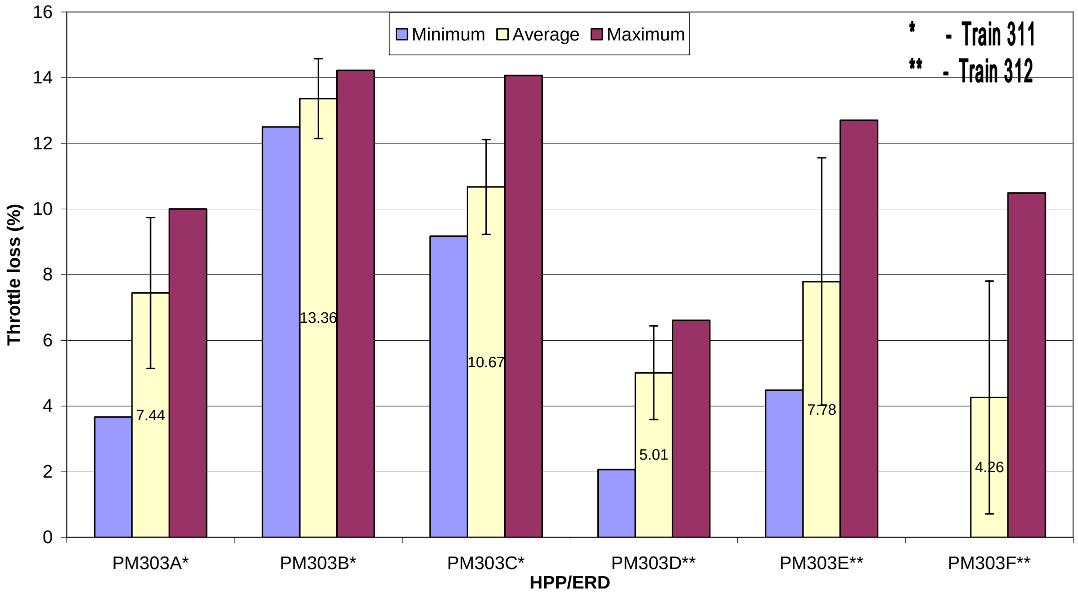


Figure 18 : Energy Lost by Throttling in Different High Pressure Pump System of Duba SWRO Plant

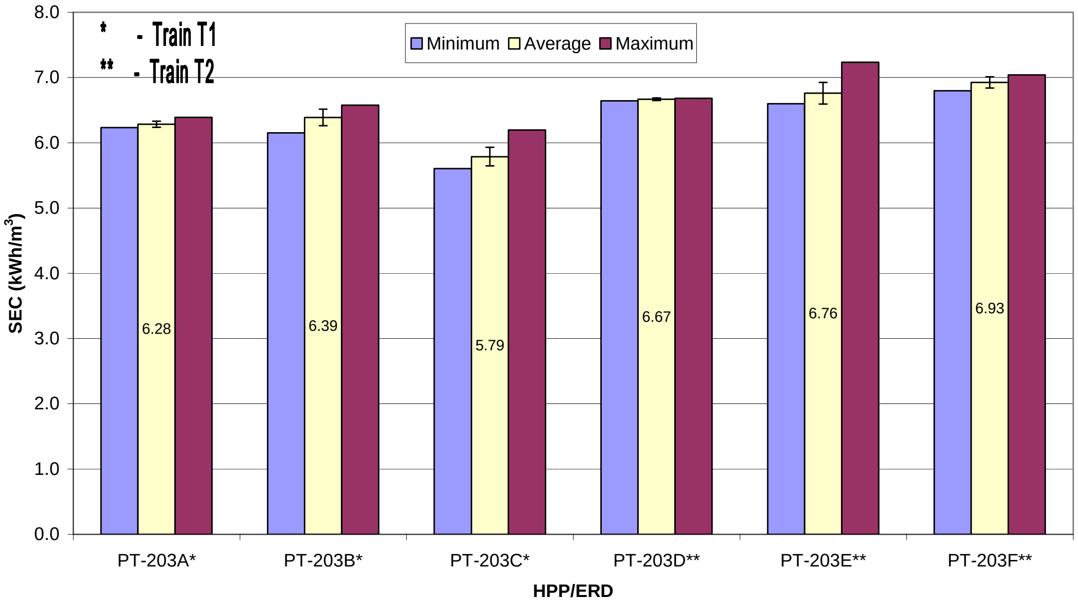


Figure 19 : Energy Consumption by Different HPP/ERDs of Haql SWRO Plant

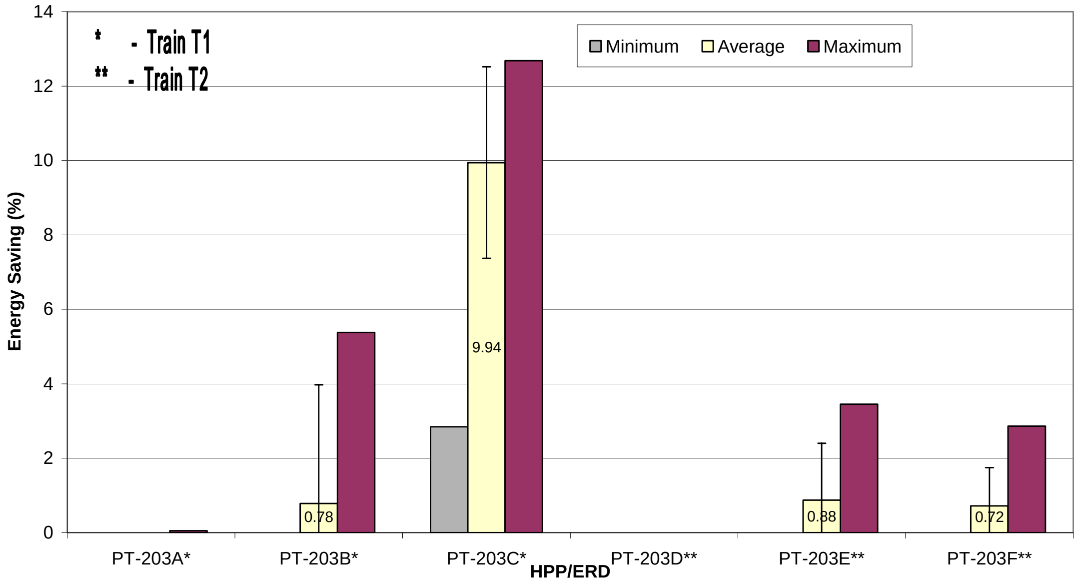


Figure 20 : Energy Saving by Different Energy Recovery Devices of Haql SWRO Plant

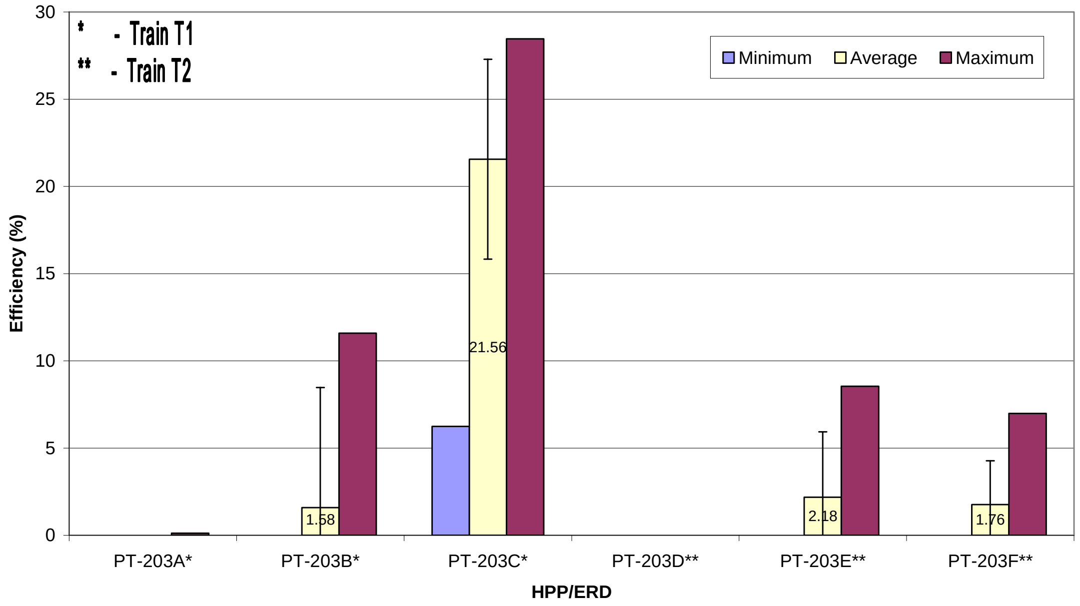


Figure 21 : Efficiency of Different Energy Recovery Devices of Haql SWRO Plant

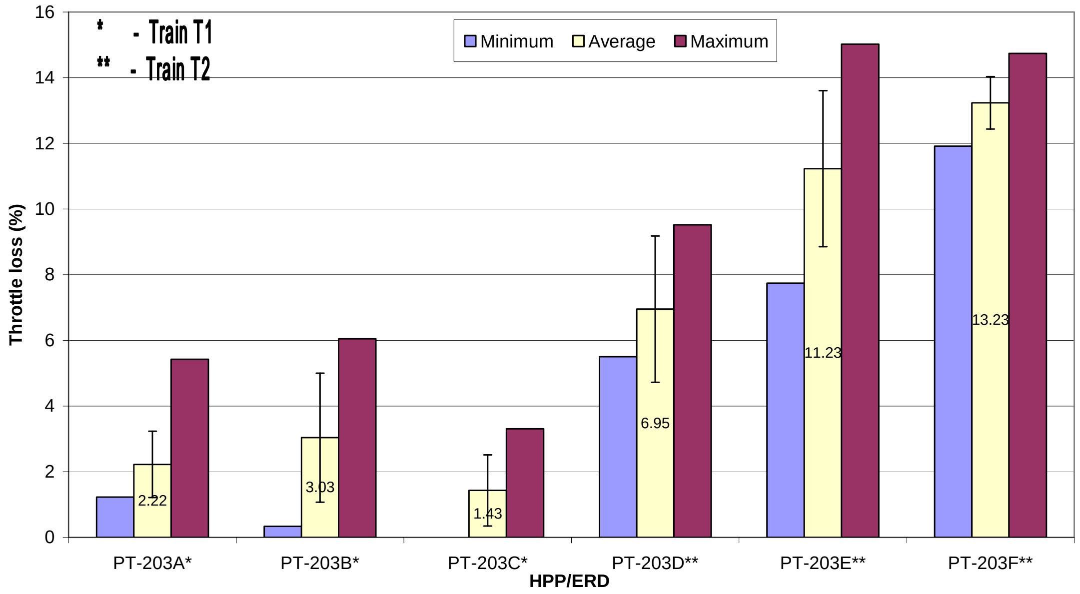


Figure 22 : Energy Lost by Throttling in Different High Pressure Pump System of Haql SWRO Plant

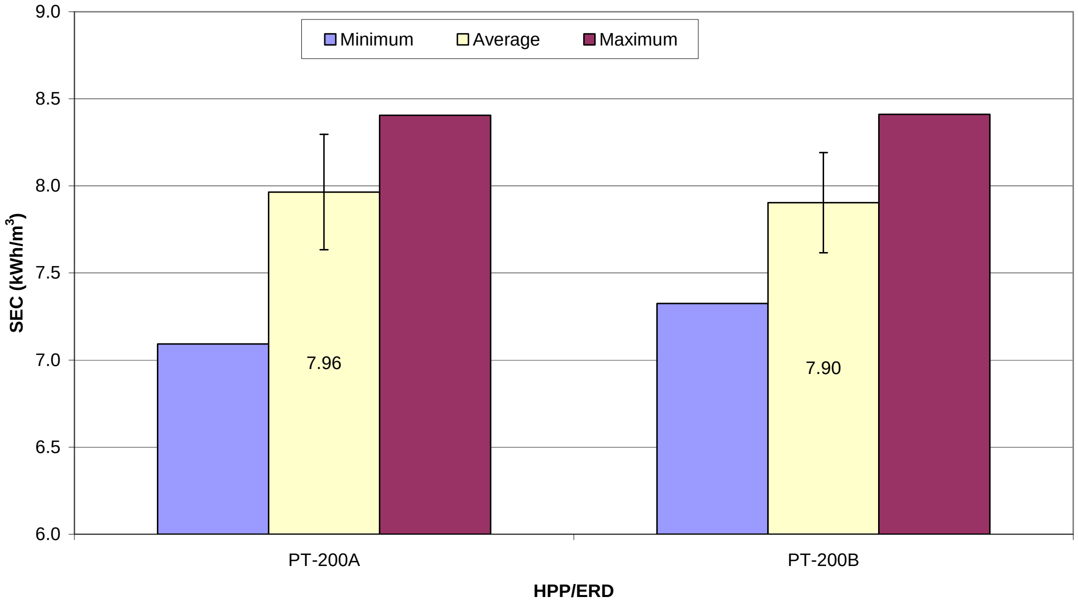


Figure 23 : Specific Energy Consumption by Different High Pressure Pump/ERDs of Ummlujj SWRO Plant

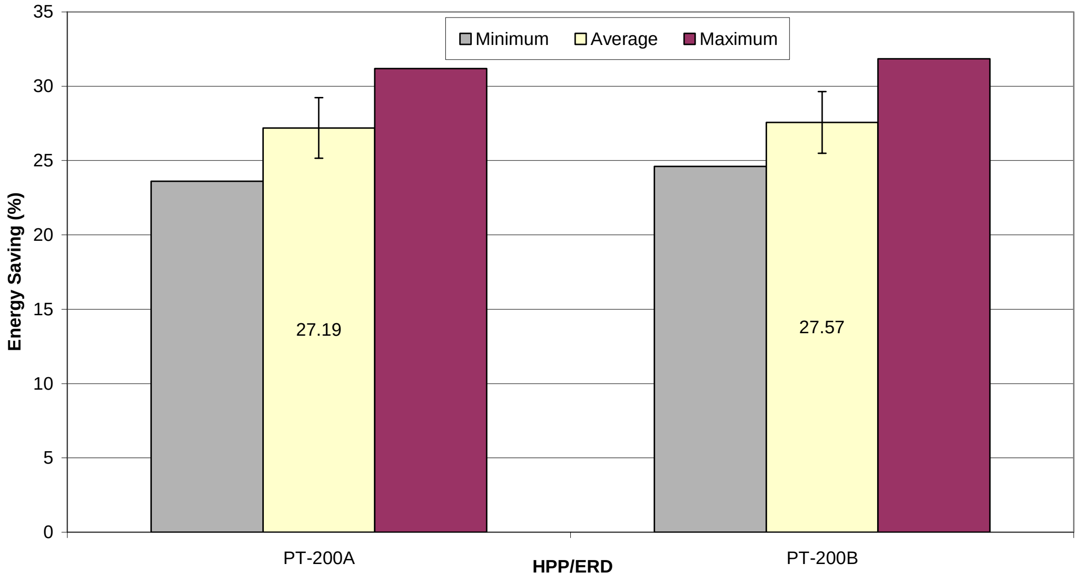


Figure 24 : Energy Saving by Different Energy Recovery Devices of Ummlujj SWRO Plant

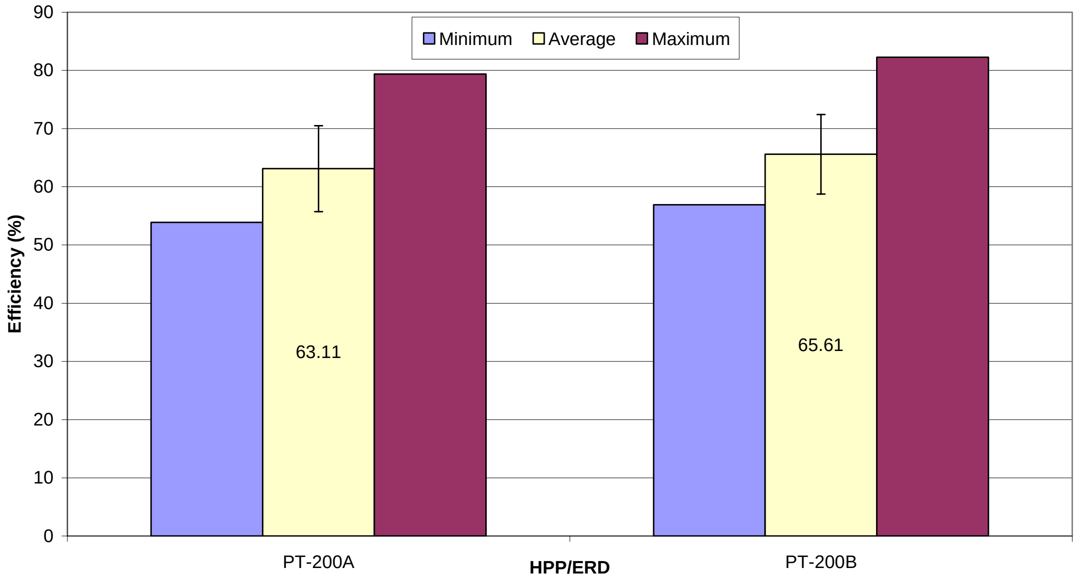


Figure 25 : Efficiency of Different Energy Recovery Devices of Ummlujj SWRO Plant

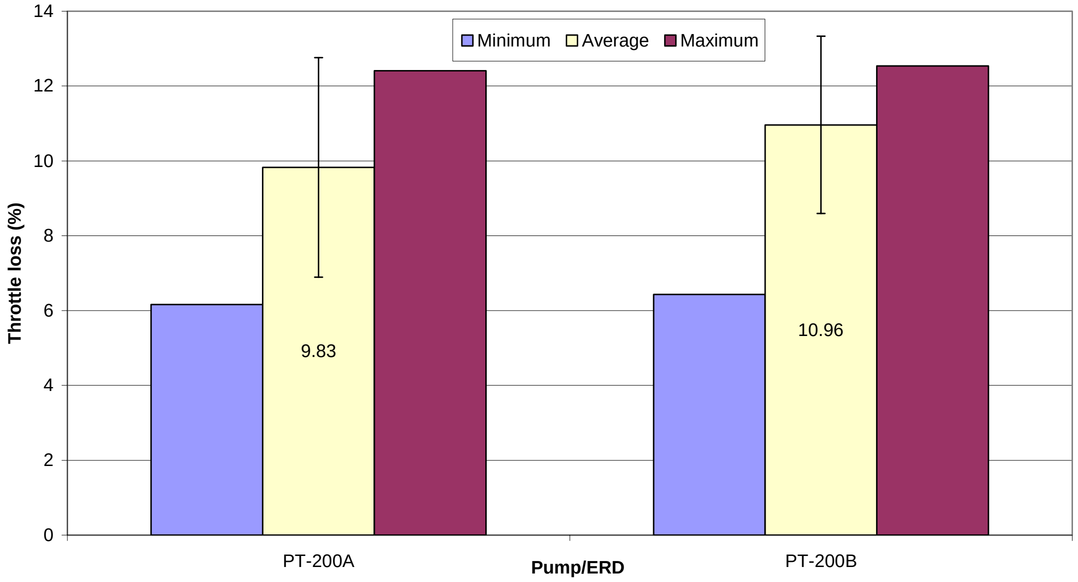


Figure 27 : Energy Lost by Throttling in Different High Pressure Pump System of Ummlujj SWRO Plant

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