PX Q400: Highly Efficient Energy Recovery Device

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SECTION 1: INTRODUCTION

Energy Recovery is the market leader for energy-saving technology in the seawater reverse osmosis (SWRO) desalination industry. The company's flagship technology is the PX® Pressure Exchanger®, an isobaric energy recovery device (ERD) that reduces energy consumption by up to 60% in desalination applications. Energy Recovery's products and services are accepted by the industry as trusted, reliable, high-performing, energy-saving solutions, as evidenced by the following:

- Over 35,000 PX ERDs have been installed in SWRO desalination facilities worldwide, producing an estimated total of 36 million cubic meters of freshwater per day,
- Over $6 billion in energy cost is saved by plant owners annually, and
- Total CO_2 emissions from desalination plants are reduced by over 19 million tons every year.

In the last decade, the PX Q300 served as the gold standard of ERDs in SWRO desalination plants. Thanks to its innovative yet simple design combined with high-quality and precision manufacturing, the PX Q300 demonstrates consistent performance, making it extremely reliable and durable, requiring low maintenance and thereby providing maximum uptime. With these exceptional benefits and a life expectancy of up to 30 years, the PX Q300 provides a low cost of ownership for the end user and plant owner.

Building on its success, Energy Recovery launched its new flagship product, the PX Q400, in late 2022. The PX Q400 offers 33% higher unit capacity and improved performance over the PX Q300, providing even more savings to Energy Recovery's customers.

This paper describes how ERDs are applied in SWRO processes. The key metrics used to quantify and evaluate the performance of energy recovery devices in desalination applications are documented. Using these metrics, the performance of the PX Q300 and Q400 are compared, demonstrating the economic benefits for the industry.

SECTION 2: OVERVIEW

2.1 Seawater Reverse Osmosis Process

In seawater reverse osmosis desalination, seawater is pressurized and applied to a semi-permeable membrane. The membrane acts as a salt filter, with freshwater or permeate passing through, while concentrated saltwater or brine is rejected by the membrane. Typically, only 40 to 50% of the freshwater content of the seawater is extracted. The resulting brine reject produced exits the membranes at high pressure.

The PX ERD captures waste energy in the brine reject and recycles it in the reverse osmosis process at up to 98% efficiency. It does this by transferring the hydraulic energy of the reject stream to the low-pressure feedwater stream by putting them in direct, momentary contact in the ducts of a rotor spinning inside the PX device. The rotor is fitted into a ceramic sleeve enclosed between two ceramic end covers with precise clearances, which, when filled with high-pressure water, create an almost frictionless hydrodynamic bearing. The rotor is the only moving part within the device – no motors, valves, or instruments that would require maintenance.

Figure 1 illustrates a typical flow schematic for a SWRO system equipped with a PX device. The brine reject stream from the RO membranes passes through the PX device or an array of PX devices operating in parallel. The pressure of the concentrate stream is transferred directly to feedwater at an efficiency of up to 98%. The pressurized feedwater stream passes through a circulation pump and merges with flow from the high-pressure pump to feed the membranes. By reducing the duty of the high-pressure pump by up to 60% compared to operation without energy recovery, PX technology dramatically reduces the energy required to desalinate. It also allows the high-pressure pump to be operated and controlled separately from the PX device(s), providing desalination plant operators with flexibility to cope with changing conditions and optimize plant performance.
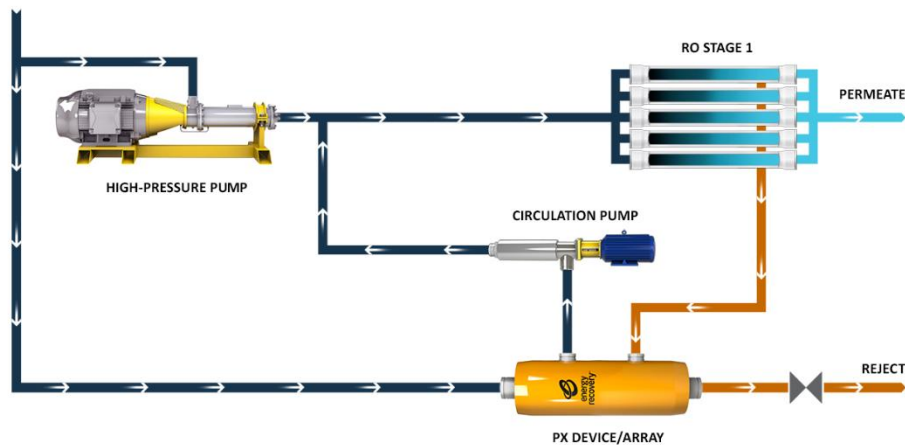
Figure 1: SWRO with PX ERD Process Flow Diagram

2.2 PX Performance

2.2A Efficiency

ERD efficiency is the measure of how well the ERD recovers the available – or otherwise wasted – energy in a RO system. Therefore, if the ERD efficiency is rated at 50%, this means that it is only able to recycle 50% of the available energy while the remaining 50% is lost.

ERD efficiency is calculated with the following equation:

$$Efficiency \quad = \quad \frac{\sum (Pressure \times Flow)_{OUT}}{\sum (Pressure \times Flow)_{IN}} \times \ 100 \ \% \tag{1}$$

The PX is known for its high efficiency, which exceeds 95%. The relatively small efficiency losses in the PX are attributed to: 1) flow reduction due to water compression, 2) pressure reduction due to viscous friction to flow, and 3) the volume loss due to lubrication of the hydrodynamic bearing. These changes reduce the terms in the numerator and increase the terms in the denominator of Equation 1.

The high efficiency of the PX is due to the energy transfer through direct contact of the two streams: low-pressure feedwater and high-pressure concentrate reject. Its efficiency is nearly constant over its flow and pressure

operating range. Other ERDs, such as turbochargers and Pelton Turbines, have efficiencies that vary with flow and pressure, peaking at around 80%. In these devices, hydraulic pressure energy is converted into the mechanical energy of a rotating shaft and then transferred back into hydraulic energy, losing 10 – 30% in each conversion.

2.2B Mixing

When the brine and seawater streams contact each other inside an ERD, slight mixing occurs. In a PX device, contact between the fluids is direct, with no intervening barrier or piston. As a result, the high-pressure seawater stream produced by the device has a slightly increased salinity compared to the seawater source.

The volume of brine that mixes into the seawater, called volumetric mixing, is a performance characteristic of the ERDs. It is defined with the following equation, where TDS is total dissolved solids, a measure of salinity, and HP and LP refer to high-pressure and low-pressure streams into and out of the ERD:

$$Volumetric\ Mixing\ = \frac{(HPin_{TDS} - HPout_{TDS})}{(HPin_{TDS} - LPin_{TDS})} \times 100 \tag{2}$$

Mixing in the ERD is diluted when the pressurized seawater stream from the device(s) merges with the discharge of the high-pressure pump. The percent salinity increase in the membrane feed stream is defined as follows:

$$Salinity\ Increase\ = \frac{(membrane\ feed\ salinity - system\ feedwater\ salinity)}{system\ feedwater\ salinity} \times 100 \tag{3}$$

SECTION 3: TEST METHODS

To evaluate the efficiency of an ERD, the device does not need to be installed and operated in an RO system. The flow paths in and out of the ERD in an RO system can be replicated without membranes using pumps configured, as illustrated in Figure 2.
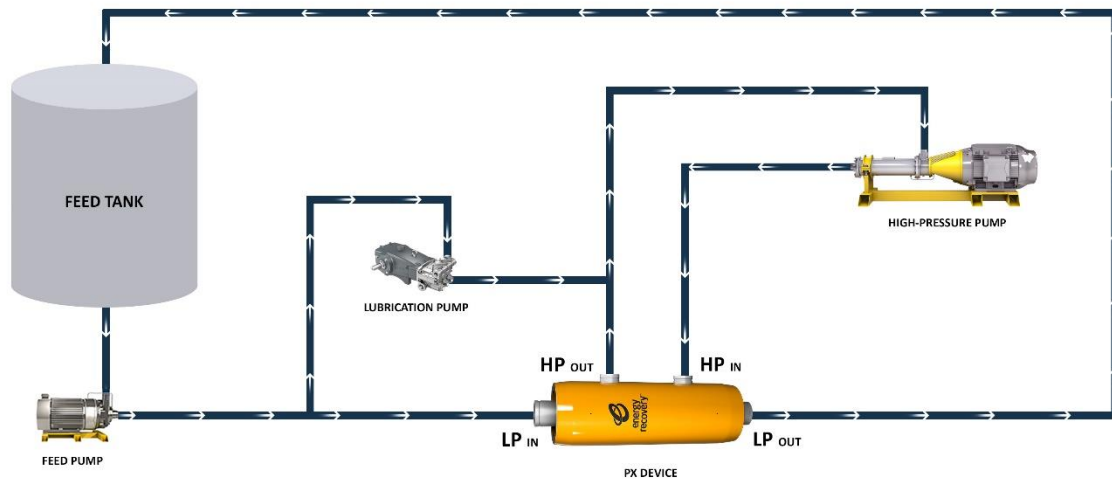
Figure 2: ERD Efficiency Test Setup Process Flow Diagram

Three pumps are required for the test setup:

1. The feed pump delivers water to the low-pressure inlet in the same way as it would in a typical RO process.
2. The high-pressure circulation pump moves water through the high-pressure regions of the ERD in a loop back to its own suction. In an RO system, the membranes would be located downstream of the circulation pump.
3. The lubrication pump maintains pressure in the high-pressure loop by replacing lubricating fluid that has passed through the ERD to the low-pressure side.

In addition, an optional return pump can be used to return water from the low-pressure outlet to the feed tank. Pressure sensors and flow meters in the four inlet and outlet streams and a flow meter in the lubrication pump inlet provide sufficient data for calculating ERD efficiency using Equation 1 above. Field tests have shown an excellent correlation between efficiency measured in the RO systems in the field and efficiency measured in the test setup.

To evaluate mixing performance, the test setup is modified so that there is a salinity difference between LPin and HPin. The main changes in the setup, shown in Figure 3, are: 1) the addition of a brine tank that feeds the high-pressure loop through the lubrication pump and 2) the diversion of the LPout stream to drain rather than recirculating it back into the feed tank.
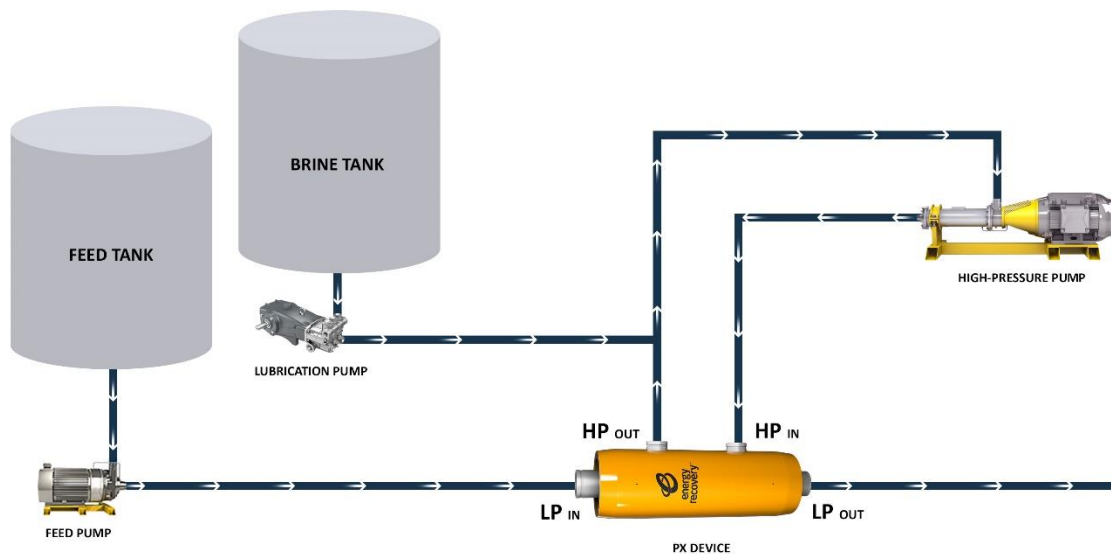
Figure 3: PX Mixing Test Setup Process Flow Diagram

The salinities at all four ports of the PX are measured and inputted into Equation 2 to compute the percent volumetric mixing value. Field tests have shown an excellent correlation between mixing measured in the RO systems in the field and mixing measured in the test setup.

SECTION 4: PX PERFORMANCE TEST RESULTS

PX Q300 and Q400 devices are tested in-house using the methods described in Section 3 above. Efficiency and mixing results are presented and discussed below.

4.1 Efficiency

Figure 4 shows the average efficiency of a PX Q400 and a PX Q300 as a function of flow rate over their normal operating range. The turbo efficiency curve was also added as a comparison to the PX to demonstrate the relative stability and high level of the PX efficiency. Efficiency is determined with flows and pressures measured as described above and calculated with Equation 1.
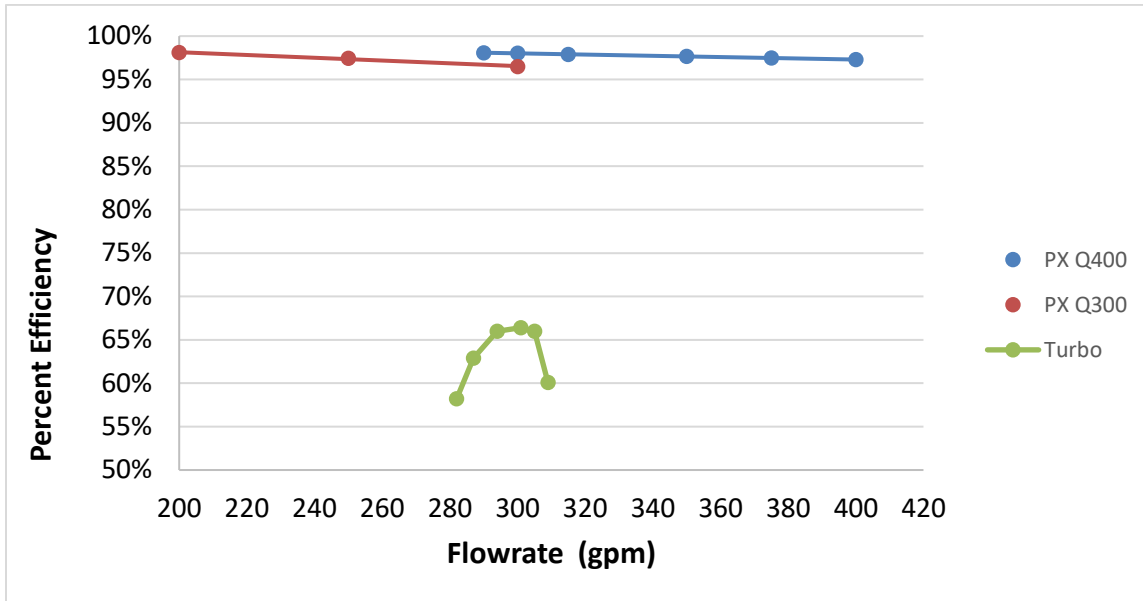
Figure 4: PX Efficiency

Although both PXs reach a maximum efficiency of 98.1% at their minimum flow, the PX Q400 demonstrates a flatter efficiency curve than that of PX Q300. As a result, the PX Q400 has a maximum efficiency of 97.3%, which is <u>0.8% greater</u> than the PX Q300's maximum efficiency of 96.5% at their respective maximum flow rates. Given that desalination plants typically operate their PXs near the maximum rated flow rates to maximize their utilization to reduce upfront investment, this higher efficiency reduces the energy consumption of a system equipped with PX Q400s.

4.2 Volumetric Mixing

Figure 5 shows the average volumetric mixing in a PX Q400 and a PX Q300 as a function of the ratio of high-pressure and low-pressure flow rates through the device. Volumetric mixing is determined from measured salinities as described above and calculated with Equation 2.
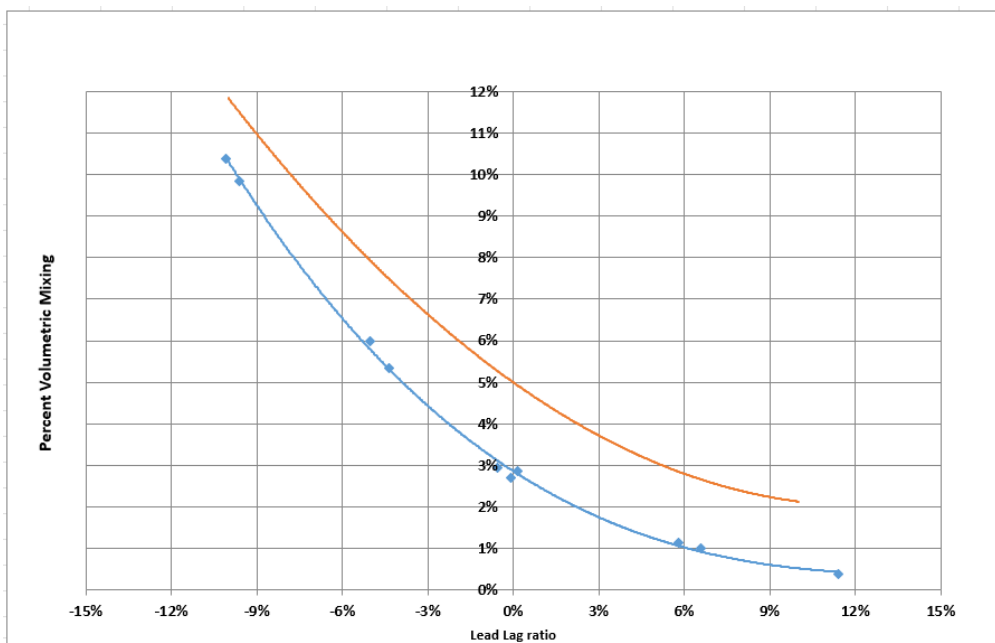
Figure 5: PX Volumetric Mixing

When the low-pressure flow rate exceeds the high-pressure flow rate, a condition called lead flow, the excess low-salinity seawater pushes the brine-seawater interface toward the low-pressure brine outlet, reducing the salinity measured at the high-pressure seawater outlet. Conversely, when the high-pressure flow rate exceeds the low-pressure flow rate, a condition called lag flow, the brine-seawater interface is pushed toward the high-pressure outlet, increasing the salinity measured at the high-pressure outlet. The flow ratio affects both the PX Q300 and Q400 in similar manners, as demonstrated by the nearly parallel shape of the curves in Figure 5.

Figure 5 shows that volumetric mixing in the PX Q400 is less than 3% at balanced flow, while for the PX Q300, the volumetric mixing is about 5%, a reduction of close to 2%. The lower volumetric mixing results in reduced membrane feed salinity, which reduces membrane feed pressure and energy consumption by the high-pressure pump. These energy and economic benefits are quantified later in this paper.

Average test results for efficiency and volumetric mixing are incorporated into product data sheets and performance calculation models including Energy Recovery's product selection and performance projection software called Power Model Pro.

SECTION 5: ECONOMIC BENEFITS FROM PX IMPROVEMENTS

In this section, we compare the performance of the PX Q300 and the PX Q400 in a typical 250 million liter per day (MLD, 95 million gallon per day (MGD)) large SWRO plant. Desalination performance was approximated using membrane projection models, specifically the LG Water Solution software platform Q+. These models estimate the membrane pressure and permeate quality at specified flow, pressure, and salinity operating points. These

membrane performance estimates are then inputted into Energy Recovery's PMP model to estimate PX performance and plant energy consumption. Energy consumption is quantified as specific energy consumption (SEC), which is the sum of the energy consumed by the high-pressure pumps divided by the permeate flow rate. SEC is widely used in the desalination industry as a measure of plant performance and is useful for comparing different membrane, pump and ERD options.

Figure 6 presents PMP model inputs for the PX Q300 and PX Q400 under the following assumptions:

- 25,000 cubic meters per day (CMD) per train capacity, 10 trains, total plant capacity of 250 MLD
- 42% recovery
- 42,000 milligrams per liter (mg/l) TDS feed water at 28°C
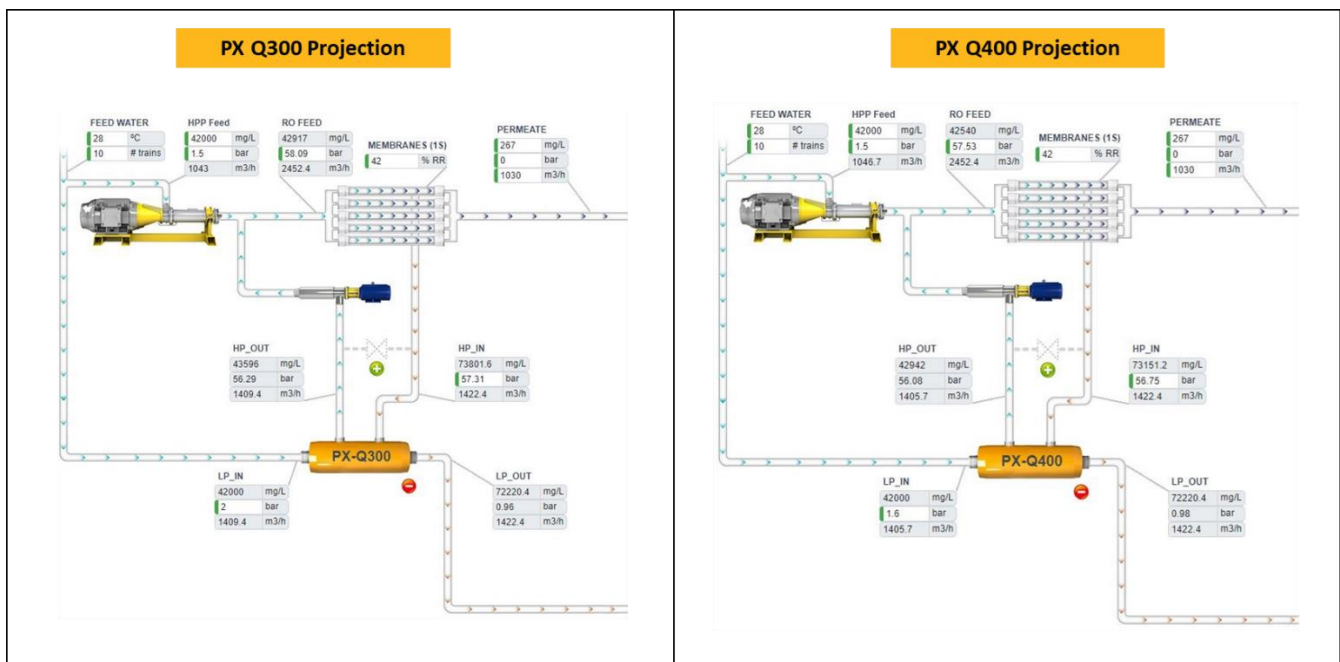- 21 PX Q300s per train or 16 PX Q400s per train

Figure 6: PX Projection Comparison with PX Q300 and PX Q400

The table below summarizes the outputs from the PMP projections.

	PX Q300	PX Q400
PX Unitary Flow	67.73 m³/h	88.9 m³/h
Salinity Increase at Membrane	2.18%	1.29%
Volumetric Mixing, VM	5.02%	3.02%
Lubrication Flow (LF) per PX Array	12.99 m³/h	16.66
LF as % of Concentrate Flow	0.91%	1.17%
HP DP	1.02 bar	0.67 bar
LP DP	1.04 bar	0.62 bar
RO Specific Energy Consumption*	2.11 kWh/m³	2.08 kWh/m³
Brine Recovery Efficiency	97.32%	97.66%
Overall PX Efficiency	95.69%	96.70%

5.1 Mixing

The lower volumetric mixing of the PX Q400s results in a lower membrane feed salinity of 42,540 mg/l vs. 40,917 mg/l for the system equipped with PX Q300s. With lower feed salinity, the PX Q400 design requires a lower membrane feed pressure of 57.53 bar vs. 58.09 bar with the PX Q300. This will favorably affect the energy consumption of the system.

5.2 Efficiency

In those train configurations, PX Q300 and PX Q400 are both operating at more than 95% of their capacity. The PX Q400 projects a device efficiency of 96.70%, while the PX Q300 is 95.69%, an improvement of 1%.

5.3 SEC Comparison

The projected SEC for the PX Q300 and Q400 designs are, respectively, 2.11 kWh/m³ and 2.08 kWh/m³. Therefore, the PX Q400 configuration offers a SEC reduction of 1.4% compared to the system equipped with PX Q300s. Note that the same SWRO system equipped with a turbocharger ERD would have an SEC of about 2.72 kWh/m³, about 30% higher than the system equipped with either PX model.

5.4 Additional Benefits

The projected SEC shown in the Power Model Pro reports is only for the high-pressure portion of the SWRO system, which does not include the low-pressure feed pump that transfers the feed to the high-pressure pump and to the PX device(s). Because the PX Q400 has a lower pressure drop through the low-pressure channels of the device (0.62 bar vs. 1.04 bar for the PX Q300), the SWRO system can be fed at a lower pressure of 1.6 bar vs. 2 bar. The 0.4 bar reduction in feed supply pressure required by the PX Q400 represents a savings of about 21 kW per train and an additional SEC reduction of 0.02 kWh/m³. The combined SEC, when including the feed supply pump, is 2.27 kWh/m³ for the PX Q300 configuration and 2.22 kWh/m³ for the PX Q400 configuration. As a result, the SEC reduction is 2.2% with the PX Q400 when including the feed supply pump energy consumption.

5.5 Economic benefits over the lifetime of the plant, 25 years

The data in the following table shows the economic benefit of the reduced energy consumption achievable with the PX Q400.

	PX Q300	PX Q400
SEC for 250 MLD (kWh/m^3)	2.27	2.22
Additional $$ Saving over 25 yrs (@$0.1/kW)	-	$11,406,250

A reduction of 0.05 kWh/m^3 SEC with the PX Q400 can provide an energy savings of 4.6M kWh per year for a 250 MLD plant. At a power cost of $0.1 per kWh, this translates to a savings of $11,406,250 over 25 years.

SECTION 6: CONCLUSION

This paper explains and quantifies how the PX Q400 saves energy and operating costs in a typical desalination system compared to the high-performing industry-standard PX Q300. With improved efficiency and mixing, the PX Q400 lowers the SEC of a typical SWRO system by over 0.05 kW/m^3 or 2% compared to the same system equipped with PX Q300s and 0.60 kWh/m^3 or over 30% compared to a turbocharger. In addition, the PX Q400 has a higher unit capacity, so fewer PX devices are required for a given SWRO train capacity. This not only reduces capital cost but also decreases plant footprint.

Please visit Energy Recovery's website: www.energyrecovery.com for a full listing of Energy Recovery's products, data sheets, case studies, and additional information useful for RO plant design and optimization.

Disclaimer: Actual results may vary based on multiple factors, including system design, RO membrane model and conditions, and operating conditions.