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Retrofits to improve desalination plants

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ABSTRACT

Legacy seawater reverse osmosis (SWRO) desalination plants used turbine-type energy recovery devices (ERDs) connected with a shaft to the high-pressure pump. These ERDs, commonly known as Pelton wheels or energy recovery turbines, were default equipment in SWRO plants until quite recently.

Today, however, over 80% of new SWRO plants are being designed and built to utilize isobaric-chamber ERDs. Isobaric ERDs such as Energy Recovery, Inc. (ERI's) PX Pressure Exchanger™ (PX™) device are positive displacement devices that operate with energy transfer efficiencies as high as 98%. High SWRO plant operating efficiency can be obtained over a wide range of membrane water recovery rates, typically between 35% and 50%. Recovery rates can be adjusted in response to changes in seawater temperature or salinity or as the membrane elements age. Flexible recovery and low-recovery operation are tremendous advantages for low-cost SWRO operation provided by isobaric ERD technology.

Removing legacy ERDs and installing modern isobaric ERDs makes it possible to reduce the power consumption of existing systems by as much as 60%. Such retrofits can also significantly increase the capacity of existing systems while adding little or no additional power requirements. These benefits can be realized at a fraction of the cost of constructing new plants. For these reasons, many owners of legacy desalination plants worldwide are upgrading their processes by incorporating isobaric ERD technology.

The authors recognize that each energy recovery technology comes with its own unique advantages and disadvantages, which should be compared and studied for each individual system. This paper, therefore, provides detailed analyses comparing SWRO energy consumption with various ERDs. It presents many examples of retrofits, including replacements of Pelton turbines and turbocharger devices. It also estimates the potential energy savings and capacity increase benefits for retrofitting some of the largest SWRO projects in the world including facilities in Fujairah, UAE and Trinidad.

Keywords: energy recovery; retrofit; SWRO; efficiency

1. Introduction

Reverse osmosis is a water desalination process widely used around the world. The osmotic pressure of a salt water solution is overcome with hydraulic pressure, forcing nearly pure water through a semi-permeable membrane and leaving concentrated brine behind. In seawater reverse osmosis (SWRO) systems, an operating pressure of between 60 and 70 bar is required. Even at these pressures, a maximum of approximately 50% of the available pure water can be extracted before the osmotic pressure becomes so high

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that additional extraction is not economically viable. The rejected concentrate leaves the process at nearly the membrane feed pressure. The combination of the high required membrane feed pressure and the high-volume reject stream have historically limited the deployment of large-scale SWRO to regions where power is inexpensive and abundant.

SWRO systems, however, consumes far less energy today than they did just a few years ago. Improved membranes, increased pump efficiencies and the implementation of energy recovery devices (ERDs) have dramatically increased the energy efficiency of SWRO. The energy requirement for SWRO can be as low as 1.6 kWh/m^3, making the process energy-competitive with many traditional fresh water supply sources [1,2].

ERDs have been employed in SWRO applications since the early 1980s to recover pressure energy from the concentrate reject stream of the SWRO membranes and return it to the membrane feed stream. Early ERDs were centrifugal devices, such as Francis turbines, Pelton turbines or turbochargers, which were limited in capacity and had a maximum net transfer efficiency of typically less than 70% at their best efficiency point [3]. More recently, isobaric ERDs, including piston-type work exchangers and the rotary PX Pressure Exchanger® device, have been developed to provide unlimited capacity and an operating efficiency of up to 98% [4]. The positive displacement pressure transfer mechanism used in these devices is similar to that in reciprocating pumps, assuring high efficiency despite flow and pressure variations. As a result, most SWRO plants being designed and built today utilize isobaric ERDs including three of the four largest SWRO plants currently in operation [5]. Many plants built with centrifugal ERDs have been retrofit or their operators are considering converting to isobaric devices to reduce energy consumption and increase production capacity [6].

2. Centrifugal energy recovery devices

Centrifugal ERDs use the hydraulic energy of the membrane reject stream to help drive a high-pressure pump. They use a turbine to convert the hydraulic energy of the concentrate stream into the mechanical energy of a spinning shaft. This mechanical energy is, in turn, converted back into hydraulic energy by the pump. The two most widely deployed centrifugal ERDs are the Pelton turbine and the hydraulic turbocharger.

2.1. Pelton turbine

The first energy recovery devices deployed in municipal-scale SWRO plants were Francis turbines or reverse-running pumps. These were replaced in the 1980s by Pelton turbines which operate at higher efficiency in high-head applications like SWRO. Pelton turbines are widely accepted in SWRO because of their familiarity and proven reliability. The turbine is mechanically coupled to either the high-pressure pump shaft or the motor to assist the motor in driving the pump that pressurizes the SWRO system. The high-pressure pump supplies all the membrane feed at the pressure required by the SWRO membranes. A typical SWRO process with a Pelton turbine is illustrated in Fig. 1.

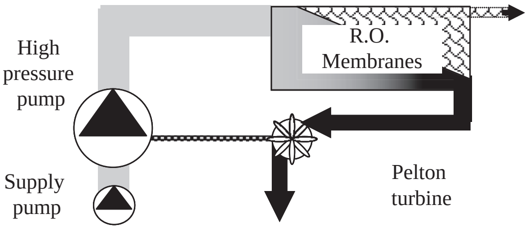


Fig. 1. SWRO process with Pelton turbine.

The water-to-water energy transfer efficiency of a Pelton turbine energy recovery system is the product of the efficiencies of the nozzle(s), the turbine and the high-pressure pump. The centrifugal impeller of the high-pressure pump will be considered first. As described by the Hydraulic Institute [7], the operating efficiency of centrifugal pumps is influenced by many factors such as the following:

- Specific Speed – Proportional to rotational speed and flow rate and inversely proportional to displacement head (pressure),
- Size – Larger pumps generally have higher specific speed and are therefore more efficient,
- Surface finish of impellers and volutes – Smoother finish results in higher efficiency,
- Internal clearances such as at wearing rings – The closer the better, and
- Flow rate – The actual rate of flow compared to the best-efficiency rate of flow.

The Hydraulic Institute has published ''best generally-achievable'' pump efficiency data as a function of pump flow rate for a number of pump styles. Efficiencies for low-pressure end-suction pumps are shown in Fig. 2.

Efficiency generally decreases at higher pressures. Oklejas presented an equation for estimating high-pressure pump efficiency as a function of flow rate [8]:

$$\text{Efficiency} = 0.043 \times \text{LN(Q)} + 0.4768 - 0.06 \times (40/\text{Q})^2 \tag{1}$$

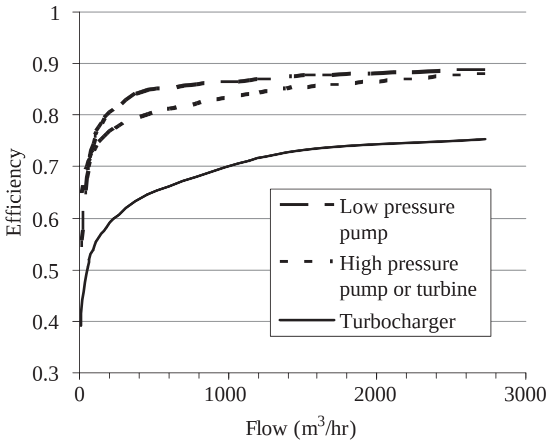


Fig. 2. Centrifugal element efficiency.

where Q represents flow measured in units of gallons per minute. This equation is plotted in Fig. 2.

The efficiency-flow relationship for turbines is similar to that for pumps. The authors were unable to find a generally applicable relationship between turbine efficiency and flow in the literature. Instead, Eq. (1) was assumed to apply. This assumption has been validated by field data, including some of the case study data presented below.

High-pressure centrifugal pumps provide a flow window of about 30% that includes the best efficiency point. High-pressure turbines have a narrower operating window because their performance is affected by both flow and pressure. The turbine and impeller can be selected such that their operating windows coincide for a particular membrane condition, however, as the membrane condition changes because of, for example, element age or feedwater temperature or salinity, the overall flexibility of the process can be limited with respect to flow variations. A well-designed pump-turbine set provides a maximum operating window of about 20%, or plus or minus 10% from the best efficiency point.

2.2. Hydraulic turbocharger

Another type of centrifugal ERD is the hydraulic turbocharger which has been used for SWRO energy recovery since the early 1990s. Turbochargers are similar in concept to Pelton turbine ERDs, with a turbine and an impeller on the same shaft but with no motor. The membrane feed stream, partially pressurized by a separate high-pressure pump, is boosted by the turbocharger impeller to the SWRO feed pressure. Both the high-pressure pump and the turbocharger handle the full membrane-feed flow. A typical SWRO process with a hydraulic turbocharger is illustrated in Fig. 3.

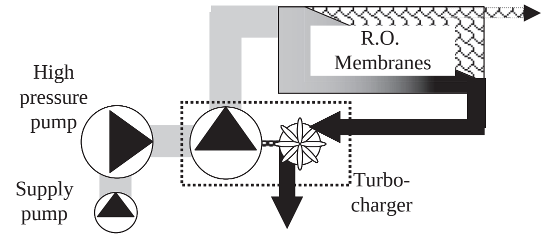


Fig. 3. SWRO process with turbocharger.

Interestingly, no data on the efficiency of these devices is available from their manufacturers or elsewhere in the literature. However, if it is assumed that the impeller and turbine individually adhere to Eq. (1), the turbocharger efficiency curve shown in Fig. 2 is derived. The validity of this assumption is borne out in the field data presented below. As for Pelton turbines, the range of flows that can be accommodated by a turbocharger is, at most, plus or minus 10% of the flow rate at the best efficiency point.

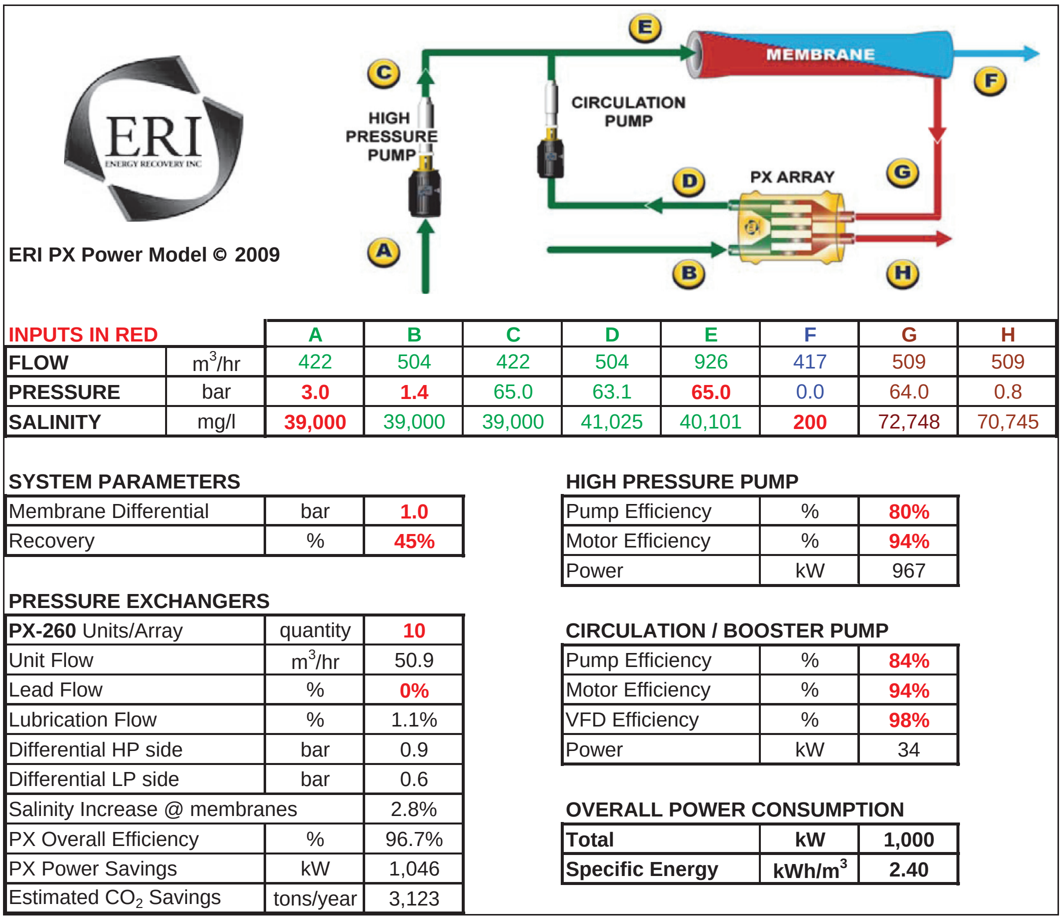
3. Isobaric energy recovery devices

Table 1 includes an illustration of a typical SWRO train fitted with isobaric ERDs. It includes a circulation pump necessary to move high-pressure water through the membrane array and the ERDs. The table lists flow, pressure, salinity and power data for a typical 10,000 cubic meters per day (m^3/day) SWRO train.

The data illustrate several points which are generally applicable to SWRO processes equipped with isobaric ERDs.

(1) The high-pressure pump and permeate flow rates are nearly equal. The high-pressure pump is sized to the permeate flow rate, not to the full membrane feed flow rate,
(2) The high-pressure pump consumes about 97% of the energy required for SWRO while the circulation pump consumes about 3%,
(3) PX devices typically operate at over 97% net transfer efficiency, reducing the energy required by the SWRO process to less than half that required with no energy recovery,
(4) The membrane feed salinity is less than 3% higher than the salinity of the system feed, and
(5) The high-pressure pump and the PX devices can be fed with different supply streams. Net positive suction head requirements for the pump may require a feed pressure greater than 3 bar. However, the minimum discharge pressure requirement for the PX devices of 0.6 bar allows a PX supply pressure of less than 2 bar.

Table 1
Typical Performance Data for a 10,000 m^3/day SWRO System



ERI PX Power Model © 2009

INPUTS IN RED		A	B	C	D	E	F	G	H
FLOW	m^3/hr	422	504	422	504	926	417	509	509
PRESSURE	bar	**3.0**	**1.4**	65.0	63.1	**65.0**	0.0	64.0	0.8
SALINITY	mg/l	**39,000**	39,000	39,000	41,025	40,101	**200**	72,748	70,745

SYSTEM PARAMETERS

Membrane Differential	bar	**1.0**
Recovery	%	**45%**

PRESSURE EXCHANGERS

PX-260 Units/Array	quantity	**10**
Unit Flow	m^3/hr	50.9
Lead Flow	%	**0%**
Lubrication Flow	%	1.1%
Differential HP side	bar	0.9
Differential LP side	bar	0.6
Salinity Increase @ membranes		2.8%
PX Overall Efficiency	%	96.7%
PX Power Savings	kW	1,046
Estimated CO$_2$ Savings	tons/year	3,123

HIGH PRESSURE PUMP

Pump Efficiency	%	**80%**
Motor Efficiency	%	**94%**
Power	kW	967

CIRCULATION / BOOSTER PUMP

Pump Efficiency	%	**84%**
Motor Efficiency	%	**94%**
VFD Efficiency	%	**98%**
Power	kW	34

OVERALL POWER CONSUMPTION

Total	**kW**	**1,000**
Specific Energy	**kWh/m^3**	**2.40**

In addition, SWRO processes equipped with isobaric ERDs, either in processes originally designed with them or in processes retrofit with them, enjoy the following benefits:

3.1. Operational flexibility

Like other positive displacement devices, isobaric ERDs provide high and nearly constant efficiency over a wide range of flows and pressures. Specifically, PX devices for medium- to large-sized SWRO trains can operate at 30% or more below their maximum rated flow, limited by their capacity, not by their performance. As a result, membrane flow can be adjusted by up to 30% without reducing process efficiency. Because the high-pressure pump and ERDs operate independently, the high-pressure pump can be operated near its best efficiency point without regard for the ERD. Alternately, the ERDs can be adjusted, using the circulation pump, to shift the high-pressure pumping duty to or from the high-pressure pump, again with the goal of maximizing the performance of the pump. This flexibility is further considered in terms of the membrane water recovery rate.

3.2. Variable recovery

The membrane water recovery rate, or simply the recovery, is the ratio of permeate flow rate to membrane feed flow rate. Implementation of variable recovery is illustrated with reference to the diagram in Table 1 above. If the flow rate of the circulation pump is set with a variable frequency drive to be equal to the flow rate of the high-pressure pump, the system will operate at 50% recovery. If the flow rate of the circulation pump is increased by 25%, the system will operate at 44.5% recovery. The ERD, driven by the flow, automatically adjusts to these flow changes to maintain

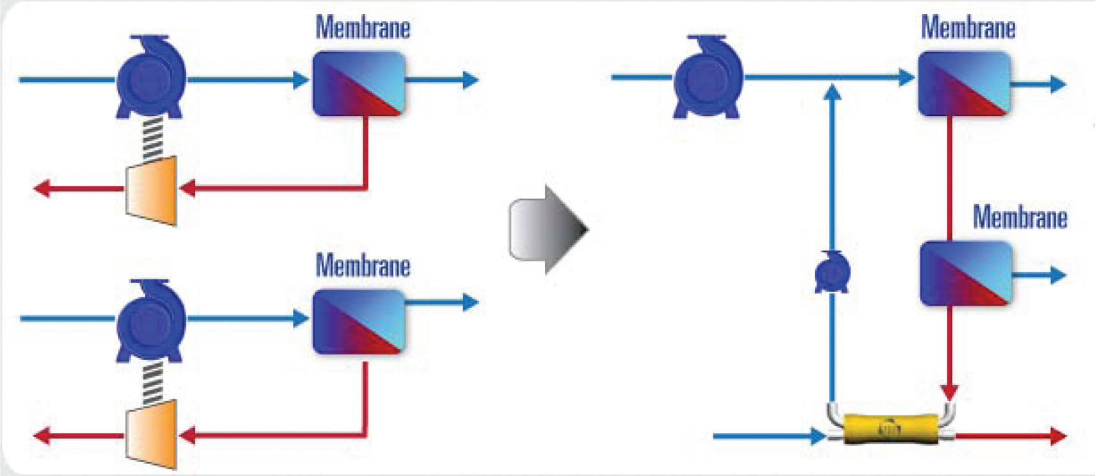


Fig. 4. Centrifugal ERD retrofit schematic diagram.

high performance. These changes are made without direct manipulation of the high-pressure pump flow rate or the permeate flow rate.

As recovery rate is reduced, the reject water concentration reduces and the osmotic pressure in the membrane elements decreases accordingly. Reducing recovery essentially dilutes the concentrate stream which reduces the membrane feed pressure. This reduces the load on the high-pressure-pump motor. As recovery rate is increased, membrane feed pressure increases but the SWRO system requires less feedwater. Such adjustments can significantly change membrane performance but have negligible affect on isobaric ERD performance which provides high efficiency regardless of changes of flow rate or pressure. Although the maximum flow rate through each energy recovery device is limited, additional units can be added or removed as necessary to accommodate a wide range of recovery-rate variation.

This flexibility allows a process operator to optimize membrane performance as seasonal variations in the seawater occur or as the membrane elements age. For instance, if heavy fouling conditions occur, the recovery rate can be lowered, increasing membrane cross flow and reducing contaminant deposition and biological growth on membrane surfaces. Similarly, the design permeate flow rate can be maintained if the seawater temperature falls or the membrane elements compact by lowering recovery. Alternately, recovery can be increased to reduce the amount of filtered feedwater required and a corresponding reduction in pretreatment requirements can be achieved. In these ways, an operator can manipulate and optimize system performance to achieve low energy consumption throughout the year. Flexible recovery and low-recovery operation are tremendous advantages for low-cost SWRO operation provided by isobaric ERD technology.

4. Retrofitting with isobaric ERDS

Retrofitting existing SWRO processes with isobaric ERDs makes it possible to reduce the power consumption of existing systems by as much as 60%. Alternately, the capacity of existing systems can be increased with little or no additional power requirements and with minimal additional equipment. If the ERDs to be added are PX devices, the footprint required is minimal. PX devices and a circulation pump can be installed between membrane racks or even in a piping trench in any orientation. For these reasons, owners of many currently-operating SWRO plants have retrofitted or are considering retrofitting with isobaric ERDs. Direct comparisons of the performance of various ERDs are provided below using data from SWRO plants that were originally built with Pelton turbines or turbochargers and were recently retrofit with PX devices.

4.1. Full retrofit

In a full retrofit of an SWRO train with a Pelton turbine or a turbocharger, the turbine or turbocharger is removed. The original high-pressure pump is typically utilized and an array of PX energy recovery devices and circulation pump are added. The number of membrane elements are approximately doubled, resulting in nearly double the permeate flow for the same size high-pressure pump. Alternately, two existing trains can be combined and one of the high-pressure pumps removed. The latter is illustrated in Fig. 4.

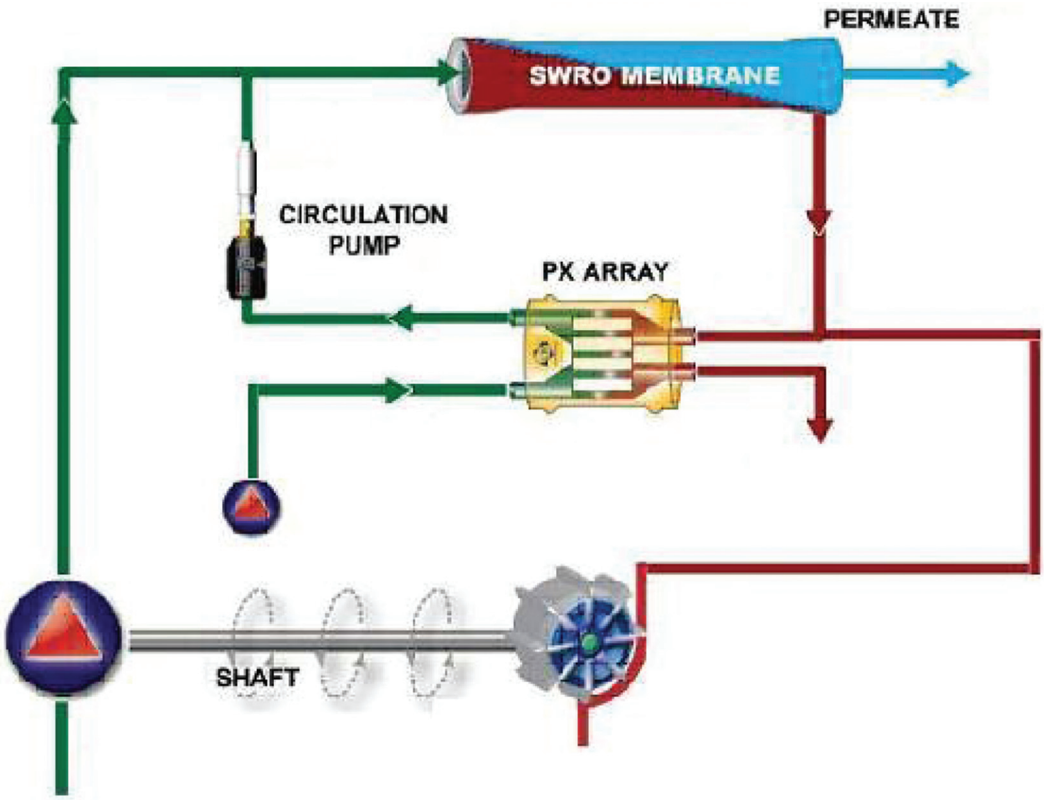


Fig. 5. Partial retrofit.

The capacity of pretreatment, post-treatment and product water conveyance systems must be increased in proportion to any increase in permeate production. In addition, because the turbine or turbines are removed, the high-pressure pump motor must be of sufficient capacity to turn the high-pressure pump. This requirement can be met in most existing Pelton installations where the high-pressure pump motors have been sized to operate without the turbine if necessary. If the turbocharger is fed with a centrifugal high-pressure pump, this pump must typically be replaced with a pump that is optimized for reduced flow and full membrane pressure. If the turbocharger is fed with a positive displacement pump, this pump can typically be used as shown in Fig. 4 provided the motor has the capacity to drive it.

4.2. Partial or hybrid retrofit

A partial or hybrid retrofit scheme can be applied to a process equipped with a Pelton turbine. This design is illustrated in Fig. 5. Additional membranes, an array of PX devices and a circulation pump are added to the existing system. No changes are made to the high-pressure pump or Pelton turbine. The amount of water diverted from the Pelton turbine to the PX devices depends upon the capacity of the high-pressure pump motor, which must operate with reduced assistance from the Pelton turbine. A partial Pelton retrofit is relatively inexpensive to implement but can increase production capacity by 20% and reduce specific energy consumption by 10%.

In addition to the flexibility of variable recovery provided by the isobaric ERDs and described above, this plant has the additional flexibility of being able to trim flows through the turbine nozzles. This allows plant personnel to keep the turbines operating near their peak efficiency points as the reject pressures and flow rates change.

5. Case studies

5.1. AWT turbocharger retrofit

The AWT plant in China had a 570 m^3/day SWRO train operating with a turbocharger. SWRO power consumption was 5.6 kWh/m^3 before the retrofit. The corresponding turbocharger net transfer efficiency was 8%, indicating that the turbocharger was being operated far from its design point. In early 2009, the plant was retrofit with an ERI PX-140S unit and a circulation pump. The original positive displacement

Fig. 6. PX installation in the Las Palmas III plant.

high-pressure pump was not altered. SWRO power consumption after retrofit was measured at 2.9 kWh/m^3. The retrofit paid for itself, including the PX device, circulation pump, piping modifications and instruments, with power savings in less than 12 months.

Had the turbocharger been operating in accordance with Eq. (1) above, specific energy consumption before the retrofit would have been approximately 4.3 kWh/m^3 or 45% higher than in the PX-device-equipped process. If this had been the case, payback for the PX-device retrofit would have occurred in less than approximately 16 months.

5.2. Emalsa Pelton turbine retrofit

In late 2008, the Emalsa Las Palmas III plant in the Canary Islands combined two trains that had been running with Pelton turbines into a single 15,000 m^3/day train with no turbines, fifteen ERI PX-220 devices and a circulation pump. The train is a two-stage, brine-concentrator design with an interstage booster pump in lieu of a circulation pump. SWRO power consumption before the retrofit was 3.49 kWh/m^3. The Pelton turbine efficiency was 59% which is much less than the efficiency predicted by Eq. (1). This indicates that the turbine was operating off peak. Specific energy consumption after the retrofit was 2.68 kWh/m^3. The payback time for the retrofit equipment cost was estimated to be less than 18 months. The PX array is shown in Fig. 6.

5.3. Newieba turbocharger retrofit

The Newieba plant near Sharm Al Sheikh, Egypt had five 1,000 m^3/day trains equipped with turbochargers. The turbochargers were operating normally at net transfer efficiencies of between 57 and 58%, which matches the efficiency estimate obtained with the Eq. (1) above. In late summer 2008, three of the five trains had been retrofitted. The turbochargers were removed, three PX-220 devices, a circulation pump and additional membranes were added to each train to approximately double the original permeate production rate. SWRO specific energy consumption dropped from approximately 4.3 kWh/m^3 to below 2.6 kWh/m^3. This energy savings is predicted to pay for the new SWRO equipment in less than 16 months. A photograph of the PX devices is given in Fig. 7.

5.4. Ridgewood Sina turbocharger and Pelton turbine retrofit

The Ridgewood Sina plant in Sharm Al Sheikh had operated one train with a turbocharger and another with a Pelton turbine, both trains with permeate production rates of 1,000 m^3/day. The turbocharger had a history of poor reliability, requiring rebuilding every 3 months. When operating normally, net transfer efficiency was measured as 57%, again consistent with the prediction of the turbocharger efficiency model above. However, the SWRO train consumed 7.7 kWh/m^3 indicating that the high-pressure pump was operating far off peak. The Pelton turbine was reported to have been operating at 67% efficiency, consistent with Eq. (1). The SWRO train equipped with the Pelton turbine consumed 5.7 kWh/m^3, which is also higher than one would predict and an indication of a problem with this pump.

The 2,000 m^3/day combined train used the high-pressure pump from the Pelton turbine train, four PX-220 devices and a new circulation pump. Specific energy consumption reduced to 2.74 kWh/m^3. The payback was less than 12 months. The PX devices were installed in a horizontal configuration shown in Fig. 8.

5.5. Larnaca partial Pelton turbine retrofit

IDE's plant in Larnaca, Cyprus is comprised of six SWRO trains fitted with Pelton turbines. In late 2008, three PX-260 devices and a circulation pump were added to each train in a partial retrofit configuration as shown in Fig. 5. Additional membrane elements were added to raise the total plant SWRO capacity from 54,000 to 64,000 m^3/day. The PX devices are now operating at nearly 97% efficiency. SWRO specific energy consumption reduced by about 6% as a result of the retrofit.

6. New retrofit opportunities

As described above, very large, modern centrifugal ERDs can operate at net transfer efficiencies that

Fig. 7. Three PX arrays at the Newieba plant.

approach 80%. Yet the energy consumption performance of even the most efficient turbine-equipped SWRO plant could be improved by up to 25% by retrofitting with isobaric ERDs. In addition, permeate production capacity can be significantly increased with minimal new construction. Three such plants are considered below.

6.1. Palmachim Pelton turbine retrofit

The Palmachim Desalination plant is one of the largest SWRO plants in Israel with a capacity of 120,000 m^3/day. Built by the Via Maris Desalination Ltd. consortium, the plant consists of six parallel SWRO trains, each with a permeate production capacity of up to 20,000 m^3/day. The plant operators have considered both a partial retrofit and a full retrofit to increase capacity. A partial retrofit would increase permeate production by 50% and reduce specific energy consumption by an estimated 11%. A full retrofit could increase production by 120% or a factor of 2.2 while reducing specific energy consumption by an estimated 18%.

6.2. Fujairah I Pelton turbine retrofit

The Degremont Suez plant in Fujairah, UAE consists of 18 trains with a permeate production capacity of 10,000 m^3/day each. If pairs of trains were combined as illustrated in Fig. 4 above, every other high-pressure pump could be removed and replaced by an array of twenty PX-260 devices. SWRO energy consumption could be reduced by 20% resulting in a payback of just over 2 years.

6.3. Trinidad Pelton turbine retrofit

The Desalcott plant in Trinidad consists of six trains with a combined permeate production capacity of about 22,335 m^3/day. If pairs of trains were combined and retrofit as illustrated in Fig. 4 above, SWRO energy consumption could be reduced by nearly 22%, providing an estimated payback time of less than 2 years.

Fig. 8. PX device installation at the Sina plant.

7. Environmental sustainability

SWRO process retrofits offer the opportunity to increase permeate production with minimal new equipment and construction. High-efficiency isobaric ERDs are available with sufficiently small footprints to be integrated into existing process layouts. For these reasons, retrofitting is an economically and environmentally favorable alternative to constructing new plants.

As discussed, an aspect of ERD retrofit plant designs that is important for managing energy consumption is flexibility. Both the partial and full retrofit designs have equal or greater flow ranges and can efficiently handle greater pressure variations compared to the original centrifugal ERD designs. This flexibility can be used to minimize production during peak power-consumption periods and maximize it during non-peak periods. Process recovery rates can also be adjusted in response to changing feedwater or membrane conditions to keep equipment operating optimally and efficiently.

Energy consumption reductions achieved through ERD retrofits can directly reduce carbon emissions. Each kWh reduction offsets between 1 and 2 kg of CO_2 emissions, depending upon the means used to generate power. In addition to saving power costs, the environmental benefit of reduced emissions may make a retrofit eligible for valuable carbon credits or other regulatory incentives.

8. Conclusions

Most modern SWRO desalination plants save energy by utilizing isobaric energy recovery devices such as the ERI PX Pressure Exchanger device. In addition, the owners and operators of many SWRO processes equipped with centrifugal ERDs such as Pelton turbines or turbochargers have retrofit or are considering retrofitting with isobaric ERDs to increase permeate production and reduce energy consumption. SWRO with isobaric ERDs provide many operating advantages over systems with legacy ERDs, including ease of operation, the flexibility of variable recovery operation and reduced carbon emissions. That these benefits can be achieved with minimal new equipment or construction makes ERD retrofits preferable to new plant construction in many cases.

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