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A fresh look at mega-scale SWRO: using brine-staged reverse osmosis to optimize energy efficiency and membrane performance

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ABSTRACT

Seawater reverse osmosis (SWRO) desalination has been in wide use for over 25 y. This paper examines limitations of the prevalent membrane configuration, based on a single stage consisting of one or more membrane housings operating in parallel with 6–7 elements per membrane housing. A brine-stage configuration using interstage pressure boosting is proposed to address limitations in single stage systems including high biofouling potential, excessive permeate salinity and high energy consumption. Membrane array optimization requires careful review of concentration polarization (Beta or CP) and the feed flow rate through each membrane element (Q_{ele}), (a proxy for cross-flow velocity). CP is the formation of a salinity gradient normal to the membrane surface generated by a combination of boundary layer formation and permeation. CP is often characterized by the term Beta, which is defined as the ratio of salinity at the membrane surface divided by the bulk feed salinity. A high Beta means that the membrane surface is exposed to elevated salinity (hence higher osmotic pressure and increased salt passage) and a greater concentration of foulants. These conditions increase the required pressure, increases permeate total dissolved solids (TDS) and promotes fouling of membrane spacers and surfaces. A high Q_{ele} is preferred to minimize boundary layer thickness and to better scour feed channel spacers and the membrane surface. This paper explores a brine staged SWRO membrane array that achieves preferred levels of Beta and Q_{ele} to achieve improved biofouling resistance and lower permeate TDS while providing a recovery of 60% in typical SWRO applications using standard membranes, pressure vessels and energy recovery devices (ERDs). Major membrane suppliers have endorsed high recovery SWRO using brine staging as described in this paper. The focus also includes optimal ways to implement brine staging over very large SWRO systems using turbochargers in a unique configuration that maximizes brine stage performance as well as energy recovery efficiency. The paper also addresses related ERD technologies and variable frequency devices that together can reduce energy consumption as well as provide a substantial reduction in capital costs (CAPEX) and operating costs (OPEX) with realistic reductions of 16% in mega-scale SWRO facilities.

Keywords: Seawater desalination; Reverse osmosis; Energy efficiency; Energy recovery; Reverse osmosis membranes

1. What are the prospects for major advances in mega-scale seawater reverse osmosis?

Advancements in membrane technology, energy recovery devices (ERDs) such as turbochargers and isobaric chambers, and the benefits from the economy of scale (25,000 m³/d trains in 500,000 m³/d facilities) appear to have reached the point of diminishing returns.

The need for affordable seawater reverse osmosis (SWRO) remains to meet growing demands and in

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response to climate change. In addition, the growing interest in zero-liquid discharge (ZLD) and recovery of minerals from brine (brine mining) are increasing the need for new solutions for high recovery systems.

This paper will address desalination cost reduction through increased recovery in SWRO applications using only well-proven technology simply arrange in a novel configuration.

2. Questions about high recovery SWRO

This paper will address the following questions regarding high recovery SWRO design and operation:

(1) What is the achievable recovery using standard SWRO membranes?
(2) Is permeate total dissolved solids (TDS) adversely affected?
(3) Does high recovery reduce facility CAPEX and OPEX (i.e., the cost of water)?
(4) What are the key technologies to achieve high recovery?
(5) Are standard SWRO membranes suitable?
    (a) Do membrane suppliers support such applications?
(6) Is membrane life affected?
(7) What about energy consumption for the SWRO system and the entire facility?
(8) What about chemical consumption?
(9) Is biofouling increased?
(10)What about the discharge of high salinity brine?

3. A brief history of high recovery SWRO

For the purposes of this paper, high recovery is defined as a recovery greater than 45% with a feed TDS of 35,000 ppm. A search of the literature shows schemes to increase SWRO recovery using single stage arrays combined with a variety of techniques such as brine recirculation, flow reversal, forward osmosis, etc.

Only a few efforts have involved a brine staged configuration. Given that brine staging is widely used in brackish water reverse osmosis (BWRO) where high recovery is the norm, the lack of sustained interest is an anomaly in the evolution of SWRO technology. An early effort in the late 1990's attempted high recovery with brine staging. However, the required pressures of over 100 bar with special membrane and pressure vessels (PVs) and energy recovery devices (ERDs) that were not fit for purpose prematurely ended development in this area. Standard SWRO membranes and ERDs are now suitable for brine staged SWRO on any scale of application.

4. Criteria to achieve economically viable high recovery SWRO

The goal is to obtain high recovery based on the following requirements:

- Standard SWRO membranes;
- Pressures less than 70 bar;
- ERDs with demonstrated efficiency, reliability and availability suitable for mega-scale SWRO.

An unexpected opportunity for further reductions in CAPEX and OPEX was identified during research involving analogous industrial processes.

5. A brief review of key membrane performance factors

Fig. 1 shows representational trends of membrane parameters along the length of a 7-long PV:

- ***Feed pressure*** – hydraulic pressure of the feed along the feed channel that decreases due to flow resistance through the membrane spacers.
- ***Osmotic pressure*** – primarily a function of the molar concentration of dissolved solids. As permeation increase, the increasing feed salinity causes a rise in osmotic pressure.
- ***NDP*** (net driving pressure) – equals feed pressure minus osmotic pressure. NDP is the available energy to drive the reverse osmosis process and represents the dominant irreversible loss in reverse osmosis membrane systems.
- ***Salt passage*** – the rate of salt diffusion through the membrane and is a function of the difference of salinity on either side of the membrane. Salt passage increases along the length of the membrane channel.
- ***Beta*** – a parameter defined as the ratio of bulk flow salinity divided by the salinity and the membrane surface. High Beta increases salt passage and permeate flux and biofouling. Note that NDP is a function of Beta hence influences the required hydraulic pressure to achieve a given permeate flux.
- ***Qele*** – An indirect measure of the cross-flow velocity through the membrane channel. A high velocity reduces Beta and can scour the membrane surface of foulants.
- ***Permeate flux*** – rate of permeation expressed in unit volume per unit area per a given time. Common units are L/m^2 of membrane area per hour (lmh).

All the parameters above are interrelated.

6. Concentration polarization and biofouling

The definition of Beta is the ratio dissolved materials adjacent to the membrane surface to bulk flow concentration. The same mechanism that contributes to salinity concentration also concentrates suspended particles. Therefore, biofouling agents are likewise concentrated. Key research

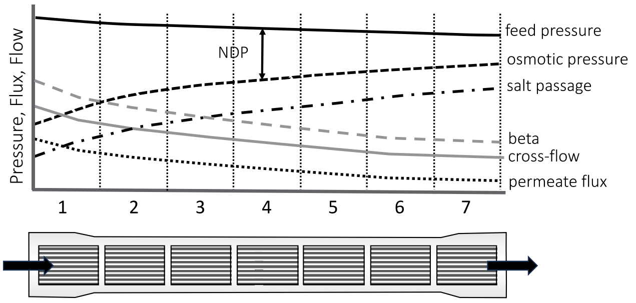


Fig. 1. Membrane parameters.

with validation at SWRO facilities in the Middle East and the Caribbean determined that formation of membrane-attached biofilms from planktonic colloidal protobiofilms are correlated with:

- Individual bacterial cells and planktonic colloidal protobiofilms that occur in all SWRO feed waters that are not removed by any pretreatment.
- First several membrane elements have the greatest permeate flux and concentration polarization (CP) that can cause synthesis of particulate protobiofilms and membrane-attached biofilms.
- There exist a critical flux and a critical CP factor that promotes the attachment of biofilms to membrane surface.

Fig. 3 shows the life forms of marine bacteria and how they transform in response to concentrations (closely related to CP) on the membrane surface. Note that the process is not related to bacterial growth, just transformations triggered by concentration of bacterial cells. Fig. 4 shows the increase in feed pressure required to maintain permeate flux to overcome the impact of biofouling. The increased feed pressure raises HP pump energy consumption by about 8%. Fig. 5 shows a 28% reduction in permeate output due to biofouling. This data was collected from an SWRO facility located in the Carribean Sea.

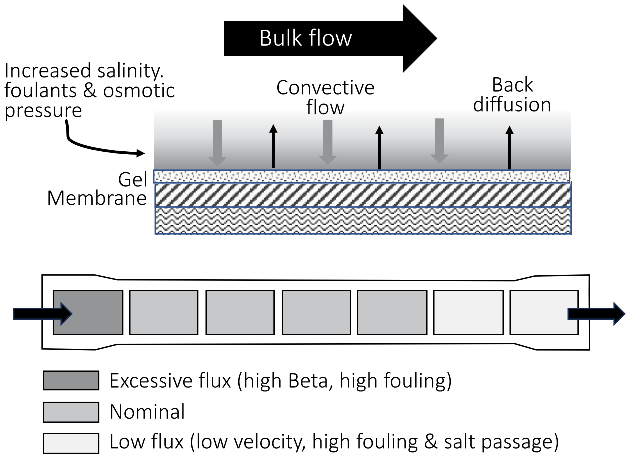


Fig. 2. Concentration polarization.

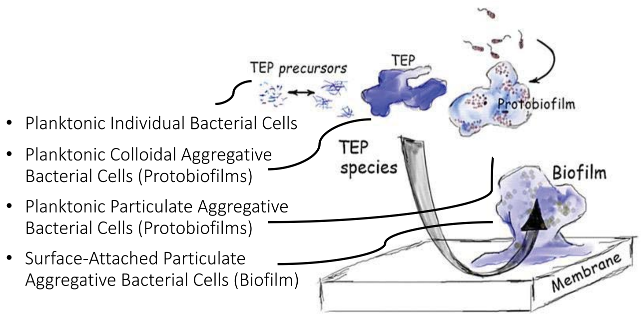


Fig. 3. Planktonic life forms and membrane biofouling.

Fig. 6 shows the relationship between CP and biofouling. Most membrane projection software includes a CP value for each element in the pressure vessel thus facilitating estimations of biofouling potential element by element.

7. Challenges of single-stage SWRO

Conflicting objectives face the array designer when the goal is high recovery:

- Need to minimize Beta in the lead elements to minimize salinity and biofoulant concentration, hence the need to reduce NDP achieved by reducing feed pressure.

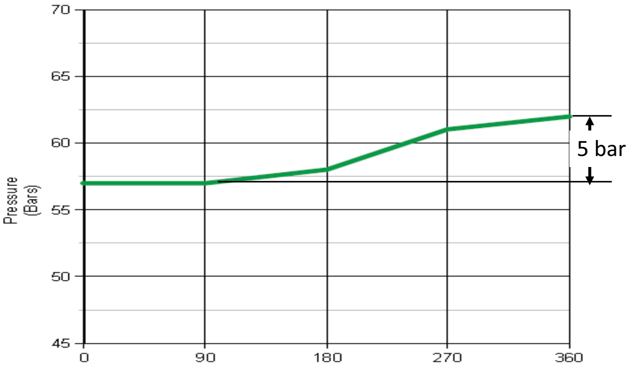


Fig. 4. Transmembrane pressure biofouling.

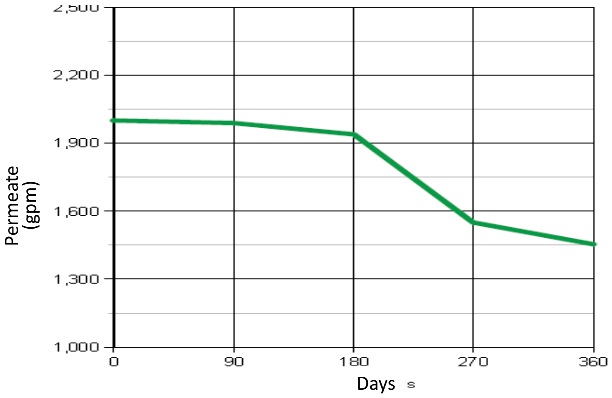


Fig. 5. Flux decline due to biofouling.

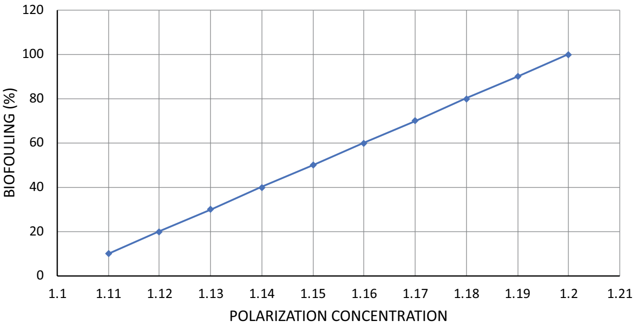


Fig. 6. Flux decline due to biofouling.

- Reduced feed pressure reduces NDP in elements toward the end of the array resulting in low flux and poor quality permeate.
- Objective to reduce CAPEX and OPEX forces the designer to accept excessive Beta, high fouling, shortened membrane life and reduced array energy efficiency.

The steady rise in recovery is evident in various large projects in the Middle East to reduce CAPEX but in exchange for high biofouling and high OPEX.

8. A two-stage membrane array

The need to reduce lead element Beta and the imperative to achieve the highest feasible recovery suggests a brine stage array. Such arrays are the de facto standard in brackish water reverse osmosis and routinely achieve recoveries of 70% and higher. Fig. 7 depicts a brine stage configuration with a booster pump between the first and second stages. The booster pump is needed in those applications where there is a significant increase in salinity thus a need to restore NDP in the second stage to maintain the desired permeate flux. Note the reduced number of PVs in the second stage to maintain Q_{ele} at optimal levels.

9. A middle east mega SWRO example

A single stage system will be compared with a two-stage system to better illustrate the key differences in membrane performance, biofouling potential and flux distribution.

Table 1 summarizes key parameters of the two systems. Note that the two-stage system has a recovery 19% higher than the one-stage system. The average element permeate flux is the same for both systems. Table 1 includes the key membrane performance parameter of maximum Beta, maximum and minimum permeate flux and minimum element flow rate. Note that the two-stage system has markedly superior values despite having higher overall recovery.

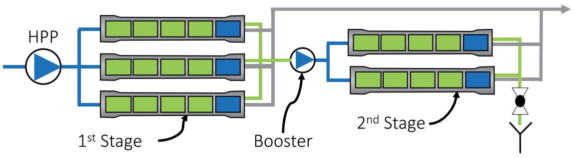


Fig. 7. Brine stage with interstage pressure boost.

Table 1
Data summary

46,000 ppm, 35°C, 0 y	Single	Two-stage
# Element/stage	7	6/6
Interstage boost (bar)	n.a.	=20
Recovery	42%	50%
Max. Beta	1.17	1.11
Max. flux (lmh)	20.3	15.9
Min. flux (lmh)	2.7	3.8
Min. element flow (m^3/h)	3.3	4.9

Fig. 8 provides detail at the element level. The lead element of the one-stage system has a 28% higher flux than the lead elements in the two-stage system. Also, the single stage system has a flux that is 29% lower for the last element in the PV suggesting a low permeate productivity.

The single stage system has a 35% higher Beta (relative to a Beta of 1.00) than the two-stage system which puts its value in the high biofoulant region per Fig. 4.

The two-stage advantage is also apparent where the lowest value of Q_{ele} is 48% higher than the one-stage system.

What are recovery limits for standard SWRO membranes and PVs? A reasonably accurate estimate can be based on the maximum allowable brine TDS. Let's examine two cases:

- Maximum brine pressure of 75 bar pressure and 9 bar NDP for the last element of the second stage.
- Maximum brine pressure of 93 bar pressure and 10 bar NDP for the last element of the second stage.

Eq. (1) defines the maximum recovery as a function of feed TDS and maximum allowable brine TDS. Eq. (2) calculates the recovery per stage to achieve the overall recovery (stage recoveries are equal).

$$R_{\max} = \left(1 - \frac{S_f}{S_b}\right) \tag{1}$$

$$R_{\text{stg}} = 1 - \left(1 - R_{\max}\right)^x \tag{2}$$

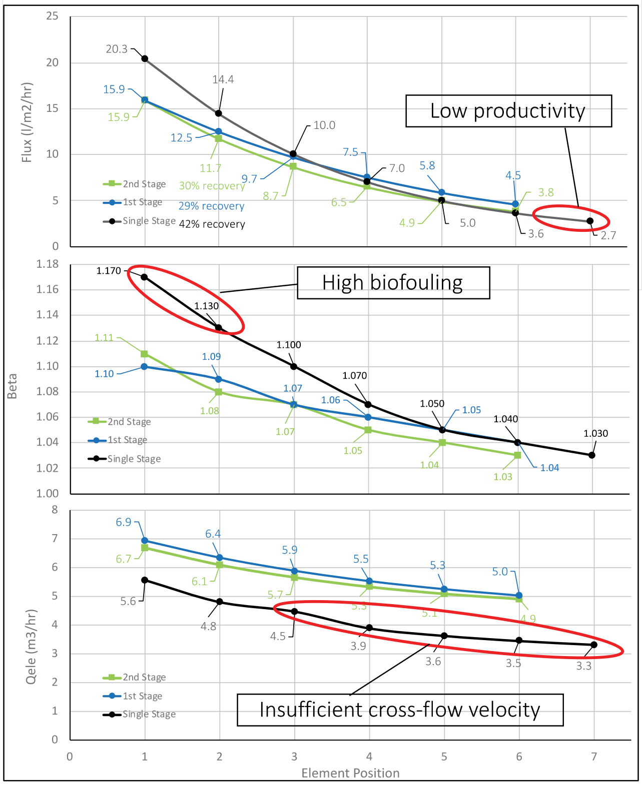


Fig. 8. Single vs. two-stage.

where S_f is the feed TDS, S_b is the brine TDS, x is the 1/# of stages, $R_{\max}$ is the upper recovery limit and R_{stg} is the recovery of one-stage.

Fig. 9 plots $R_{\max}$ and R_{stg} over the indicated feed TDS range. Typical recovery for single stage systems is included. Note that the 80 K brine case has an overall recovery 56% and stage recovery of 34% with a feed TDS of 35 K. The 100 K brine case has a recovery of 65% and stage recovery of 40.5% with a feed TDS of 35 K. In both examples, stage recovery is lower than the single stage system at much lower recoveries.

10. Brine staging and permeate TDS

Reduced Beta in two-stage arrays suggest reduced salt passage due to a lower salt concentration adjacent to the membrane surface. Fig. 10 plots blended TDS of a two-stage system as a function of recovery. Feed TDS is 38,000 ppm. For reference, permeate TDS of a single stage system at 45% recovery is displayed. Both arrays have the same average element flux rate and use the same membrane types. The two-stage system has approximately a 3:2 PV configuration.

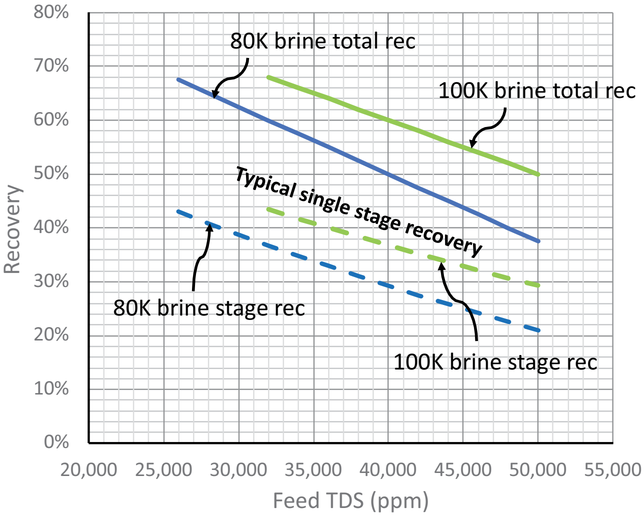


Fig. 9. Allowable recovery ranges.

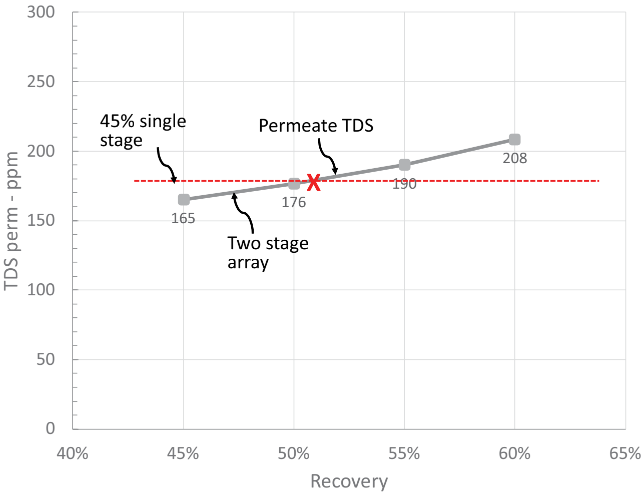


Fig. 10. Permeate total dissolved solids vs. recovery.

Note that the two-stage array has a lower blended permeate TDS up to approximately 52% recovery compared with the single stage system operating at 45% recovery.

The first stage permeate is relatively low. If exceptionally low permeate TDS is required, only the second stage needs to be processed through a second pass.

11. High salinity brine

Although high recovery does not increase the amount of dissolved solids discharged to the environment, the brine is more concentrated. Dilution with ambient seawater using eductors to drive mixing and diffusers to reduce local salinity concentrations can reduce brine salinities to that of low recovery systems.

12. Brine staging and energy consumption

As with permeate TDS, the two-stage system can have a reduced energy consumption due to a reduced Beta relative to a single stage system.

$$\text{SEC}_p = \frac{E_p}{R} \tag{3}$$

where E_p is the pretreatment energy (kWh/m³) and R is the recovery.

$$\text{SEC}_m = \frac{\left(E_{\text{in}} - E_{\text{out}}\right)}{Q_p} \tag{4}$$

where E_{in} is the hydraulic energy input (kW) and E_{out} is the hydraulic energy output (kW).

$$\text{SEC}_t = \text{SEC}_p + \text{SEC}_m \tag{5}$$

The specific energy consumption of the membrane arrays (SEC_m) is defined as the energy in kWh dissipated in the membrane array per m³ of permeate. SEC_m is calculating from all hydraulic energy inputs minus all hydraulic energy outputs of the membrane array. The remainder is energy dissipated in the membrane array.

Fig. 11 plots SEC_m as a function of recovery. The feed is 38,000 ppm. For reference, SEC_m for a single stage system at 45% recovery is shown. The two-stage system has a superior membrane efficiency up to approximately 53% relative to the single stage system.

High recovery reduces the size and energy consumpmtion of the feed supply and pretreatment system. SEC_p is the specific energy consumption of the feed supply and pretreatment system. For this analysis, the total pumping power is based on 7.0 bar incuding 3.0 bar suction pressure to the high pressure pump (HPP) at 84% wire-to-water efficiency. SEC_p is plotted as a function of recovery in Fig. 11.

SEC_t is the sum of SEC_p and SEC_m and is plotted as a fucntion of recovery in Fig. 11. Note that the two-stage array has a lower SEC_t up to approximately 58% recovery.

13. Implementation of SWRO brine staging

ERDs, ubiquitous on SWRO systems, reduce power consumption of the HPP. In the case of brine staged systems, an interstage booster is needed.

Two types of ERDs presently dominate ERD applications: isobaric chambers and turbochargers. Isobaric chambers are unsuited for two-stage systems for several reasons due to a fixed relation between feed and brine flows and feed discharge pressures that must be less than brine pressures.

Fig. 12 shows implementation of a brine stage array with a turbocharger providing interstage pressure boosting and a second turbocharger that boosts the feed pressure. This configuration is called a "BiTurbo". The interstage turbo provides the required pressure boost. Turbo efficiencies have reached to the point where only about 50% of the brine hydraulic energy is required to provide the optimal level of interstage pressure boost. FEDCO turbos are uniquely suited for the BiTurbo system.

13.1. Turbocharger features

- Capacity to 3,200 m^3/h feed;
- Models rated to 120 bar;
- Over 5,000 units in field operation;
- Super Duplex 2507 standard;
- CFD optimized flow path;
- Every unit built to customer duty;
- Quiet and smooth operation;

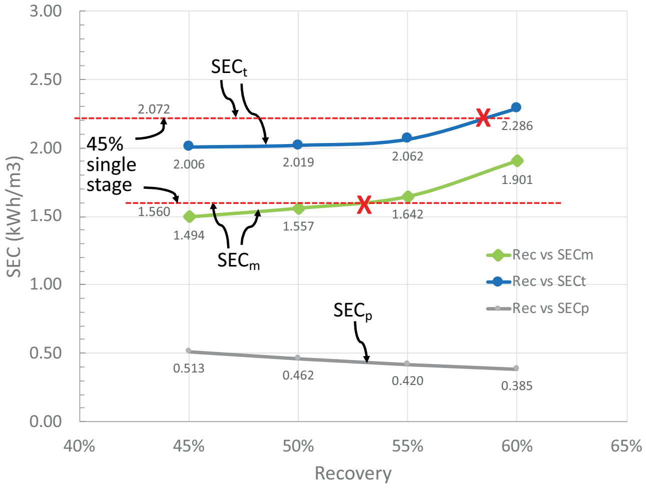


Fig. 11. Specific energy consumption vs. recovery.

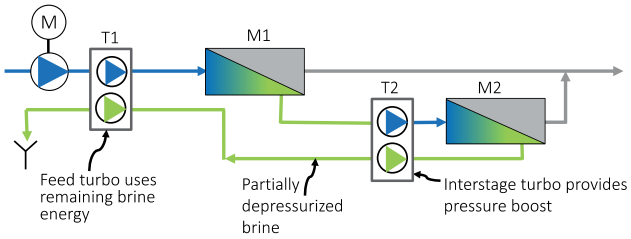


Fig. 12. BiTurbo brine stage system.

- Zero schedule maintenance;
- Discharge brine at any backpressure;
- Lubricated by feed water;
- No brine intrusion to feed;
- Automatically boosts feed pressure.

Fig. 13 shows an implementation with an interstage Fig. 13 shows an interstage turbo only. This configuration would be used with BWRO systems or very small SWRO systems. Fig. 14 maps the application range of the BiTurbo and interstage turbo.

14. ERDs fit for purpose

Fig. 15 shows a turbo and operating parameters as a feed pressure booster located between the HPP and the first stage.

15. State-of-the-art FEA and CFD

- All FEDCO turbos use custom-designed hydraulic paths.
- Best efficiency point customized to client duty points.
- Proprietary design and CNC code generation software: hydraulic paths optimized using customer membrane projections.

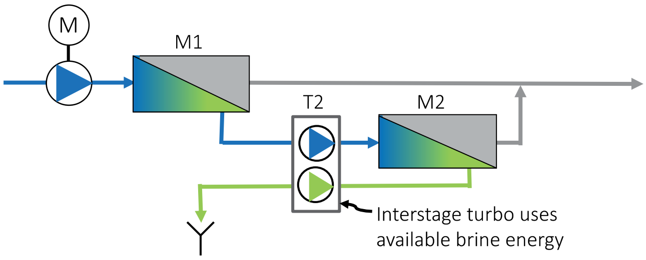


Fig. 13. Interstage turbo.

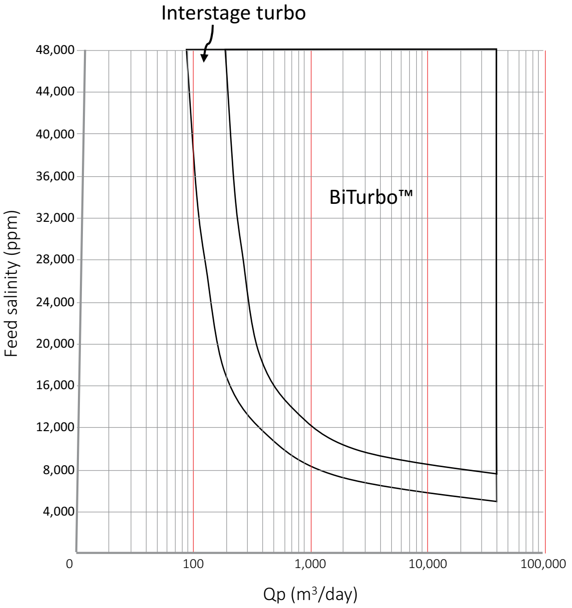


Fig. 14. Approximate application range.

- All product designs based on state-of-the-art FEA and CFD.
- All turbochargers, SSTs and Hydraulic Energy Management Integration (HEMIs) use custom-designed hydraulic paths for maximum efficiency.
- Impellers machined from bar stock or forgings in Super Duplex 2507.
- Best efficiency point matches customer duty point.
- 100% product testing – full power at up to 2.5 megawatts.

Figs. 16 and 17 show several internal design elements as well as the integral auxiliary brine nozzle that allows adjustment of brine flow and pressure.

Fig. 18 indicates that turbochargers have the hydraulic range for the largest SWRO trains contemplated and the field experience to provide assurance of high reliability and availability.

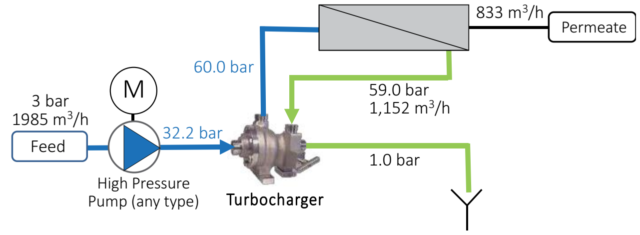


Fig. 15. Typical turbo application.

16. Optimized second pass configuration

Fig. 19 illustrates a BiTurbo with a second pass train. The second pass processes an amount of permeate from the second stage of the BiTurbo to achieve the desired blended TDS as measured by a salinity sensor. Note that the second pass feed can be less than, equal to, or greater than the second stage feed flow up to the entire permeate output of the BiTurbo. The pipe circled in red in Fig. 19 allows the foregoing operational range. Note the presence of a low-pressure ERD on the second pass brine stream.

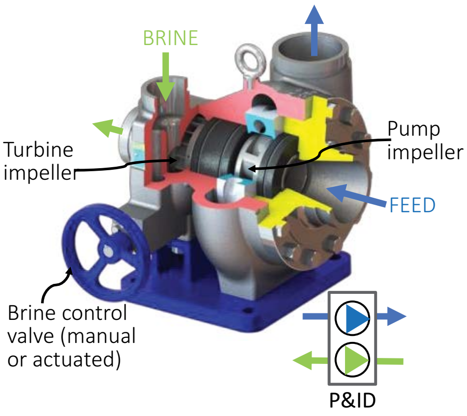


Fig. 16. Turbo features.

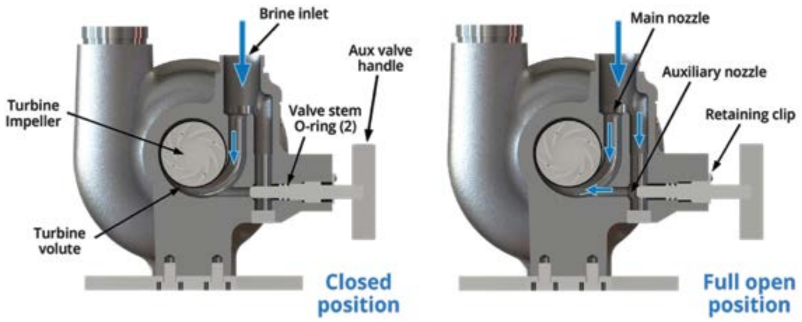
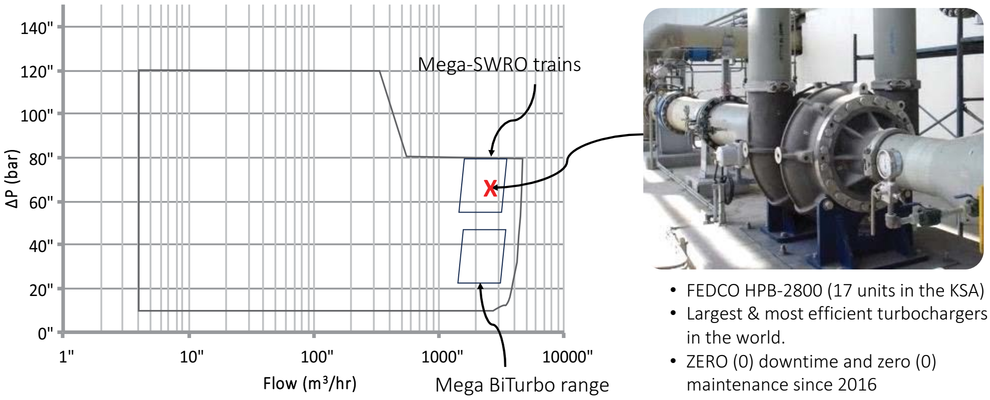


Fig. 17. Brine flow control. Close aux. valve to reduce brine flow. Open aux. valve to increase brine flow.



- FEDCO HPB-2800 (17 units in the KSA)
- Largest & most efficient turbochargers in the world.
- ZERO (0) downtime and zero (0) maintenance since 2016

Fig. 18. Hydraulic range and installation photo of HPB-2800 turbo.

17. High recovery and membrane suppliers

Nitto Hydranautics has endorsed the BiTurbo configuration and its applications for high recovery SWRO. Nitto has added the BiTurbo configuration to their membrane projection software. Several high recovery BiTurbo systems are currently operating using Nitto membranes including ultra-high-pressure applications (Fig. 20).

LG Chemicals similarly supports and endorses the BiTurbo for high recovery SWRO applications. LG Chemicals indicate that longer membrane life can be expected and the number of CIP applications reduced due to the more favorable operating conditions in a BiTurbo vs. a single stage system.

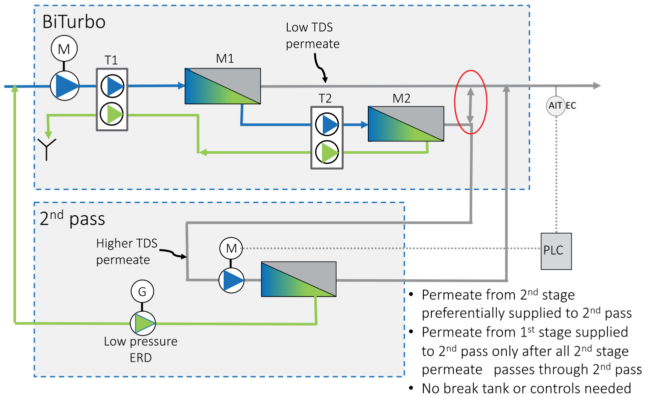
18. Industry collaboration

Fluid Equipment Development Company, LLC (FEDCO) with membrane suppliers, pressure vessel suppliers and Saline Water Conversion Corporation (SWCC) via the Desalination Technology Research Institute (DTRI) in Saudi Arabia have formed several collaborations related to the BiTurbo.

Fig. 21 shows a BiTurbo system at FEDCO's Collaboration Center. The system can reproduce a wide range of feed salinities and temperatures. A cooling system ensures stable temperature over the duration of a test run. Six (6) PVs can be configured in various two-stage arrangements. Precision flow meters and pressure transducers with data logging fully characterize membrane performance. This information is used by the membrane suppliers to improve the accuracy of their membrane projection software. The system will be upgraded for 120 bar operation on the second stage in the near future.

Fig. 22 shows a brine mining demonstration system located near Jubail, Saudi Arabia a the DTRI facility. Features include:

- Built by PACT Engineering (Dubai);
- Owned by FEDCO;
- Hydranautics membranes;
- Nanofiltration brine will be used for other processes;
- FEDCO BiTurbo configuration;
- Feed UF membranes;
- Brine TDS at 110,000 ppm from BiTurbo



- Permeate from 2nd stage preferentially supplied to 2nd pass
- Permeate from 1st stage supplied to 2nd pass only after all 2nd stage permeate passes through 2nd pass
- No break tank or controls needed

Fig. 19. Second pass configuration.

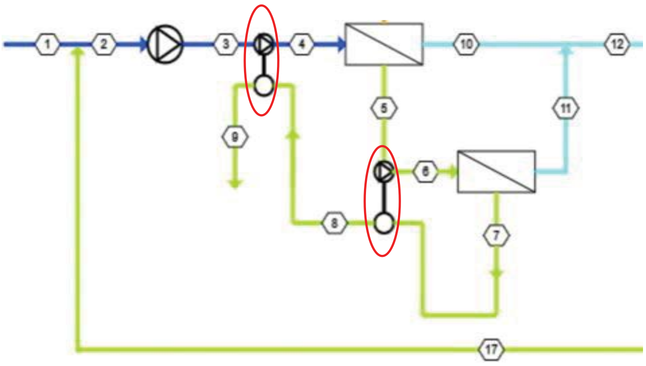


Fig. 20. MSMD BiTurbo diagram (turbos highlighted in red).

Fig. 21. BiTurbo test system.

Fig. 22. BiTurbo brine miner demonstrator.

- Concentrator brine is high purity NaCl to 210,000 ppm (under development);
- Brine will be crystallized.

Fig. 23 shows a simplified P&ID of the brine mining system. With a suitably designed system, break tanks are not needed.

Field locations of the BiTurbo were selected to gain operating experience in a variety of geographies, markets and competencies (Fig. 24).

19. BiTurbo control

As with standard SWRO systems, permeate and brine flows are the main process control values. The HPP discharge pressure via variable frequency devices (VFD) control is adjusted as needed to obtain the permeate flow setpoint. Brine flow is adjusted as needed by setting the auxiliary nozzle in feed turbo, T1.

Turbos T1 and T2 are designed and manufactured to best fit the duty points of each application. Turbos have an inherent self-regulating response to changes in feed and brine flow. If brine flow increases and permeate flow decreases, feed boost increases thereby partially restoring permeate flow and reducing brine flow. In the inverse scenario, the turbo reduces boost thereby partially restoring feed and brine flow to the duty point conditions. This self-regulating functionality allows T2 to operate in a fully passive mode without the need for active controls (Fig. 25).

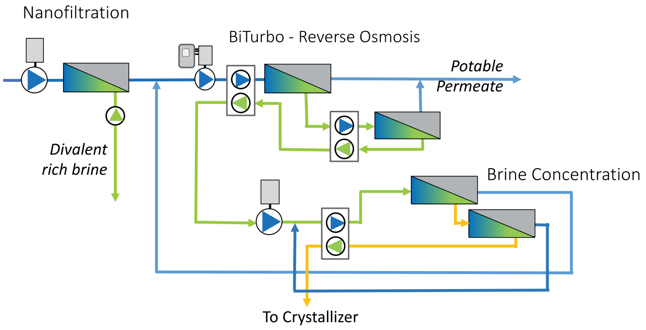


Fig. 23. BiTurbo brine miner.

20. Enhancements to the BiTurbo system

The Hydraulic Energy Management Integration (HEMI) is a turbo with its rotor connected to an electric motor. HEMI functions include:

- Provides regulation of feed flow to the membrane;
- Provides regulation of brine flow;
- Provides brine energy recovery.

Fig. 26 illustrates the HEMI functionality. The HPP is started by either DOL or soft starter and runs at the speed dictated by the power supply (50 or 60 Hz). The HPP discharge pressure is 30 bar. The membrane feed pressure varies from 55 to 65 bar. The turbo responds by varying its pressure boost as explained earlier. However, to achieve precise control of the feed pressure, the motor will increase

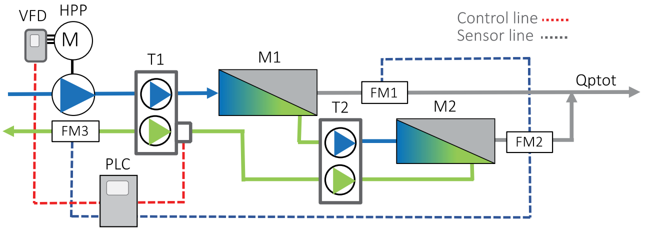


Fig. 25. Basic BiTurbo control scheme.

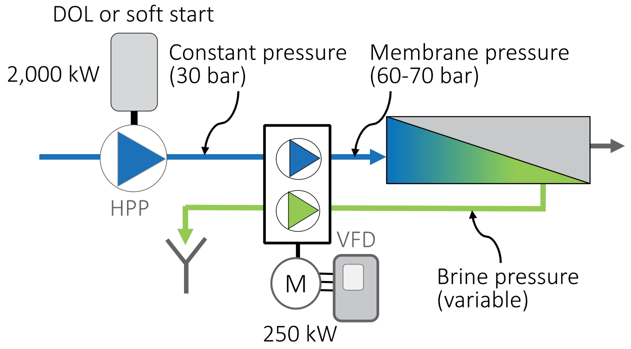


Fig. 26. HEMI functionality.

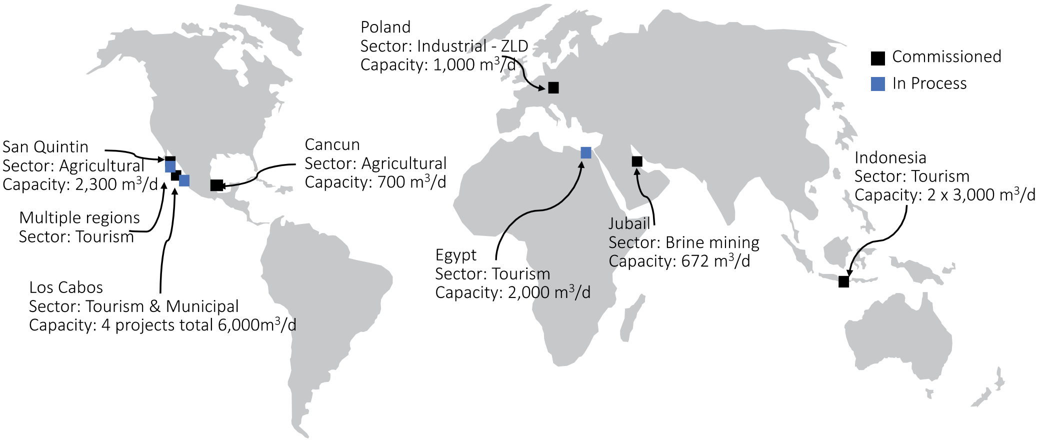


Fig. 24. Initial BiTurbo installations.

the rotor speed as necessary to obtain the exact amount of feed pressure.

Fig. 27 shows that the membrane pressure is achieved by the summation of the HPP inlet pressure (3 bar), the HPP differential pressure (27 bar) and the balance from the HEMI feed pressure boost (25 to 35 bar). Note that the HEMI motor provides a small fraction of the Turbo feed boost with the rest from the integral turbine. The motor power output is zero at the lowest membrane conditions.

The HEMI motor power is typically rated 10% to 15% of the rating of the HPP. The HEMI motor is low-voltage and driven by a low-voltage VFD.

The main justification of the HEMI is the elimination of a multi-megawatt medium voltage VFD required by the HPP, associated with high CAPEX, OPEX and dissipation of 3.5% of the electrical power used by the HPP.

The combination of the inherently more efficient membrane configuration combined with the HEMI high efficiency and elimination of VFD losses on the HPP yields an SEC that is lower than isobaric chamber ERDs even though operating at higher recovery.

Fig. 28 shows a HPB-2800 HEMI under full power testing. The HEMI is mounted sideways to simplify installation and removal of test piping.

21. Centralized VFDs

As outlined earlier, the HEMI does not require a VFD on the HPP to provide feed and brine flow and pressure control. However, during train startup, a gradual increase in feed pressure remains required to help purge air and to minimize mechanical stress on the membranes and instrumentation.

SWRO plants have several means of feed pressure regulation including feed throttle vales, jockey pumps under VFD control and VFDs on the HPP. Feed throttle valves and VFDs on the HPP allow a gradual feed pressure ramp up during startup and ramp down during train shutdown.

Mega-scale SWRO facilities have up to 40 trains each with a multi-megawatt medium voltage VFD. The cost of these VFDs include:

- Purchase cost of many millions of dollars;
- High installation costs;
- Climate-controlled rooms;
- Wastes up to 3.5% of electrical energy;
    - 3% VFD, 0.5% reduced motor efficiency;
- High maintenance;
- Considerable floor space.

The HEMI provides full control of feed and brine flows and pressures during SWRO operation. However, other means are required to bring feed pressure to the normal range of train operation before engagement of the HEMI.

In pipeline systems, pumps need to be gradually ramped up or ramped down in speed to avoid water hammer. Once the pump is at duty speed, no further adjustment in the motor speed is required. A “centralized VFD” configuration allows a single VFD to start individual pumps, bring them to speed and then disengage with the pump switched to DOL power. One (1) VFD can support ten (10) or more pumps resulting in very substantial CAPEX and OPEX savings.

This operating mode matches the HEMI in an SWRO system. The centralized VFD brings the HPP up to its DOL speed (exact speed based on 50 or 60 Hz power supply). Once at speed, the power is switched to line power and the VFD is disengaged. The single VFD may have a 3% duty cycle. A second VFD can provide 100% backup. Fig. 29 shows the basic equipment arrangement and functionality; train #1 is operating, train #2 is starting and train #3 is not operating. Advantages include:

- VFD maintenance reduced due to low duty cycle (less than 3% run time expected);
- 3.5% energy savings from elimination of VFD losses and unfavorable electrical waveform to motor;
- CAPEX savings of 50% to 60% vs. standard VFD configuration.

An experienced electrical engineering service provider has confirmed that the centralized VFD configuration is suitable for SWRO service that uses the HEMI and have provided the cost savings estimates.

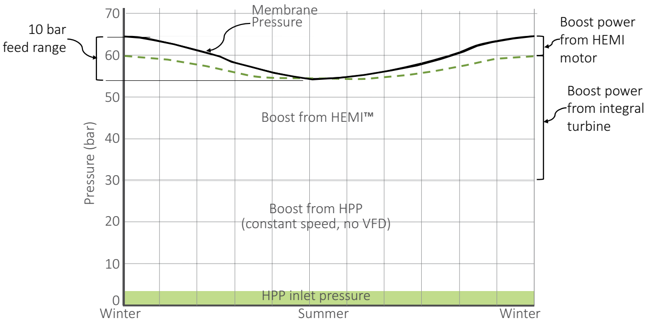


Fig. 27. HEMI power flow.

Fig. 28. HPB-2800 HEMI under test.

22. CAPEX and high recovery

The positive impact of high recovery design and operation can best be estimated by a simple reduction in the number of trains. For example, raising recovery from 42% from 52% reduces the number of trains from 40 to 32 trains. The entire facility would be reduced by 20% in size, quantity of equipment, real estate requirements, etc. Several cost categories are affected less favorably such as post-treatment, product storage and distribution. Also, permitting and engineering would have less of a proportional reduction. Fig. 30 provides a breakdown of CAPEX factors in mega-scale SWRO systems.

The BiTurbo has a beneficial impact on the membrane array by reducing PVs, elements, racks and headers plus an interstage turbo. Conversely, the elimination of 40 medium voltage multi-megawatt VFDs and associated costs can offset the second stage costs. Although deserving a detailed study and certainly subject to project-specific factors, a reasonable estimate would be a 15% reduction in total project cost.

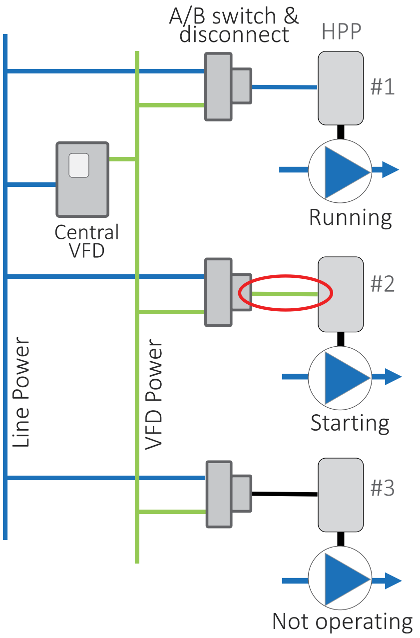


Fig. 29. Central variable frequency devices/high pressure pump arrangement.

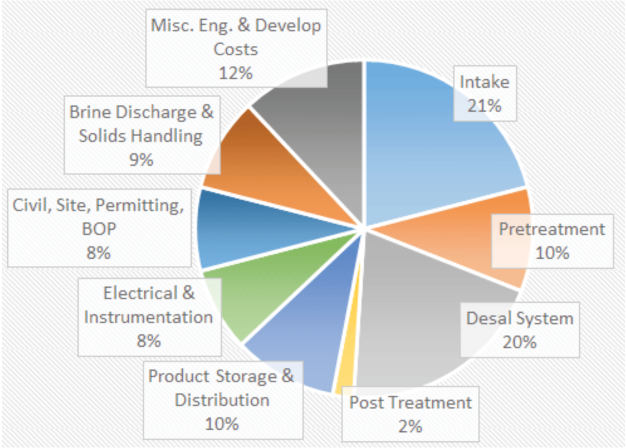


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Fig. 30. CAPEX factors for mega seawater reverse osmosis.

Another approximation of CAPEX savings is through the relationship between CAPEX and plant capacity presented in Fig. 31. A capacity reduction of 20% results in a 17% reduction in CAPEX per the displayed curve fit equation.

In many SWRO applications, recoveries of up to 60% are feasible and economically justifiable. The CAPEX reduction would be approximately 26% from raising the recovery from 42% to 60%.

A CAPEX reduction will be assumed to be 16%.

23. OPEX and high recovery

An OPEX reduction is expected from high recovery due to reduced chemical consumption from lowered feed flow, fewer CIP applications, reduced cartridge filter consumption, reduced sludge generation and reduced membrane replacement.

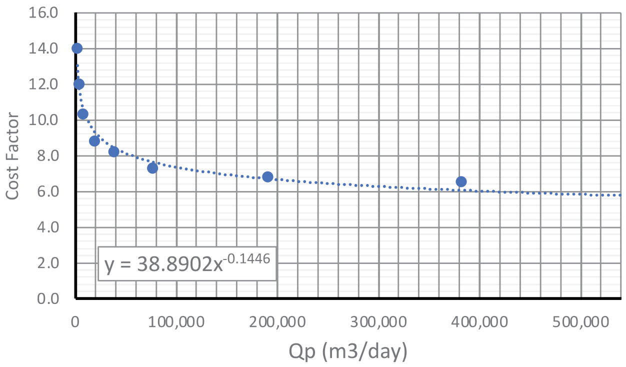
Fig. 32 presents a breakdown of OPEX expenses including amortization of project CAPEX costs showing a total cost of water at $0.76/m^3 including distribution. If amortization costs are removed, the cost becomes $0.47/m^3. This may be considered high in some regions however the proportions of the various costs are reasonable for large SWRO systems.

The table in Fig. 33 displayed the OPEX costs for 42% recovery as given in Fig. 31. The column titled "52%" reflects the estimated impact of increased recovery. The longer membrane life is based on estimates from a major membrane supplier. All other savings are from reduced volumes of feed water to lift and process.

The total OPEX reduction is 14.4% including amortization of project financing. Excluding financing costs, the savings is 7.5%.

24. Environmental impact

The underlying advantage of higher recovery SWRO on the environment is simply a reduction in everything associated with desalination. Examples include:



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Cost = Cost Factor x Q_p x 264

Fig. 31. CAPEX vs. capacity.

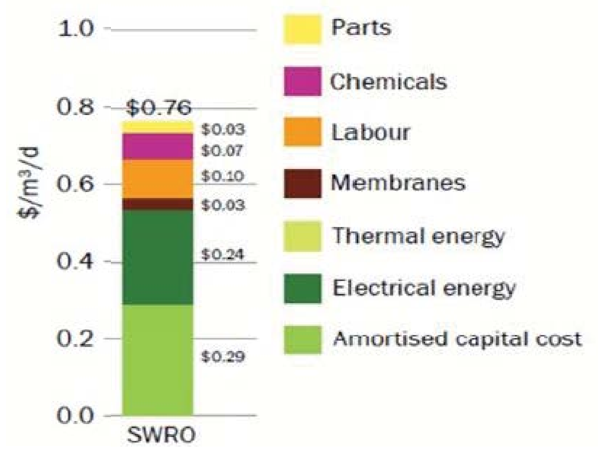

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Fig. 32. CAPEX vs. capacity.

(1) Less consumption of everything needed for SWRO
  - Energy
  - cartridge filters
  - sludge generation
  - chemical consumption
  - less capital equipment, less disposal costs

(2) Smaller facility and infrastructure
  - Reduced high alloy pipes and valves
  - Fewer motors, less electrical components
  - Less land, reduced beach impact

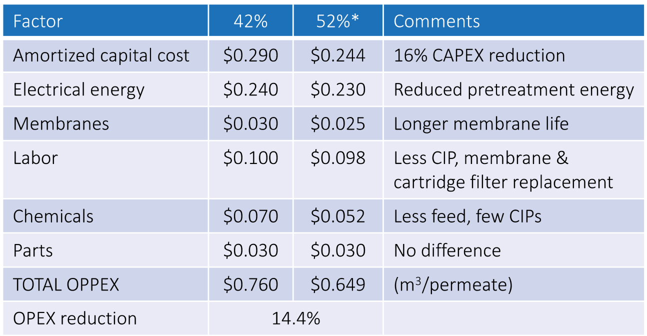
(3) Reduced water draw
  - Smaller intakes and outfalls
  - less impact on aquifers
  - Less draw from oceans – lessened impact on sea life

(4) Reduced CO_2
  - Less materials
  - faster project implementation
  - Lower facility energy consumption

25. Conclusion

Questions answered:

(1) Achievable SWRO recovery?
  - Up to 60% SWRO with standard membranes and PVs.
  - higher for ZLD/brine mining applications up to 120 bar.



Factor	42%	52%*	Comments
Amortized capital cost	$0.290	$0.244	16% CAPEX reduction
Electrical energy	$0.240	$0.230	Reduced pretreatment energy
Membranes	$0.030	$0.025	Longer membrane life
Labor	$0.100	$0.098	Less CIP, membrane & cartridge filter replacement
Chemicals	$0.070	$0.052	Less feed, few CIPs
Parts	$0.030	$0.030	No difference
TOTAL OPPEX	$0.760	$0.649	(m^3/permeate)
OPEX reduction	14.4%		

Fig. 33. CAPEX vs. capacity.

(2) What about permeate TDS?
  - Lower than a single stage.

(3) Impact on CAPEX and OPEX?
  - 10%–25% reduction as reasonable estimates.

(4) Key technology?
  - Brine staging with turbo interstage pressure boost and HEMI turbo on first stage.
  - All components have decades of field experience in SWRO systems of every size.

(5) Are standard membranes suitable?
  - Yes, and endorsed for high recovery brine stage configurations by major membrane suppliers.

(6) Membrane Life?
  - Longer than single stage systems.

(7) Energy consumption?
  - Typically lower on a facility level than current technology.

(8) Chemical consumption?
  - Reduced per m^3 of permeate.

(9) Biofouling?
  - Significantly reduced due to reduced CP and higher crossflow velocities.

(10) Discharging high salinity brine?
  - Diffusers/eductors can mix the brine with ambient seawater before discharge to the environment to achieve salinity concentrations equal to low recovery systems.