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Desalination

China's Mega-Desalination Plant Experience

A white paper on the long-term energy efficiency of China's largest desalination plants.

AUTHOR:
Rodney Clemente

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EXECUTIVE SUMMARY

The gap between fresh water supply and demand is steadily widening in the People's Republic of China, home to approximately 20 percent of the world's population. Demand for water supplies continues to grow as both personal and industrial consumption surges. Underground water resources, meanwhile, are already overused and over polluted, and the deep wells now being drilled are frequently tapping into arsenic-rich aquifers, posing safety risks to as much as 30 percent of the country's population.

China's lack of quality fresh water poses serious health risks to 30% of its 1.4 billion inhabitants.

To help combat shortages, desalination, in the form of sea water reverse osmosis (SWRO), has become an integral part of China's long-term water management strategy. Historically used on a small scale, desalination is now becoming more widely accepted for large-scale water production, particularly in highly populated coastal areas. In recent years, China announced plans to grow its desalination capacity to 2.2 million cubic meters per day (m^3/day) or 581 million gallons per day (MGD) by 2015, and Chinese water authorities formed partnerships with global water treatment companies to construct large SWRO facilities.

The Tianjin Dagang and Qingdao SWRO plants provide an excellent model for future desalination projects in China.

So far, this initiative has resulted in the construction of the nation's two largest SWRO plants — the Qingdao and Tianjin Dagang SWRO desalination facilities. Designed, constructed and operated by Abengoa and Hyflux, respectively, the two plants together add 200,000 cubic meters per day (52 million gallon per day) of installed capacity to China's water network. Half of that comes from the Tianjin facility, which began delivering desalinated water to the northern China city's industrial zone in July 2009. Three years later in eastern China, Qingdao's municipal water supply began receiving a comparable amount of water from the new SWRO plant there. Both of these state-of-the-art facilities use the latest desalination technologies, including rotary-type isobaric energy recovery devices (ERD).

By considering not only initial capital expenses, but also operational and maintenance expenses, material alternatives and expected uptime of the Energy Recovery System (ERS), these plants demonstrate how sustained long-term energy efficiency can be achieved in large-scale SWRO plants. By displaying proper system design and energy recovery device (ERD) selection, both mega-plants provide an excellent model for future desalination projects in China.

PROCESS
DESIGN OVERVIEW

Large-scale desalination systems — those with capacities of more than 50,000 m³/day (13 MGD) — can be found operating throughout the world. Before the Tianjin and Qingdao SWRO facilities came online, however, the largest SWRO facility in China was the YuHuan SWRO, a 34,560 cubic meters per day (9 million gallons per day) facility built in conjunction with the 2008 Beijing Olympic Games.

Tianjin Dagang Desalination Plant

The following year, the eight-train, 100,000 m³/d (26 MGD) Tianjin Dagang Desalination Plant came online to provide water for the petrochemical processing industry as well as other industrial uses. Constructed using a design-build-own-operate approach, the plant is today owned and operated by Hyflux, a Singapore-based water solutions company, with minority ownership by JGC Corporation of Japan. It is designed for future expansion to 150,000 m³/d (40 MGD).

The SWRO plant receives feed water from the Bo Sea that has been pretreated using an ultra-filtration membrane system supplied by Hyflux. One of the largest of its kind, this pretreatment system processes approximately 250,000 m³/d (66 MGD) of feed water.

Seawater intake pumps deliver this feed water through the pretreatment system to eight independent seawater reverse osmosis trains, each of which is designed to deliver up to 12,500 m³/d (3.3 MGD) of permeate water. [See Figure 1.] Equipped with a single main high-pressure pump, membrane rack, energy recovery system and circulation pump, each train is designed to run from 12.5% to 100% capacity in increments of 12.5%.

Qingdao Desalination Plant

Unlike the Tianjin plant, which provides water for industrial use, the Qingdao Desalination Plant in eastern China sends up to 100,000 m³/d (26 MGD) of drinking water it produces to the municipal grid. Since coming online in June 2012, the SWRO plant's six trains have supplied as much as 15 to 20 percent of the water used by the city's nearly three million residents. Abengoa, a Spanish engineering, procurement and construction company, is majority owner of the plant, in partnership with local municipalities and the Qingdao SODA Company.

The Qingdao plant operates similarly to the Tianjin plant. Feed water from the Jiaozhou Gulf is pretreated by an ultra-filtration membrane system that can process up to 250,000 m³/d (66 MGD) of feed.

In this case, seawater intake pumps deliver feed water through the UF pretreatment system to three main high-pressure pumps and the plant's energy recovery system. Given the plant's semi-pressure design, each high-pressure pump supplies two membrane trains with an individual energy recovery system and circulation pump per RO train.

Since 2012, the Qingdao plant has been supplying 15-20% of the city's fresh drinking water to three million residents.

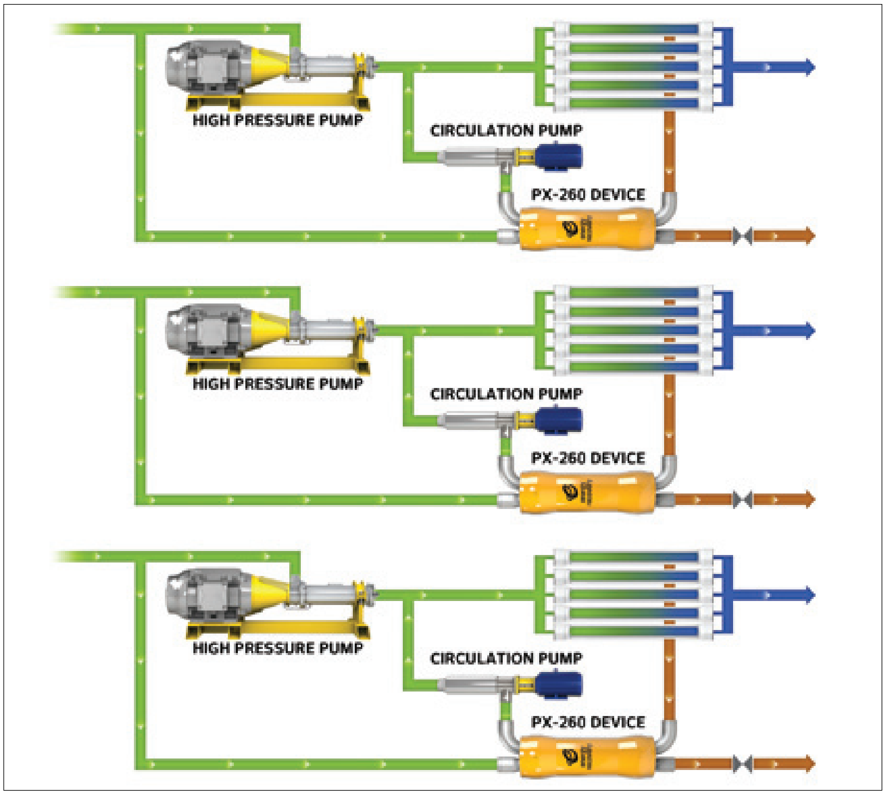

Figure 1 — Individual Train Design

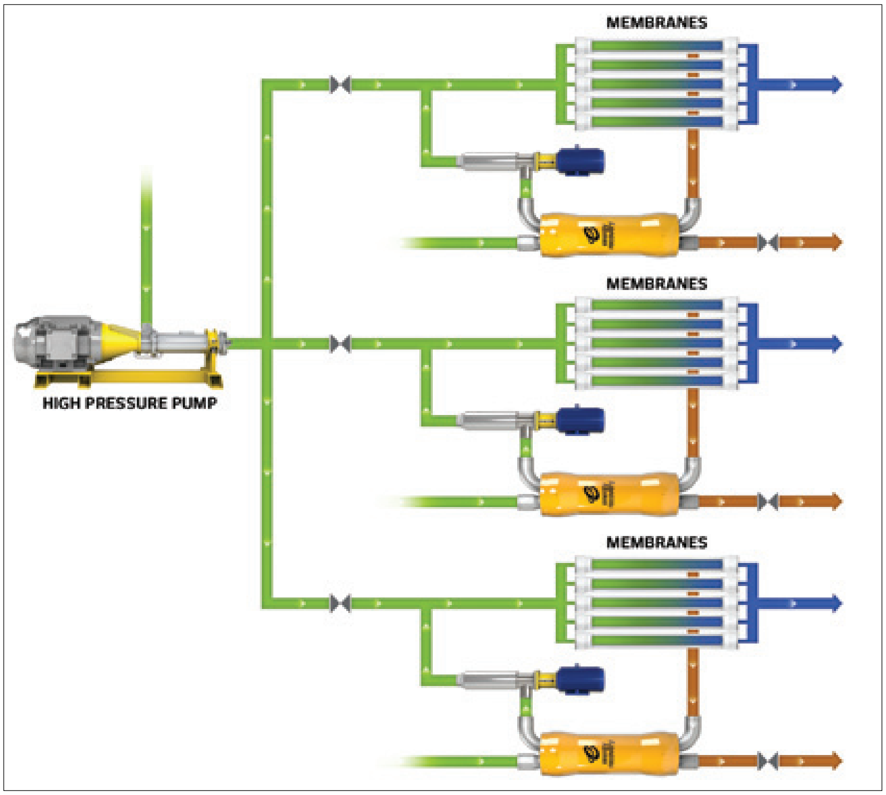

Figure 2 — Semi-Pressure Center Design

THE ENERGY-SAVING ROLE OF THE **PX PRESSURE EXCHANGER**

The high-pressure pumps used in the SWRO process consume the highest percentage of energy in the SWRO process. Plant operators can recover a majority of this wasted energy and transfer it back to the SWRO feed stream using energy recovery devices (ERDs) that reduce the amount of pressure and flow energy a high-pressure pump must deliver.

The ERD currently proven to be the most effective and efficient is Energy Recovery's PX Pressure Exchanger®. The PX device is a rotary-type isobaric device that transfers pressure from the high-pressure membrane concentrate to treated low-pressure seawater. This process reduces the power consumed of the plant's high-pressure pumps by up to 55% - 60%.

The PX device reduces the power consumed by the plant's high pressure pump by as much as 55-60%.

Pressure transfers from the membrane concentrate to seawater when the two streams are put in direct, momentary contact within the PX rotor. This ceramic rotor is fit into a ceramic sleeve between two ceramic end covers that create an almost frictionless hydrodynamic bearing. Half of the rotor ducts are exposed to high pressure, and half are exposed to the low-pressure stream. Ducts of the rotor, which are turned by the flow, pass a sealing area that separates high and low pressure circuits. (See Figure 3.)

The PX device rotor contains no pistons or physical barriers; it is designed so that the interface between the concentrate and the seawater in a duct never reaches the end of the rotor before the duct is sealed. When the rotor is not spinning, flow passes directly through the device, making PX device operation during startup and shutdown virtually automatic.

The Tianjin plant employs a total of 144 PX-220 ERDs, with 18 PX units serving each of its eight seawater reverse osmosis trains. The Qingdao plant utilizes a total of 102 PX-260 devices, with 17 PX units serving each of its six trains.

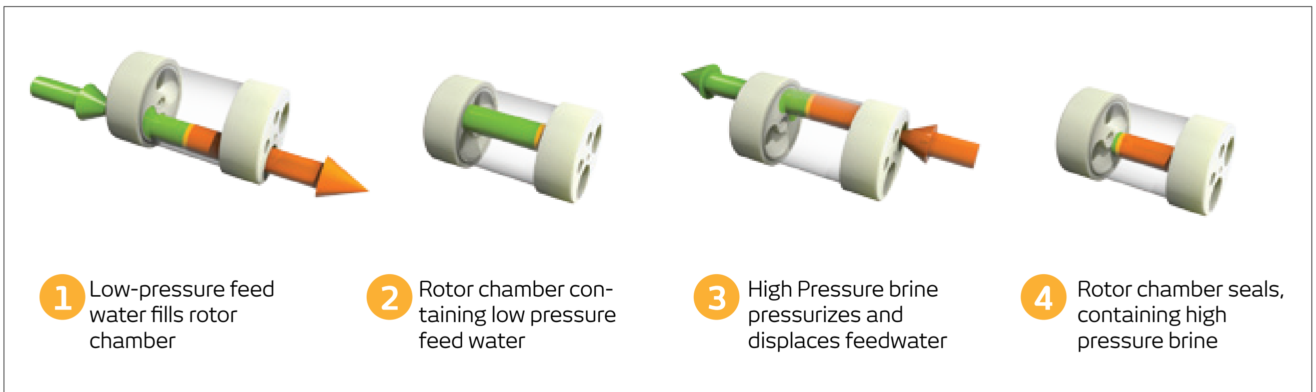

Figure 3 — How the Pressure Exchanger Works

ERD LIFE-CYCLE COST

Measuring PX Performance

The PX device's pressure-transfer efficiency can be calculated using a simple formula:

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

A PX-220 and PX-260's efficiency is guaranteed to be greater than 95% under most seawater reverse osmosis process conditions. In other words, efficiency loss does not exceed five percent in either device. About half of this loss is due to viscous resistance of flow through the device. The remainder is lost to lubrication flow through the hydrodynamic bearing. Given its positive displacement nature, this performance is approximately constant over the PX device's operating range.

Mixing between the concentrate and seawater streams is minimized by the short contact time between the streams (less than 0.05 seconds) and by the aspect ratio of the rotor ducts, which are long and narrow. Mixing, measured as an increase of the salinity of the membrane feed compared to the seawater salinity, in a seawater reverse osmosis system operating at 45% recovery is guaranteed to be less than 3%.

Salinity Increase = (SMF – SFW) / SFW

Where:

SMF = membrane feed salinity, and
SFW = system feed water salinity
ERD life-cycle cost

The Tianjin and Qingdao facilities both demonstrate the value of selecting equipment based on its total life-cycle cost, rather than the cost of the initial capital expenditure.

Both plants chose PX ERDs after considering not only their initial cost, but also their long-term operation and maintenance benefits, as well as their projected uptime and ability to deliver high plant availability. The goal: to maximize the capital investment, while minimizing operational costs.

Over the 20-to 30-year design life of a large SWRO facility such as the Tianjin and Qingdao facilities, operating costs tend to have a greater impact on total life-cycle costs than the initial capital investment. The biggest contributor to operational expenses is the energy cost. The PX devices were specifically chosen to help reduce the plant's overall power consumption and greenhouse gas emissions. Isobaric ERDs such as the PX Pressure Exchanger can help reduce the overall power consumed in a plant by up to 60%, compared to no ERD, and by 15-20%, compared to other ERD technologies. In facilities like the Tianjin and Qingdao plants, that can mean savings of up to 7,500,000 - $8,000,000 a year per facility.[1]

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[1] Estimates are based on 45% membrane recover, 60 bar membrane feed pressure and $0.10 per kWh.

ERD LIFE-CYCLE COST (CONT.)

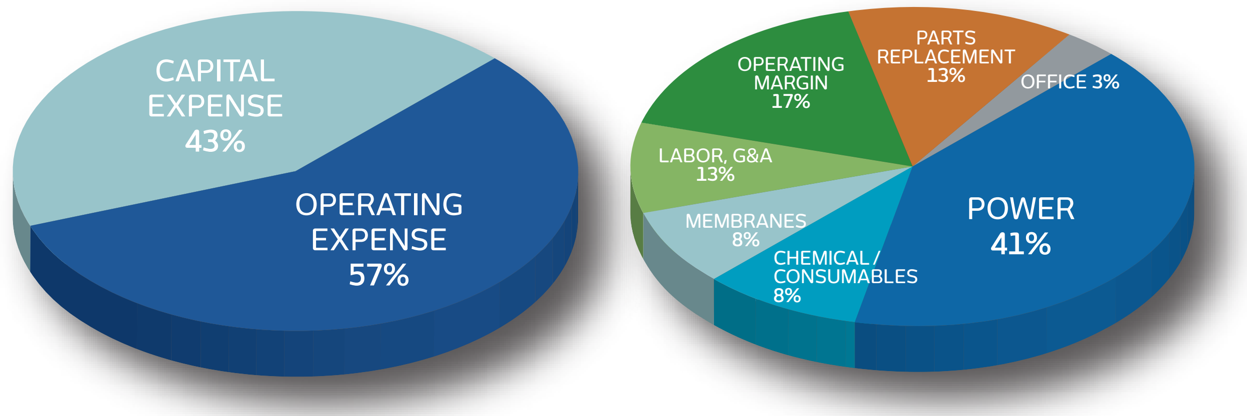


Figure 4 – Life-Cycle Analysis Charts

Over the years, many factors contribute to the dramatic decline in energy consumption in SWRO processes, including:

Membrane Development

Design improvements have resulted in membranes that have higher flux rates, lower pressures and greater surface areas, while still maintaining necessary high salt rejection rates. These membrane improvements have enabled membrane feed pressures to drop from 70-74 bar (1015–1073 PSI) to 64-68 bar (928-986 PSI) over the past decade, with comparable feed water characteristics. These enhancements have also impacted system design, resulting in higher overall membrane recoveries. While membrane recovery of 35-38% was typical a decade ago, today's SWRO systems are designed with recoveries in the 40-45% range; aggressive designs call for up to 50+% membrane recovery.

Pump Designs

Pump manufactures have also increased the hydraulic efficiencies of their designs. Many early high-pressure pumps used in SWRO facilities were designed for oil & gas and other applications outside of the water industry. More recently, pump manufactures have designed pumps specifically for SWRO service. These applications call for process lubricated bearings and improved impeller/diffuser surface finishes. The use of computational fluid dynamic software helps minimize frictional loses, while ensuring proper material selection suitable to withstand seawater service. Variable Frequency Drives (VFD's) have also become common for pump control, replacing the previously used and wasteful feed control valves.

System Designs

SWRO system designs have also improved, with designers becoming more focused on eliminating losses throughout the system. Today's pretreatment technologies, for example, require dramatically less energy than former versions. The elimination of throttle valves and the use of variable frequency drives minimize energy loss, while lower pipe velocities minimize frictional losses in the process piping. System designs are also taking advantage of larger, more efficient high-pressure pumps that are, in some cases, approaching 90% efficiency.

ERD DURABILITY
AND MAINTENANCE

ERD Advancements

By far the largest contributor to the decrease in power consumption over the past three decades has been due to advances in energy recovery devices. (See Figure 5.)

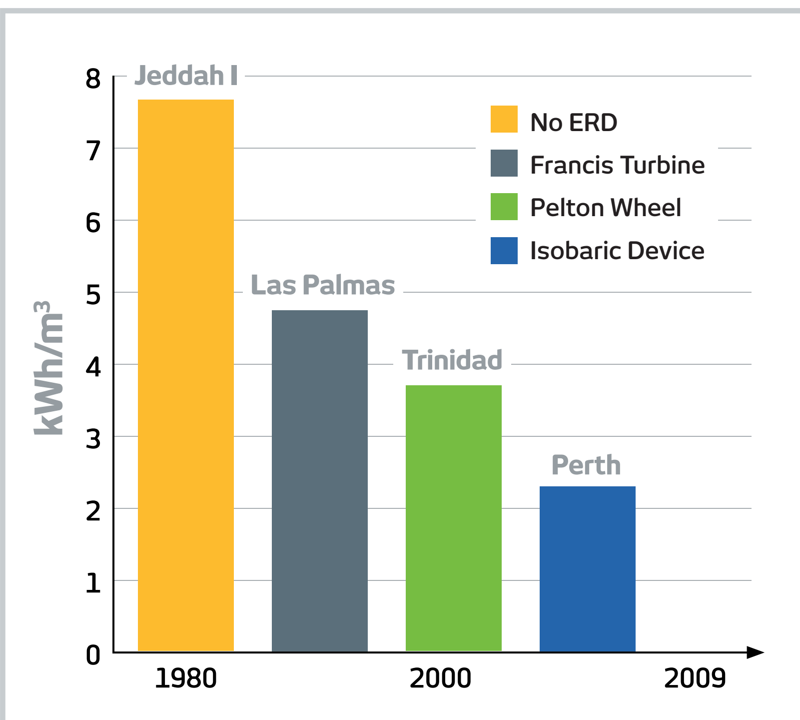
There are two major types of ERDs: centrifugal ERDs and positive-displacement isobaric ERDs. Centrifugal ERDs include reverse running pumps, impulse-type turbines and turbochargers. Isobaric ERDs include rotary-type pressure exchangers and piston-type work exchangers. Very large centrifugal-type ERDs achieve approximately 78-80% efficiency, while isobaric ERDs today reach 95 to 97% efficiency. The 15% difference in efficiency between the two types has resulted in most of today's mega-plants choosing isobaric-type ERDs.

Durability and Maintenance

Long-term, trouble-free performance of an SWRO process and its enabling technology depends, in large part, on the reliability of the materials that comprise it.

One of the more advanced and unique materials now in use in these applications is high purity (>99%) aluminum oxide (alumina) ceramics. Given its hardness, self-lubricating properties, high compressive strength and chemical resistance, alumina ceramics create an ideal fluid bearing for seawater applications, which combine corrosive and potentially two-phase (solid/fluid) environments. The primary components of a PX device, including the rotor, sleeve and end covers, are all manufactured out of these high purity ceramics.

Figure 5 – Specific Energy Consumption Trend



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ERD DURABILITY AND MAINTENANCE (CONT.)

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To date, none of the ceramic components within the PX devices deployed in the Tianjin and Qingdao SWRO facilities have ever been replaced, and no routine maintenance is scheduled on the devices.

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Pump manufactures have also increased the hydraulic efficiencies of their designs. Many early high-pressure pumps used in SWRO facilities were designed for oil & gas and other applications outside of the water industry. More recently, pump manufactures have designed pumps specifically for SWRO service. These applications call for process lubricated bearings and improved impeller/diffuser surface finishes. The use of computational fluid dynamic software helps minimize frictional loses, while ensuring proper material selection suitable to withstand seawater service. Variable Frequency Drives (VFD's) have also become common for pump control, replacing the previously used and wasteful feed control valves.

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Projected wear of the PX is miniscule giving these alumina ceramic devices a minimum 25year design life, significantly reducing the replacement and maintenance cost of this technology.

THE VALUE OF **AVAILABILITY AND UPTIME**

Availability refers to the probability that a system or piece of equipment will operate satisfactorily at any given time when used under specified conditions. The availability of the equipment installed in an SWRO facility is extremely important to the quality and quantity of the final produced product – drinking water or produced water for other industrial uses. The three critical components in the reverse osmosis process that require maximum availability include the main high-pressure feed pumps, the reverse osmosis membranes and the energy recovery system.

PX Array Redundancy

To help ensure maximum availability, PX arrays typically provide users with built-in redundancy. If one PX unit's rotor stops for any reason, the PX arrays can be inherently equipped with a "spare" so it can continue to run until the next scheduled maintenance with little to no loss of productivity. An array with at least one more PX unit than the minimum required for the train size results in an installed spare unit. An installed spare unit not only increases performance but boosts the on-line availability of the PX array. PX units that need service can be removed from the array. Blinds can then be installed on the manifolds and the system can continue to operate. Since the PX device is a passive device, no damage to an inoperable unit will occur, furthermore, an inoperable device will not cause damage to the units that continue to operate. Nor will it cause other equipment to malfunction.

The Tianjin PX array design utilizes the PX-220 model pressure exchangers, which have a maximum allowable unitary flow of 50 m3/d (220 gpm). With future expansion in mind, the PX array was designed to have an average unitary flow of approximately 40.3 m3/hr (177 gpm), which translates into an 81% utilization rate. Since availability was a top priority, the PX arrays were designed to operate with three units, as illustrated in the table below.

Table 1 — Tianjin PX Array Utilization

# of **PX**s in operation	Utilization	Unitary Flow	Unitary Flow	Notes
		(m3/h)	(gpm)	
N (baseline design*)	81%	40.3	177.3	*18-PX220
N – 1	85%	42.7	187.9	
N – 2	91%	45.4	199.8	
N – 3	97%	48.4	213.0	
N – 4	104%	51.9	228.4	> 100% utilization is not recommended.

THE VALUE OF AVAILABILITY AND UPTIME(CONT.)

Table 2 — Qingdao PX Array Utilization

# of PXs in Operation	Utilization	Unitary Flow	Unitary Flow	Notes
		(m3/h)	(gpm)	
N (baseline design*)	83%	48.9	215.2	*17-PX260
N – 1	88%	51.9	228.4	
N – 2	94%	55.4	243.8	
N – 3	100%	59.3	260.9	> 100% utilization is not recommended.

Economic Impacts of Downtime

During SWRO design and procurement, there are many variables to consider in a CAPEX and OPEX analysis, including initial capital investment, maintenance costs, replacement costs and operational costs. Plant and equipment availability is often overlooked. Yet, the economic impact of downtime is significant, as illustrated in the chart below.

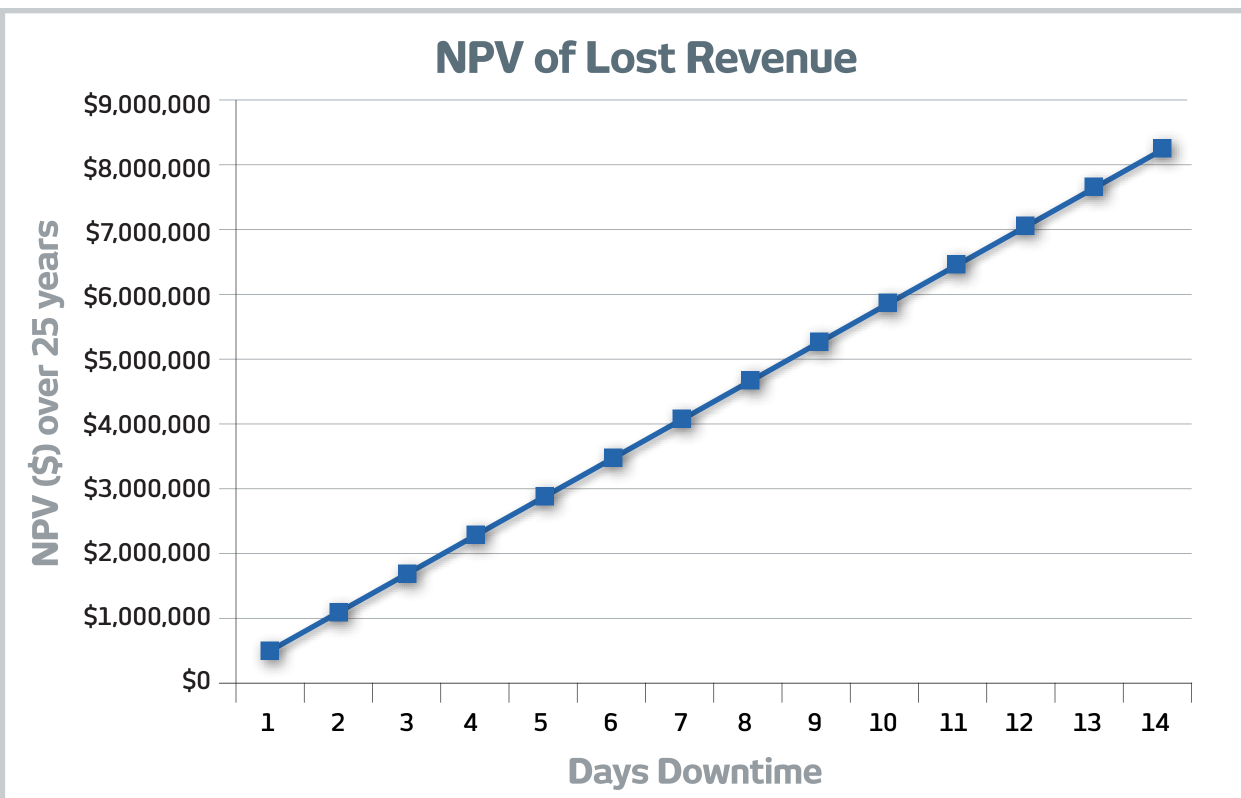

Figure 6 — Net Present Value (NPV) of Lost Revenue resulting from downtime over the 25-year life of a SWRO facility.

*Assumptions – Energy Cost 0.1$/kWh, Interest 8%, Plant Size 100,000m³/d,Years 25

THE VALUE OF AVAILABILITY AND UPTIME (CONT.)

Two of the most important measures in determining product reliability are failure rate and mean time between failures. Failure rate refers to the times when production must be stopped to perform service on a PX device.

A study was conducted to measure the availability of the PX devices installed at the Perth SWRO facility over a four-year period. In that study, all production shutdowns were found to be related to external leaks on the membrane pressure vessels or to stalled ERD rotors, rather than the need to replace ceramic cartridges or other critical working components. Plant operating log data shows that the leaks and stalled rotors each contributed to approximately 50% of the shutdowns. Stalled rotors were caused primarily by debris infiltration.. More specific causes were not recorded.

The mean time between failures (MTBF) for a single PX device installed at Perth is 43,258 hours, or 5.22 years. It is important to note that the mean time between failures refers to leak repairs or debris removal, and not a "failure" of any PX device components resulting in replacement. The PX devices at Perth have yet to reach the end of their useful life and are performing today at level comparable to their initial performance observed during commissioning. Plant maintenance logs indicate that approximately 100 hours of unscheduled maintenance time was spent on the ERDs over a four-year operating period. The operational availability is 99.7% over the study period.

PX devices installed in mega-plants around the world were also analyzed in the same availability study. Only plants operating at 100 percent capacity for 95 percent or more of the year were evaluated. In total, the extended study analyzed PX device availability in nearly one million m3/d (264 MGD) of installed capacity, with the average availability being 99.8%.

Table 3 — ERD Reliability Statistics

Total Operating Period	33,120 hrs
*Failure Rate	2.3 x 10-5
*MTBF	43,258.8 hrs.
ERD Availability	99.7%

SUMMARY

The PX energy recovery devices utilized in the mega plants in China continue to perform at a constant and high efficiency.

The efficiency of the ERD array has been proven to operate above 96% over the current operational period (year-to-date). The mixing performance of the ERD has also demonstrated to be constant over-time and less than 2.8% salinity increase at the membranes when operated at balance flows or 0% over-flush. The integrity of the components and advanced material sciences used has also shown that the PX energy recovery devices have the lowest life-cycle cost of any energy recovery device available on the market today.

When performing a total life cycle cost of energy recovery devices, the following items need to be thoroughly considered; energy recovery system efficiency, maintenance, durability and availability. These life cycle cost factors were used in the selection of the ERDs used in the state-of-the-art Tianjin and Qingdao SWRO facilities.

The efficiency of the ERD array has been proven to operate above 96%.

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CONTACT US

Name: Rodney B. Clemente,
VP of Technical Service & Aftermarket – Energy Recovery – USA
Address: 1717 Doolittle Drive
San Leandro, California, 94577
USA

Email: rclemente@energyrecovery.com

Website: www.energyrecovery.com

Tel: +1 (510) 483 – 7370

More Information

For the latest information about our product and services, please visit our website:
www.energyrecovery.com

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