ENERGY RECOVERY DEVICES IN ADVANCED AND EMERGING REVERSE OSMOSIS APPLICATIONS

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ABSTRACT

In reverse osmosis (RO) desalination processes, a substantial fraction of the feed exits the membrane array as a high-pressure reject stream. Energy recovery devices (ERDs) are used to capture otherwise-wasted hydraulic energy and recycle it into the RO process. ERD types include reverse-running pumps, impulse turbines, turbo boosters and isobaric devices. These devices are credited with reducing the energy required for seawater desalination by 50% or more. In addition, isobaric ERDs have made very large desalination plants more feasible by reducing the size of the high-pressure pump required for a given amount of permeate production. The utility and wide application of ERDs for high-pressure RO processes is well-proven and well-documented.

Multi-stage RO and membrane brine concentration processes provide potential new applications for ERDs. ERDs can increase the productivity of existing desalination systems, decrease the energy requirements of existing systems or enable greater energy efficiency in new desalination processes. While some process designs have been widely applied, such as those using ERDs as interstage booster pumps, others have been presented in the literature but have not been widely adopted, such as dual turbocharger systems or stage-and-a-half systems with isobaric ERDs.

Most typically, ERDs must be considered in the design stage of a desalination project. Because turbo boosters have zero or limited impact on water composition, they do not significantly affect membrane design. Use of isobaric ERDs, however, requires consideration of the mixing between brine and feed water that inherently occurs in these devices. While isobaric ERD manufacturers can estimate bulk salinity impacts of their devices, they do not account changes in concentrations of individual ionic species, which have different membrane rejection characteristics. A few membrane manufacturers' design programs incorporate isobaric ERD mixing and performance into their projections but others do not.

The author presents the estimated total cost of ownership of advanced and emerging membrane brine desalination system over a range of final brine concentrations. Energy consumption and capital, operating and total costs for systems equipped the two major types of ERDs are quantified and assessed. Equations that define and quantify isobaric ERD mixing and its impact on membrane feed salinity are presented. The paper concludes that energy recovery devices in multi-stage RO and RO-based brine concentration applications are advantageous, although which type of ERD is best is less clear.

Keywords: Energy recovery devices, reverse osmosis, brine concentration, OARO

I. INTRODUCTION

This paper provides an overview and analysis of the opportunity for applying energy recovery devices (ERDs) in advanced and emerging reverse osmosis (RO) desalination applications. This paper deals exclusively with high-pressure RO desalination and brine concentration systems and does not consider other means of desalinating such as thermal or electro-separation techniques in any detail. While this paper presents an analysis of use of these devices in these systems, no mechanical or product details are given. The reader is referred to device manufacturers for such information. Although previously an employee of Energy Recovery, Inc., the author is not currently affiliated with any energy recovery or pump company.

II. OVERVIEW OF ERDS

In RO desalination processes, a substantial fraction of the water pressurized and fed to the system exits the membrane array as a high-pressure reject stream. Multiple types of devices have been developed to capture otherwise wasted pressure energy and convert it into useful energy or recycle it into the RO process. Perhaps the earliest ERD was a turbine patented by Lester Pelton in 1883 for gold mining operations. Of the various devices applied over the years, turbo chargers or turbo boosters, reverse-running pumps and isobaric devices have emerged as the most widely used due to their efficiency and practicality [1].

Figure 1 illustrates a typical configuration of a turbo booster in an RO process. Feed water is partially pressurized by a high-pressure pump and fed to the impeller side of the turbo booster. Pressure is boosted and fed to the membranes. Brine exiting the membranes enters the turbine side of the turbo booster. The turbine is connected by a shaft to the impeller. The turbine discharge pressure is typically maintained at a minimum of 1 bar to inhibit cavitation in the device, but discharge pressure can be higher as may be advantageous, for example, for conveying brine.

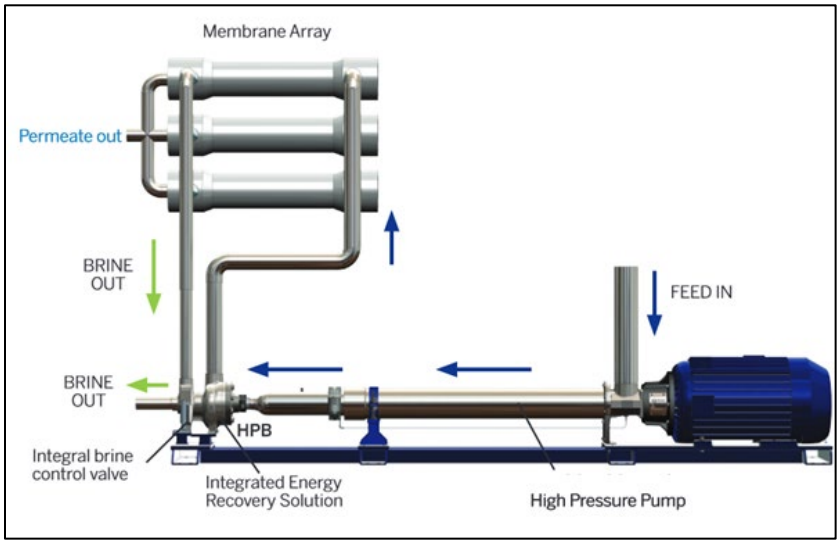


Figure 1. Illustration of a Turbo Booster in a Typical RO System. Image by Fluid Equipment Development Co. [2]

Figure 2 illustrates a typical configuration of an isobaric ERD or ERD array in an RO process. A percentage of the feedwater approximately equal to the permeate flow is fed to the membranes through a

high-pressure pump. Brine exiting the membranes enters the ERD array where its pressure is transferred to the rest of the feedwater. Pressurized feedwater from the ERD merges with the discharge of the high-pressure pump to feed the membranes. The brine discharge from the ERD is typically maintained at a minimum of 1 bar pressure to inhibit cavitation in the device, but discharge pressure can be higher as may be advantageous, for example, for conveying brine. Because isobaric ERDs do not impel flow, a circulation pump is used in the high-pressure stream, usually downstream from the ERDs, to move high pressure fluid through the ERD and the membrane array.

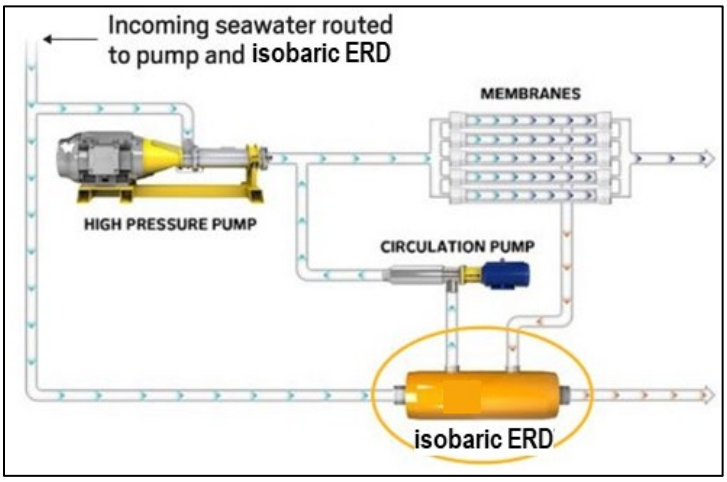


Figure 2. Isobaric ERD in a Typical RO System. Image by Energy Recovery Incorporated. [3]

In all isobaric ERDs, contact between the feed and brine results in an increase in feed salinity and a decrease in brine salinity. The mixing effect is quantified as volumetric mixing. Volumetric mixing is defined with reference to Figure 3. "Balanced flow" is the condition of the flow rate of high-pressure inlet stream G equaling the flow rate of low-pressure outlet stream H, and similarly, D=B.

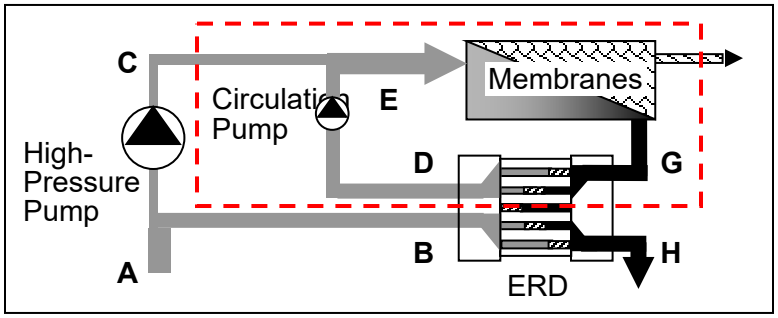


Figure 3. Schematic Diagram of SWRO System with Isobaric ERD

The following equation applies:

$$M = \frac{C_D - C_B}{C_G - C_B} \quad (1)$$

where M = volumetric mixing

C_X = salinity of stream X as defined in Figure 3

A derivation of equation (1) from a mass balance around an ERD is provided in reference 4 [4]. The salinity increase at the membrane feed caused by mixing is a function of the volumetric mixing, the amount of leakage through the particular ERD and the membrane recovery rate. Some membrane projection programs allow entry of ERD information and use it to account for mixing in their calculations while others do not. To quantity the salinity impact of ERD mixing for membrane design or other design exercises that do not compute it internally, the following equation may be applied. Balanced flow was assumed in the derivation of equation (2).

$$S_m = \{S_f*[1-M*(1-R-L)]-S_p*[R*M*(1-R-L)]/(1-R)\}/[1-M*(1-R-L)/(1-R)] \quad (2)$$

where M is defined above

S_m is the salinity at the membrane feed
S_f is the salinity of the feedwater
S_p is the salinity of the membrane permeate
R is the permeate recovery rate percentage
L is ERD leakage as a percentage of the membrane feed flow

Equation (2) was previously published correctly in conference proceedings [4], however, its subsequent publication in a journal [5] contained several errors.

A simple empirical estimate of salinity increase with mixing for typical SWRO operating conditions is as follows:

$$SI \approx R*M*1.04 \quad (3)$$

where SI = the ratio of the membrane feed salinity to the feedwater salinity

An alternative to turbo boosters or isobaric ERDs for recovery of brine energy are reverse running pumps, including axial piston motors (APMs). Flow through the pump turns a motor that applies a current to the local line. Water to wire efficiencies of up to 80% are reported [6].

II. OVERVIEW OF MEMBRANE BRINE CONCENTRATION

For inland desalination processes, brine can be a significant financial and environmental challenge. For some seawater desalination plants, constrained intakes or pretreatment systems can limit the ability to increase freshwater production. Concentration or desalination of brine is desired in these applications but has been inhibited by the cost and technical limits of existing thermal and membrane desalination methods and components.

One way to minimize the impact of brine is to make less of it by maximizing permeate recovery rate. Single RO stages are limited to a maximum of about 55% recovery for high-TDS brackish, seawater and brine feeds. Higher single stage recovery rates result in overflux of lead membrane elements and insufficient crossflow in tail elements. Hence, to achieve higher recovery rates without overflux, multiple stages are required. Figure 4 illustrates a simple multiple-stage RO system.

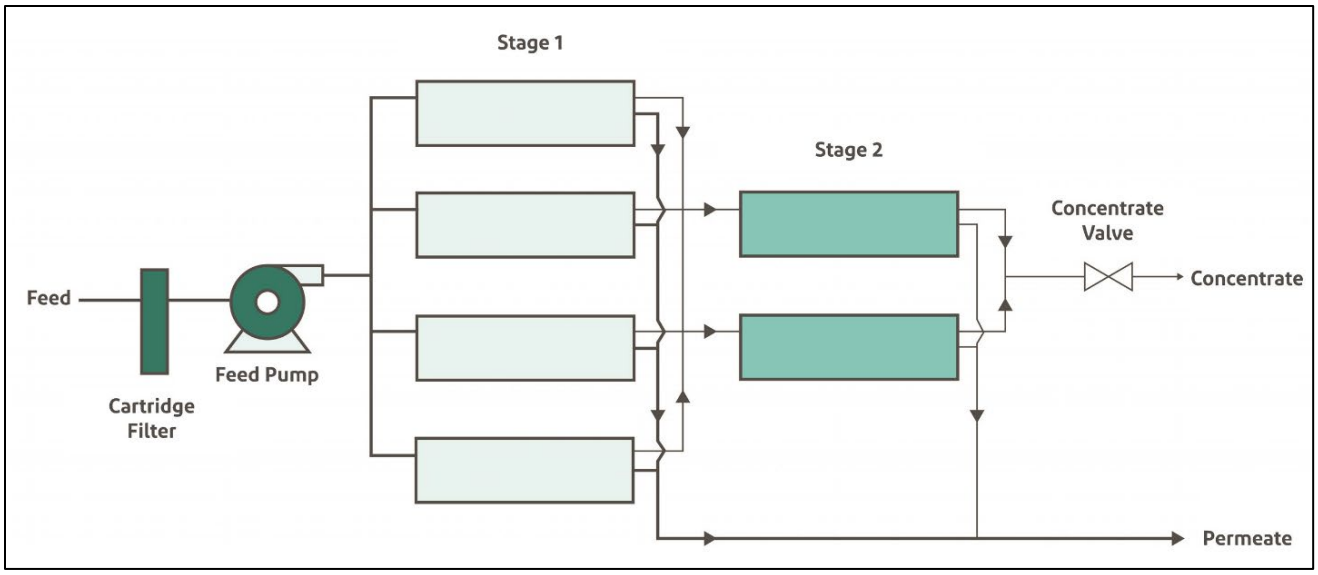


Figure 4. Multiple Stage RO System. Image by Dupont Filmtec [7]

Brine from the first stage is fed to the second stage where additional desalination occurs, elevating overall recovery and final brine concentration. A boost pump or boost device may be implemented between stages to elevate the pressure as needed to overcome the elevated osmotic potential of concentrate from upstream. Downstream stages typically have fewer pressure vessels in parallel so that recommended minimum concentrate velocities are maintained. Additional stages can be added in series, with or without interstage boosting, to achieve higher recovery rates and higher final brine concentrations. However, conventional reverse osmosis is limited by the maximum 1,200 psi (83 bar) pressure rating of most available membranes and equipment. This, in turn, limits final brine concentrations to about 75,000 mg/l total dissolved solids (TDS), more or less depending upon the salt composition. The concentrate valve in Figure 3 can (and typically would) be replaced with an energy recovery device in high pressure RO applications.

Disc-tube RO (DTRO) and ultra-high-pressure RO (UHPRO) membranes have pressure ratings of up to 1,800 psi (120 bar). They are applied in process configurations like the ones illustrated in Figures 1-4. Pumps, pressure vessels and other equipment rated for higher pressure operation are obviously required. At the time this paper was written, such high-pressure pumps, membranes and ERDs were commercially available but on a limited basis.

Recently-introduced osmotically-assisted reverse osmosis (OARO) processes offer means to achieve high recovery rates and high final brine concentrations at operating pressures of 1,200 psi (83 bar) or less [8,9,10]. By applying a dilute salt solution to the permeate side of the membranes, the osmotic pressure barrier is reduced, lowering the feed pressure required to achieve high brine concentrations. Salt solution can be pumped into the permeate envelope of spiral membranes or into the lumens of hollow fibers, or salt can be allowed to pass through the membranes into the permeate side. Figure 5 provides a simple illustration of an OARO process.

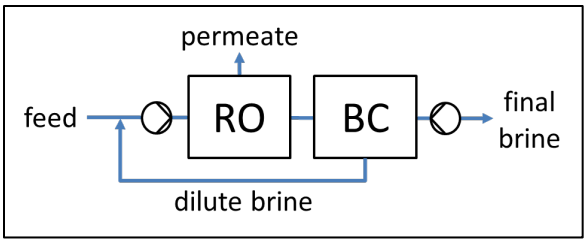


Figure 5. Osmotically-Assisted Reverse Osmosis Process

where,
RO = reverse osmosis stages, passes and membranes
BC = brine concentration stages and membranes

Feed to the RO stage or stages is desalinated, producing permeate and partially concentrated RO brine. RO brine flows under pressure to the brine concentrator consisting of one to six stages. Fully concentrated brine leaves the process through a throttle valve or an energy recovery device, as will be further discussed in this paper. Dilute brine and salty permeate from the BC membranes is returned to the feed of the RO or to an upstream BC stage.

III. ERD APPLICATION IN MULTI-STAGE AND BC APPLICATIONS

Process engineers primarily use energy recovery devices to decrease the energy requirements of newly-constructed conventional desalination systems, but they can also be applied to increase the productivity of existing systems, as discussed in references 11-13 [11, 12, 13], and to achieve greater energy efficiency and productivity in high recovery and brine concentration applications, as discussed in this paper. The optimum choice of energy recovery device type and its position in the system are reflected in the minimum projected total cost of water production. Generally turbochargers offer lower capital cost but less efficient energy recovery performance while isobaric ERDs offer the inverse. However, as will be shown, the differences as quantified by total cost of water production can diminish at high recovery rates.

1. Two-Stage SWRO Systems

Figures 6-9 illustrate two-stage seawater RO (SWRO) process designs with inter-stage boost which can be used for concentrating seawater to up to 95,000 mg/l TDS. Not shown but considered in the analysis is a two-stage SWRO process with no energy recovery device. Figure 6 shows a turbo booster feeding the first RO stage, powered by second stage brine energy. Figure 7 shows a two-turbo design [14] in which second stage brine pressure is partially let down through a turbo booster feeding the second stage, and then fully depressurized in a turbo booster feeding the first stage. Figure 8 shows an isobaric ERD using second stage brine energy to pressurize some of the first stage feed. Because the second stage brine pressure is higher than the first stage feed pressure, the pressure must be throttled down through a valve. However, the surplus of pressure eliminates the need for a circulation pump. Figure 9 illustrates a "1-1/2" stage design wherein the second stage is fed a combination of first stage brine and additional first stage feed pressurized by an isobaric ERD [15, 16].

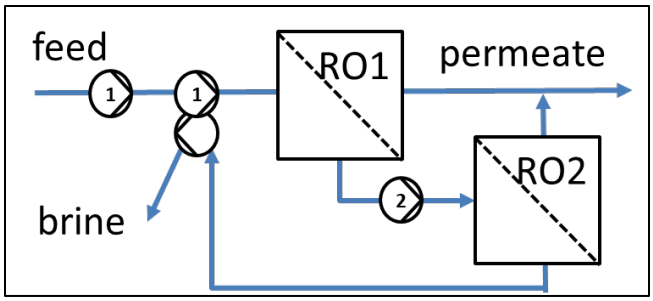


Figure 6. Single Turbo Booster

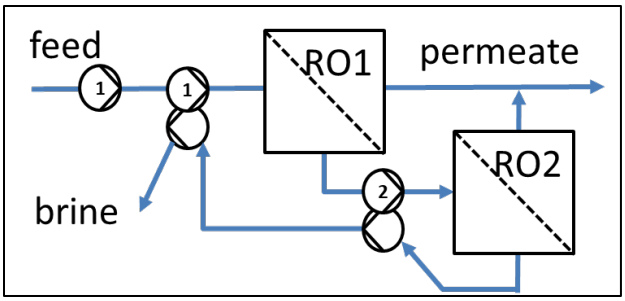


Figure 7. Two Turbo Boosters

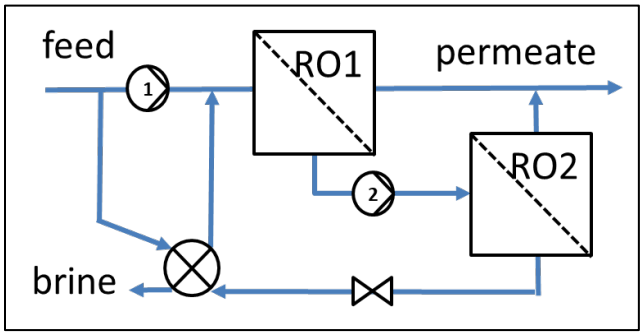


Figure 8. 2 Stages with Isobaric ERD

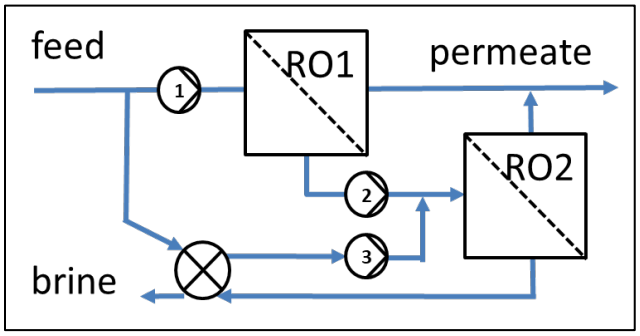
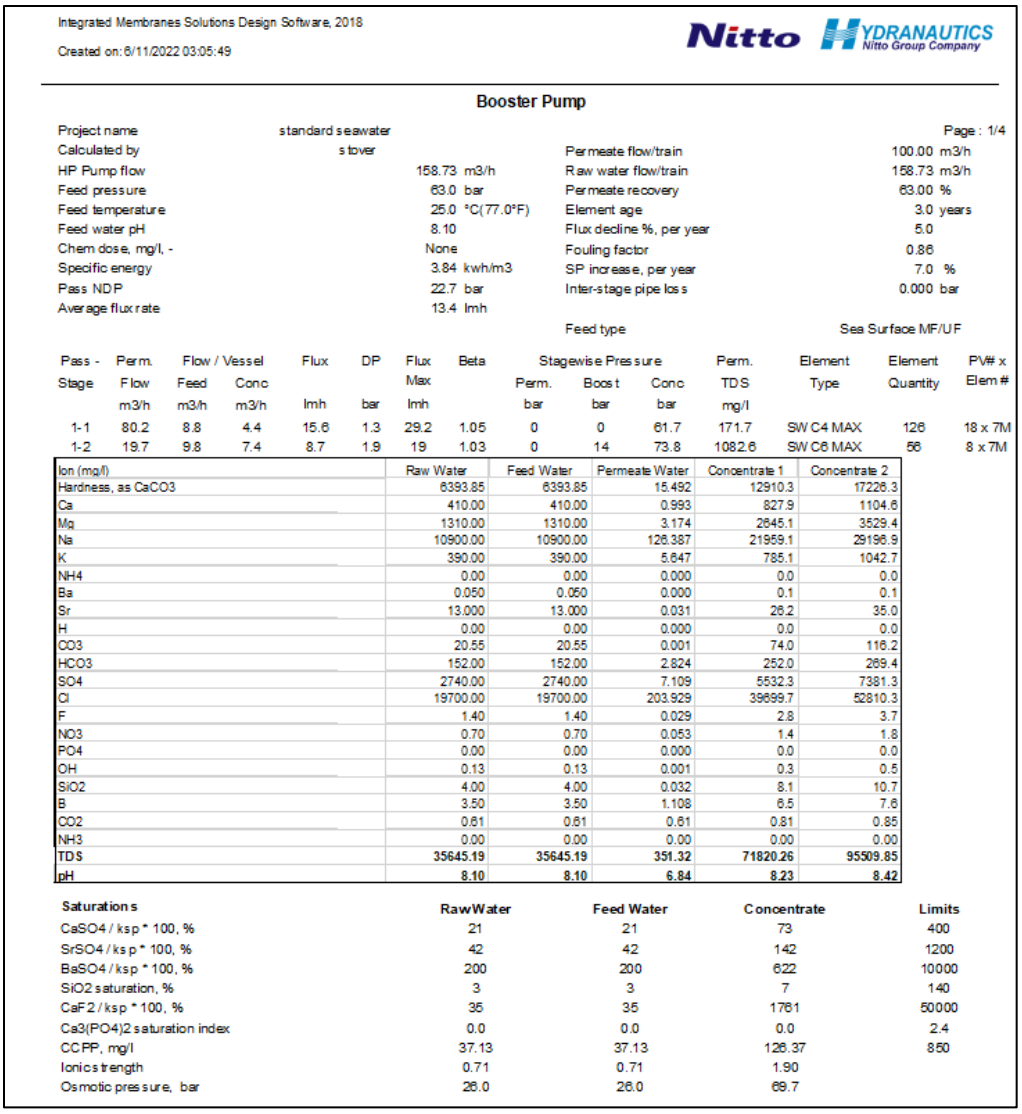


Figure 9. 1-1/2 Stages with Isobaric ERD

Flows, pressures and pump energy consumptions for the assumed systems are given in Table 1. Membrane performance was estimated with IMS Design membrane projection software [17]. An example projection report is given as Figure 10 below. A typical seawater composition of about 35,000 mg/l TDS was used as the feed in each case. Overall recovery rate was 63%. The pump and turbo booster efficiencies listed in Table 1, which are wire to water and include pump, motor and variable frequency drive, were recommended by a manufacturer [18] and are consistent with the author's experience. Isobaric ERD differential pressures drops were assumed to be 1 bar, leakage 1% and volumetric mixing 5%.

Table 1. Energy Consumption Comparison of 2-Stage SWRO Processes

1st stage	no ERD	1 turbo	2 turbo	isobaric 2 stg	isobaric 1-1/2 stg
feed pump flow (m3/h)	158.7	158.7	158.7	158.7	158.7
feed pump pressure (bar)	1.0	1.0	1.0	2.0	2.0
feed pump efficiency	69.0%	69.0%	69.0%	69.0%	69.0%
feed pump energy (kW)	6.4	6.4	6.4	12.8	12.8
pump 1 flow (m3/h)	158.7	158.7	158.7	100.5	100.5
feed pressure (bar)	63.0	63.0	63.0	63.0	63.0
brine flow (m3/h)	78.6	78.6	78.6	78.6	49.8
brine pressure (bar)	61.7	61.7	61.7	63.8	61.7
turbine 1 inlet pressure (bar)	-	73.8	50.1	-	-
turbine 1 outlet pressure (bar)	-	1.0	1.0	-	-
turbo booster 1 efficiency	-	74.4%	74.4%	-	-
turbo booster 1 boost (bar)	-	20.1	13.5	-	-
pump 1 pressure (bar)	63.0	42.9	49.5	65.1	63.0
pump 1 efficiency	77.3%	77.3%	77.3%	77.3%	77.3%
pump 1 energy (kW)	353.6	239.2	276.4	227.8	220.3
2nd stage					
brine flow (m3/h)	58.8	58.8	58.8	58.8	58.8
pressure boost (bar)	14.0	14.0	14.0	14.0	9.8
feed pressure (bar)	75.7	75.7	75.7	77.8	71.5
brine pressure (bar)	73.8	73.8	73.8	75.9	70.9
turbo booster 2 efficiency	-	-	79.0%	-	-
turbine 2 outlet pressure (bar)	-	-	50.1	-	-
pump 2 efficiency	67.7%	67.7%	-	67.7%	67.7%
pump 2 energy (kW)	33.8	33.8	-	33.8	23.6
circulation pump pressure (bar)					2.3
circulation pump efficiency	-	-	-	-	67.7%
circulation pump energy (kW)	-	-	-	-	5.5
total energy (kW)	**394**	**279**	**283**	**274**	**262**
specific energy (kWh/m3)	**3.94**	**2.79**	**2.83**	**2.74**	**2.62**



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Booster Pump

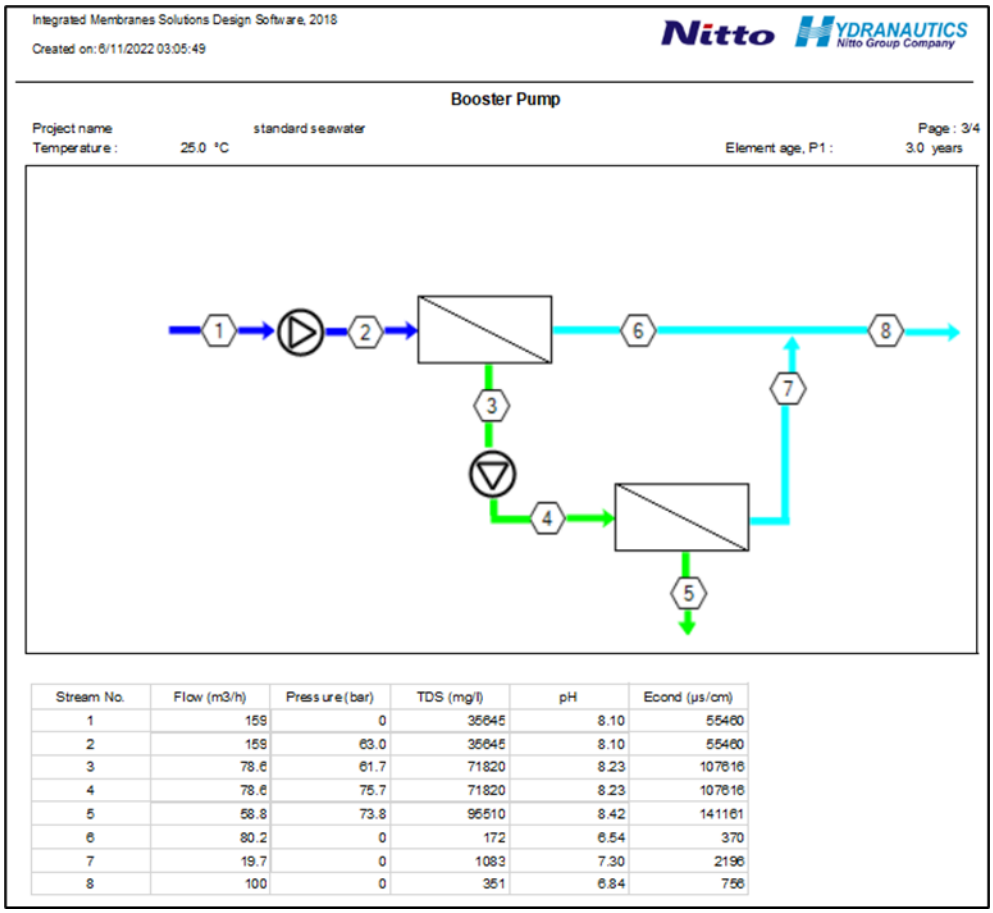
Project name	standard seawater					Page : 1/4
Calculated by	stover			Permeate flow/train	100.00	m3/h
HP Pump flow	158.73	m3/h		Raw water flow/train	158.73	m3/h
Feed pressure	63.0	bar		Permeate recovery	63.00	%
Feed temperature	25.0	°C(77.0°F)		Element age	3.0	years
Feed water pH	8.10			Flux decline %, per year	5.0	
Chem dose, mg/l, -	None			Fouling factor	0.86	
Specific energy	3.84	kwh/m3		SP increase, per year	7.0	%
Pass NDP	22.7	bar		Inter-stage pipe loss	0.000	bar
Average flux rate	13.4	lmh				
				Feed type	Sea Surface MF/UF	

Pass - Stage	Perm. Flow	Flow / Vessel Feed	Flow / Vessel Conc	Flux	DP	Flux Max	Beta	Stagewise Pressure Perm.	Stagewise Pressure Boost	Stagewise Pressure Conc	Perm. TDS	Element Type	Element Quantity	PV# x Elem #
	m3/h	m3/h	m3/h	lmh	bar	lmh		bar	bar	bar	mg/l			
1-1	80.2	8.8	4.4	15.6	1.3	29.2	1.05	0	0	61.7	171.7	SW C4 MAX	126	18 x 7M
1-2	19.7	9.8	7.4	8.7	1.9	19	1.03	0	14	73.8	1082.6	SW C6 MAX	56	8 x 7M

Ion (mg/l)	Raw Water	Feed Water	Permeate Water	Concentrate 1	Concentrate 2
Hardness, as CaCO3	6393.85	6393.85	15.492	12910.3	17226.3
Ca	410.00	410.00	0.993	827.9	1104.6
Mg	1310.00	1310.00	3.174	2645.1	3529.4
Na	10900.00	10900.00	126.387	21959.1	29196.9
K	390.00	390.00	5.647	785.1	1042.7
NH4	0.00	0.00	0.000	0.0	0.0
Ba	0.050	0.050	0.000	0.1	0.1
Sr	13.000	13.000	0.031	26.2	35.0
H	0.00	0.00	0.000	0.0	0.0
CO3	20.55	20.55	0.001	74.0	116.2
HCO3	152.00	152.00	2.824	252.0	269.4
SO4	2740.00	2740.00	7.109	5532.3	7381.3
Cl	19700.00	19700.00	203.929	39699.7	52810.3
F	1.40	1.40	0.029	2.8	3.7
NO3	0.70	0.70	0.053	1.4	1.8
PO4	0.00	0.00	0.000	0.0	0.0
OH	0.13	0.13	0.001	0.3	0.5
SiO2	4.00	4.00	0.032	8.1	10.7
B	3.50	3.50	1.108	6.5	7.6
CO2	0.61	0.61	0.61	0.81	0.85
NH3	0.00	0.00	0.00	0.00	0.00
TDS	35645.19	35645.19	351.32	71820.26	95509.85
pH	8.10	8.10	6.84	8.23	8.42

Saturations	RawWater	Feed Water	Concentrate	Limits
CaSO4 / ksp * 100, %	21	21	73	400
SrSO4 / ksp * 100, %	42	42	142	1200
BaSO4 / ksp * 100, %	200	200	622	10000
SiO2 saturation, %	3	3	7	140
CaF2 / ksp * 100, %	35	35	1761	50000
Ca3(PO4)2 saturation index	0.0	0.0	0.0	2.4
CCPP, mg/l	37.13	37.13	126.37	850
Ionic strength	0.71	0.71	1.90	
Osmotic pressure, bar	26.0	26.0	69.7	

Figure 10a. IMS Design Membrane Projection Report for 2-Stage SWRO [17]



Stream No.	Flow (m3/h)	Pressure (bar)	TDS (mg/l)	pH	Econd (µs/cm)
1	159	0	35645	8.10	55460
2	159	63.0	35645	8.10	55460
3	78.6	61.7	71820	8.23	107616
4	78.6	75.7	71820	8.23	107616
5	58.8	73.8	95510	8.42	141161
6	80.2	0	172	6.54	370
7	19.7	0	1083	7.30	2196
8	100	0	351	6.84	756

Figure 10b. Process Flow Diagram from IMS Design Membrane Projection Report [17]

With reference to the data in Table 1 above, the multi-stage SWRO system with no energy recovery device had the highest estimated energy consumption as expected. The single-turbo system was estimated to consume slightly less energy than the two-turbo system, while the systems with isobaric ERDs consumed the least, the 1-1/2 stage design having the lowest energy consumption for the operating conditions and efficiencies assumed for this exercise. All specific energy values for systems with ERDs were within 8%.

It should be noted that the availability of interstage booster pumps suitable for the service required in the above systems was not verified but is an important consideration. The combination of the relatively high boost pressure and the high suction pressure necessitate use of a specialty pump with a balanced mechanical seal. On the other hand, turbo boosters are readily capable of meeting the required duties and typically do not have mechanical seals.

Additional analysis was conducted in the effort to minimize specific energy consumption for 1-1/2 stage design with isobaric energy recovery. For the process conditions in Table 1, the data in Table 2 show lower specific energy requirements as stage 2 recovery increases while maintaining a constant overall recovery rate. However, high recovery in the second stage decreases concentrate flow to below membrane manufacturer's minimum recommended crossflow, as flagged with red font.

Table 2. Varying Stage Recovery in a 63% Recovery Stage-and-a-Half Isobaric ERD System

Stage 1 Recovery	Stage 2 Recovery	Total Energy (kW)	Specific Energy (kWh/m^3)	Minimum Concentrate Flow (m^3/h)	Maximum Element Flux (lmh)
40.0%	50.4%	253	2.53	2.50	34.3
45.0%	48.2%	254	2.54	2.70	32.9
50.5%	45.6%	258	2.58	2.90	31.1
55.0%	43.2%	264	2.64	3.30	31.1

In addition to energy consumption and associated cost, capital costs and other operating costs are impacted by energy recovery device selection. Capital costs of systems equipped with turbo boosters and isobaric ERDs will be considered and compared in the MLD section below.

2. High Recovery and Ultra High Pressure SWRO Systems

In SWRO applications, at least half the water that is pretreated for desalination is returned to the sea or otherwise disposed of. Retrofitting SWRO systems with brine concentrators can increase an existing plant's permeate production capacity without additional intake, outfall or pretreatment works. This section provides an economic assessment of competing means of desalinating a 65,000 mg/l TDS feed at 48% recovery to produce high quality permeate and a final brine with a TDS of 125,000 mg/l. This final brine TDS cannot be achieved with conventional SWRO equipment rated to 1,200 psi (83 bar) because of the high osmotic pressure of the final brine. Therefore, either OARO, DTRO or UHPRO is required.

The OARO process scheme chosen for analysis is illustrated in Figure 5 above, with a single brine concentrator stage. For this analysis, the author has used Gradiant's CFRO^{TM} process for OARO performance estimation. The UHPRO scheme is a single stage as illustrated in Figure 2 above. Both systems are equipped with isobaric ERDs. Both systems were designed to operate at an average first pass flux of 8.5 lmh. Both include full second pass RO to achieve permeate with less than 100 mg/l TDS. Capital costs were amortized over 20 years at 6% cost of capital. Operating costs include power at $0.06/kWh, spare equipment and membranes, clean-in-place chemicals and antiscalant. RO and UHPRO membrane performance was assessed with WAVE membrane projection software [19] and OARO membrane performance with Gradiant-proprietary test data. The OARO system operates at a maximum of 1,146 psi (79 bar) while the UHPRO system operates at 1,546 psi (106 bar). The economics of the two systems are presented in Table 3 and in Figure 11.

Table 3. Economic Comparison of OARO and UHPRO

	OARO	UHPRO
Permeate m^3/day	15,000	15,000
Recovery Rate	48%	48%
Specific Energy kWh/m^3	4.53	4.86
CAPEX/m^3 (6% int, 20 years)	0.12	0.28
OPEX/m^3 (power, spares, chems)	0.36	0.55
Total /m3 permeate	0.48	0.82

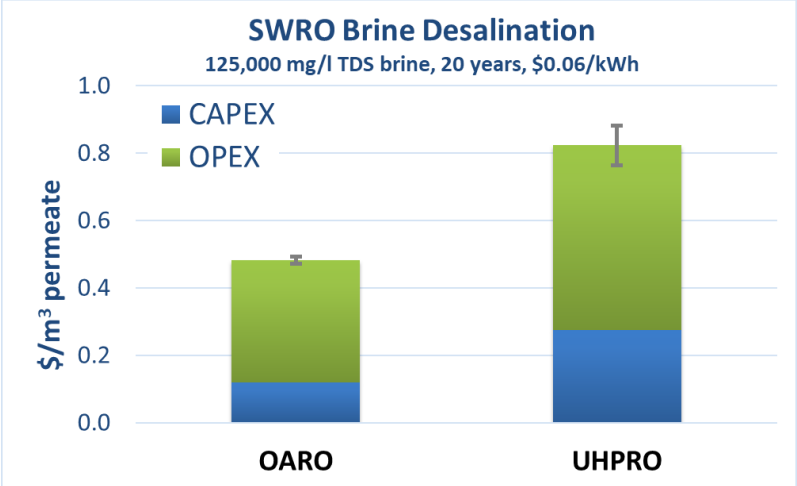


Figure 11. OARO vs UHPRO Costs

Specific energy consumption in the example OARO system was slightly lower than in the UHPRO system because compaction of UHPRO membranes elevates the transmembrane pressure required for a given flux. Compaction is accounted for in projections with UHPRO membranes with a flow factor of 0.3-0.5 [20]. For reference, a new membrane with zero compaction is modelled with a flow factor of 1.0, so compaction in UHPRO operation reduces membrane productivity by a factor of 2-3. In addition, some UHPRO manufacturers recommend high minimum concentrate velocities of at least 6 m^3/h (26 gpm) per pressure vessel, which is about double the minimum recommended velocity for SWRO membranes and may necessitate brine recirculation [21]. Both compaction and brine recirculation impact energy consumption. However, the biggest difference between the two systems is the cost of membranes and high-pressure equipment which can be up to three times higher for UHPRO systems compared to OARO systems designed for the same duty.

3. Minimum Liquid Discharge (MLD) Membrane Brine Concentration

Unlike UHPRO systems, which are limited to final brine concentrations of about 125,000 mg/l TDS, OARO systems offer the ability to concentrate brines to 250,000 mg/l TDS or more depending upon the composition of the dissolved salts [7,8,9]. Such minimum liquid discharge (MLD) systems can be used in lieu of evaporators to achieve brine concentrations near saturation.

Process flow diagrams of OARO MLD systems equipped with turbo boosters or isobaric ERDs or arrays are given as Figure 12. The net flows around the processes are the feed in, RO-quality permeate out and final brine out. Dilute brine and saline permeate streams are recycled in the processes. A portion of the final brine may or may not be returned to the brine concentrator (BC) stages. In all cases, the primary source of pressure is a high-pressure pump feeding the RO stage. Additional smaller pumps in the brine concentrator stages inject permeate either into the permeate sides or the feed sides of upstream stages. Concentrated brine is depressurized through an energy recovery device also feeding the RO stage. Alternately, an interstage pump can be replaced or supplemented with an ERD driven by brine energy as illustrated in Figure 11c. Many possible process configurations are not shown, including those for very high TDS sources that are fed directly to the BC stages.

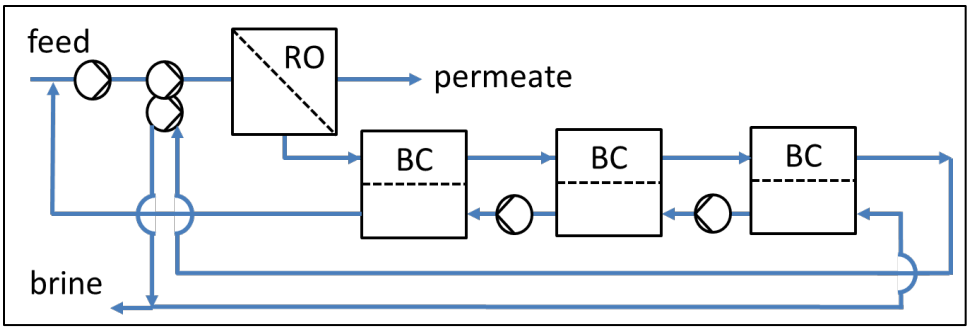


Figure 12a. OARO Process with Turbo Booster

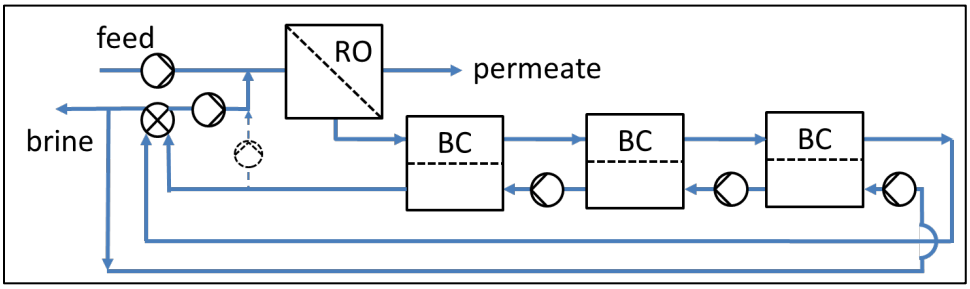


Figure 12b. OARO Process with Isobaric ERD (Array) with Possible Additional Pump Shown in Dashed Lines

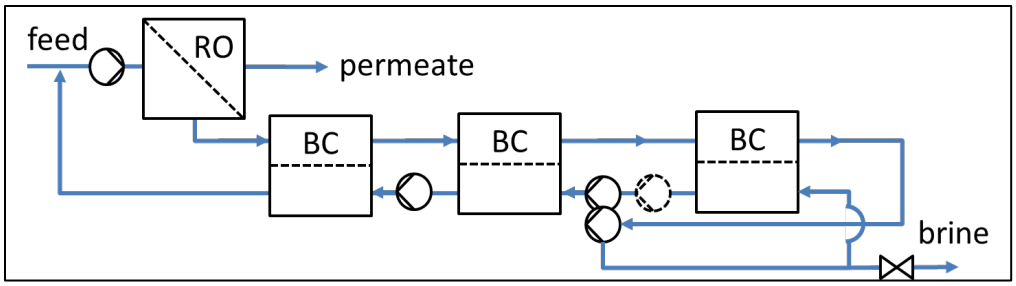


Figure 12c. OARO Process with Turbo Booster Between BC Stages with Possible Additional Pump Shown in Dashed Lines

In OARO systems as in all RO systems, the optimum choices of energy recovery device and system operating conditions are reflected in the minimum total cost of water production. Specific energy consumption, capital cost (CAPEX), operating cost (OPEX) and total cost of water production for SWRO brine concentration processes were computed as a function of final brine concentration and presented in Figures 13, 14 and 15. The feed for all data was standard 35,000 mg/l TDS seawater concentrated to 65,000 mg/l TDS in an upstream SWRO process not included in the energy or cost calculations. Feed flow rates for all cases was 25,000 m^3/d. Energy recovery devices were applied to the RO stage feed for final brine concentrations of 165,000 mg/l TDS or lower and between BC stages as illustrated in Figure 12c for higher final brine concentrations. Specific energy includes only the high-pressure pumps illustrated in Figure 12. CAPEX was amortized over 20 years with 6% cost of capital. OPEX includes energy at $0.06/kWh, antiscalant, clean in place chemicals, spare parts and membranes.

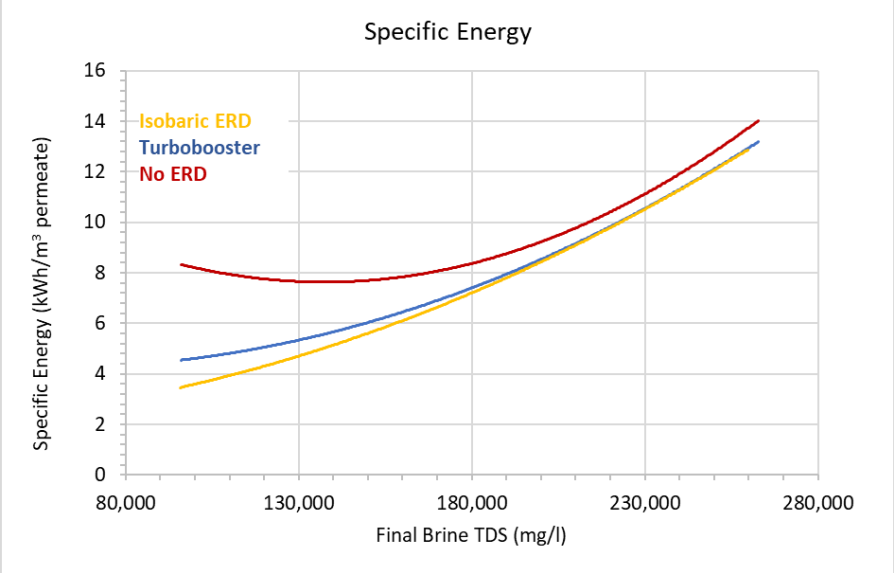


Figure 13. OARO Energy Consumption per Unit of Permeate vs Final Brine Concentration

Figure 13 shows that energy recovery devices can cut OARO energy consumption in half compared to operating with no ERDs. However, the advantages of using an ERD decrease with increasing final brine concentration. This is because the amount of brine and therefore the amount of energy available to recover from the brine decrease with increased recovery. Note that the apparent minimum in specific energy consumption at around 145,000 mg/l for the no-ERD case is an anomaly of varying recovery rate while maintaining a constant feed flow rate. Absolute energy consumption in units of kW increases monotonically with increasing final brine concentration for all three ERD options as illustrated in Figure 14 below.

Figure 13 also shows that, while energy consumption with isobaric ERDs is lower than with a turbo booster at lower final brine concentrations, the difference vanishes at higher brine concentrations. This is because isobaric ERD mixing increases the salinity of recycled permeate, elevating upstream pumping energy requirements. Mixing is an efficiency loss that is magnified in the highest TDS BC stages because they are less efficient than the lower TDS stages. Specifically, a greater volume of dilute brine must be recycled to upstream stages in a system with ERD mixing compared to a system without mixing.

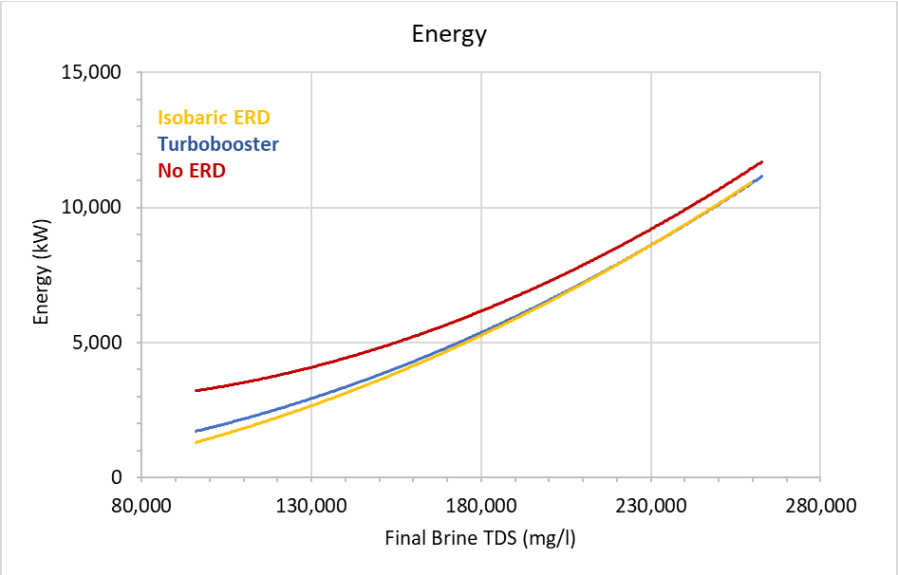


Figure 14. OARO Energy Consumption vs Final Brine Concentration

The OPEX curves in Figure 15 follow the same trends as the specific energy curves in Figure 13 and for the same reasons because about 67% of OPEX is the cost of power with the assumptions made in the analysis.

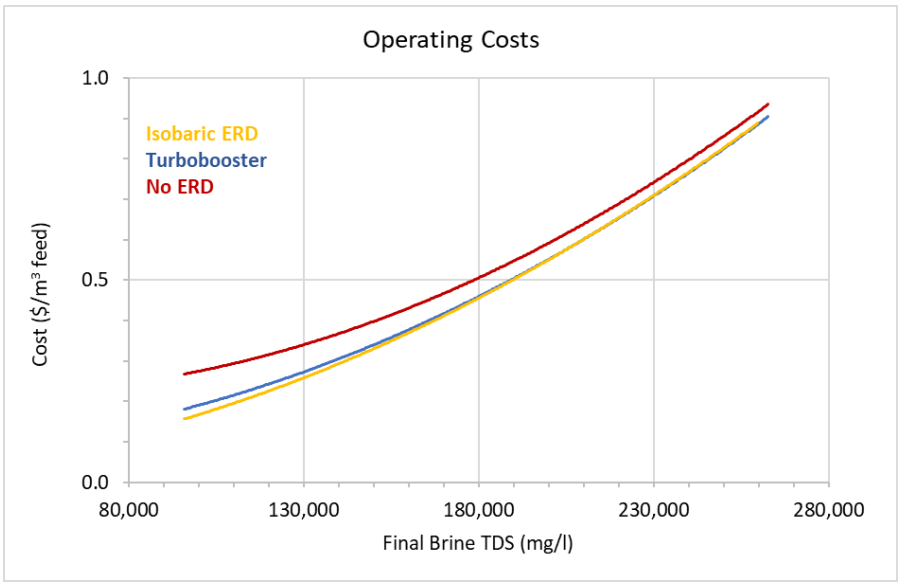


Figure 15. OARO OPEX per Unit of Feed vs Final Brine Concentration

Total system capital cost divided by feed flow (specific capital cost) as a function of brine concentration for the three ERD options is presented in Figure 16. Costs were nearly identical over a broad range of brine TDSs, illustrating both that ERD costs and cost differences between the ERDs are almost negligible relative to other system costs.

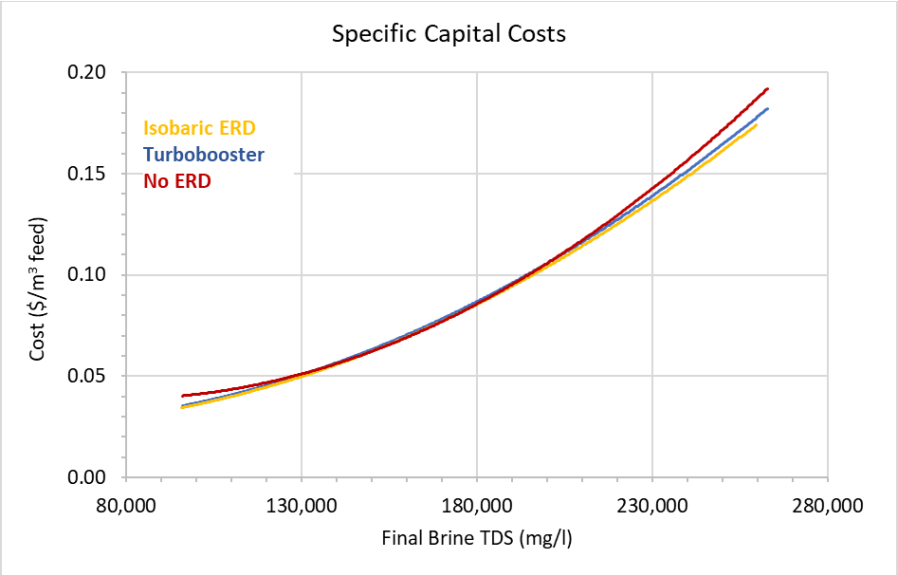


Figure 16. OARO CAPEX per Unit of Feed vs Final Brine Concentration

Figure 17 shows that use of energy recovery devices in OARO decreases the total cost of water treatment by 25% or more for final brine concentrations of up to 100,000 mg/l TDS compared to systems with no ERD. The cost savings advantage of using ERDs decreases at high final brine TDSs as the quantity of brine reduces. Also, at high brine concentrations, the total cost of treatment is nearly the same regardless of which type of ERD is applied for the same reasons the CAPEX and OPEX curves converge in Figures 15 and 16.

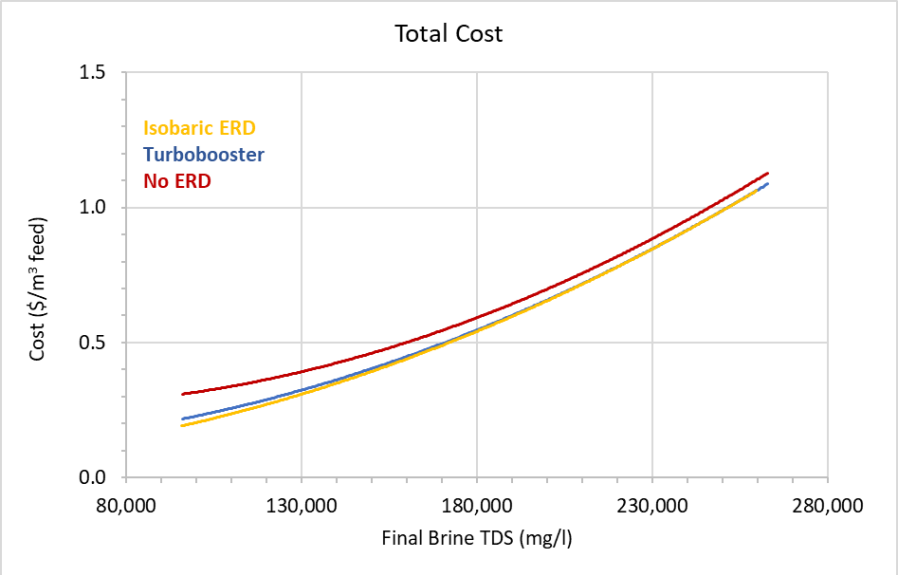


Figure 17. OARO Total Cost per Unit of Feed vs Final Brine Concentration

Although energy consumption and capital cost of MLD systems equipped with turbo boosters and isobaric ERDs may be similar over a broad range of brine TDS endpoints, other factors including maintenance and system complexity, control and flexibility can differ and should be considered. Isobaric ERDs must be operated with a high-pressure circulation pump (the system illustrated in Figure 8 being one exception), but a circulation pump is not required with a turbo booster. If the feed and brine flows to

an isobaric ERD are not equal, additional pumps may be required. Figure 12b illustrates incorporation of an additional high-pressure pump in the case of excess low-pressure supply in an OARO system with isobaric ERD(s). Similarly, if the pressure delivered by an interstage turbo booster is not sufficient, an additional high-pressure pump must be operated in series with the ERD as illustrated in Figure 12c. Generally, a system with fewer moving components can have lower maintenance requirements, all else equal. Also, simpler systems can be more reliable than complex systems.

Regarding process control, because high-and low-pressure flows through an isobaric ERD are independent, systems equipped with them can therefore be more challenging to operate. On the other hand, isobaric ERDs are positive displacement devices with substantially flat efficiency curves while turbo boosters are centrifugal devices with efficiencies that vary with flow and pressure. As such, systems equipped with turbo boosters can suffer from reduced performance and/or higher energy consumption if operating conditions shift from those corresponding to the best efficiency point including, for example, membrane aging or changes in water salinity or temperature.

Perhaps the most important aspect of the analysis in this section is exhibited in Figure 17: the cost of brine treatment with OARO can be less than \$1.00/m^3 treated regardless of energy recovery type. This compares favorably with the total cost of mechanical vapor compression evaporation, which can be over \$3.50/m^3 for small and mid-sized systems [19], and with the cost of desalinated water production with green-field SWRO, which can range from \$0.30 to \$2.00/m^3.

To further explore the relative cost of brine desalination and green-field SWRO, the total cost of water production per unit of permeate flow with OARO as a function of brine TDS is presented in Figure 18 below. Applying the same capital and operating cost assumptions to SWRO processes consuming 3.5 kWh/m^3 energy and adding estimated costs for the intake, outfall and pretreatment works that would be required, total cost of water ranged from \$0.57 to 0.62/m^3 over the system sizes considered. This analysis suggests that desalinating SWRO brine with OARO up to 150,000 mg/l final brine TDS can be less expensive than desalinating seawater.

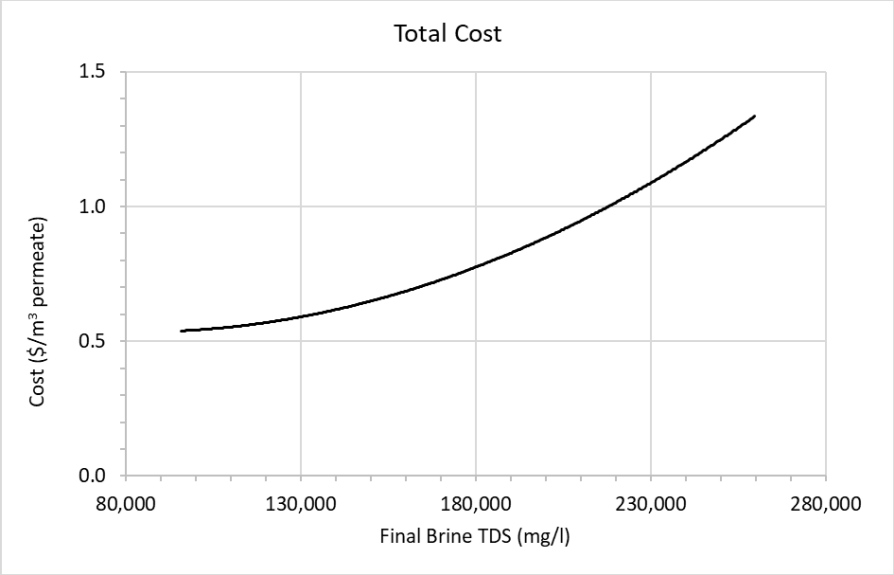


Figure 18. OARO Total Cost per Unit of Permeate vs Final Brine Concentration

VI. OPPORTUNITIES FOR FURTHER RESEARCH AND DEVELOPMENT

The application of membranes to brine concentration is in its infancy, and the employment of ERDs in those applications is even more immature. Due to the wide array of possible OARO process configurations, the opportunities for achieving cost savings through creatively employing these devices is vast.

V. CONCLUSIONS

Incorporating energy recovery devices in high-recovery RO desalination and membrane brine concentration applications can reduce the total cost of water treatment by 25% or more compared to operating without energy recovery. Isobaric ERDs provide greater cost savings than turbo boosters in seawater brine concentration applications up to 100,000 mg/l TDS final brine concentrations. However, at higher brine concentrations, the specific energy and costs requirements are about the same regardless of ERD choice. Therefore, other factors associated with ERD choice such as system complexity and flexibility become more important. For the process assumptions made in the analysis presented in this paper, SWRO brine can be concentrated to up to 250,000 mg/l TDS with OARO for less than $1.00 per m^3 of brine treated ($2.54 per 1000 gallons), which is substantially cheaper than brine concentration with an evaporator. Permeate production from SWRO brine with OARO can be cost competitive with greenfield SWRO desalination. The data and discussion presented in this paper suggest that there are significant opportunities for achieving cost savings in advanced and emerging reverse osmosis applications through application of ERDs and other possible process innovations.

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