

# Energy Recovery Devices for Seawater Reverse Osmosis

The author discusses in detail the evolution of energy recovery devices and how they benefit seawater reverse osmosis operations and economics.

By Richard L. Stover



Figure 1. Yu Huan, China 36,000 m<sup>3</sup>/day desalination plant

**B**efore the conception of seawater reverse osmosis (SWRO) in the 1950's, reducing energy consumption during desalination processes has been a primary driver of innovation and engineering development. The first large municipal SWRO, which began operating in Jeddah, Saudi Arabia in 1980, consumed about 8 kilowatt-hours per cubic meter (kWh/m<sup>3</sup>) of the water produced. This was less than half the energy required by state-of-the-art distillation processes. Yet, most of the hydraulic energy put into a SWRO process was wasted in the form of a pressurised brine waste stream discharged from the membranes. Since then, many energy recovery devices (ERDs) have been designed to prevent the wastage of energy in a SWRO process. Their effectiveness and reliability were widely considered to have made large-scale SWRO economically viable through recent advances in the energy recovery technology. Energy requirement

for SWRO are now as low as 1.6 kWh/m<sup>3</sup>, making the process energy-competitive with many traditional fresh water supply sources.

## The evolution of SWRO ERDS

### Pelton turbine

Turbines were the first energy recovery devices deployed in municipal-scale SWRO plants. Initially, francis turbines were applied, but they were replaced in the 1980s by pelton turbines that operated at higher efficiency in high-head applications like SWRO. The design of the latter stems from a device patented in 1883 by Lester Pelton for gold-mining operations in California. Pelton turbines are widely accepted in SWRO because of their familiarity and proven reliability. Manufacturers of pelton turbines for SWRO include Calder AG, Sulzer Pumps, Ltd. and Grundfos A/S.

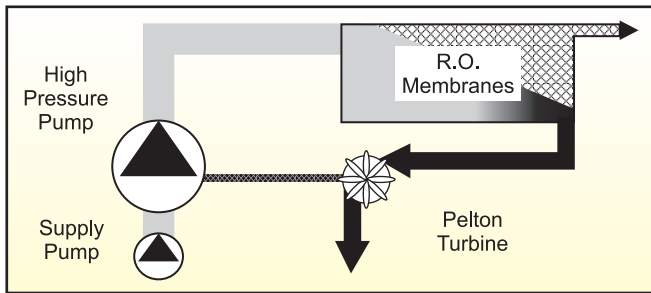


Figure 2. SWRO process with pelton turbine

A pelton device is a tangential flow impulse turbine. Pressurised water ejected through one or more nozzles is directed against a series of spoon-shaped buckets mounted around the edge of a wheel. Each bucket reverses the flow of water, leaving it with diminished energy and the resulting impulse spins the turbine. The buckets are mounted in pairs to keep the forces on the wheel balanced as well as to ensure smooth, efficient momentum transfer of the fluid jet to the wheel. The wheel is mounted on the high-pressure pump shaft, which together with a motor drive the pump that pressurises the SWRO system. A typical SWRO process with a pelton turbine is illustrated in Figure 2.

The energy transfer efficiency of a pelton turbine 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 shall be considered first. As described by the Hydraulic Institute, the operating efficiency of centrifugal pumps is influenced by many factors. The main factors are:

- Pump specific speed, NS. Designs with values of NS between 2,000 and 4,000 are the most efficient. Specific speed for any pump can be calculated with the following equation:

$$NS = N \times Q^{0.5} / H^{0.75}$$

Where, 'n' is rotating speed in revolutions per minute (rpm), 'Q' is rate of flow at best efficiency in gallons per minute (gpm), and 'H' is the total head in feet of liquid.

- Pump size. Larger the size of the pump more is the efficiency.
- Surface finish of impellers and volutes. Smoother finishing results in higher efficiency.
- Internal clearances such as at wearing rings. Closer the rings, the better it is.
- The actual rate of flow compared to the best efficiency rate of flow.

Maximum attainable efficiency levels for centrifugal impellers at their best efficiency points can be estimated through the above equation and survey information published by the Hydraulic Institute. Peak efficiency, achieved at a specific speed of about 3,000 and a flow rate greater than 2,300 cubic meters per hour (m<sup>3</sup>/hr) or 10,000 gpm, is 89%. Assuming the impeller would

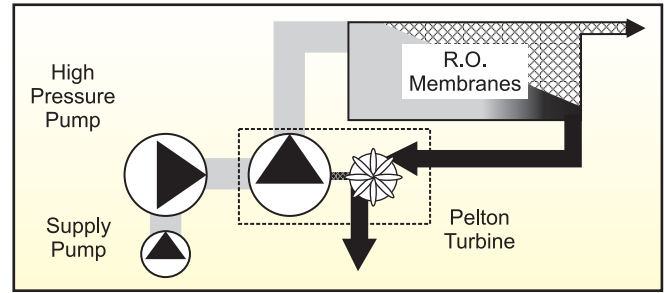


Figure 3. SWRO process with turbocharger

deliver a total head of 67 bar or 2,200 feet of head, the rotation speed would be over 9,700 rpm according to the equation. This is an exceedingly high rotation speed for a large device and inconsistent with large alternating current motors which typically operate at less than 3,600 rpm.

Therefore, we draw the conservative conclusion that 89% is the maximum attainable efficiency for an SWRO centrifugal pump impeller. Impulse turbine efficiencies run slightly higher than impeller efficiencies, but are influenced by the factors listed above. Using a similar estimation approach, the theoretical maximum attainable efficiency for a large, high-head, high-rpm hydraulic turbine is about 90%. Assuming 1% loss in the nozzle, the maximum possible overall energy transfer efficiency for a pelton turbine energy recovery system is the product of these peak efficiencies: 89% x 90% x 99% = 79%.

### 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 they don't have a motor. Current manufacturers of turbochargers include Pump Engineering Inc. and Fluid Equipment Development Company.

One or more nozzles direct the SWRO reject stream onto a tangential-flow pump turbine directly connected to a centrifugal impeller spinning in the SWRO feed stream. The feed stream, partially pressurised by a high-pressure pump, is boosted by the turbocharger impeller to the SWRO feed pressure. The turbocharger and the high-pressure pump are not directly connected, providing a degree of flexibility in the operation of these devices. Also, turbochargers have a relatively small footprint and are easy to install. A typical SWRO process with a hydraulic turbocharger is illustrated in Figure 3.

The turbocharger's impeller and turbine are close-coupled mixed-type of centrifugal elements incorporating both axial and radial-flow features. The impeller of the high-pressure pump, that operates in series with the turbocharger, can be of any type and

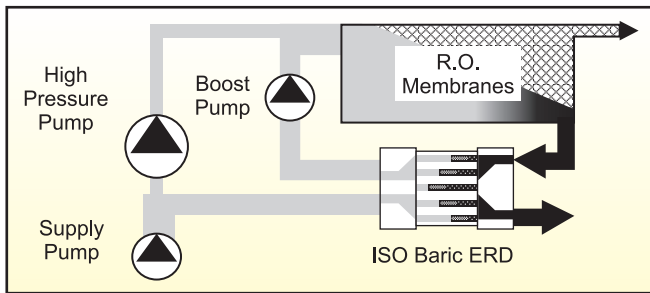


Figure 4. SWRO process with isobaric ERD

are considered to be the same as the turbocharger impeller. The maximum efficiency of each of these elements, based on the analysis presented above, is 89% or 90%. This is slightly higher than the impeller in a pelton-turbine recovery system because the high-pressure pump in the latter operates with a higher head and therefore a slightly lower efficiency. The maximum attainable overall transfer efficiency of a large, high-rpm hydraulic turbocharger is the product of the weighted-average efficiency of the impellers, the efficiency of the nozzle(s) and the efficiency of the turbine:  $90\% \times 90\% \times 99\% = 80\%$ . Turbocharger efficiency declines in accordance with the factors listed above for centrifugal impellers or as the flow rate or pressure of the reject stream strays from optimal. A brine control valve and/or nozzle controls can however be used to adjust performance.

### Piston pressure exchanger

To avoid the efficiency losses associated with the energy-conversion steps inherent in centrifugal devices, engineers have developed positive-displacement (PD) piston isobaric devices for SWRO in the 1980s. These devices place the SWRO reject and fresh feed in contact with an intervening piston in pressure-equalising or isobaric chambers. Early versions include the Diprex by Aqua Design and a direct-piston design by Union Pump. Current manufacturers of piston isobaric devices include Calder AG, RO Kinetics and KSB.

Pressurised feedwater from the ERD combines with the discharge of the high-pressure pump to feed the membranes. The high-pressure pump operates at the full membrane pressure but supplies only the flow rate of the permeate. A booster pump in series with the ERD is necessary to circulate high-pressure water through the membranes. A typical SWRO process with an isobaric ERD is illustrated in Figure 4.

Piston isobaric devices completely decouple the ERD and the high-pressure pump. The advantage of this feature has been taken with the advent of the pressure-centre SWRO designs. In these systems, the high-pressure pump or pumps feed a manifold, which in turn feeds multiple SWRO trains. For example, two high-pressure pumps could feed four or more SWRO trains. The

design accommodates larger and more efficient high-pressure pumps. Alternately, an unlimited number of isobaric ERDs can be operated in parallel in a large SWRO-train sized to run with the largest, most efficient high-pressure pump available.

The piston isobaric devices require dynamic control to operate their valves and to limit piston movement. Each ERD must be operated individually and in conjunction with the other devices in the array to minimise overflush/bypass and to prevent excessive pulsations and water hammer. Despite the piston, the long contact time (20 to 60 seconds) between the brine and seawater in the isobaric chambers results in some intermixing, resulting and an increase in the membrane feed salinity of up to 1.5%. However, piston isobaric devices operate at an efficiency that is limited only by the energy loss in moving the pistons and valves and can exceed 95%. Their efficiency is relatively constant despite flow and pressure variations and is independent of device capacity. Multiple isobaric devices operate in parallel in arrays with no loss of efficiency.

### Rotary isobaric device

The high efficiency of an isobaric PD device and the operational simplicity of centrifugal ERDs are combined in the rotary isobaric device, first applied to the SWRO systems in 1997. Energy Recovery Inc is the sole manufacturer of rotary isobaric devices; with the trade name PX Pressure Exchanger. In an SWRO system equipped with a rotary isobaric device, the membrane reject is directed to the membrane feed. The process flow scheme is the same as illustrated in Figure 4. A rotor, moving between the high-pressure reject stream and a low-pressure seawater supply stream, removes the brine and replaces it with the seawater. Pressure transfers directly from the high-pressure reject stream to a feed stream with no intervening piston in the flow path. This results in a slightly higher degree of mixing between the streams than in a piston isobaric device (1 to 2.5%), eliminating the friction and wear that occurs on the pistons. Mixing is minimised with long, small diameter chambers and short brine-seawater contact time (0.05 seconds).

The rotor spins freely, driven by the flow at a rotation rate proportional to the flow rate with no shaft or shaft seal. No controls are needed to operate the pressure transfer mechanism. The rotor and associated components are made with a ceramic material that is immune to corrosion and highly resistant to wear. Rotary isobaric devices can be used in pressure-centre designs, and unlimited capacity is achieved by arraying multiple devices in parallel. Total energy transfer efficiencies of up to 98% are possible, and efficiency is relatively constant regardless of flow and pressure variations.

### Energy recovery performance comparison

A direct comparison of the performance of various ERDs based on field data is virtually impossible because of the inherent differences between SWRO systems and operating conditions. However, the following hypothetical systems can be considered for comparison:

- Small train: 1,000 m<sup>3</sup>/day permeate flow, 45% recovery and 69 bar nominal membrane feed pressure
- Large conventional train: 15,000 m<sup>3</sup>/day permeate flow, 45% recovery and 69 bar nominal membrane feed pressure
- Large low-energy train: 15,000 m<sup>3</sup>/day permeate flow, 40% recovery and 50 bar nominal membrane feed pressure (state-of-the-art low energy SWRO membranes)

The standard hydraulic calculations were performed to derive SWRO specific energy for each of these cases. Pump and ERD performance characteristics for this analysis were made based on published operating data and equipment manufacturer's data. The values were assumed based on the information published by the Hydraulic Institute, available in standard engineering reference texts and/or derived with professional engineering judgment. A summary of the analysis is presented in Table 1.

The data in Figure 6 reflects the following differences in SWRO-system and ERD performance:

- The specific energy of systems with pelton turbines and turbochargers (centrifugal systems) is higher than in isobaric systems because the efficiency of isobaric ERDs is much higher.



Figure 5. Perth, Australia 144,000 m<sup>3</sup>/day desalination plant (train #1)

ERD Type	Small System	Large Conventional System	Large Low-Energy System
Pelton Turbine	4.35	3.19	2.44
Turbocharger	4.29	3.19	2.42
piston Isobaric	-	2.79	1.93
Rotary Isobaric	3.45	2.78	1.92

Figure 6. SWRO specific energy (kWh/m<sup>3</sup>)

- Large systems operate at lower specific energy than small systems because of larger, higher-efficiency pumps. However, using a positive displacement high-pressure pump in a small system can reduce its specific energy to levels comparable with very large systems.
- Low-energy systems have low specific energies because of the low membrane-feed pressure.
- Larger low-energy systems with isobaric ERDs can utilise pressure centre designs with larger, higher-efficiency pumps to achieve a lower specific energy than centrifugal systems.
- Centrifugal systems have larger, higher-efficiency, high-pressure pumps than the isobaric systems, but the higher efficiency of isobaric ERDs results in lower specific energy with the latter.
- Isobaric systems operate with higher membrane feed pressures than centrifugal systems because of the mixing in the ERDs in the former. The difference is overwhelmed by the higher efficiency of the isobaric ERDs.
- Rotary and isobaric systems operate at approximately the same specific energy. Mixing and efficiency are higher in the former and tend to cancel out.
- No specific energy is reported for piston isobaric devices for the small SWRO train because there are no commercially available devices for such applications.
- Turbocharger systems consume slightly less energy than Pelton-turbine systems because the high-pressure pump in the latter operates at higher pressure and therefore lower efficiency.

### ERD selection

SWRO energy performance is clearly a primary factor in ERD selection, the degree to which 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 peripherals and detailed consideration of life-cycle cost issues such as maintenance downtime and operational flexibility.

### Recovery and flux variation

Recovery and flux variation can occur naturally as the temperature and salinity of the seawater changes and aging of the SWRO system components begins. Centrifugal ERDs are generally robust

enough to withstand flow and pressure variations. Their design, however, is optimised for a particular operating window. The degree to which centrifugal ERD performance varies as a function of recovery and membrane flux changes depending upon the characteristics of a particular device and must be considered in the SWRO design process. As positive displacement devices, isobaric ERDs deliver more constant performance with little efficiency variation over their operating range, but the flow variation may be limited by device capacity. In addition, with an isobaric ERD, recovery can be altered without directly changing high-pressure pump operation. This is a distinct advantage of operating an SWRO system with these devices.

### Ease of operation

Of the devices considered here, it's the piston isobaric device, which requires direct operational control. Centrifugal ERDs and the rotary isobaric device are flow-driven and self-adjusting. An advantage offered by the rotary isobaric device over centrifugal devices is fail-safe operation and redundancy. In medium and large SWRO trains where several rotary devices are arrayed in parallel, the loss of one rotor due to debris or damage has minimal impact on the SWRO membrane performance. As there are no intervening pistons, flow passes through the device and a plant can typically continue running until scheduled maintenance solves the problem. Failure of any other type of ERD typically necessitates shutdown of the SWRO train.

### Maintenance

ERD maintenance must be considered in SWRO system operation because of the direct costs and the associated system downtime. Centrifugal ERDs and the rotary isobaric device require no periodic maintenance. Piston isobaric ERDs require periodic maintenance of the piston and the all the valves and subsystems necessary for device operation.

### Civil works

With the exception of the relatively large and heavy piston isobaric device, the ERDs considered here have small footprints, lighter weights and produce minimal lateral loads. Pelton turbines are mounted on the high-pressure pump shaft, and must be accounted for when laying out the pump skid.

### Device life

Factors that adversely affect the longevity of SWRO equipment include corrosion, vibration and abrasion (wear). ERD's are typically made with high-quality stainless steel alloys which offer resilience against damage by debris. Pulsations produced by piston isobaric ERDs have been known to damage SWRO equipment. Pressure transfer in the rotary isobaric device occurs in a ceramic

rotor enclosed in ceramic components. This material is more brittle than most metals, but three times harder than steel and immune to corrosion. Moreover, vibrations and pulsations are negligible.

### Conclusion

Energy recovery devices have become essential to SWRO operations, primarily because they significantly reduce energy consumption in these systems. Quantifying device performance involves employing relatively straight-forward hydraulic calculations. ERD selection, like all other aspects of engineering design, involves some degree of compromise. Isobaric ERDs deliver higher efficiency than centrifugal devices, but centrifugal devices are generally better characterised and are easier to maintain and operate. Rotary isobaric devices provide a unique combination of isobaric and centrifugal features with high energy transfer efficiency, no maintenance, and easy operation

#### About the Author

Mr. Richard Stover, PhD, Chief Technical Officer with Energy Recovery Inc (ERI) has 20 years of experience in research, development and manufacturing engineering. His technical expertise includes fluid mechanics, hydraulic systems and process design. He was a co-recipient of the European Desalination Society's Sidney Loeb award for his work on the PX™.

### About Energy Recovery, Inc.

Energy Recovery, Inc. (ERI) is the leader in manufacturing highest efficiency, energy recovery products and technology. Their PX Pressure Exchanger® (PX®) is driving the rapid growth in the seawater reverse osmosis (SWRO) industry, and making desalination affordable worldwide. The PX is based on a rotary positive displacement pump that recovers energy from the high-pressure waste stream of SWRO desalination systems at up to 98% efficiency—with no downtime or scheduled maintenance. Since its introduction in 1997, the PX technology has emerged as the industry standard solution for seawater desalination. To date, ERI has sold over 2,500 devices worldwide, producing over 1.8 million m<sup>3</sup>/day of capacity, and saving customers 230 MW of energy, or \$162 million a year in operating costs. The world's largest energy recovery device manufacturer\* delivers:

- Proven SWRO Power Consumption as Low as 1.6 kWh/m<sup>3</sup>
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\*2006 ERI Desalination Industry Survey

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