HIGH RECOVERY SEAWATER REVERSE OSMOSIS

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ABSTRACT

Recovery rate in desalination is defined as the ratio of product water flow rate to system feed flow rate. In reverse osmosis, the optimal recovery rate produces the lowest total cost of desalinated water production for the particular project. Generally higher recovery rates result in lower specific capital costs and higher operating costs, the latter due to the higher energy consumption associated with higher salinity brine. Lower recovery rates result in lower energy consumption but higher specific capital costs, as higher capacity equipment is necessary for a given amount of permeate.

Since the early 2000s, seawater reverse osmosis (SWRO) membrane permeability has increased, lowering feed pressure requirements, and energy recovery device (ERD) efficiency has increased. In some regions, the cost of power has decreased with the implementation of solar power. Recently, the cost of capital has begun to increase, tripling since 2020. These shifts have led some municipalities and engineering, procurement and construction (EPC) companies to consider SWRO design and operation at higher recovery rates.

Several new SWRO process technologies have been developed to enable high-recovery high-pressure desalination. They include ultra-high-pressure RO, multistage SWRO with various ERD configurations and osmotically-assisted RO (OARO). All of these technologies can raise SWRO recovery rates to over 60%, corresponding with brine concentrations of up to 130 g/l total dissolved solids (TDS).

The author provides an overview of new high-recovery SWRO technologies. The economics and other practical considerations for implementing these technologies are compared with each other and with those of conventional SWRO conducted at more traditional 42-45% recovery rates. This analysis demonstrates that high-recovery SWRO with OARO and isobaric ERDs provides the lowest total cost of water production compared to available alternatives. It also shows that the optimal recovery rate for SWRO is greater than 50% with current desalination technology, contemporary costs of power and interest rates. These results make a compelling case for implementing high-recovery SWRO for desalination projects, especially where the cost of capital is high; intakes, outfalls or pretreatment are cumbersome or expensive; and/or the cost of power is low.

Keywords: Recovery rate, energy recovery devices, seawater reverse osmosis, osmotically-assisted reverse osmosis, total cost of water, SWRO, OARO, TCOW

I. INTRODUCTION

Recovery rate in desalination is defined as the ratio of product water flow rate over system feed flow rate. In reverse osmosis, the dominant technology for seawater desalination, recovery is permeate flow divided by pretreated feed flow. The optimal recovery rate in seawater reverse osmosis (SWRO) is the rate that produces the lowest total cost of desalinated water production for the particular project. Generally higher recovery rates result in lower specific capital costs and higher operating costs, the latter due to the higher energy consumption associated with the higher salinity brine. Lower recovery rates result in lower energy consumption but higher specific capital costs, as higher capacity equipment is necessary for a given amount of permeate.

The advent isobaric energy recovery devices (ERDs) in the early 2000s, with hydraulic efficiencies of over 95%, substantially eliminated the energy wasted in the brine stream from SWRO processes. This made it economical to reduce SWRO recovery rates from then typical 50% to 42-45%. Lower recovery combined with the increased permeability of spiral thin film composite membranes compared to traditional hollow fiber membranes resulted in lower feed pressures and RO specific energy consumption rates as low as 2 kWh/m^3 of permeate produced.

Also since the 2000s, the cost of power has decreased with the implementation of solar power in some regions. Recently, the cost of capital has begun to increase, tripling since 2020 [1]. Some researchers suggest that the cost of capital will far exceed the cost of energy with renewable-energy-powered desalination [2]. These shifts have led some municipalities and engineering, procurement and construction (EPC) companies to consider SWRO design and operation at higher recovery rates.

This paper addresses high-pressure RO desalination and brine concentration systems but does not consider other means of desalinating such as thermal or electro-separation techniques. While this paper presents an analysis of the use of membranes, pumps and energy recovery devices in these systems, only limited product details are given for the sake of minimizing commercial content in a technical forum. The reader is referred to the relevant manufacturers for such information. At the time of this writing, the author is unaffiliated with any desalination equipment manufacturer, membrane company or system integrator. As such, this paper is offered as an objective assessment of publicly-available information.

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. Many types of devices have been developed to capture otherwise wasted pressure energy and convert it into useful energy and/or recycle it into the RO process. Of the various devices applied over the years, turbo chargers or turbo boosters and isobaric devices have emerged as the most widely used due to their efficiency and practicality [3].

Figure 1 illustrates a typical configuration of a turbo booster in an RO process. Feed water is partially pressurized by a high-pressure pump. Pressure is increased through the pump side of the turbo booster. Brine exiting the membranes depressurizes through the turbine side of the turbo booster. The turbine discharge pressure is 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.

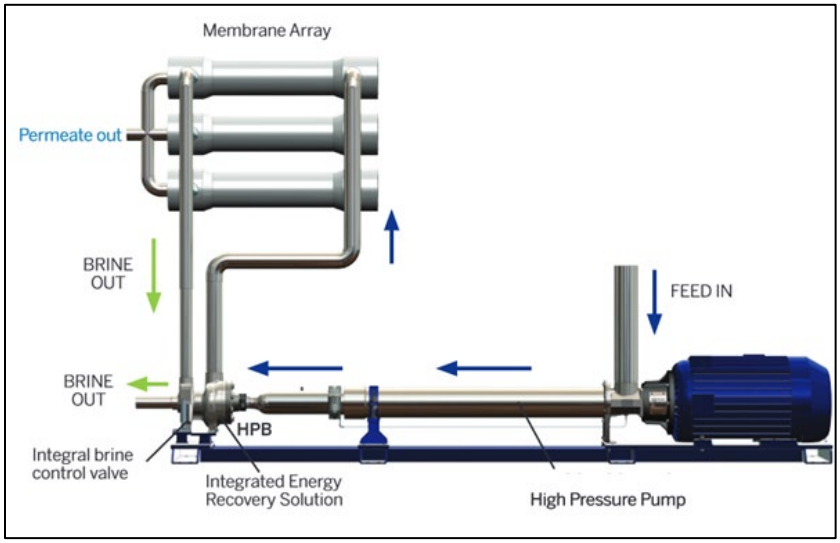


Figure 1. Turbo Booster in a Single-Stage RO System [4]

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 membrane 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 maintained at a minimum of 1 bar pressure 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 pump is used to move high pressure fluid through the ERD and the membrane array.

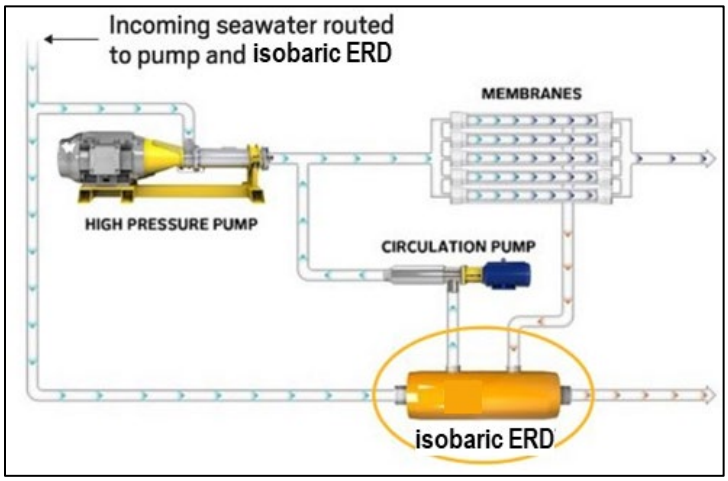


Figure 2. Isobaric ERD in a Single Stage RO System [5]

III. OVERVIEW OF MEMBRANE BRINE CONCENTRATION

Traditional means to concentrate brines employ thermal evaporation. However, the capital costs and energy consumption of thermal technologies are prohibitive for many applications. This section presents

considerations for using membranes to achieve high brine concentrations and, therefore, high recovery rates.

1. Maximum Pressure Considerations

Osmotic pressure increases sharply with concentration. Conventional reverse osmosis is typically limited to a maximum operating pressure of 1,200 psi (83 bar) by the 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. Ultra-high-pressure RO (UHPRO) can be operated at pressures of up to 1,800 psi (124 bar), increasing brine concentrations to as high as 130,000 mg/l TDS. The performance and cost of UHPRO is further discussed below.

2. Scaling Considerations

There is potential risk of the precipitation of sparingly soluble salts, or scaling, on membrane surfaces at high brine concentrations. Figure 3 is an antiscalant projection that shows that up to 69% recovery or 114 g/l total dissolved solids (TDS) is feasible from standard seawater without antiscalant dosing [6]. Sulfate salts and calcium fluoride are the primary scaling species of concern. A number of commercial antiscalant projection programs indicate that final brine concentrations of up to 300 g/l TDS are possible with use of proprietary products [7,8,9], however it is not clear that these products have been tested to these brine concentration levels. Therefore, caution should be exercised when designing or operating to avoid scaling at high recovery rates.

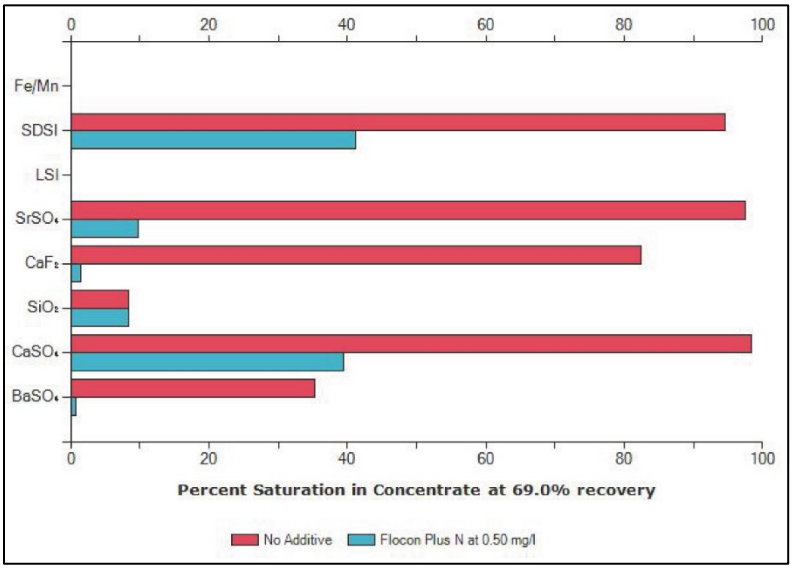


Figure 3. Sparingly Soluble Salt Concentrations at 69% Recovery [6]

3. Osmotically-Assisted RO

Conventional RO feed pressures increase with recovery rate because the osmotic pressure of RO permeate is negligible. However, if the permeate is salty, the feed pressure required is proportional to the difference between the osmotic pressure of the feed/brine and that of the permeate. This is the phenomenon exploited by osmotically-assisted RO (OARO) technology to enable the production of ultra-high brine concentrations at relatively low feed pressures.

There are two general means to raise permeate salinity: one directly, using hollow fiber membranes. This was the approach originally proposed by Syd Loeb [10]. The other utilizes spiral membranes that permit high salt passage [11,12]. This is a new class of membranes with the same form factors as standard SWRO membranes [13,14]. Both means are deployed in 4 to 12 stages, with a greater number of stages required to achieve higher concentration factors. However, OARO staging differs from conventional multi-stage RO staging, as illustrated in the figures below. In the traditional multi-stage RO process shown in Figure 4, feed pressure is boosted with one or more interstage pumps to overcome the increasing osmotic pressure of the concentrating feed/brine stream. While effective, this approach is limited by the maximum pressure rating of RO membranes and equipment and also requires interstage pumps that can accept high pressure at their intakes. Also, if high-efficiency isobaric-energy-recovery is to be employed to minimize energy consumption, pressure must be throttled through a valve upstream or downstream of the ERD to meet the discharge pressure of the high-pressure pump. Alternately, a less energy-efficient turbine-type ERD must be used.

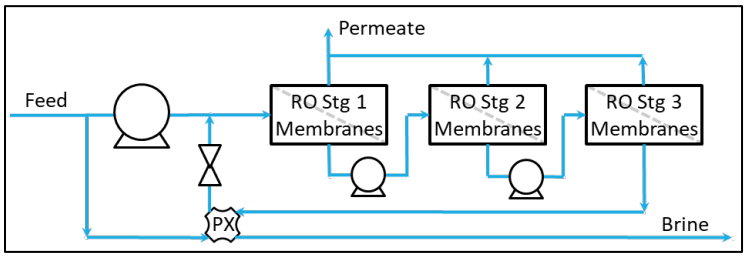


Figure 4. Traditional Multi-Stage RO Process with Interstage Boosting

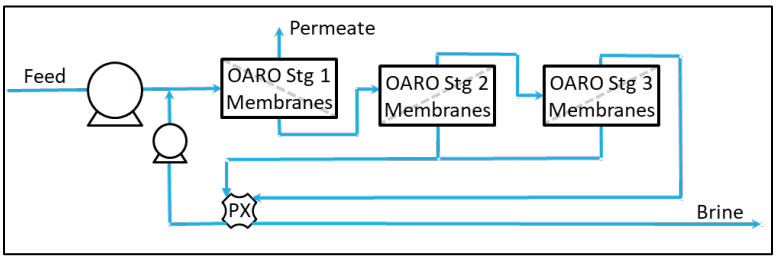


Figure 5. Process Diagram for OARO with Spiral Membranes

In the OARO process illustrated in Figure 5, feed pressure is not boosted between stages. Pressure decreases slightly through each successive stage because of hydraulic resistance through the feed/brine channels, commonly termed differential pressure drop. Therefore, OARO membranes with higher water permeability and lower salt retention are selected for stages fed with higher salinity [15]. This concept is similar to internal staging or hybrid designs commonly used in RO systems, with "tighter" membranes at the head of the process and "looser" membranes in the tail [16]. Proper arrangement of membrane types in an OARO array forms a permeance ramp that balances flux, maximizes concentration per stage while minimizing the amount of salty permeate recycled in the process [17].

IV. MULTI-STAGE HIGH-PRESSURE RO

Single RO stages are limited to a maximum of about 55% recovery in 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 recovery rates higher than 55%, multiple stages are employed. Brine from the first stage flows under pressure to the second stage where additional

desalination occurs, elevating overall recovery. Each additional stage in series increases recovery rate and final brine concentration.

1. Two-Stage SWRO Systems

Figures 6 and 7 illustrate alternative two-stage seawater RO (SWRO) process designs for concentrating seawater to up to 102 gram per liter (g/l) TDS corresponding with 65% recovery. Feed, brine and reject flows and TDS values, shown in the figures, were set equal to allow direct comparison between the two designs. The pressures, concentrations, fluxes and recovery rates shown in Figures 6 and 7 were from membrane projections [18,19], mass balances and energy balances conducted for these systems using the known performance of commercially-available membranes, pumps and energy recovery devices. Full water analyses were used, starting with a standard seawater composition. Pump efficiencies were 73-74% wire to water. The second pass, comprised of three stages, is shown as a single stage in the figures for convenience.

Figure 6 shows a two-turbo or BiTurbo design [20] in which second stage brine pressure is partially let down through a turbo booster feeding the second stage, and then further depressurized in a turbo booster feeding the first stage. Boosting feed pressure to the second stage increases flux in the second stage, providing flux balance. To minimize the pressure boost required, a more permeable membrane is chosen for the second stage. Specifically for this example, Dupont Filmtec SW30XHR and SW30XLE are used in an internally-staged arrangement in stage 1, Filmtec Seamaxx in stage 2 and Nitto Hydranautics ESPA4 in the second pass. Pressures, fluxes and recovery rates are incorporated into Figure 6.

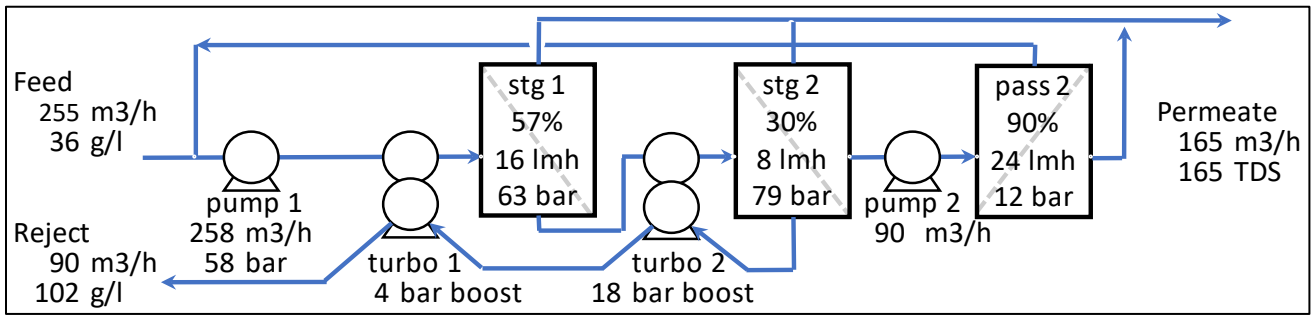


Figure 6. Two-Stage 65% Recovery SWRO with Two Turbo Boosters

In the example modeled for Figure 6, the second stage permeate TDS is over 1,200 mg/l, necessitating second pass polishing. Second pass brine at just over 11,000 mg/l TDS is returned to the primary RO feed. The turbine flow of turbo 2 in Figure 6 is 70% of the pump flow through the device, set by the recovery rate of the second stage. The similarity of the sizes of the turbine and pump wheels in turbo 2 make for a relatively efficient turbo booster, assumed to be 74% for this analysis. However, the turbine of turbo 1 is only 35% the size of the pump, making for a relatively inefficient turbo booster, assumed to be 63% for this analysis. Indeed, the boost provided by turbo 1 is only 4 bar.

Figure 7 shows a two-stage system with OARO membranes in the second stage and isobaric energy recovery between the final brine and first stage feed. Second-stage permeate TDS, at over 15,000 mg/l, is returned to the first stage feed. A separate second pass is not required to meet the same permeate quality as for the process in Figure 6 because the first stage acts like a second pass for the second stage in Figure 7. However, the combined feed rate to the first stage is greater than in the BiTurbo design, increasing high pressure pump size, cost and energy consumption. The OARO system in Figure 7 utilizes the permeance ramp concept, with second stage membranes that have higher water and salt

permeability than the first stage, such that the feed pressure available for the second stage provides sufficient flux without interstage boosting. Specifically for this example, Dupont Filmtec SW30XHR and SW30HRLE are used in an internally-staged arrangement in stage 1 and Fortilife XC120 in stage 2.

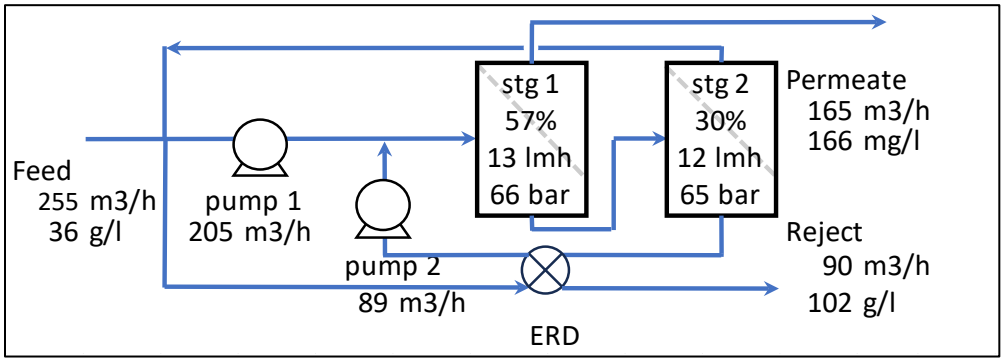


Figure 7. Two-Stage 65% Recovery SWRO with Isobaric ERD and OARO

Cost details for the process options shown in Figures 6 and 7 are compared in the first two columns in Table 1 below. Only the cost of equipment, freight and engineering design are included in capital cost (CAPEX) totals. Capital costs were distributed over 20 years assuming 8% interest. Operating costs (OPEX) include replacement membranes, parts, chemical, consumables and power, with a power tariff of $0.06/kWh. Only power consumed by the RO equipment was considered. For the same size system at the same recovery rate producing the same quality of permeate, the OARO design with isobaric ERD requires about 10% less energy and about 13% less total cost per unit of permeate produced compared to the two-turbo-booster design.

Table 1. Cost Comparison of High Recovery SWRO Options

	BiTurbo	Isobaric ERD	UHPRO	OARO
Feed m^3/d	**6,116**	**6,098**	**5,549**	**5,549**
Permeate m^3/d	**3,960**	**3,960**	**3,960**	**3,960**
Recovery Rate	**65%**	**65%**	**71%**	**71%**
CAPEX ($)	3,175,238	2,668,216	4,230,921	2,909,125
OPEX ($/y)				
Membranes, 5 yr life	50,960	41,160	87,620	55,490
Spares, 5% of equip cost	29,739	23,770	43,533	24,123
Cartridge filters, 1 mo life	12,480	12,288	11,328	11,328
Chemicals	42,308	42,192	38,791	38,912
Specific Energy, kWh/m^3	3.62	3.26	3.47	3.57
Power @ $0.06/kWh	313,799	282,391	300,765	309,427
Total OPEX	449,285	401,801	482,036	439,280
COST ($/$m^3$ permeate)				
CAPEX (8% int, 20 years)	$ 0.22	$ 0.19	$ 0.29	$ 0.20
OPEX (power, spares, chems)	$ 0.31	$ 0.28	$ 0.33	$ 0.30
Total /m^3 permeate	**$ 0.53**	**$ 0.46**	**$ 0.63**	**$ 0.51**

Capital, operating and total costs per cubic meter (m^3) of permeate for the two processes described above, shown in the bottom lines in Table 1 above, are also presented as the two left-most bars in Figure 8. Capital costs are estimated to be 16% less with the OARO second stage and isobaric ERD, which is

not surprising given the significantly simpler design, as illustrated by comparing Figures 6 and 7. Lower operating costs by about 11% add to the savings of this approach, for a total cost reduction of 13%.

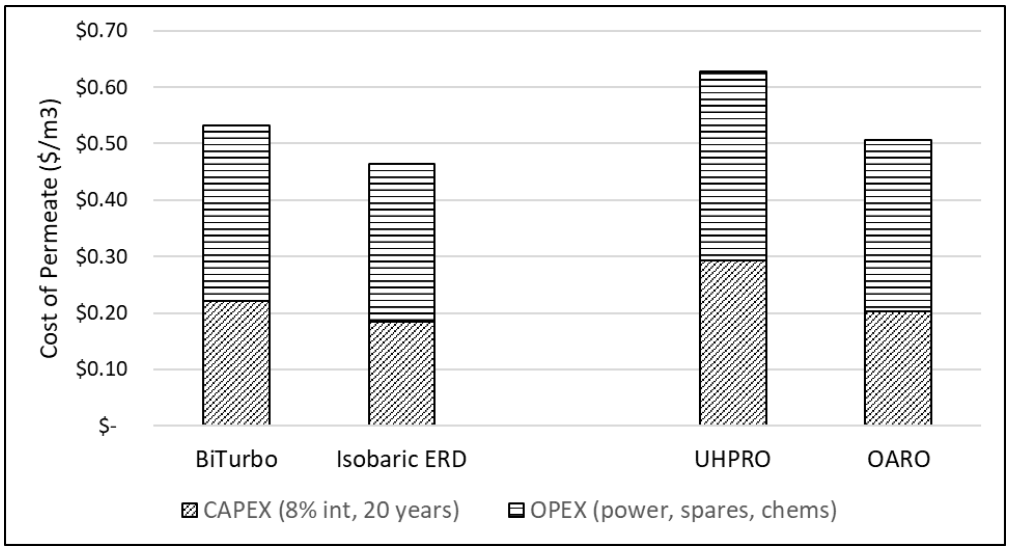


Figure 8. Specific Capital, Operating and Total Costs

2. Three-Stage SWRO Systems

This section describes process designs and provides an economic assessment of competing means of desalinating seawater at 71% recovery to produce high quality permeate and a final brine with a TDS of 126 g/l. Such a high 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, OARO or UHPRO is required.

The competing processes considered are illustrated in Figures 9 and 10 below. In the UHPRO design in Figure 9, pressure is broken after the first stage through isobaric ERDs that help feed that stage. Partially concentrated feed to the second stage is pressurized with a second high-pressure pump and a second ERD(s) using brine energy from the third stage. Second and third stage equipment, including all pumps, ERDs, pressure vessels, membranes, pipes and fittings, are rated for 120 bar service. Although high pressure brine from the first stage could nominally be boosted for feed to the second stage, to the author's knowledge, no commercially-available pumps exist that can both provide the desired head and withstand the high suction pressure required for this application. Feeding the second-stage at low pressure enables use of a high-efficiency positive-displacement pump, assumed to be 78% efficient for this analysis, to feed the second stage. Also, because isobaric ERDs are highly efficient, the losses incurred by breaking brine pressure after the first stage, as shown in Figure 9, are minimal. If a suitable interstage boost pump was available for this application, brine pressure would need to be throttled before or after the isobaric ERDs to meet the feed pressure of the first stage, with significant loss of energy. Alternately, a portion of the first stage feed could be boosted with final brine pressure through interstage ERD(s) for feed to the second stage with some entropic losses stemming from the corresponding interstage dilution [21]. Having considered these alternatives, the scheme shown in Figure 9 provides the lowest energy consumption practically achievable with available equipment. As in the two-stage designs above, permeate salinity from the later stages is relatively high, averaging about 1,500 mg/l TDS, necessitating second pass polishing.

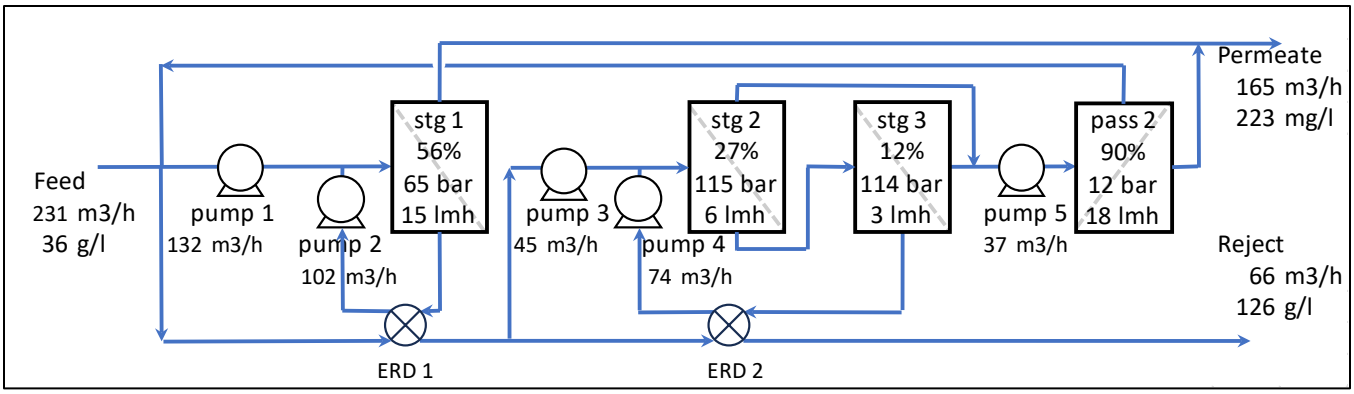


Figure 9. Three-Stage 71% Recovery SWRO with UHPRO

An OARO process for 71% recovery is illustrated in Figure 10 below. As for the above two-stage OARO design, the membrane arrays are fed with a single high-pressure pump and energy is recovered from last stage brine through isobaric ERDs. Second- and third-stage permeate are recycled to the first stage feed, which achieves the permeate quality target without need for a second pass. Also, first-pass operating pressures being less than 83 bar enables use of standard SWRO pumps, ERDs and pressure vessels.

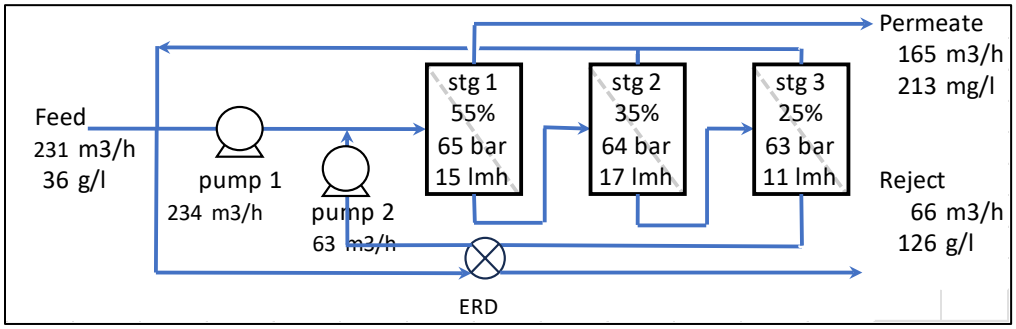


Figure 10. Three-Stage 71% Recovery SWRO with OARO

In the above examples, Hydranautics SWC4 and SWC5 were used in an internally-staged design in the first stage of both systems, Filmtec XUS180808 was used in stages 2 and 3 and Filmtec BW30HRLE in the second pass in Figure 9, and Hydranautics PRO-XC2 in the second stage and third stages in Figure 10. Flow rates, average fluxes, feed pressures and recovery rates for the stages are indicated in the figures.

Estimated capital, operating and total costs for the two three-stage processes above are listed in the right-most two columns in Table 1 above and presented as the two bars on the right in Figure 8 above. Energy consumption is about 3% higher for the OARO design, however, all other costs are lower than for the UHPRO system. Two major factors contributing to the cost difference are the price premium of 120 bar UHPRO components and membranes, conservatively estimated to be two times the price per unit of 83 bar SWRO equipment, and lower flux through UHPRO membranes due to compaction. The price premium affects both capital costs and replacement costs. Compaction is accounted for in the UHPRO membrane projections with a flow factor of 0.4 [22]. For reference, new membranes with zero compaction are 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 flow rates of at least 6 m^3/h (26 gpm) per pressure vessel, which is about double

the minimum recommended velocity for SWRO membranes, necessitating brine recirculation equipment and energy [22].

To estimate specific costs, capital costs are distributed over 20 years, assuming 8% interest, and a power tariff of $0.06/kWh is applied. Capital costs are 31% less with the OARO second and third stages, which is not surprising given the significantly simpler design, as illustrated in Figure 10. Lower operating costs by about 9% add to the savings with OARO compared to UHPRO, for a total cost reduction of over 19%.

V. OPTIMUM RECOVERY RATE

The cost analyses presented above were limited to RO equipment. A full cost of water analysis, required to assess optimum recovery rate, must include the balance of plant. The two lowest-cost high-recovery cases from above are compared to a conventional single stage SWRO operating at 45% recovery in Table 2 and Figure 11 below. Capital and operating cost information for the conventional plant is from a cost analysis published by Global Water Intelligence dated 2015 [23] ("GWI data"). Those costs were adjusted to 2024 dollars with a published price index [24]. The size of infrastructure works such as intake, outfall, pretreatment and civil structures depends upon the recovery rate. Their cost for lower and higher recovery systems were estimated with the six-tenths rule [25] using the 45% recovery case as the basis. A specific energy consumption rate of 2.5 kWh/m^3 permeate was computed for the conventional case, with an additional 1 kWh/m^3 assumed required for the balance of plant. Other assumptions and cost factors from the analyses above were incorporated into Table 2.

Table 2. Cost Comparison of High Recovery SWRO Options

	2 Stage 65%	3 Stage 71%	1 stage 45%
Feed m^3/d	**6,098**	**5,549**	**8,800**
Permeate m^3/d	**3,960**	**3,960**	**3,960**
Recovery Rate	**65%**	**71%**	**45%**
CAPEX ($)			
Intake/outfall	542,575	512,698	676,114
Pretreatment	723,433	683,596	901,484
Civil costs	1,014,993	959,102	1,264,804
RO equipment	2,223,513	2,424,270	2,044,700
Additional equipment	995,792	1,057,309	979,493
Installation	672,797	701,681	690,269
Design engineering	643,861	696,316	604,839
Total CAPEX	6,816,965	7,034,971	7,161,704
OPEX ($/y)			
Parts	43,883	47,458	55,053
Chemicals	89,020	81,001	128,455
Labor	109,851	109,851	109,851
Membranes	41,160	55,490	31,920
Power	351,987	375,179	307,673
Total OPEX	635,901	668,980	632,952
CAPEX (8% int, 20 years)	$ 0.47	$ 0.49	$ 0.50
OPEX (power, spares, chems)	$ 0.44	$ 0.46	$ 0.44

Total /m³ permeate	**$ 0.91**	**$ 0.95**	**$ 0.94**

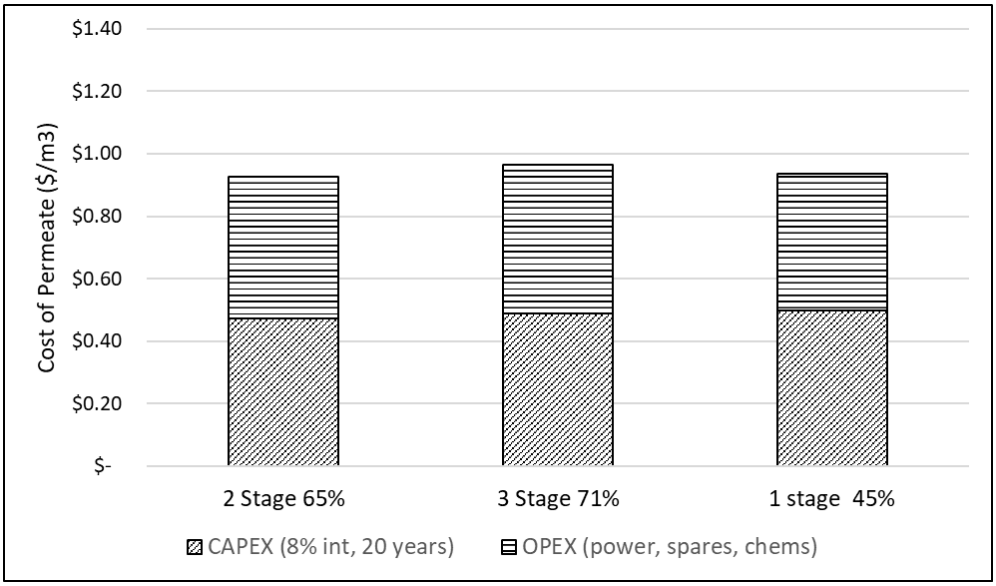


Figure 11. Full Installation Costs for Conventional and High Recovery SWRO

Despite the higher energy consumption associated with producing higher brine concentrations at 65 or 71% recovery, the data in Table 2 and Figure 11 demonstrate that the total cost of permeate production is comparable or even less than for operation at a more traditional 45% recovery rate. Infrastructure costs are far greater for the lower recovery system. Hence economic trends that raise these costs, such as elevated interest rates or materials cost increases or shortages, would further favor higher recovery rate design and operation. Power cost savings at lower recovery are substantially eliminated by the higher costs of chemicals and parts required to maintain a larger, lower-recovery-rate desalination plant, such that total OPEX for the higher-recovery-rate designs was estimated to be nearly equal or lower than total OPEX at lower recovery rates. Hence, economic trends that reduce the cost of power, such as the availability of low-cost photovoltaic solar power, or increase the cost of chemicals, for example, would further favor higher recovery.

These results beg the question: what is the optimum recovery rate for SWRO? In response, a recovery rate optimization analysis is conducted on a single-stage system over a range of recovery rates with a fixed permeate production rate. To assure the same permeate TDS over the recovery rates considered, internal staging with lower-rejection membranes is used in low-recovery designs, and a small split-partial second pass is added to the higher recovery designs. As before, capital costs are distributed over 20 years assuming 8% interest, a power tariff of $0.06/kWh, and the GWI data is again used with the 2024 price index and size scaling adjustments. Specific capital and operating costs for recovery rates ranging from 36% to 54% are presented in Figures 12 and 13.

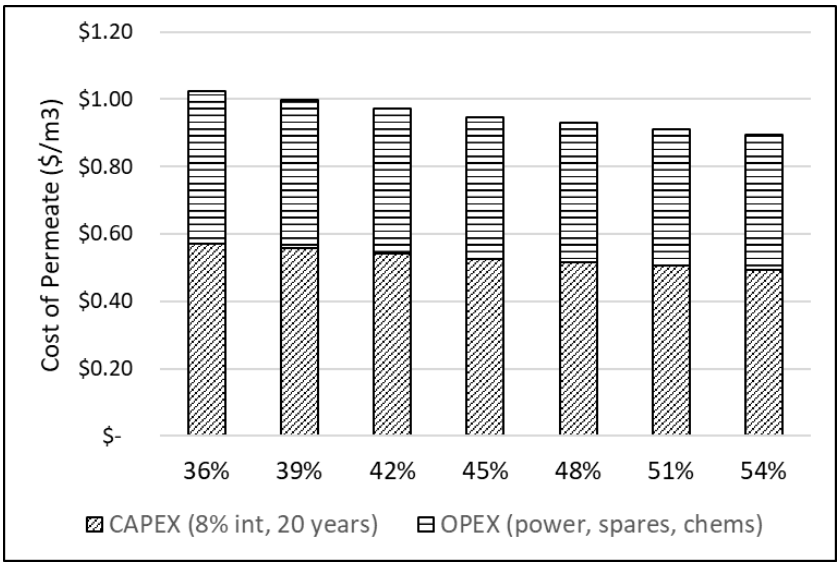


Figure 12. Full Installation Costs vs Recovery Rate for a Single Stage System

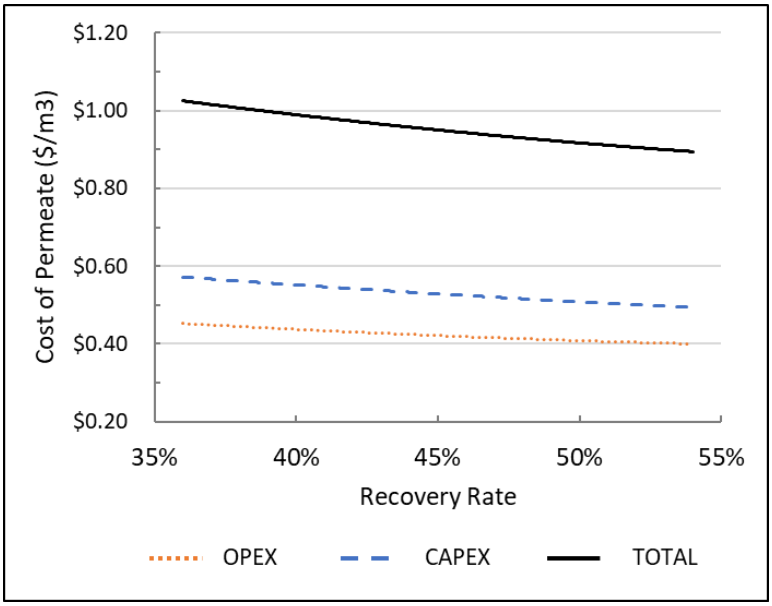


Figure 13. Full Installation Costs vs Recovery Rate for a Single Stage System

Figures 12 and 13 indicate that the lowest total cost of permeate production corresponds to a recovery rate of greater than 54%. As indicated in Figure 11, total costs increase between 54 and 71% recovery, such that the curves in Figure 13 are expected to inflect upward at much higher recovery rates. However, for a single-stage system, recovery rate is limited by membrane array and element design limits but not by optimum total-cost-of-water consideration.

VI. CONCLUSIONS

This analysis demonstrates that high-recovery SWRO with OARO and isobaric ERDs provides lower total cost of water production than high-recovery SWRO with two turbo boosters at 65% recovery. It also shows that total cost of water with OARO is significantly lower than with UHPRO at 71%

recovery. The optimum recovery rate for SWRO with current desalination technology, contemporary costs of power and interest rates appears to be higher than the 42-45% commonly applied. Rather, recovery rates of up to 54%, corresponding to the maximum recommended recovery for single-stage systems, provide the lowest total costs. These results make a compelling case for implementing high-recovery SWRO for desalination projects, especially where the cost of capital is high; intakes, outfalls or pretreatment are cumbersome or expensive; and/or the cost of power is low.

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