Desalination and Water Treatment
www.deswater.com

51 (2013) 772–779
January

doi: 10.1080/19443994.2012.714811

Taylor & Francis
Taylor & Francis Group

The availability and security of water production using reliable energy recovery technologies

Rolando Bosleman*, Rodney Clemente*

Energy Recovery Inc., 1717 Doolittle Drive, San Leandro, CA 94577, USA
Tel. +1 510 746 2571; Fax: +1 510 483 7371; emails: rbosleman@energyrecovery.com, rclemente@energyrecovery.com

Received 12 March 2012; Accepted 18 July 2012

ABSTRACT

The term availability can be defined as the probability of 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 (SWRO) facility 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 reverse osmosis (RO) membranes, and the energy recovery device (ERD) system. The role that ERDs play is undeniably critical to the success or failure of an RO facility's ability to produce and deliver water economically. 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 (>50,000 m^3/d), the ERDs responsible for reducing energy consumption are only 1–2% of the entire initial capital cost—a small fraction—but one that can offer a substantial return on investment through energy savings. Selecting the proper ERD system can save millions of dollars over the life of a plant and provide owners and operators with a secure and reliable means of water production. This paper will focus on the economic benefits and importance of the availability of ERDs in SWRO desalination plants.

Keywords: Availability; Desalination; Energy; Reliability; Economics; Downtime

1. The role of energy recovery devices

Energy recovery devices (ERDs) play a critical role to the success or failure of an reverse osmosis (RO) plant, and as such, the selection of an appropriate ERD system can save millions of dollars over the life of the plant, as well as provide peace of mind for the plant operator. Specifically, isobaric, rotary-type ERDs reduce power consumption at an seawater reverse osmosis (SWRO) plant by as much as 60%. Having the highest availability technology—above 99%—provides significant advantages including a quick return on investment for any plant. Therefore, when an ERD is unavailable or is down, it 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, profits lost due to unplanned downtime can be twice as much as the initial capital investment. From this perspective, it is evident that the uptime of the ERD system is critical to the economics of a plant.

2. The effects of downtime

To date, numerous economic models have been developed by by Engineering, Procurement and

*Corresponding authors.

Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, April 23–26, 2012, Barcelona, Spain

Construction, Original Equipment Manufacturer, 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 owners and operators are in the business of water production. Even though the ERDs are only 1–2% of capital costs, any failure will completely shut down the plant and cause significant financial ramifications. A system that experiences significant unplanned downtime can result in massive losses in revenue. Chart 1 shows the economic impact of downtime over the 25 year life of a SWRO facility based on a selling price of $0.60 per cubic meter of water. Detailed economic evaluations are offered later in the document within the Availability Survey section.

3. ERD design optimization

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

- 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.

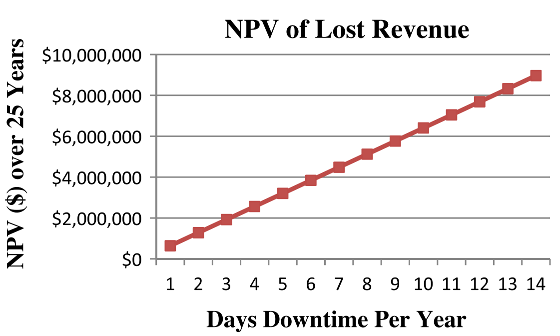


Chart 1. NPV of lost revenue downtime over 25 year life SWRO facility. (*Assumptions—energy cost 0.1$/kWh, interest 8%, plant size 100,000 m^3/d, years 25.)

Efficiency: Both types of isobaric ERDs available in the market (rotary and piston) have claimed to reach 98% efficiency. Out of the available ERD's in the market, only the ERI 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.

Availability: The next section of this paper provides the theory and supporting data behind the high availability (over 99.8%) of isobaric rotary-type devices, 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 isobaric rotary-type devices that have only one moving part. Unpublished field data further support the high unplanned downtime of piston-type isobaric ERD within plants across the world.

4. 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. An "Availability Survey" included in this paper provides such data examining how field observations of plant availability, when utilizing piston-type isobaric ERD's, support the availability and security conclusions of the Energy Recovery, Inc. (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 stand-alone 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.

Operating PX arrays provide 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.

4.1. 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 would not 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 us take into account the following illustrative example: A dark room with four lamps (A, B, C, and D) and four different light requirements.

4.2. System modeling and behavior

Of the systems described in Table 1, 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.

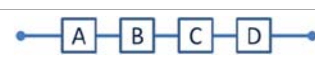
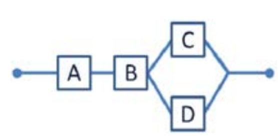
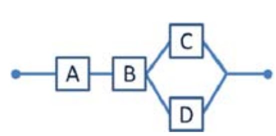
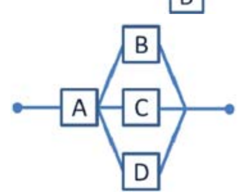
In the case of a PX™ array, medium-to-large-sized arrays can still operate acceptably with one or multiple stopped units, continuing to reflect a parallel system for reliability. From a reliability perspective, modeling a PX array as a series–parallel system is a much closer approximation, since the 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;

Table 1
Engineering systems representation and main operational characteristics

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

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 does not 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 ERD 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 2. Three different scenarios for probabilities are given for a piston-type isobaric device.

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 3, summarizes the minimum number of PX units vs. piston-type isobaric ERDs for a specific array size that needs to operate for the ERD not to require unplanned maintenance.

Table 2
Unitary probability of two different isobaric ERDs

Type of ERD device	Success	Failure
PX-300 device	0.985	0.015
Piston-type isobaric ERD	(a) 0.925	(a) 0.075
	(b) 0.950	(b) 0.050
	(c) 0.975	(c) 0.025

5. The Availability Advantage

The "Availability Advantage" is defined as the difference in availability between a rotary-type system such as the PX™ device array system and a piston-type isobaric device, for a set of 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.

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.

The reduction in downtime as a consequence of the PX™ technology Availability Advantage compared

Table 3
Operational characteristic of PX™-300 ERD and piston-type isobaric ERD array system

Array capacity (gpm)	PX-300 array system		Piston-type, isobaric array system	
	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

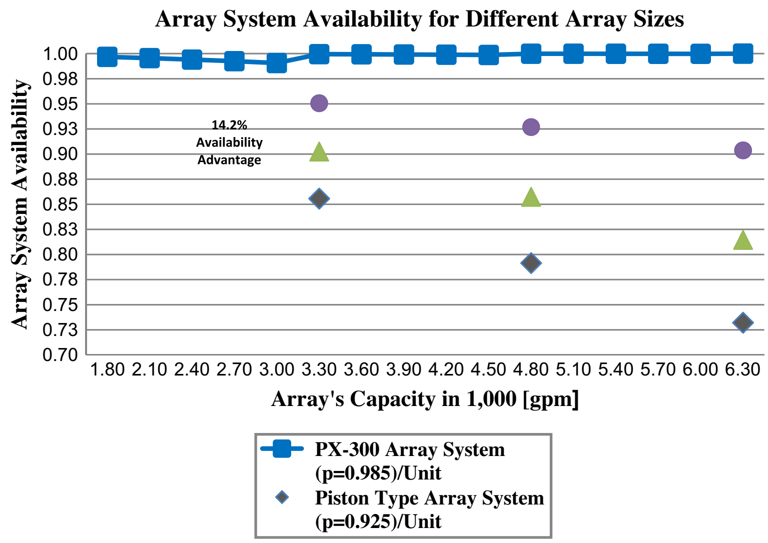


Chart 2. Availability Advantage of PX array over piston-type isobaric array.

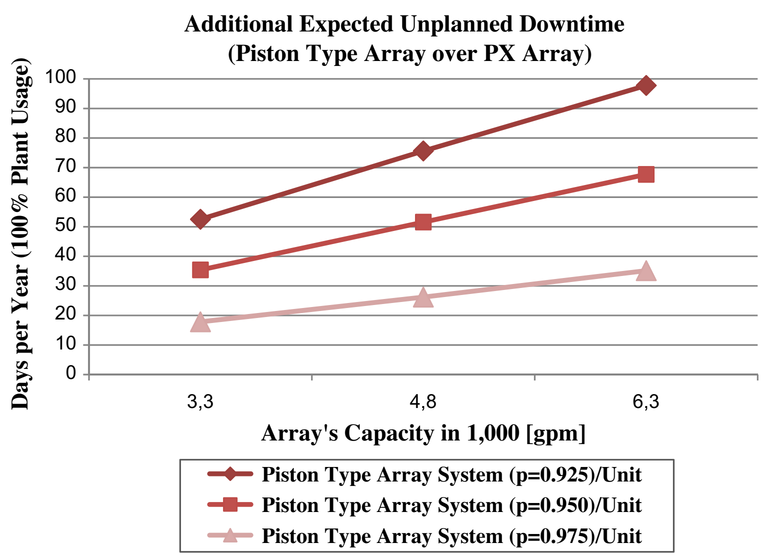


Chart 3. Downtime decrease due to higher availability.

with piston-type ERDs is displayed in Chart 3. The chart displays the three scenarios defined in Table 4.

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

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.

6. Availability survey: a detailed analysis

Recently ERI conducted a detailed availability survey from four different SWRO desalination facilities that currently use the piston-type ERDs. These plants range

Table 4
Availability advantage for different array sizes

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

in production capacities from 30,000 to 330,000 cubic meters per day and are located worldwide—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 100,000 m^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 Table 5.

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

Table 5
Downtime operating costs

Daily downtime operating cost	
Life of plant (years)	25 years
Facility cost of capital (interest rate)	8%
Plant size	100,000 m^3/d
Overall water price	$0.60 USD/$m^3$
Specific energy consumption	3.50 kWh/m^3
Energy cost	$0.10 $/kWh
Operating expenses (cost to produce)	$0.35 USD/$m^3$
Gross profit from water sales	$0.25 USD/$m^3$
Gross margin	41.67%
Gross profit per day	$25,000 USD/d
NPV of 1 day downtime	$266,869 USD/Proj Life

Using the average unplanned downtime for a rotary-type isobaric device such as the PX™ technology and competing piston-type isobaric ERD technology, the expected total cost of ERDs can be calculated. Expected maintenance costs for the competing technology, based on published data, are estimated for annual maintenance costs of installing an ERD.

Given their 99.8% availability, PX units have virtually zero downtime and require no maintenance. To illustrate the cost comparison between ERD technologies, a total ERD cost analysis is shown in Table 6.

As shown above, the 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.

Table 7 shows the life cycle cost differential of using ERI PX devices in comparison with other isobaric 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 other, piston-type, isobaric ERDs.

A holistic approach should be taken when comparing technologies in order to analyze all aspects of an ERD investment. The information in Table 8 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.

Table 6
Comparisons costs of unplanned downtime (other technologies)

Cost comparisions: ERI vs. other isobaric technologies		
	ERI	Other isobarics
CAPEX		
Cost of ERD for current plant	$1.80	$1.50 Million USD
Unplanned downtime cost		
Average downtime[a]	0.7	12.0 days/year
Lost contribution profit due to downtime	$17,500	$300,000 USD/year
NPV of unplanned downtime cost	$186,809	$3,202,433 USD/Proj Life
Maintenance cost		
Yearly maintenance as% of total ERD cost[b]	0.50%	2.00%
Annual maintenance cost	$9,000	$30,000 USD/year
Maintenance cost—life of plant	$225,000	$750,000 USD
NPV (life of plant) —maintenance cost	$96,073	$320,243 USD

[a]ERI's PX Technology has a proven availability of 99.8% and zero planned downtime.
[b]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 7
Lifecycle cost summary

	ERI	Other isobarics	
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 8
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 (Competition downtime = PX CAPEX)	6.74	days
Remaining life cycle cost of competition = Life cycle cost of PX technology (Competition maintenance + downtime = PX CAPEX, downtime, maintenance)	6.60	days

7. 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. It impacts both investors and operators of the plant over the long life of the project. Energy recovery systems are extremely crucial to the plant uptime as they can potentially cripple water production should they fail or require high maintenance. Selecting the wrong ERD technology can cost the owner and/or the operator of a SWRO plant more than twice the initial capital expenditure for the ERD solution. Specific technologies, such as the ERI

PX™ Pressure Exchanger™ arrays, have inherent reliability and availability advantages over other isobaric energy recovery c devices. One design advantage, among many others such as high-efficiency guarantees and lifetime performance, is the partially redundant nature of the system.

For a calculation of how much ERD downtime can cost your plant operation, visit our website at: http://www.energyrecovery.com/index.cfm/0/0/142-Uptime-Calculator-for-Operators.html.