Water Reclamation with Reverse Osmosis – Staging and Energy Recovery

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ABSTRACT

Reverse osmosis (RO) technology is a required unit operation in water reclamation systems that produce potable water from treated municipal effluent. Staging design can have a major influence on permeate productivity and scaling potential in these systems, a “detached” third stage can increase process reliability and permeate productivity, and incorporation of energy recovery devices can significantly lower power consumption, all benefiting operating cost. This research considers RO process design options to increase energy efficiency and/or permeate recovery rate in potable reuse.

INTRODUCTION

Reverse osmosis (RO) technology is critical in water reclamation systems designed to produce potable water from treated municipal effluent. This research considers RO process design and operating parameters that impact the most important water reclamation plant operating metrics, namely reliability, permeate productivity, flexibility, and energy efficiency.

A predominant challenge to reliability is avoidance of membrane fouling and scaling. Fouling or scaling can significantly decrease membrane productivity, necessitate maintenance interventions, and reduce membrane longevity. Effective pretreatment is vital to mitigate fouling and scaling risks; however, optimal RO system design and operation are equally important. Factors influencing fouling and scaling potential include membrane selection, flux distribution, and crossflow throughout an RO system. The latter are enhanced or constrained by the system's staging design.

Generally, high permeate recovery rates are desired, thereby maximizing permeate production and minimizing concentrated residual generation. Sparingly soluble salts such as silica and hardness limit maximum recovery rate from municipal wastewater to 85-94%. Single stage recovery rates are typically limited to 40-55% by membrane performance, such that multiple stages in series are required for achieving target recovery rates. However, the use of multiple stages can complicate design considerations.

Although municipal wastewater is notoriously consistent in terms of composition, RO process flexibility is desired as water temperature changes and as membranes age and foul. Therefore, process designs that facilitate flexible operation, especially at elevated recovery rates, are beneficial.

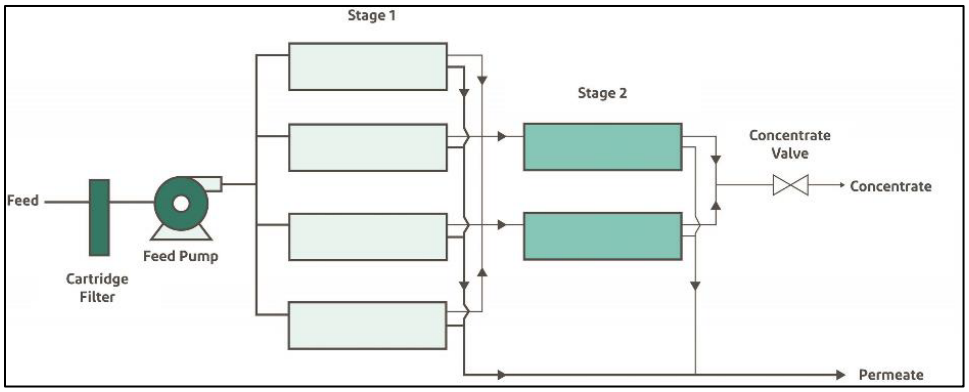
Energy efficiency is also a primary concern, given that energy consumption is often one of the highest operating cost components in RO systems used for water reclamation. Emerging low-pressure energy recovery devices (ERDs) can significantly reduce energy consumption and operating costs. ERD type and incorporation are both critical for maximizing the energy-saving potential of these devices. For example, adding low pressure ERDs to an existing system can both save energy and allow a poorly performing high-pressure pump to operate at a more optimal duty point.

REVERSE OSMOSIS PROCESS STAGING

Recovery in reverse osmosis (RO) systems, defined as the ratio of permeate flow to feedwater flow, is a measure of system efficiency. Recovery rate is proportional to the number of membranes in series. RO systems are arranged with multiple stages to increase system recovery without exceeding the single-element recovery limits. Each stage provides 40-55% recovery, so two stages are needed for 75% recovery and three stages for 87.5% recovery, etc. To compensate for the permeate that is removed and maintain adequate concentrate crossflow through each stage, the number of pressure vessels in parallel in each stage is decreased in the direction of feed flow. Typical staging ratios for 6-element pressure vessels in brackish water applications are 2:1

in the first pass and 3:1 in the second pass. A typical two-stage system using a staging ratio of 2:1 is shown in Figure 1. (Dupont, 2024)

Figure 1: *Two-Stage Reverse Osmosis System (Dupont, 2024)*

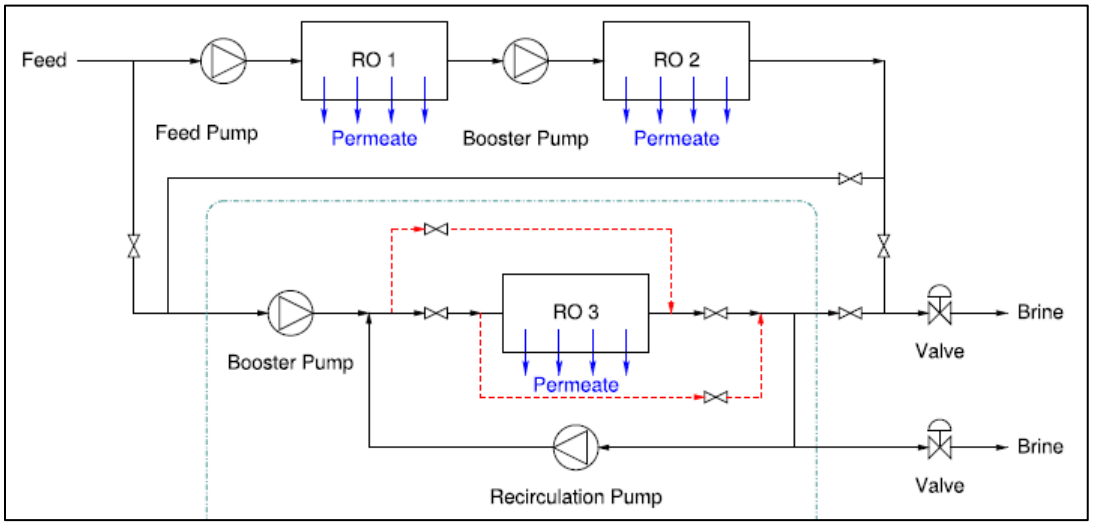


Reverse osmosis treatment of municipal wastewater typically operates at about 85% recovery, thereby staying well below concentration factors that risk precipitation of sparingly soluble salts. This can be achieved in three stages. Precipitation, if it occurs, is most severe on the membrane surfaces of the third stage, where concentrations are the highest. Several process designs have been proposed as an alternative to a simple 3-stage arrangement, nominally enabling higher recovery and reduced scaling risk. These alternative designs include flow reversal reverse osmosis (FRRO), closed circuit reverse osmosis (CCRO), and pulse flow reverse osmosis (PFRO) systems that periodically flush feed-brine channels with low-salinity feedwater. However, studies have shown that, while the energy consumption requirements of these alternative designs are similar to conventional 3-stage systems, frequent pauses for flushing are required, reducing productivity over the long term. Other challenges include inadequate flushing, which elevates energy consumption, or excess flushing, which reduces recovery rate (Wang, et.al., 2022). Also, because all membranes in a system are periodically exposed to maximum salinity, clean in place (CIP) requirements can be more extensive than in a conventional multi-stage system where only the third stage is exposed to the maximum salinity.

For applications with especially high scaling potential, the third stage can be detached from the first two. Second stage brine pressure is broken through a brine valve or energy recovery device to recover brine energy, then this stream is repressured to feed the third stage. The third stage can then be serviced independently when required while the first two stages operate continuously.

An example of this approach is the variable configuration RO (VCRO) process, which is an enhanced detached-third-stage design illustrated in Figure 2 (Li & Li, 2024). VCRO allows the operator to independently flush or clean, recirculate brine through, or reverse flow to the third stage, thereby enabling the high recovery rates and scaling resistance benefits offered by FRRO, CCRO, and PFRO, while the first two stages operate continuously like a traditional RO system. It is also possible to equip the system with a redundant third stage, which can be financially viable since the third stage typically houses less than 15% of the total number of membrane elements and thus requires a relatively small footprint.

Figure 2: *Variable Configuration RO (VCRO) with Detached Third Stage (Li, 2024)*



In addition to recovery rate, membrane flux is an important consideration in RO process design. Excessively high flux can result in local premature fouling, while low flux means underutilization of membranes. Flux balance can be achieved with pressure boosting between stages and/or permeate throttling. The system depicted in Figure 2 above includes booster pumps for flux balancing. Another method employs a mixture of membrane types within each stage, with low permeability membranes in the front of the vessels and high permeability membranes in the back (Michols, et.al., 2005). Such a membrane arrangement is called hybrid or internally staged. These flux balancing approaches can be combined.

ENERGY RECOVERY DEVICES

In RO processes, a substantial fraction of the water pressurized and fed to the membranes exits the membrane array as a high-pressure reject stream. Several types of devices have been developed to capture otherwise wasted pressure energy and recycle it into the RO process. Of these, turbochargers or turbo boosters and isobaric devices have emerged as the most widely used due to their efficiency and practicality (Stover, 2004). To date, these have most commonly been applied in high pressure RO applications such as seawater desalination. Nearly 100% of modern seawater RO systems with greater than 50 gpm permeate production capacity employ energy recovery devices (ERDs).

Figure 3 illustrates a typical configuration of a turbo booster in a single-stage RO process. Feed water is partially pressurized by a high-pressure (HP) pump and fed to the pump side of the turbo booster. Brine exiting the membranes depressurizes through the turbine side of the turbo booster, rotating an impeller running on the same shaft as the turbine. Feed with boosted pressure flows to the membranes. Energy is saved through reduction of HP pump pressure. The turbine discharge pressure is maintained at a minimum of 15 psi (1 bar) to inhibit cavitation in the device, but discharge pressure can be higher as may be advantageous, for example, for conveying brine. Turbo boosters arranged as shown in Figure 3 are not recommended for recovery rates of greater than 60% because the impeller becomes more than 2.5 times the size of

the turbine. Devices with such a large flow disparities suffer from low efficiency and limited flexibility.

Figure 3: *Turbo Booster ERD in a Single-Stage RO System*

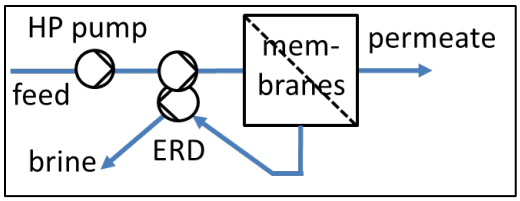


Figure 4: *Isobaric ERD in a Single Stage RO System*

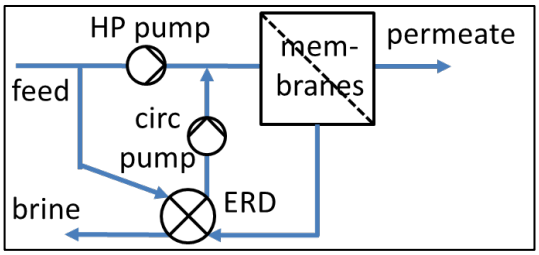


Figure 4 illustrates a typical configuration of an isobaric ERD or ERD array in a single-stage RO process. A percentage of the feedwater approximately equal to the permeate flow is fed to the membranes through a HP pump. Brine exiting the membranes enters the ERD array where its pressure is transferred to the balance of the membrane feedwater. Pressurized feedwater from the ERD merges with the discharge of the high-pressure pump to feed the membranes. Energy is saved through reduction of high-pressure pump flow. The depressurized brine discharge from the ERD is maintained at a minimum of 15 psi (1 bar) to inhibit cavitation in the device(s), but discharge pressure can be higher as may be advantageous, for example, for conveying brine. Because isobaric ERDs do not impel flow or boost pressure, a circulation (circ) pump is employed in the high-pressure loop connecting the membranes and the ERD. In multi-stage systems, this pump can be positioned between stages to serve as both an interstage boost pump and an ERD circulation pump.

Turbochargers and isobaric energy recovery devices are available for low pressure (< 450 psi or 31 bar) applications. Their use in multi-stage systems, such as those used to treat municipal wastewater, are presented and assessed in the following sections.

ENERGY RECOVERY IN MULTI-STAGE RO DESIGNS

As described above, energy recovery devices are used to recycle energy from the brine stream of an RO process to one of the membrane feed streams. In a multi-stage RO system equipped with isobaric energy recovery, the ERD can feed the first stage as illustrated in Figure 6. Such a system without an ERD is illustrated in Figure 5. Both systems are equipped with an interstage booster pump to balance flux between stages. In the case with isobaric ERDs, the boost pump also serves as a circulation pump. A third process configuration option for the same plant is illustrated in Figure 7. Termed 1.5 stages, the isobaric ERD feeds the second stage with system feedwater, which merges with first stage brine (Cameron, 2008; Bosleman, 2019). To achieve the same overall recovery rate as the systems illustrated in Figures 5 and 6, the stages in Figure 7 must operate at higher recovery rates.

Figure 5: *Two Stage System with No ERD*

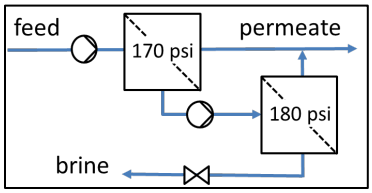


Figure 6: *Two Stage System with Isobaric ERD*

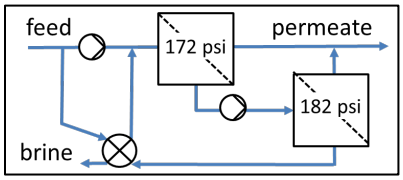
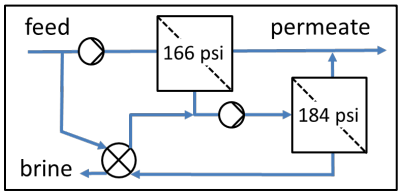


Figure 7: *1.5 Stage System with Isobaric ERD*



CASE 1 – WATER RECLAMATION PLANT I – A water reclamation plant in Southern California is configured as illustrated in Figure 5 above. The permeate flow rate is about 3,500 gallons per minute (gpm) and operates at a recovery rate of about 85%. The interstage booster pump feeds the second of three stages. Stages 2 and 3 in Figure 5 are combined for simplicity. The pressures shown in Figure 5 are feed pressures measured in the plant. The pressures shown in Figures 6 and 7 were estimated for the plant's water composition, membrane design, and overall recovery rate but with flows altered to accommodate implementation of isobaric ERDs.

Estimated energy consumption rates for the three systems, annual savings versus no ERD, and return on investment (ROI) for retrofit equipment are presented in Table 1. SEC is defined as high pressure plus interstage boost pump energy consumption divided by permeate flow in units of 1,000 gallons (kgal) per hour. Savings were computed with a power tariff of $0.13/kWh. ROI is the capital cost of the retrofit installation divided by the savings in months (m).

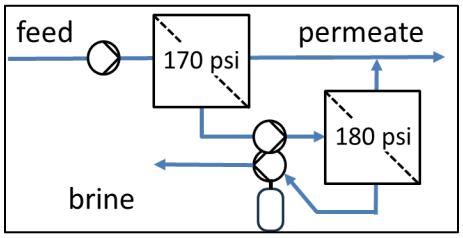
Table 1: *Energy Consumption and Savings for Southern California Water Reuse Plant I for Retrofit with Isobaric Energy Recovery*

System Design	SEC (kWh/kgal)	Savings vs No ERD ($/y)	ROI for Retrofit (m)
No ERD	5.6	N/A	N/A
Two Stage with Isobaric ERD	5.0	58,000	12
1.5 Stage with Isobaric ERD	4.8	75,000	10
Two Stage with Motor Driven Turbo Booster	5.4	27,000	18

Although the first stage feed pressure will increase slightly with the implementation of isobaric ERDs due to minor internal mixing within the ERDs, in the two-stage configuration illustrated in Figure 6, energy consumption will reduce because of the reduction in high pressure pump flow. With the 1.5 stage configuration illustrated in Figure 7, flow to the first stage and pressure drop through the stage will reduce, resulting in a lower feed pressure despite the elevation of stage recovery rate from 47% to 55%. As a result, the 1.5 stage design will provide the lowest energy consumption. The cost to retrofit isobaric energy recovery will be paid back with energy savings in less than one year.

The same plant employs motor-driven turbo boosters as interstage boosters on some trains. This process design is illustrated in Figure 8 below. The approximate energy consumption performance is presented as the last line in Table 1 above. The motor, equipped with a variable frequency drive, enables adjustment of turbo booster speed. However, because turbo booster turbines operate optimally at about 10,000 revolutions per minute (rpms) and the motors used operate at about 3,500 rpm, the turbo boosters only provide about 40% energy recovery efficiency. Although they do not save as much energy as isobaric ERDs, their 15-30% lower installed capital cost makes motor driven turbo boosters potentially financially viable in this application.

Figure 8: *Two Stages with Motor Driven Turbo Booster*



Isobaric ERDs are modular, so if greater ERD capacity is required for a larger plant, more devices are implemented in parallel. Performance of multiple devices operating in parallel is about the same as a single device. Therefore the above conclusions are independent of flow rate.

CASE 2 – WATER RECLAMATION PLANT II – Another water reclamation plant is considering implementing either a turbocharger to boost interstage pressure (“interstage turbo”) or an isobaric energy recovery device to reduce high pressure pump flow with a motor-driven interstage boost pump. The alternative ERD designs are illustrated in Figures 9 and 10 below, while the plant without energy recovery would simply have an interstage boost pump and a brine valve after the second stage. The first stage of the RO train will operate at about 210 psi and the second stage at 230-240 psi. The combined permeate flow from the two stages will be 1,600 gpm. Isobaric ERDs for this plant will cost about $45,000 including peripheral equipment such as a device rack, required instruments, and extra piping. However, the size and cost of the high-pressure pump is reduced, such that the net capital cost premium for isobaric energy recovery for this $1M plant will be about $3,000 which is within the rounding error of these estimates. The cost to build the plant with a turbocharger is actually about $36,000 less than the cost without it because the turbo eliminates the more expensive interstage boost pump and associated controls and reduces the duty of the high-pressure pump. Therefore, the ROI for implementing either energy recovery device type is instantaneous.

Figure 9. *Interstage Turbo*

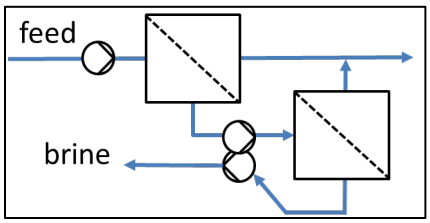


Figure 10: *Isobaric ERD with Interstage Booster Pump*

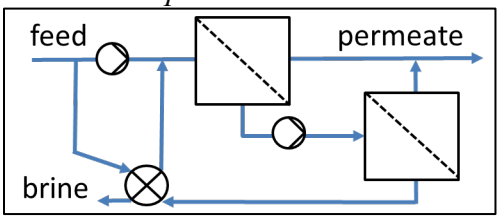


Table 2 below compares the capital cost and annual power cost of the two ERD alternatives. The isobaric device installation is more expensive than the turbocharger installation by about $40K, however, 6.4% less power is required, providing a savings of $15K per year. Maintenance costs are about the same for the two systems, with the turbocharger requiring periodic bearing service but avoiding the cost of interstage boost pump service while PX devices typically require no service. The resulting payback for the isobaric ERD system premium is 2.7 years. In addition, with easily adjustable interstage boost pressure and with positive displacement energy recovery, the isobaric ERD design will provide greater flexibility in the face of changing water quality and aging and fouling membranes, which is a valuable operational advantage that doesn't show up as a cost.

Table 2: *Cost Analysis for Water Reclamation Plant II Equipped with Interstage Turbo Booster versus Isobaric ERD*

System Design	Power ($/y)	Capital Cost ($)	ROI (y)
Interstage Turbo	234,000	972,000	baseline
Isobaric ERD	220,000	1,012,000	2.7

CASE 3 - WATER RECLAMATION PLANT III – Another southern California water reclamation plant employs a motor-driven interstage turbo booster to feed a third stage as illustrated in Figure 11 below. The interstage turbo booster suffers similar low efficiency as the device described in Case 1 above, for the same reason, namely the motor slows the turbo booster to far below its optimum rotation speed. SEC for this stage is about 1.2 kWh/kgal. However, of greater concern for the plant is that the third stage is producing almost 30% less permeate than it was designed for despite the turbocharger motor operating at 100% of its rated speed.

Figure 11. *Motor-Driven Interstage Turbo Booster*

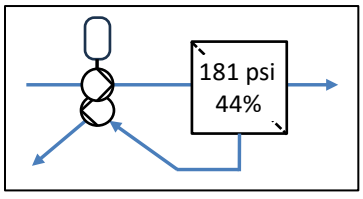
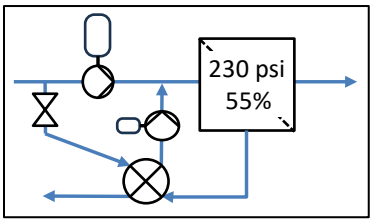


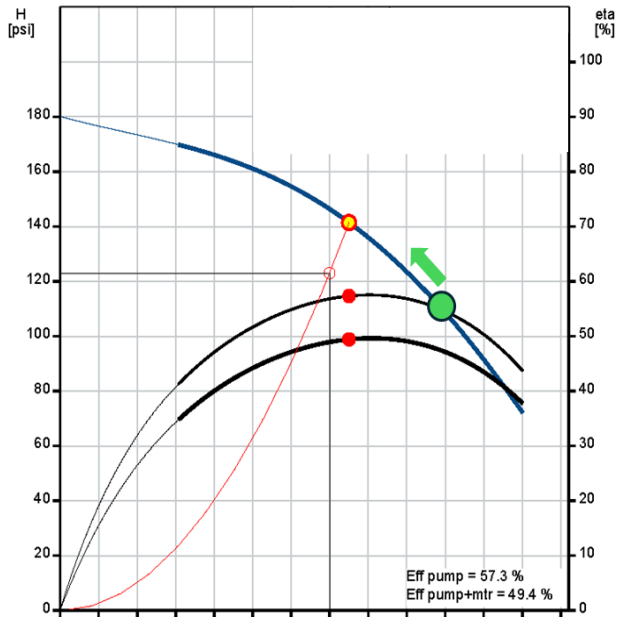
Figure 12: *Isobaric ERD with Interstage Booster Pump and Circulation Pump*



An alternative process design using an isobaric ERD, an interstage boost pump, and a circulation pump is illustrated in Figure 12 above. For this plant, replacement of the interstage turbo with a smaller conventional interstage booster pump will allow operation at a higher pressure and a higher recovery rate. Specifically, feed pressure will increase from the current 181 psi to an estimated 230 psi and recovery rate will increase from 44% to 55%. The resulting SEC will be the same as with the turbo booster (1.2 kWh/kgal) but permeate production will increase by 27% with no other process changes. The equivalency of SEC between these two designs is particularly interesting because the pressure of the feed stream to the ERD is broken through a valve. This energy loss is made up for by the higher efficiency of the isobaric device. The economics are not only related to energy efficiency, but also to water production and the costs of alternative methods to produce more water at the site such as adding an additional train. It's difficult to calculate payback without more information, but the added capacity would be expected to be significantly cheaper than adding an additional RO train in parallel.

CASE 4 - WATER RECLAMATION PLANT III – A large demonstration train is operating without energy recovery at another water reclamation plant in Southern California. The centrifugal high-pressure pump is operating at lower head and higher flow than anticipated in the design, resulting in reduced permeate production. Implementation of isobaric energy recovery feeding the first stage in parallel with the high-pressure pump as illustrated in Figure 6 above would provide the following 3 benefits: it would 1) supplement membrane feed flow, 2) decrease high pressure pump flow, and 3) elevate feed pressure. Anticipated movement of the high-pressure pump duty point on its curve is illustrated in Figure 13, with the green dot located at the current duty point and the small yellow dot the new duty point. Permeate production should increase by about 17% while energy consumption should reduce by almost 13%. The economics of this approach are also primarily tied to the ability to make more drinking water without additional membranes, and this would be likely be the lowest CAPEX & OPEX approach to add additional capacity at this facility.

Figure 13: *Movement of High-Pressure Pump Duty Point with Implementation of Isobaric ERD*



CASE 5 – MULTI-STAGE PROCESS WITH AND WITHOUT DETACHED THIRD STAGE – In the four systems described above, the third stage is fed with pressurizing brine from the second stage. Alternately, as described in the introduction, second stage brine pressure can be broken through a valve then repressured to feed the third stage. Doing so offers the opportunity to take the third stage offline for flushing or cleaning without stopping permeate production with the first two stages, increasing overall process reliability and long term permeate productivity. However, there is an energy penalty for operating with a detached third stage unless energy recovery devices are applied.

Three three-stage systems are illustrated in Figures 14 through 16, using the flows, fluxes and recovery rates from the water reclamation plant described in Case 1 above. The third stage in Figure 14 is fed only with second stage brine pressure. Feed to the third stage in Figure 15 is repressurized after passing through a brine valve, resulting in about a 25% increase in energy consumption compared to the non-detached third stage system. Note, however, that with a properly selected third stage pump, some or all of the second stage brine pressure could be passed through to the third stage when the third stage is operated, reducing third stage pump power demand. In Figure 16, isobaric ERDs are incorporated to feed the first stage and the third stage using second stage and third stage brine energy, respectively. Overall energy consumption will increase by about 3% compared to the non-detached third stage design, but the process will provide all the benefits of a detached third stage including being able to implement a semi-batch, flow reversal, or similar strategy to increase overall recovery without adding the CAPEX required to implement these processes into the first two stages. In other words, this approach significantly reduces CAPEX while minimizing OPEX when maximizing system recovery.

Figure 14: *Non-Detached Third Stage*

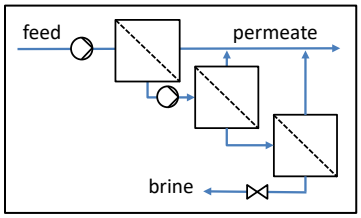


Figure 15: *Detached Third Stage*

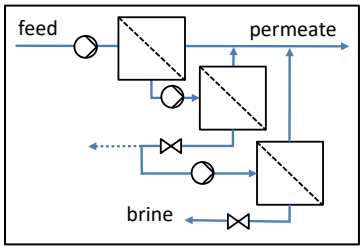
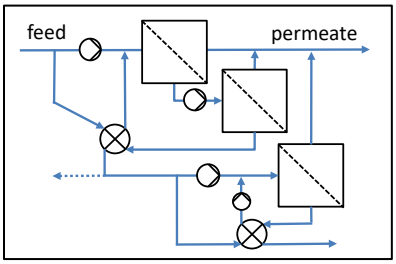


Figure 16: *Detached Third Stage with Isobaric ERD*



CONCLUSIONS

This paper presented a range of established and novel RO process design alternatives for water reuse applications, focusing on staging design, ERD type, and ERD installation alternatives. Utilizing real operational data from three existing water reclamation plants and design data from two additional plants, the study provided a quantitative evaluation of process and device alternatives while addressing a balance of qualitative performance factors. Isobaric ERDs with interstage boost pumping were found to provide the lowest specific energy consumption performance compared to 1) turbochargers and 2) no ERDs, returning the cost of capital investment in the devices in less than one year in some cases and providing additional permeate production with minimal energy cost penalty in other cases. Furthermore, ERDs can enable detachment of a third stage and access to the operating benefits of these designs with minimal energy increase compared to conventional (a.k.a., non-detached) 3-stage systems. The findings have potential implications for enhancing the efficiency of water reclamation operations, both domestically and internationally.

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