The Availability Advantage of Reliable Energy Recovery Technologies

Energy Recovery Inc

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A White Paper on Uptime Savings for Desalination Plants

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Executive Summary

➔ Economics of Highly Available Systems

Availability can be defined as the probability that a system or piece of equipment when used under the specified conditions operates satisfactorily at any given time. The availability of the equipment installed in a seawater reverse osmosis facility (SWRO) is extremely important to the price, quality and quantity of the final product – water. There are three critical components in the SWRO processes; the main high-pressure feed pumps, the RO membranes, and the energy recovery device (ERD) system. This paper focuses on the economic benefits and importance of the availability of energy recovery devices in SWRO desalination plants.

The largest operating expense for an SWRO facility is the power consumed, which accounts for approximately 30% of the total RO operating expense. Typically for large facilities (>50,000m3/d), the ERDs responsible for reducing energy consumption are only a fraction of the initial capital cost (~1-2%) of the entire plant, but offer major return on investment through energy savings.

The role that ERDs play is undeniably critical to success or failure of an RO facility. Selecting the proper ERD system can save you millions of dollars over the life of your plant and provides peace of mind.

Specifically, isobaric, rotary-type ERDs, such as Energy Recovery Inc (ERI) PX Pressure Exchanger™ (PX™) Devices reduce consumption at an SWRO plant by as much as 60%. ERI's best-in-class PX system provides the highest availability with an average of 99.8% uptime. The *investment (ROI) of implementing PX technology is less than one year compared to an equivalent system without a PX energy recovery system*. From this perspective, it is evident that the uptime of the ERD system is critical to the economics of a plant. ERD downtime results in strict penalties, unplanned maintenance cost, and most importantly, a loss of revenue from diminished water sales and wasted cost of capital investment. In fact, margin loss due to unplanned downtime can be twice as much as the initial capital investment.

Using binomial distribution, the probability of not having an unscheduled maintenance at any point in time for a PX device is 18.32% higher than an isobaric piston-type ERD system with the same capacity.

This paper provides details on the different systems available, delivers case examples of the effects of downtime,-and recommends economic considerations for selecting the most reliable devices with the highest uptime available on the market today.

The Economics of Downtime

In the SWRO industry, many economic models have been developed by EPC, OEM, and consulting firms in order to evaluate the economics of purchasing equipment between competing technologies. However, a frequently overlooked variable in these models is ERD system availability. For ERDs, the primary line items include, capital cost of the ERDs, installation cost, operating cost (i.e. device efficiency), and maintenance cost (i.e. spare parts).

SWRO plant operators are in the business of selling water. Even though the ERD's are only 1 - 2% of capital costs, any failure will completely shut down the plant and cause significant financial ramifications for the plant operator. A system that experiences significant unplanned downtime can result in massive losses in revenue. Chart 1 below shows the economic impact of downtime over the 25 year life of a SWRO facility based on a selling price of $0.60 per m^3 of water. Detailed economic evaluations are offered later in the document within the Case Examples section,

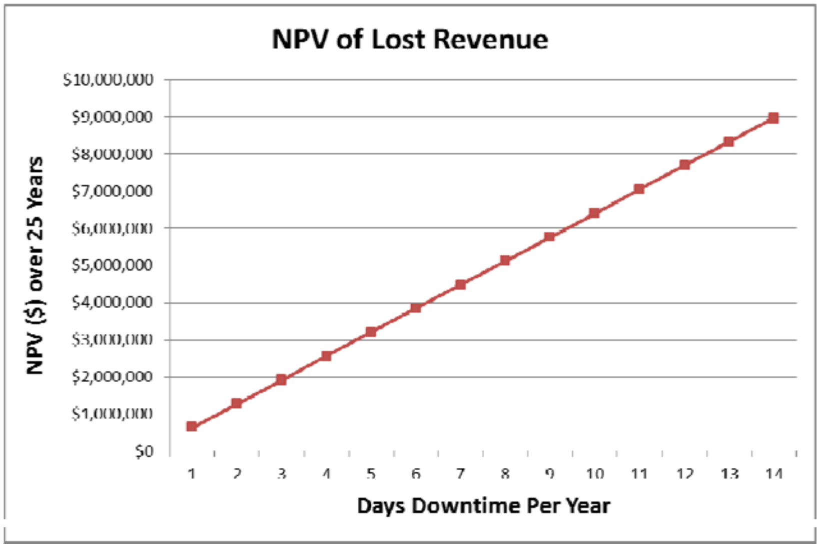


CHART 1. NPV of Lost Revenue DOWNTIME OVER 25 YEAR LIFE SWRO FACILITY

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

Less is More

The PX™ Pressure Exchanger™ (PX™) Technology

Simplicity, efficiency and uptime are important features when comparing energy recovery technologies for energy intensive SWRO plants. In an SWRO system equipped with a modular technology such as PX Pressure Exchanger ERDs, the membrane reject is directed to the membrane feed as illustrated in Figure 1 below. A free spinning rotor driven only by flow and moving between the high-pressure and low-pressure streams, displaces the brine and typically replaces it with an equal volume of seawater. Pressure transfers directly from the high-pressure membrane reject stream to a low-pressure seawater feed stream without a physical piston in the flow path. Unlimited capacities can be achieved by arraying multiple devices in parallel. The devices consist of few parts, including one moving rotor enclosed with a sleeve and a pair of sealing end-covers, increasing the simplicity and reliability of the PX device.

Typically, the fewer moving components within a device,
the greater its reliability.

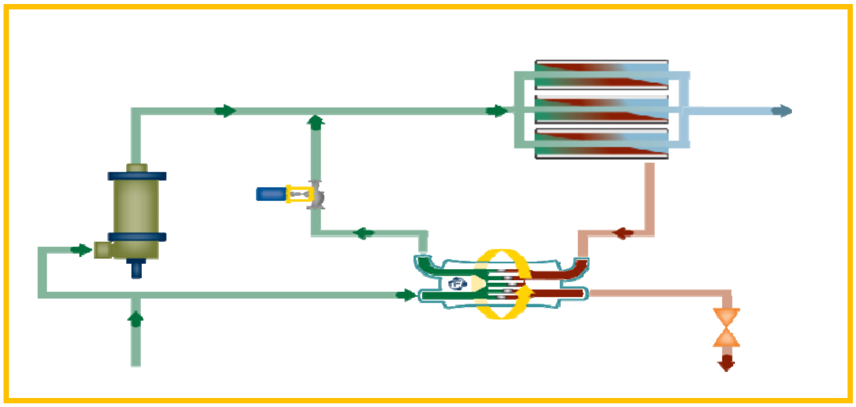


FIGURE 1. Typical SWRO PX™ Device Equipped System

Because SWRO applications are very demanding, combining corrosive and abrasive conditions with cavitation energy, the materials that make up an ERD also play a major role in the overall reliability and uptime. PX™ devices are composed of highly reliable alumina (ceramic) material which is critical to long term and trouble-free seawater reverse osmosis desalination processes.

Advanced, high purity aluminum oxide (alumina), the core ceramics material used in ERI PX devices, is known for outperforming plastics such as PET, Acetal, UHMW, which can become relatively soft and dimensionally unstable. In addition to material stability, trapped debris can cause problems in sliding polymeric components such as pistons or poppet valves, a feature that can be found in piston-type ERDs.

Due to its hardness, compressive strength, and chemical resistance, alumina is the ideal material for use in ERIs PX devices for high pressure desalination applications[1].

➔ Designed for a lifetime: the next generation of PX technology

ERI continues to innovate and improve on the design of the PX devices with the release of the PX-Q300 model. ERI has developed a proprietary ceramic formula that increases the strength, durability, and performance of the device. With the PX-Q300 device, ERI continues to push the design envelope of its technology and has incrementally decreased the volumetric and frictional losses resulting in an efficiency increase of approximately 1% at normalized flow when compared to the PX-260. The PX-Q300 provides exceptional performance, a design life of 25 years and quieter operations – below 81 decibels. Most importantly, the new ERI PX-Q300 offers a 97.2% minimum warranted efficiency – the highest in the industry.

➔ An optimum ERD design: SWRO plants wish list

The most important factors to be considered for designing an ERD system for a SWRO plant are:

- Energy recovery of highest efficiency, for its operational range.
- Maximum availability and therefore minimum downtime due to unscheduled maintenance.
- Minimal to no disturbance to other key components in the plant (pump and membranes), while keeping under control:
  - Salinity increase and related pressure variation at the inlet of the membranes
  - Flow/Pressure conditions of the inlets and outlets of the ERD system
- Ease of service.

Efficiency*:* Both types of isobaric ERDs available in the market (rotary and piston) have claimed to reach 98% efficiency. Only the PX™-Q300 unit can guarantee 97.2% efficiency, while other PX models have delivered more than 96% efficiency in the field over the long term. The efficiency of these devices will remain high throughout the life of the system which is designed to last 25 years. Further information about this efficiency guarantee is included in a recently published "Highest Efficiency Energy Recovery White Paper", Sept 2011[2].

Availability: The next section of this paper provides the theory and supporting data behind the high availability (over 99.8%) of PX arrays, depending on the size of the array. There is a long and proven history in the field to support the theory. Likewise, the section also shows complexities of isobaric piston-type devices and the reasons why they have a significantly lower availability. Primarily, these units have multiple moving parts that require high maintenance as opposed to ERI PX devices which have only one moving part. Unpublished field data further supports the high unplanned downtime of piston-type isobaric ERD within plants across the world.

➔ High Availability and Built-in Redundancy

Unit Availability vs. System Availability

Mathematical and reliability models are often used to predict complex system performance; however, they need to be verified with empirical data to support conclusions. Case studies provided in this paper provide such data examining how field observations of plant availability, when utilizing piston-type isobaric ERD's, support the availability conclusions of the ERI system analysis.

When talking about availability, it is easy to confuse the unitary device availability with system availability. Some devices are grouped in arrays that make them work as a "team" or system, and the system's availability from a reliability standpoint is different than a standalone unit. Two devices with the same availability characteristics can have very different system availability when performing as a single complete system, under different system's success requirements.

If one PX™ unit's rotor stops for any reason, the train can continue to operate until the next scheduled maintenance takes place, with minimal loss of productivity.

Operating PX arrays provides users with built-in redundancy. In the unlikely event that one PX unit rotor stops for any reason, the system can continue to operate until the next scheduled maintenance takes place, with minimal loss of productivity.

Reliability Characteristics of Engineering Systems (overview)

In order to model, represent, and understand correctly the reliability behavior of engineering systems, such as an array of PX units, the following concepts should be introduced:

Series System: In a system connected in series, from a reliability point of view, all the components must work to ensure system success. In this type of system, if one component fails the system won't be able to perform until the faulty component is repaired (unscheduled maintenance).

Parallel System: In a system connected in parallel, only one component needs to be working for system success. In these types of systems, if all but one component fails, the system will continue to perform, however, at a sub optimal performance.

Series-Parallel System: In a system connected in series-parallel, a minimum number of components must be operational to maintain the performance level while allowing potential failure of some components.

Let's take into account the following Illustrative example: A dark room with four lamps (A, B, C, and D), and four different light requirements.

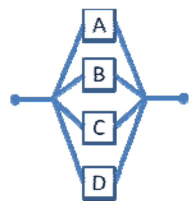
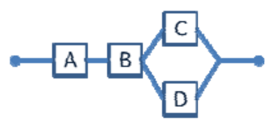
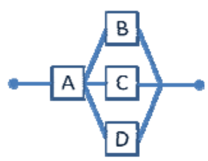
Different Light Requirements	System Type	System Reliability Representation	Operational Flexibility
All bulbs working	Pure Series		None. A, B, C, and D must be operational.
At least 1 bulb working	Pure Parallel		One must work, regardless of which one.
At least 3 bulbs working (only C or D can fail)	Series and Parallel		A and B must work, and C or D allowed to fail.
At least 2 bulbs working (only B or C or D can fail)	Parallel and Series		A must work, and B or C or D allowed to fail.

FIGURE 2. Engineering Systems Representation and Main Operational Characteristics

PX™ Arrays – System Modeling and Behavior

Of the systems described above in Figure 2, in PX technology and competing piston-type isobarics, the devices within the array are hydraulically connected in parallel. From a reliability modeling perspective, an array of piston-type isobaric devices performs similar to a series system. This is because of the large size of individual piston-type ERD units; a failure of one train could result in either a significant reduction in flow or a substantial increase in salinity at the membranes. Both cases require the entire system to be shut down, meaning the system can work only if each one of their devices works. **There is zero flexibility with a piston-type isobaric ERD.**

In the case of a PX™ array, medium to large sized arrays can still operate acceptably with one or multiple stopped units, continuing to reflect a parallel system for reliability. From a reliability perspective, modeling a PX array as a series-parallel system is a much closer approximation, since the array can be represented as a combination of two sub-systems in series; one being a series system containing one short of the minimum number of units needed to operate to avoid unacceptable salinity increases, and the other being the remaining units represented in parallel.

The following table summarizes the difference between the hydraulic connection within the array, and the reliability representation to model the system.

Array of ERDs	Hydraulic Connection	Reliability Representation
PX Device Array	Parallel	Series-Parallel (binomial)
Piston-type Array	Parallel	Pure Series

A series-parallel system approximation has many of the reliability characteristics of an array of PX units; however it still lacks one important feature - all PX units are functionally identical and fully interchangeable from a reliability standpoint. A true series-parallel system doesn't consider the benefits of this unique PX technology trait. Due to the PX device unique functional interchangeability, a "binomial distribution" is therefore the most accurate representation of a PX array.

The capability of a system to perform, even while some units are distressed, is known as a **partially redundant system**. These systems are especially capable of accommodating distressed units until the next scheduled maintenance. A PX array has this partial redundancy advantage, enabling a desalination plant to minimize unplanned maintenance, and as a consequence reducing unplanned downtime from an energy recovery device breakdown.

In order to illustrate the inherent operational advantages of a partially redundant ERD system, we will compare an array of rotary isobaric PX devices, with a piston-type ERD array below.

For clarity, key terms have been defined as follows:

- **Probability of Success**: The probability of having a device available and performing, meaning if there is a failure of any of the components, the device will continue performing.

- **Probability of Failure**: The probability of having a device not available, meaning the device is incapable of performing due to a failure that affects a critical component of the device.

Based on field information and unpublished data, the following individual probability numbers for each of the ERD systems will be taken into account and can be seen in Table 1. Three different scenarios for probabilities are given for a piston-type isobaric device.

Unitary Probability		
Type of ERD Device	**Success**	**Failure**
PX-300 Device	0.985	0.015
Piston-type isobaric ERD	a) 0.925 b) 0.950 c) 0.975	a) 0.075 b) 0.050 c) 0.025

TABLE 1. Unitary Probability of Two Different Isobaric ERDs

It is important to remember that a PX™ system (array) is capable of collectively performing as a large ERD even if some units are distressed (stuck rotor), since minor salinity increases can be accommodated by the rest of the plant. For our comparison, a membrane pressure increase of ~5.5 [bar] or less is considered to be satisfactory. Rather than shutting down the entire process to repair or replace a part, the system will be able to perform at this level until the next scheduled maintenance, mitigating the economic impact of unplanned downtime which ultimately costs time and money. Table 2 below, summarizes the minimum number of PX units versus piston-type isobaric ERDs for a specific array size that needs to operate for the ERD not to require unplanned maintenance.

Table 2 below summarizes the minimum number of operational units in an array by capacity for each of the two isobaric technologies to not require unplanned maintenance.

	PX-300 Array System		Piston-type, isobaric array system	
Array Capacity [gpm]	Number of Units/Array	Minimum Units/Array Needed to Work	Number of Units/Array	Minimum Units/Array Needed to Work
3,300	11	9	2	2
4,800	16	13	3	3
6,300	21	17	4	4

TABLE 2. Operational Characteristic of PX™-300 ERD and Piston-Type Isobaric ERD Array System

The Availability Advantage

The "Availability Advantage" is defined as the difference in availability between a PX™ device array system and a piston-type isobaric device, for a set system capacity. Using a binomial distribution to represent an array of PX units, and a series array to represent the competing technology, a side-by-side comparison is provided. Making use of the previous tables in this paper and applying a binomial distribution, an illustration of the PX technology Availability Advantage is shown in Chart 2 below:

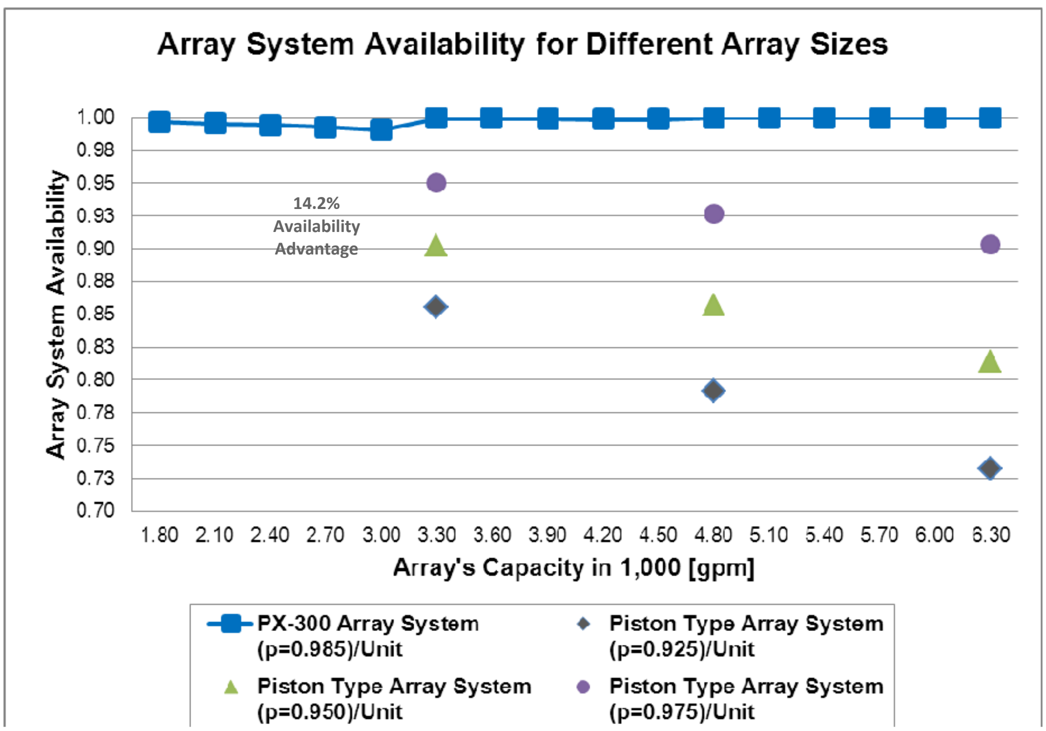


CHART 2. Availability Advantage of PX Array Over Piston-Type Isobaric Array

Chart 2 clearly indicates that the Availability Advantage increases for larger arrays of PX™-300 devices. **For a PX ERD system, the more units in an array, the higher the inherent availability of the plant**. Conversely, in the case of a piston-type isobaric ERD system, larger systems offer increasingly lower availability due to their series nature.

ERD Array Type	3,300 [gpm] Array Capacity	4,800 [gpm] Array Capacity	6,300 [gpm] Array Capacity
PX-300 Array (p=0.985)	0.99949	0.99866	0.99999
a) Piston-type Array (p=0.925)	0.85563	0.79145	0.73209
Availability Advantage	**0.14387**	**0.20721**	**0.26789**
b) Piston-type Array (p=0.950)	0.90250	0.85738	0.81451
Availability Advantage	**0.09699**	**0.14128**	**0.18548**
c) Piston-type Array (p=0.975)	0.95063	0.92686	0.90369
Availability Advantage	**0.04887**	**0.07180**	**0.09630**

TABLE 3. Availability Advantage for Different Array Sizes

The reduction in downtime as a consequence of the PX technology Availability Advantage compared with piston-type ERD's is displayed in Chart 3 below. The chart displays the three scenarios defined in the above Table 3.

Availability Advantage increases for larger arrays where the probability of not having an unplanned maintenance is on average 18.32% higher with a PX device array than a piston-type isobaric ERD system of the same capacity.

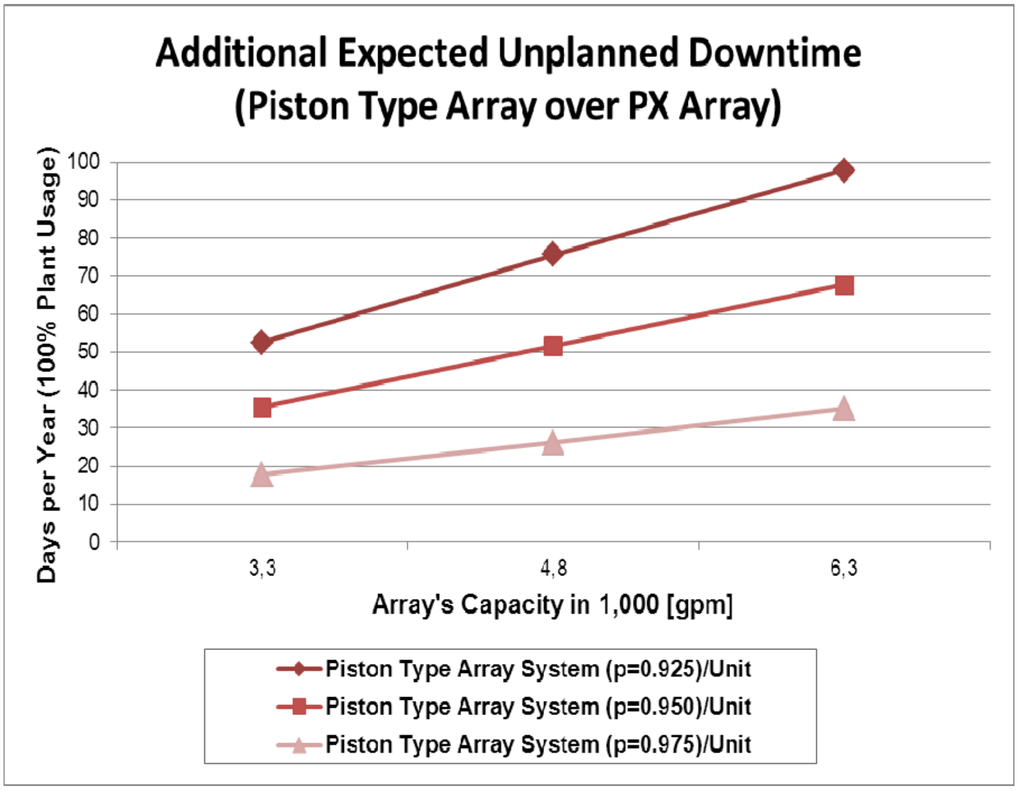


CHART 3. Downtime Decrease Due to Higher Availability

➔ PX™ technology: robust reliability that saves money

A PX array performs as a partially redundant system comprised of reliable units that are simple, interchangeable and functionally identical. The opposite is the case in a piston-type isobaric ERD system, since only one of its components has to fail to make the whole system fail. This advantage of an ERI PX array then translates into a higher availability when compared to a piston-type isobaric ERD array. **In fact, the larger the piston-type isobaric ERD capacity, the lower the inherent availability when working in arrays or systems**.

➔ Case Studies: the economic impacts of ERD system availability

ERI conducted a detailed availability survey from four different SWRO desalination facilities that currently use the piston-type ERDs. These plants range in production capacities from 30,000 – 330,000 m3/ day and are located around the globe - including the Caribbean, Middle East and Australia.

Based on the survey, the average days of unplanned downtime attributed directly to piston-type ERD failure is 25.5 days. As a very conservative estimate, less than 50% of this average value (1 day per month) was used in calculating the estimated loss of margin for a typical plant. To keep the math simple, an estimated average plant capacity of 100,000m^3/ day at a cost of capital of 8% per year over a 25 year plant life was considered. All other assumptions are included in green in the table below:

Daily Downtime Operating Cost		
Life of Plant (Years)	25	Yrs
Interest Rate	8%	
Baseline (Plant Size)	100,000	m3/d
Overall Water Price	$0.60	USD/m3
Specific Energy Consumption	3.50	kWh/m3
Energy Cost	$0.10	$/kWh
Operating Expenses (Cost to Produce)	$0.35	USD/m3
Gross Profit from Water Sales	$0.25	USD/m3
Gross Margin	**41.67%**	
Gross Profit per Day	**$25,000**	**USD/d**
NPV of 1 Day Downtime	**$266,869**	**USD/Proj Life**

TABLE 4. Downtime Operating Costs

Based on the above calculations, one day of water production loss could equal an estimated $25,000 in margin ($60,000 in revenue) reductions alone. **For the life of the project, every one day of downtime (planned or unplanned) per year could cost over $266,000 of gross margin.**

Using the average unplanned downtime for PX™ technology and competing piston-type isobaric ERD technology, the expected total cost of energy recovery devices can be calculated. Expected maintenance costs for the competing technology, based on published data, is estimated for annual maintenance costs of installing an ERD.
Given their 99.8% availability, PX units have virtually zero unplanned downtime and require no maintenance. To illustrate the cost comparison between ERD technologies, a total ERD cost analysis is shown below.

COST COMPARISIONS - ERI vs. Competing Isobaric Technologies			
	ERI	**COMPETITION**	
CAPEX			
Average CAPEX of ERD per 100,000 m3/d	$1.80	$1.50	MILLION USD
Cost of ERD for Current Plant	$1.80	$1.50	**MILLION USD**
UNPLANNED DOWNTIME COST			
Average Downtime*	0.7	12.0	Days/Year
Lost Gross Profit due to Downtime	$17,500	$300,000	USD/Year
NPV of Unplanned Downtime Cost	**$186,809**	**$3,202,433**	**USD/Proj Life**
* ERI's PX Technology has a proven availability of 99.8% and zero planned downtime			
MAINTENANCE COST			
Yearly Maintenance as % of Total ERD Cost*	0.50%	2.00%	
Annual Maintenance Cost	$9,000	$30,000	USD/Yr
Maintenance Cost - Life of Plant	$225,000	$750,000	USD
NPV (Life of Plant) - Maintenance Cost	**$96,073**	**$320,243**	**USD**

**Note: ERI's PX unit has zero required maintenance. A 0.5% provision has been included as a conservative estimate. The 2% for competitive technology is from published data of a leading competitor*

TABLE 5. Comparisons Costs of Unplanned Downtime (Competing Technologies)

As shown above, the margin loss due to unplanned downtime can be significantly greater than the initial capital investment. The availability of equipment (uptime) should be the primary consideration in the selection process of ERD technologies for desalination plants.

ERI PX™ technology has proven to have 99.8% availability with less than* 0.5%** ***of initial capital expenditure of annual maintenance costs.

Table 6 below shows the life cycle cost differential of using ERI PX devices in comparison to competing technologies when taking capital expense, unplanned downtime and maintenance cost factors into consideration. As the bolded black and red numbers indicate, **the total lifecycle costs for ERI PX technology are estimated to be less than half of piston-type, isobaric ERDs.**

Life Cycle Cost Summary			
	ERI	**Competition**	
CAPEX	$1,800,000	$1,500,000	USD
Unplanned Downtime	$186,809	$3,202,433	USD
Maintenance Cost	$96,073	$320,243	USD
Total	**$2,082,882**	**$5,022,676**	**USD**

TABLE 6. Lifecycle Cost Summary

A holistic approach should be taken when comparing technologies in order to analyze all aspects of an ERD investment. The information in Table 7 offers insight into how many days of unplanned downtime will allow for a break even investment. Based on these calculations, for example, a piston-type isobaric ERD for a new project is not permitted to have more than one extra day per year of unplanned downtime when compared to PX™ systems.. At that point in time its lifecycle costs exceed the cost of PX technology. Since most piston-type ERDs have significantly more unplanned downtime as proven earlier in the paper, the PX ERD is the optimal solution for an SWRO plant.

Break Even Analysis		
NEW PROJECT		
No. of excess unplanned downtime days to make PX Technology the most economical solution		
	0.98	**days**
EXISTING PROJECT		
No of unplanned downtime days that justify retrofitting the plant with a new PX Technology		
Competition unplanned downtime days = Capex for PX Technology	**6.74**	**days**
(Competition Downtime = PX CAPEX)		
Remaining life cycle cost of Competition = Life cycle cost of PX Technology	**6.60**	**days**
(Competition Maintenance + Downtime = PX CAPEX, Downtime, Maintenance)		

TABLE 7. Break Even Analysis

➔ One vs. many

A commonly accepted principle in mechanics is that the more moving parts within a piece of equipment, the higher the probability of failure of the entire unit. The inherent design of a piston-type isobaric ERD includes many moving parts in comparison with a PX™ device which has only one moving part, the rotor. A typical piston-type isobaric ERD has the following moving components within a single unit (see Table 8).

PX Energy Recovery Device	Piston-type, isobaric energy recovery device
Rotor	Main Piston (2)
	Check Valve (4 total): Connecting Rod Springs Face
	Relief valves
	Linear Exchange Valve - Seals (2) - Connecting Rod - Driving Actuator System

TABLE 8. List of moving parts in Isobaric ERD Technologies

Known reasons for failures of moving components are highlighted below:

- Check valve seals wear when opened and slammed shut at a rate of 4-6 cycles per minute (~7,000 times a day).
- Linear Exchange Valve stalls due to actuator/ seals failures (most frequently observed failure).
- Piston flap failures that increase mixing.

- Piston damage due to slamming.
    - Rings and gaskets wear replacements.
- Proprietary control system that requires synchronization with client-side control system.
- Elaborate oil-hydraulic rams that require several circulations and connections.
- Proximity switches on housing and hydraulic rams require set up and adjustments.
- Vessel cracks (limited warranty~1 year)

As we highlighted throughout this paper, ERI PX technology has significant advantages with regards to uptime and availability for plants. Competing technology characteristics such as those noted below need to be considered in the overall lifecycle cost analysis of any desalination plant prior to selecting an ERD system that is worth the investment.

- Probability of Unplanned Downtime
- Impact of Decreased Availability
- Inherent Design Characteristics (many parts vs. few parts)
- Routine Maintenance and Repair – (up to 2% of initial capital investment)
- Long Commissioning & Start-up
- After Market Service and Support

Summary

ERD system availability is highly critical to the final product quality and quantity of water that SWRO systems can produce. Availability is the key economic driver in deciding on the proper ERD system to implement in any desalination plant. Specific technologies, such as the ERI PX™ Pressure Exchanger™ arrays have inherent reliability and availability advantages over comparable piston-type isobaric devices. One design advantage, among many others such as high efficiency guarantees and lifetime performance, is the partially redundant nature of the system.

Selecting an ERD technology based on the initial capital expenditure alone is a fatal mistake. The lost margin from an unavailable plant is significantly higher than the capital expense for ERD.

Selecting an ERD technology based on the initial capital expenditure alone is a ***fatal*** mistake, with margin losses from unplanned downtime often costing more than the initial capital investment of ERI PX devices. Additionally, actual plant studies highlighting economic losses are clear examples of this mistake. In the lifetime of a plant, millions of dollars of wasted time, money and valuable water can be eliminated if all of the important factors of a plant's availability in its operations are carefully planned and evaluated. Other key considerations that need to be taken into the lifecycle calculation include; installation, commissioning, efficiency, longevity as well as system availability. ERDs are typically 1-2% of the initial capital expenditure of the entire plant, and omitting the value of availability of the ERD system can be a painful and expensive lesson learned.

The ERI PX technology is the best economic solution in energy recovery. If just one additional day per year of unplanned downtime is expected from other competing technologies, the PX solution becomes the optimal choice.

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2. Highly Efficient Energy Recovery Devices, Energy Recovery Inc. September 2011.

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