# SWRO FOR MINING APPLICATIONS - EFFICIENCY, FLEXIBILITY AND RELIABILITY

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## ABSTRACT

*Most high-pressure membrane desalination plants being designed and built today for seawater applications save energy by utilizing isobaric energy recovery devices (ERDs) such as the ERI PX Pressure Exchanger® device. Isobaric ERDs seal the high-pressure portion of a reverse osmosis process and make the high-pressure pump flow rate and the membrane recovery rate independent. As a result, the operation and control of a reverse osmosis process equipped with an isobaric ERD differs substantially from one with a centrifugal ERD such as a Pelton wheel. Most importantly, far less energy is consumed by high-pressure membrane desalination process equipped with isobaric ERDs.*

*The authors present an overview of energy recovery devices for RO applications with examples drawn from several seawater applications, including a mining project in South Africa. Process energy consumption and operational flexibility are discussed. Cost benefit analyses are provided for seawater RO systems to identify best available energy recovery technologies for various operating conditions.*

## INTRODUCTION

Membrane desalination is a pressure-driven process. A significant amount of the energy imparted into the feedwater flowing to the reverse osmosis (RO) membranes leaves the membranes in the concentrated reject water. A number of devices have been developed to recover pressure energy from the reject stream of seawater RO processes. Turbine-based, centrifugal energy recovery devices have been employed since the early 1980s. These devices are still in use where inexpensive power is available. However, it is the widespread adoption of positive-displacement “isobaric” energy-recovery devices since 2002, together with improved membrane performance, that has made membrane desalination an affordable and widely-accepted technology deployed around the world (1).

Isobaric energy recovery devices such as the ERI PX Pressure Exchanger® device can reduce the energy consumption of a seawater RO system by as much as 60% compared to a system with no energy recovery device or by as much as 30% compared to a system with a centrifugal energy recovery device (2). Since energy prices are rising and energy consumption can comprise as much as 75% of the total operating costs of a seawater RO plant, it has become almost inconceivable to build a seawater RO process without using isobaric energy recovery technology. In addition to cost savings, isobaric energy recovery devices provide significant operating flexibility by maintaining high energy transfer efficiency performance over a wide range of flow rates and membrane recovery rates. PX technology also provides fail-safe redundancy. Should a device go offline for any reason, the remaining units will still operate offering energy recovery savings.

## CENTRIFUGAL ENERGY RECOVERY DEVICES

The first ERDs were designed to use the hydraulic energy of the SWRO reject to drive a high-pressure pump. Francis turbines were initially applied but were replaced in the 1980s by Pelton turbines which operate at higher efficiency in high-head applications. The design of the latter was derived from a device patented in 1880 by Lester Pelton for gold-mining applications in California (3). Pelton turbines are widely accepted in SWRO because of their familiarity, simplicity and proven reliability. A schematic illustration of a SWRO process with a Pelton turbine is illustrated in Figure 1.

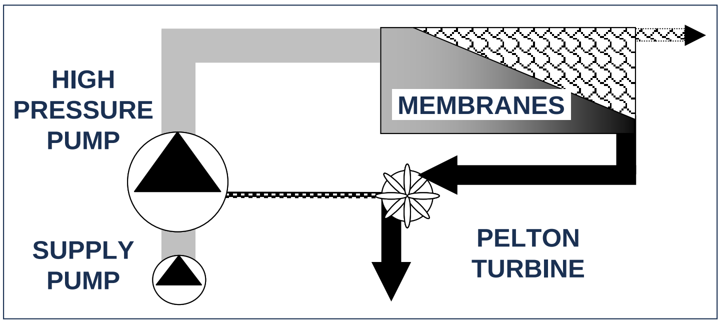


Figure 1 – SWRO Process with Pelton Turbine

The energy transfer efficiency of a Pelton turbine recovery system is the product of the efficiencies of the turbine and the high-pressure pump. Maximum attainable efficiency levels for turbines and centrifugal impellers at their best-efficiency points can be estimated with survey information published by the Hydraulic Institute (4). Peak efficiency, achieved at a specific speed of about 3,000 and a flow rate of greater than 2,300 cubic meters per hour ($m^3$/hr) is about 89%. The maximum possible overall energy transfer efficiency for a Pelton turbine energy recovery system is: $89\% \times 89\% = 79\%$.

Another type of centrifugal ERD is the hydraulic turbocharger which has been used for SWRO energy recovery since the early 1990s. Turbochargers also have a turbine and an impeller on the same shaft but have no motor. The impeller is fed with partially pressurized water such that the turbocharger functions as a booster pump for the membrane feed. The maximum attainable overall transfer efficiency of a hydraulic turbocharger is similar to that of a large Pelton turbine system: about 80%. Turbocharger and Pelton turbine efficiencies decline as the flow rate or pressure of the reject stream strays from optimal, but a brine control valve and/or nozzle controls can be used to adjust performance (2).

## ISOBARIC ENERGY RECOVERY DEVICES

To avoid the efficiency losses associated with the energy-transformation inherent in centrifugal devices, engineers developed positive-displacement isobaric devices for SWRO starting in the 1980s. These devices place the SWRO reject and seawater feed in contact in pressure-equalizing or “isobaric” chambers. There are currently two commercially-available types of isobaric ERDs including several piston-type work exchangers and the ERI PX Pressure Exchanger device. Piston devices have large chambers, pistons separating the concentrate and seawater, valves and control systems to switch flow between the chambers and limit the travel of the pistons (5). The PX device has small chambers, no pistons and no direct controls. Piston-type work exchangers were historically considered to be better-suited to large SWRO trains because of their relatively large unit size. However, the largest SWRO trains operating today – 25,000 m$^3$/day in Hamma Algeria – are supplied with PX devices operating in arrays (6).

The positive-displacement mechanisms employed by all isobaric ERDs provide high hydraulic-transfer efficiency but also allow some mixing of the concentrate and feedwater. The degree of mixing is a characteristic of the particular ERD and a function of the ratio of concentrate and feedwater flow rates to the ERD. Mixing is of particular interest in a PX device because no piston separates the concentrate and seawater. Mixing between the streams is limited by the short duration of the contact – less than 0.05 seconds – and the aspect ratio of the rotor ducts which are long and narrow, assuring plug flow.

A typical process configuration for an SWRO system equipped with isobaric energy recovery devices is illustrated in Figure 2. Concentrate rejected by the membranes flows to the isobaric ERD(s), driven by a booster (circulation) pump. The ERDs replace the concentrate with seawater. This flow merges with the discharge of the high-pressure pump to feed the membranes. Water leaves the system as permeate from the membranes or as spent low-pressure concentrate from the ERDs.

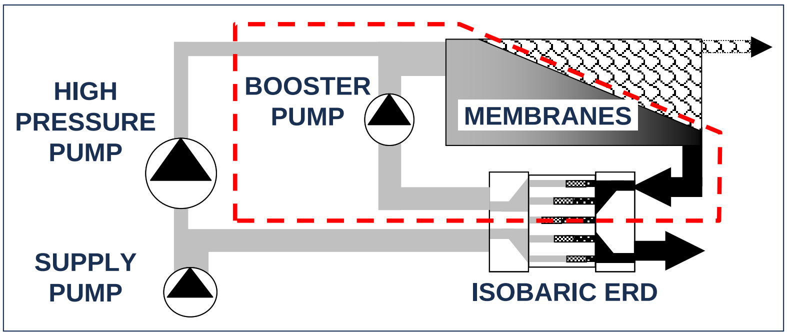


Figure 2 – Schematic of SWRO System with Isobaric ERDs (PX Array)

Isobaric ERDs separate the high- and low-pressure streams and seal the high-pressure portion of the process. To illustrate how this affects SWRO system operation, a dashed-line box is drawn around the high-pressure portion of the process and through the ERD in Figure 2. Nearly all the water that enters the dashed-line box from the high-pressure pump leaves as permeate. A small amount – less than 1% of the reject concentrate – is lost through the ERD. In the case of the PX device, this flow refreshes the hydrodynamic bearing that lubricates the PX rotor. High-pressure pump flow and permeate flow are always nearly equal in isobaric-device-equipped SWRO systems regardless of membrane pressure or booster pump flow rate.

Table 1 presents flow, pressure, salinity and power data for a typical 10,000 cubic meters per day (m$^3$/day) SWRO train equipped with PX ERDs. The data illustrate several points which are generally applicable to SWRO processes equipped with isobaric ERDs.

- The high-pressure pump and permeate flow rates are nearly equal. The high-pressure pump is sized to the permeate flow rate, not the membrane feed flow rate.

- Isobaric ERDs are deployed in arrays and operated in parallel in sufficient number to match the concentrate flow rate.

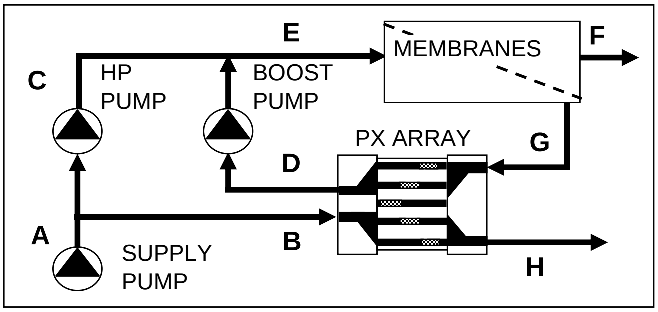
- The high-pressure pump consumes about 97% of the energy required by an SWRO while the booster pump consumes about 3%.

- Isobaric ERDs operate at greater than 95% net transfer efficiency, reducing the energy required by the SWRO process to less than half that required with no energy recovery.

- The high-pressure pump and the ERDs 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 an isobaric ERD (1 bar) allows a 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 © 2007**



| | | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|---|
| **FLOW** | m$^3$/hr | 420 | 506 | 420 | 506 | 926 | 417 | 509 | 509 |
| **PRESSURE** | bar | 3.0 | 1.7 | 66.0 | 64.3 | 66.0 | 0.0 | 65.0 | 1.0 |
| **SALINITY** | mg/l | 40,000 | 40,000 | 40,000 | 42,078 | 41,135 | 200 | 74,628 | 72,564 |

**SYSTEM PARAMETERS**

| | | |
|---|---|---|
| Permeate Flow | m$^3$/day | 10,000 |
| Recovery | % | 45% |

**PRESSURE EXCHANGERS**

| | | |
|---|---|---|
| **PX-260** Units/Array | quantity | 9 |
| Unit Flow | m$^3$/hr | 56.6 |
| Lead Flow | % | 0% |
| Lubrication Flow/Array | m$^3$/hr | 3.3 |
| Differential HP side | bar | 0.7 |
| Differential LP side | bar | 0.7 |
| Salinity Increase @ membranes | | 2.8% |
| PX Overall Efficiency | % | 97.4% |
| ?PX Power Savings | kW | 1,128 |

**HIGH PRESSURE PUMP**

| | | |
|---|---|---|
| Pump Efficiency | % | 84% |
| Motor Efficiency | % | 93% |
| Power | kW | 941 |

**CIRCULATION / BOOSTER PUMP**

| | | |
|---|---|---|
| Pump Efficiency | % | 84% |
| Motor Efficiency | % | 93% |
| VFD Efficiency | % | 97% |
| Power | kW | 31 |

**OVERALL POWER CONSUMPTION**

| | | |
|---|---|---|
| **Total** | **kW** | **972** |
| **Specific Energy** | **kWh/m$^3$** | **2.33** |

## ENERGY RECOVERY PERFORMANCE COMPARISON

A direct comparison of the performance of various ERDs using SWRO field data is essentially impossible because of inherent differences between systems and operating conditions. However, hypothetical systems can be considered for the sake of comparison. The basic equations for computing energy consumption in SWRO systems (2) were applied to the following cases:

1. Small Train: 1,000 m$^3$/day permeate flow, 45% recovery, 69 bar nominal membrane feed pressure
2. Large Conventional Train: 10,000 m$^3$/day permeate flow, 45% recovery, 69 bar nominal membrane feed pressure

3. Large Low-Energy Train: 10,000 $m^3$/day permeate flow, 40% recovery, 50 bar nominal membrane feed pressure (state-of-the-art low energy SWRO membranes)

Pump and ERD performance characteristics for this analysis were based on published operating data and equipment manufacturer's data when available. Otherwise, values were assumed based on information published by the Hydraulic Institute, available in standard engineering reference texts and/or based upon professional engineering judgment. Only the energy consumed by the high-pressure pump and booster pump was considered on the basis that pre- and post-treatment is substantially independent of ERD type. A summary of the analysis is presented in Table 2.

Table 2 – SWRO Specific Energy (kWh/$m^3$)

| ERD TYPE | SMALL SYSTEM | LARGE CONVENTIONAL SYSTEM | LARGE LOW-ENERGY SYSTEM |
|---|---|---|---|
| Pelton Turbine | 4.32 | 2.72 | 2.29 |
| Turbocharger | 4.26 | 2.69 | 2.26 |
| Isobaric ERD | 3.39 | 2.34 | 1.75 |

The data in Table 2 reflect the following differences in SWRO-system and ERD performance:

- The specific energy of systems with Pelton turbines and turbochargers (centrifugal systems) are 15 to 30% higher than that of isobaric systems because the efficiency isobaric ERDs is much higher.

- The specific energy consumption of piston-type work exchanger and PX device systems are essentially identical despite the difference in mixing in these devices.

- Isobaric systems operate with slightly higher membrane feed pressures than centrifugal systems because of mixing in the ERDs in the former, but this difference is overwhelmed by the higher efficiency of the isobaric ERDs.

- Turbocharger-system specific energies are slightly higher than Pelton turbine-system specific energies because the high-pressure pump in the latter operates at higher pressure and therefore lower efficiency.

- Large systems operate at lower specific energy than small systems because of larger, higher-efficiency pumps. SWRO trains built with isobaric ERDs can accommodate very large, high-efficiency pumps in large trains or in pressure-center designs.

- Large low-energy systems have even lower specific energies because of low membrane feed pressure.

The importance of reducing SWRO process energy consumption depends strongly upon the cost and availability of power at the installation. This must be balanced with the capital cost of the device(s), the design and cost of any necessary peripheral equipment and life-cycle cost issues such as operation, reliability, maintenance and equipment longevity.

Ease of Operation **–** Centrifugal ERDs and PX devices are easy to operate, flow-driven and self-adjusting to changes in flow rates. Piston-type work exchangers require actuators, instruments and computer controllers.

Reliability – Centrifugal ERDs and PX devices have a strong track record for reliability in SWRO applications. In the unlikely event of device failure, however, PX devices offer several advantages over centrifugal devices including fail-safe operation and redundancy. In medium and large SWRO trains where several PX devices are arrayed in parallel, one rotor out of service has minimal impact on SWRO membrane performance while a stopped centrifugal ERD typically stops the SWRO operation. If additional capacity is needed, additional PX devices can be added to operate in parallel with existing units.

Maintenance – ERD maintenance must be considered in SWRO system operation because of the direct costs and the associated system downtime. Centrifugal ERDs and piston-type work exchangers require periodic changes to seals and bearings. PX devices require no periodic maintenance and no service of seals or bearings.

Device Life – Factors that adversely affect the longevity of SWRO equipment include corrosion, vibration and abrasion (wear). Centrifugal ERDs are typically made with stainless steel alloys which offer resilience against damage by debris, however, all metal eventually corrodes, wears and fatigues in the harsh conditions of SWRO plants. Piston-type work exchangers suffer from pulsations and fatigue created by the cycling of the chambers. Pressure transfer in the PX device occurs in a ceramic rotor enclosed in ceramic components. This material is more brittle than most metals, but is three times harder than stainless steel and never corrodes in seawater.

## SWRO FOR MINING APPLICATIONS

SWRO with isobaric ERDs is well suited for water supply for mining. For these applications, conventional freshwater sources can be non-existent or unreliable. The temperature and quality of the SWRO feedwater can vary significantly (7). Trains may be designed with capacities of 25.000 $m^3$/day or more to accommodate large, high-efficiency centrifugal pumps (6). SWRO processes with isobaric ERDs meet these challenges with high reliability, low energy consumption, unlimited capacity and operational flexibility.

The reliability of SWRO technology has been proven in hundreds of desalination installations worldwide. Energy consumption can be lower than the energy required to pump water from conventional freshwater sources (8). Essentially infinite capacity can be achieved by arraying membranes and ERDs in parallel. But perhaps the greatest benefit provided by isobaric ERD-equipped SWRO processes is the flexibility provided by variable recovery operation.

Isobaric ERDs provide high constant energy transfer efficiency over a wide range of flows and pressures. As a result, the membrane water recovery rate can be varied without increasing the energy required to produce a unit of permeate. This flexibility allows a process operator to optimize membrane performance as seasonal variations in the seawater occur or as the membrane elements age by adjusting the speed of the booster pump. Numerous best-efficiency operating points can be found which is a tremendous advantage for low-cost SWRO operation.

The significance of variable recovery is illustrated with reference to Figure 2 above. If the flow rate of the booster 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 booster pump is increased to double the flow rate of the high-pressure pump, the system will operate at 33% recovery. As recovery rate is reduced, membrane pressure reduces and the load on the high-pressure-pump motor reduces. As recovery rate is increased, membrane 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 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.

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. Alternately, recovery can be increased when feedwater temperatures are high to minimize permeate salinity. In this way, an operator can manipulate and optimize SWRO 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 (9).

## CONCLUSIONS

Most high-pressure membrane desalination plants being designed and built today save energy by utilizing isobaric energy recovery devices such as the ERI PX Pressure Exchanger device. SWRO systems equipped with isobaric ERDs consume 15 to 30% less energy than comparable systems equipped with centrifugal ERDs such as Pelton turbines when the Pelton turbine is operating at its best efficiency point. In addition, SWRO with isobaric ERDs provide many operating advantages over other system designs, including ease of operation and the flexibility of variable recovery operation.

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