THE GWI NETWORK

THE FUTURE OF HIGH-RECOVERY RO

Unlocking the potential of the world's leading desalination technology

May 2022

GWI GLOBAL WATER INTELLIGENCE | FEDCO

Executive summary

On Tuesday 29th March 2022, the GWI Network ran a virtual session on the future of high-recovery reverse osmosis in the desalination sector, in partnership with FEDCO. Panellists included leading voices in the development and application of high-recovery reverse osmosis (RO) systems, bringing together stakeholders in system design, membrane and hydraulic equipment supply, and environmental research to explore the future of increasing RO recovery rates. This white paper presents the advantages, available technologies, and potential growth opportunities of high-recovery RO.

Although the idea of high-recovery reverse osmosis is not a new one, its viability in seawater applications has been historically limited by available components. It is only in recent years that the development of new membranes and hydraulic equipment has made high-recovery SWRO a practical and cost-effective option for improving the process of desalting water. A growing number of companies are using these new membranes, pressure vessels, and pumps to produce new system configurations capable of maximising recovered water volumes while minimising both capital and operational costs.

The advantages of high-recovery RO

Retrofits and modularity

The technological landscape of high-recovery

What happens with the reject brine?

The road to high-recovery SWRO

Bringing value to ZLD/MLD applications

High-recovery RO energy usage and cost

The market opportunities for high-recovery RO

Glossary

SWRO – Reverse osmosis treatment of seawater, typically with a salinity range of 20,000 to 50,000 ppm TDS.

BWRO – Reverse osmosis treatment of brackish water, typically with a salinity range of 3,000-20,000 ppm TDS.

Energy recovery device (ERD) – A device used to recover energy that would otherwise be wasted, such as the pressure of a brine stream, and reuse it to help drive the desalination process. This includes turbochargers such as those manufactured by FEDCO.

Flux – The rate at which water passes through a membrane. Typically measured in litres/m^2/hour (LMH).

Concentration polarisation – A phenomenon in which solutes form a dense, polarised layer next to a membrane surface which eventually restricts flow through the membrane.

Membrane scaling – The precipitation of mineral deposits onto the surface of a membrane, potentially blocking pores, impeding performance, and shortening membrane lifespan.

Membrane biofouling – Obstruction of a membrane by biological contaminants such as algae, impeding membrane performance and shortening membrane lifespan.

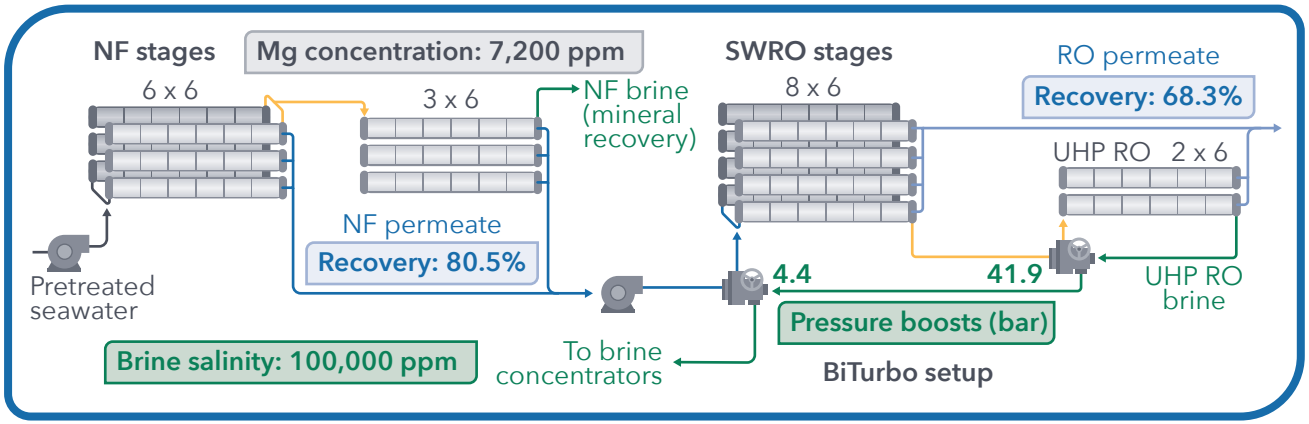
Specific energy consumption (SEC) – The total energy consumed to produce a unit volume of product, e.g. kWh/m^3 or kWh/kgal.

Zero and minimal liquid discharge (ZLD/MLD) – The process of either completely (ZLD) or significantly (MLD) reducing the volume of liquid effluent discharged to the environment.

New horizons for high-recovery RO

FEDCO

Saudi Arabia's Desalination Technology & Research Institute (DTRI) is piloting multi-stage, ultra high pressure reverse osmosis for use in an industrial-scale brine mining operation. In partnership with the Saline Water Conversion Corporation (SWCC), the world's largest desalination plant operator, the project lays the foundation for both extracting precious minerals from the ocean, and reaching new horizons in high recovery desalination.



The pilot unit uses nanofiltration (NF) to precondition the feed, which prevents scaling in the SWRO/UHP RO stages and produces a magnesium-rich brine. The NF produces 40 m^3/hr of permeate with a salinity of 48,000 ppm, at an energy consumption of 1.6 kWh/m^3 of permeate. The first SWRO stage operates at 60 bar, before an interstage, ultra-high pressure HPB turbocharger boosts the feed to 100 bar for the second stage UHP RO array. A second turbocharger recovers the remaining hydraulic energy from the feed stream to maximise energy efficiency. The RO system achieves a recovery of 68% and discharges brine at 100,000 ppm. The RO system uses 3.6 kWh for every cubic metre of permeate produced.

Reverse osmosis has previously struggled to concentrate brine beyond 100,000 ppm without turning to complex and capital-intensive system configurations. The HPB Ultra enables simpler and safer high recovery RO, even at the highest feedwater concentrations.

Key takeaways

- *68+% recovery in Gulf seawater is viable and affordable*
- *This can be achieved using commercially available and proven equipment*
- *Two-stage NF ahead of RO enables production of Mg-rich brine, and reduces scaling for downstream SWRO*
- *Pushing membrane technology to brine concentrations of 100,000+ ppm dramatically reduces evaporator size, and therefore cost of brine production*

The advantages of high-recovery RO

Increasing recovery rates can save money and improve efficiency throughout a desalination treatment train

RO is a well developed technology but it is not fully mature. One of the key areas in which the technology can still be improved is recovery rate. Traditionally, continuous single-stage SWRO systems are operated to recover around 30–50% of the feedwater as permeate. However, running at higher recovery rates brings several significant benefits to a desalination process, from pretreatment to brine management.

The benefits of high-recovery RO over traditional RO systems:

Pretreatment and intake capex reductions

Increasing the recovery rate of a water production RO system means less feedwater is needed to produce the same volume of desalinated water. This means a smaller pretreatment system and seawater intake can be used, reducing plant footprint and construction costs.

Pretreatment and intake opex reductions

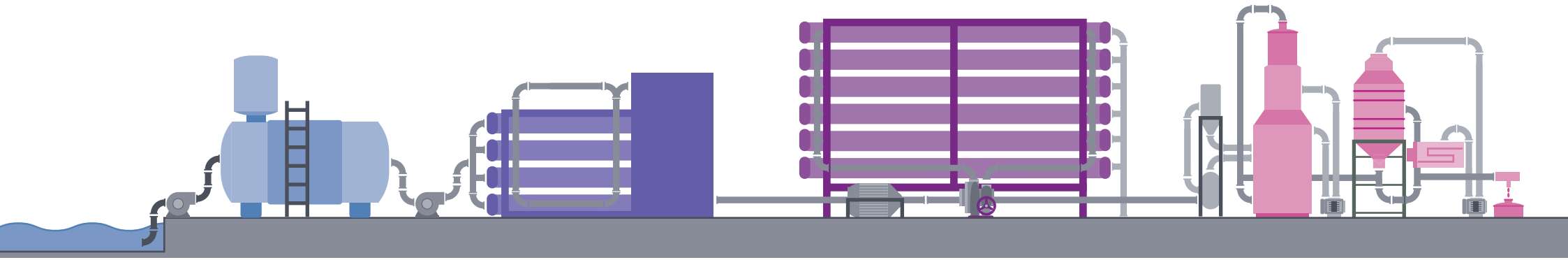
Smaller pretreatment and intake systems also provide savings to operational costs which help to offset any additional opex from the high-recovery RO process itself. Reduced pretreatment means reduced chemical and energy usage, while smaller intake pumps help reduce energy consumption further.

Additional operational benefits

Some modern high-recovery RO systems are designed to more effectively balance flux rates across membrane elements and disrupt concentration polarisation layers. This helps improve membrane efficiency, performance and longevity.

ZLD/MLD cost reductions

High-recovery RO also offers value outside of water production for the zero and minimal liquid discharge (ZLD/MLD) markets. Its ability to concentrate brine to higher TDS values means it can be used to reduce the required size and energy requirements of a costly evaporator or crystalliser.



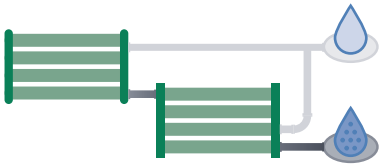
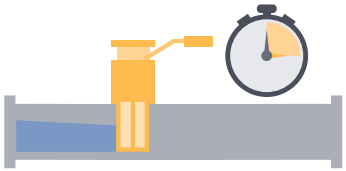
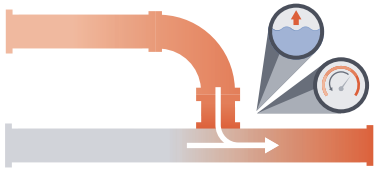
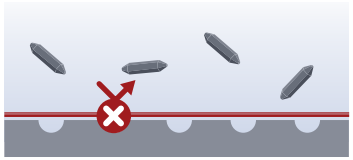
The technological landscape of high-recovery

There are multiple approaches to increasing recovery rates currently on the market

Although high-recovery RO can often be talked about as a single idea, it is a goal rather than a specific approach. To reach this goal, the two key membrane-centric obstacles are scaling and pressure limitations, with several approaches to addressing them.

> The industry has seen a lot of emphasis on improving desal system recovery to both make more effective use of the feedwater and minimise the complications and cost of concentrate disposal. There are a growing number of options available to increase RO system recovery and even more potential options that are currently under development.
>
> **Tom Pankratz – Editor, WDR**

Approaches:

	Utilise multiple stages	Operate in timed modes	Reduce osmotic pressure gradient	Disrupt or resist scale formation	Increase pressure
					
Description	Multi-stage RO allows for higher recovery rates while keeping cross-flow velocity high and flux balanced across the system, reducing scaling potential and allowing membranes to operate in relaxed conditions.	Halting brine discharge until desired conditions are met allows for more water to be recovered, and means recovery can be easily controlled by varying the time interval between discharges.	Bringing down the osmotic pressure gradient across the membrane reduces the pressure requirements and permits more water to be recovered from high-salinity streams without damage.	Changes to hydraulic conditions to disrupt scale formation, or specifically designed membrane coatings and cleaning methods, allow an RO system to run beyond standard operating conditions without damage.	Increasing operating pressure allows for more water to be recovered but requires specialist components and brings additional operational challenges.
E.g.	BiTurbo™	Semi-batch RO, Pulse flow RO	Counterflow RO, Osmotically assisted RO, Impact RO™	Osmoflo Brine Squeezer™, Flow-reversal RO	Ultra-high pressure RO

Design considerations

Begin with the membrane

Traditional RO configurations restrict options for optimising membrane efficiency. Configurations should be chosen to allow the membranes to best meet desired recovery and permeate quality.

Potential for hybrid configurations

Many of the approaches listed can theoretically be used in combination with each other, allowing for even higher recovery rates where needed, such as in brine minimisation applications.

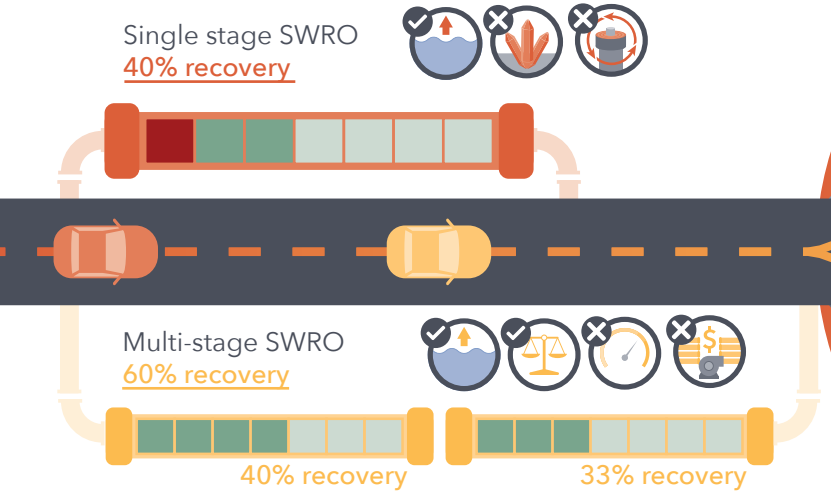
The road to high-recovery SWRO

New components mean multi-stage SWRO is now viable

Historical approach to SW & BW

In BWRO, multiple stages are commonly used to provide higher recovery rates, yet SWRO has historically involved just a single stage. However, producing more water from a single stage results in overfluxed lead elements, increasing scaling potential and decreasing membrane lifespan. The solution is to use multiple stages.

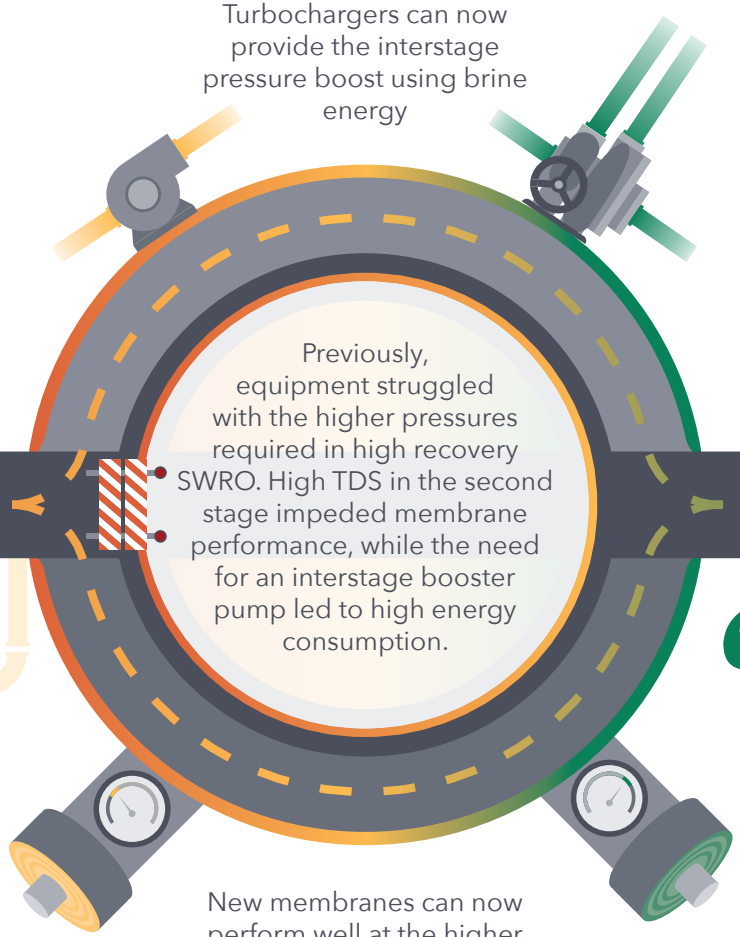
Single stage SWRO
40% recovery



Multi-stage for SWRO

A multi-stage configuration allows pressure to be increased across the system as the TDS and osmotic pressure of the feedwater increases, balancing load across elements and avoiding overfluxing. Multi-stage SWRO setups have been built in the past but were historically limited by the performance of available components.

Turbochargers can now provide the interstage pressure boost using brine energy

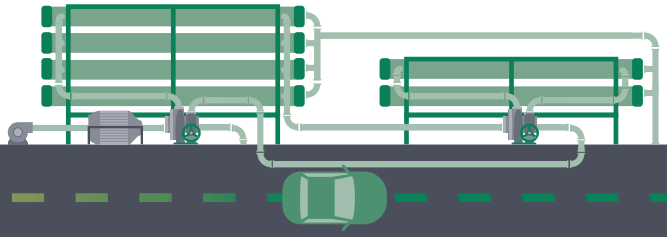


Previously, equipment struggled with the higher pressures required in high recovery SWRO. High TDS in the second stage impeded membrane performance, while the need for an interstage booster pump led to high energy consumption.

New membranes can now perform well at the higher pressures of later stages

Result: Running SWRO like BWRO

As in brackish water applications, it is now possible to run a cost-effective and reliable multi-stage, high-recovery SWRO system. Where still higher recovery rates are required, such as in ZLD applications, UHPRO stages can be included.



> Essentially, today you can make a seawater type system and run it like a brackish water system with multiple stages.
>
> **Craig Bartels – VP Technology, Hydranautics**

Semi-batch in seawater

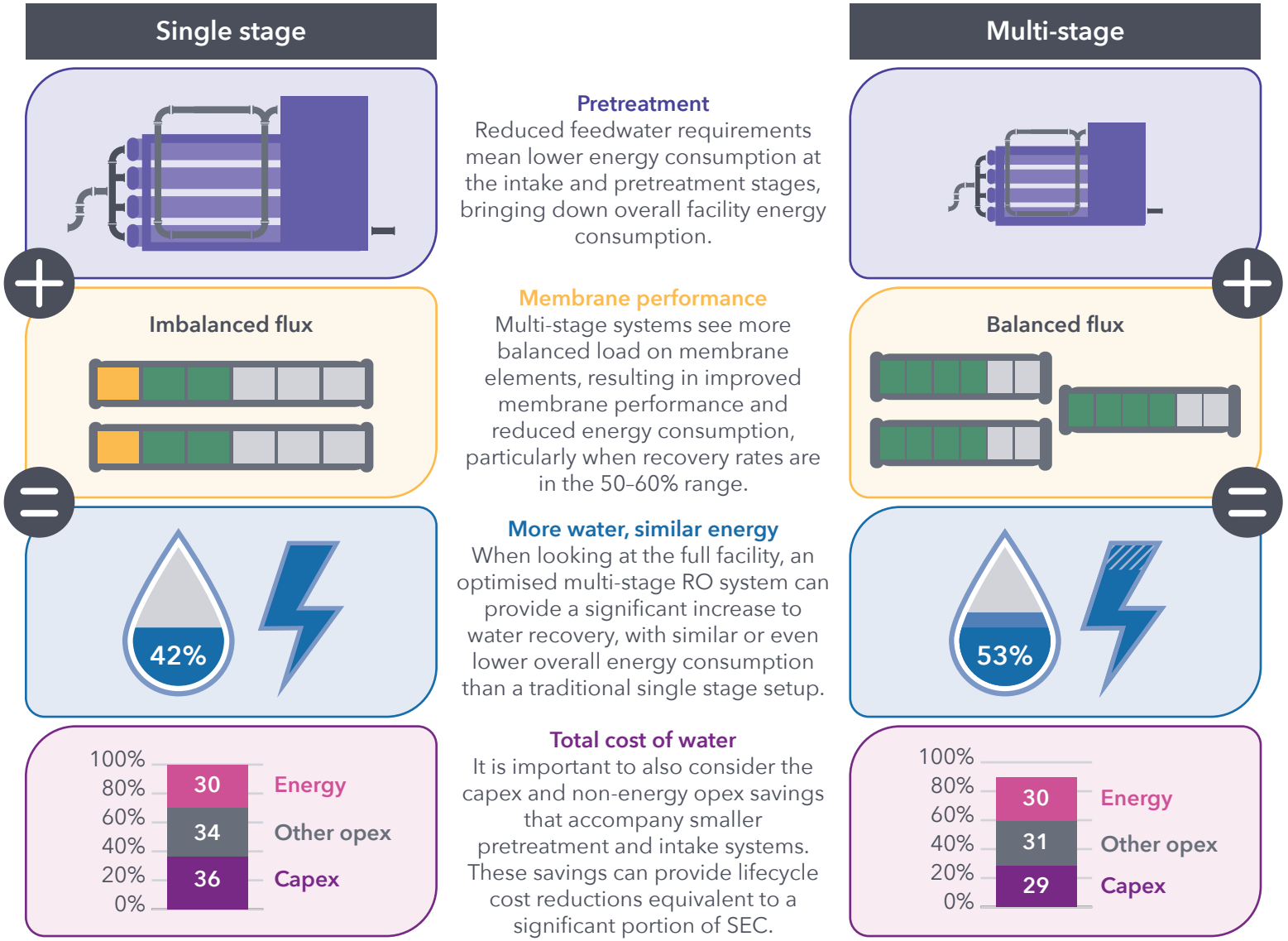
The potential for using semi-batch RO with seawater is being investigated with a grant from Singapore's PUB in 2021, building on commercial success in BWRO applications.

High-recovery RO energy usage and cost

When comparing energy usage and cost, it is important to look at the facility as a whole and its full lifecycle

Minimising RO energy consumption is currently a major focus for reducing the cost of desalinating water. However, when weighing up the value of high-recovery RO, it is important to take a holistic, big-picture approach that considers the desalination process at the facility level, rather than only at the RO system level. The impact on lifecycle cost of capex and non-energy opex savings provided by smaller pretreatment and intake systems should also be considered.

> We should really be talking about facility energy consumption. With multi-stage RO, where membrane performance is optimised and there is less water to be pretreated, from our analysis and some field data, we actually saw lower SEC at higher recovery. There's certainly an upper limit but at 53–55% recovery, you can show a lower facility SEC than with single stage systems using commonly used ERDs at 42%, for example.
>
> **Eli Oklejas – President, FEDCO**



Pretreatment
Reduced feedwater requirements mean lower energy consumption at the intake and pretreatment stages, bringing down overall facility energy consumption.

Membrane performance
Multi-stage systems see more balanced load on membrane elements, resulting in improved membrane performance and reduced energy consumption, particularly when recovery rates are in the 50–60% range.

More water, similar energy
When looking at the full facility, an optimised multi-stage RO system can provide a significant increase to water recovery, with similar or even lower overall energy consumption than a traditional single stage setup.

Total cost of water
It is important to also consider the capex and non-energy opex savings that accompany smaller pretreatment and intake systems. These savings can provide lifecycle cost reductions equivalent to a significant portion of SEC.

Retrofits and modularity

High-recovery RO can often be easily added to an existing system

Unlike the shift from thermal desalination technologies to membrane-based ones, upgrading an existing plant to utilise high-recovery technology does not inherently require the construction of a capex-heavy new plant. Often high-recovery configurations can be applied to existing SWRO plants with fairly minimal changes to existing infrastructure.

In the last 10 years, 23 million m^3/d of SWRO capacity has been installed globally. Retrofitting these plants to increase recovery by 1/4 could provide around 6 million m^3/d of additional water.

OR

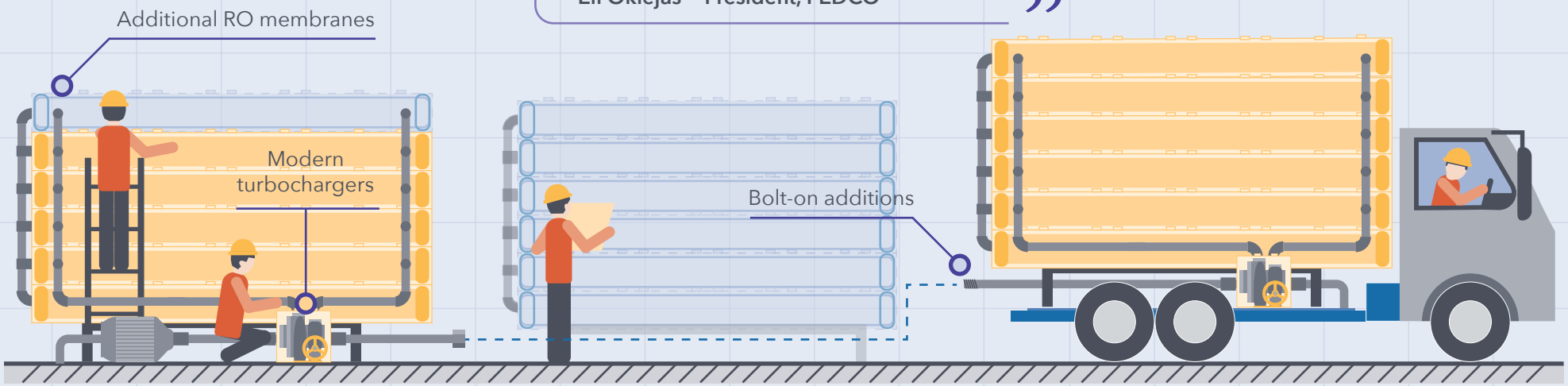
Easy reconfiguration

Reconfiguring an existing plant to make use of some high-recovery processes like multi-stage systems can be done relatively easily and inexpensively, particularly for smaller-scale installations.

> For small trains, it's very easy to do – if they don't have energy recovery, simply add a turbocharger and [pressure vessels] housing appropriate membranes. For larger plants, you have to look at a whole array of factors, but often it makes [economic] sense to reconfigure the plant to get that 30-40% extra production.
>
> **Eli Oklejas – President, FEDCO**

'Bolt-on' additions

High recovery RO can sometimes be added as a 'bolt-on' additional stage to existing processes without requiring a major retrofit of existing equipment.

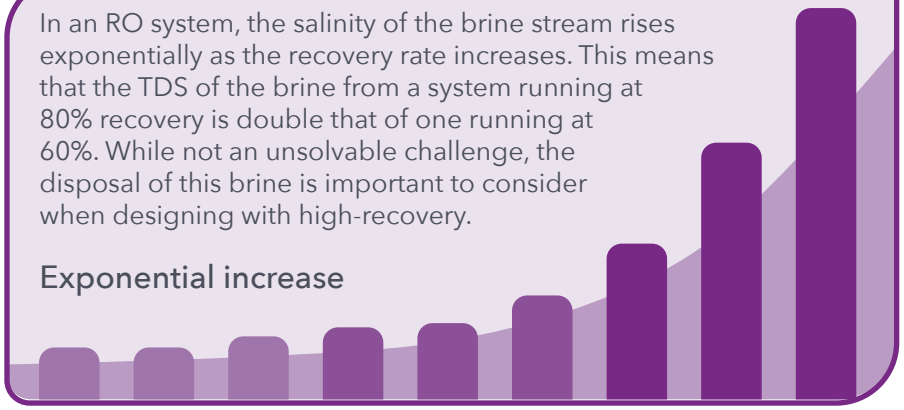


What happens with the reject brine?

Higher recovery makes brine discharge more challenging

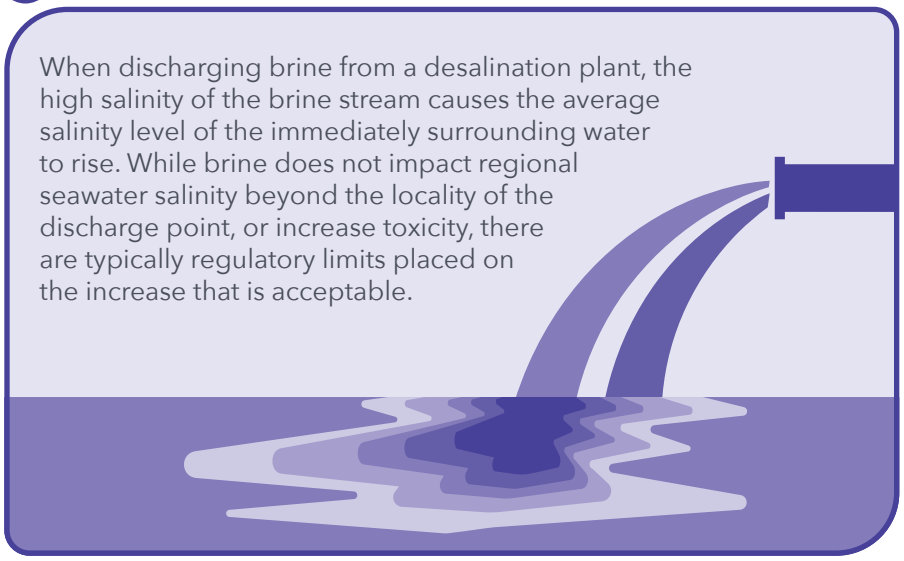
The issue

In an RO system, the salinity of the brine stream rises exponentially as the recovery rate increases. This means that the TDS of the brine from a system running at 80% recovery is double that of one running at 60%. While not an unsolvable challenge, the disposal of this brine is important to consider when designing with high-recovery.



Why it matters

When discharging brine from a desalination plant, the high salinity of the brine stream causes the average salinity level of the immediately surrounding water to rise. While brine does not impact regional seawater salinity beyond the locality of the discharge point, or increase toxicity, there are typically regulatory limits placed on the increase that is acceptable.



Solutions

In California, where discharge regulations are particularly stringent, there are several solutions seeing use:

1. **In-plant dilution/flow augmentation**
   Diluting brine with seawater from the intake can reduce the effective salinity of the discharge. However, this can require additional capital-intensive intake infrastructure.
2. **Co-mingling**
   Dilution can also be achieved by mixing brine with effluent from other plants such as WWTPs. However, this requires a suitable nearby plant.
3. **Optimised diffusers**
   Well-modelled diffusers with more ports and higher velocities can help distribute brine discharge to reduce its impact. However, higher velocity brine shear can negatively affect marine life.

Each of these solutions has benefits and drawbacks, and there is still room for new innovations that can address the problem of high-salinity brine discharge more effectively.

> The challenge here is that higher recovery means there is lower volume but higher salinity brine. As salinity increases with the discharge, it becomes more challenging to manage what that footprint looks like. This is a real permitting concern in California and something that needs to be considered as calculations are completed for where the brine may end up. However, there's always a new and interesting way to try to solve these challenges.
>
> **Tim Hogan – Principal & Owner, TBW Environmental Research and Consulting**

Bringing value to ZLD/MLD applications

High-recovery RO is also useful for helping dispose of brine in alternative ways beyond discharge

While the more concentrated brine from high-recovery RO presents an additional challenge for brine discharge, it also offers a highly effective solution to reducing brine concentration costs for zero and minimal liquid discharge (ZLD/MLD). Increasing volumes of brine require concentration for cost effective disposal, and there is mounting regulatory pressure for ZLD/MLD in key brine treatment markets like China and India, meaning anything that can reduce cost has significant value.

> The operating and capital costs of an evaporator are significantly higher than a multi-stage membrane system. However, the systems are getting more complex. Designers have to look at how to balance the opex and capex of those systems and get the interrelated parts all working together.
>
> **Craig Bartels – VP Technology, Hydranautics**

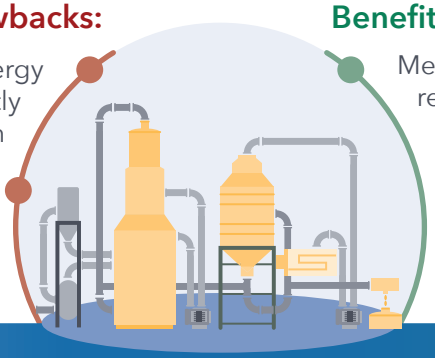
True ZLD requires evaporators and crystallisers

Drawbacks:

- Extremely energy intensive and costly operation
- Significantly higher installation cost than a membrane system

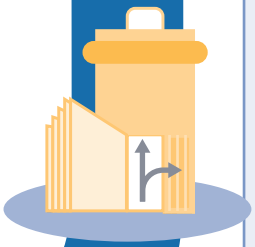
Benefits:

- Meet concentration requirements



Future development of a brine refining industry

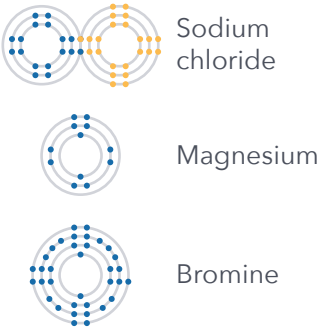
Value can be extracted from brine by concentrating useful salts. This could open new doors for the brine management market and expand the opportunities for high-recovery RO to add value by bringing down treatment costs.



Further innovation

Development of new brine concentration membranes that allow more dissolved solids to pass through, reducing the osmotic pressure gradient. This means brine can be concentrated beyond 200,000 ppm TDS without the use of a thermal unit and at conventional pressures.

However, additional salt passage reduces permeate quality



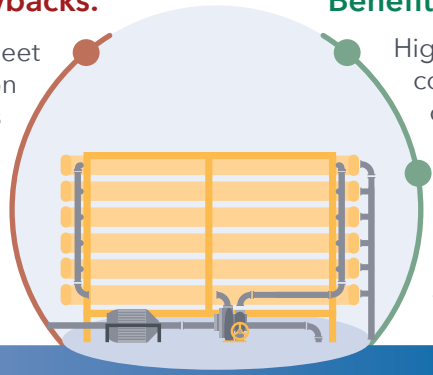
High-recovery RO can be installed ahead of thermal equipment

Drawbacks:

- May not fully meet concentration requirements

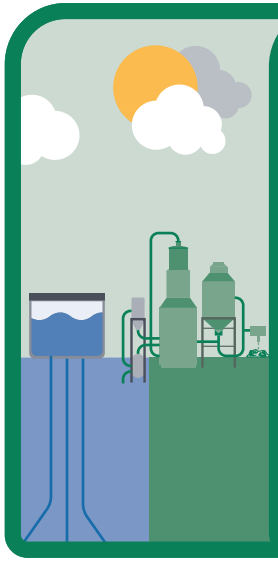
Benefits:

- Highly energy- and cost-efficient to operate
- Reduced brine volume going to evaporator, meaning a smaller thermal unit



Where are the opportunities for high-recovery RO?

There are opportunities for high-recovery RO to add value across the desalination market



Water supply

For water production applications, reduced feed volume requirements mean high-recovery RO can provide capex savings for greenfield projects and reduced opex for both green and brownfield projects.

Brine concentration

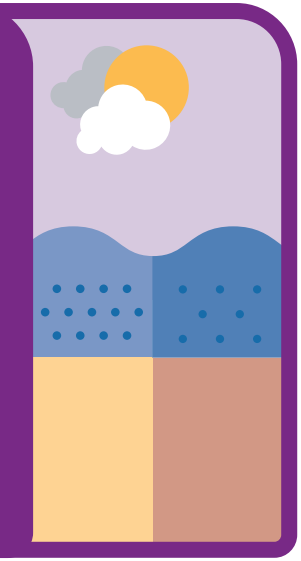
In ZLD/MLD applications, a high-recovery RO system ahead of any thermal units can provide significant opex savings and reduce the cost of complying with increasingly stringent and widespread discharge regulations. Developing a brine mining or refining industry could expand these opportunities further.

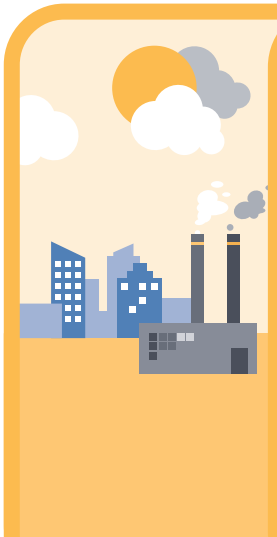
Multi-stage SWRO

Multi-stage high-recovery systems such as FEDCO's BiTurbo™ are already common in the brackish water market but, due to the development of new, more effective membranes and hydraulic equipment, can now offer their financial and operational benefits to the seawater market too.

Semi-batch with seawater

The potential for semi-batch RO configurations, such as DesaliTec's Closed Circuit RO, to be used in seawater applications is being explored but is still at an early stage.





Municipal

Due to the comparatively expensive nature of desalination as a water source, cost reduction is a key priority, providing opportunities for high-recovery RO to reduce capex and opex in the large-scale municipal desalination market.

Industrial

Likewise in the industrial sector, a focus on cost, combined with growing demand for ZLD (a traditionally expensive process) offers strong opportunities for high-recovery RO to provide savings to end users.

New build projects

There are strong opportunities for high-recovery RO in greenfield projects, where the reduced volume of feedwater needed for target production allows for significant savings in both opex and capex as well as reduced plant footprint.

Retrofits

In existing projects, high-recovery RO can reduce opex and increase water production without significant changes to existing pretreatment or intake infrastructure – particularly at small-scale installations where retrofit complexity is lowest.

Conclusion

KEY LESSONS

High-recovery RO can provide significant value to the desalination sector, allowing designers to either significantly reduce the cost of new plants or extract maximum value from existing plant infrastructure.

In examining the viability and cost efficacy of high-recovery RO, it is important to take a big picture perspective at the facility level that also considers the impact of capex and non-energy opex on lifecycle cost, not just SEC.

CHEAPER WATER

Higher recovery rates open the doors for cost reductions for new and old RO processes in capital, footprint and energy while maximising water production.

BWRO TO SWRO

It is now possible to practically and cost-effectively apply established BWRO techniques, such as the use of multiple stages, to seawater applications, due to the development of modern membranes and hydraulic equipment.

CHEAPER ZLD

High-recovery RO offers significant value to ZLD/MLD applications, where utilising a cost-effective membrane process in place of an expensive thermal unit can bring down capex and opex.

BRINE DISPOSAL

Higher concentration brine is a double-edged sword, requiring consideration of how to handle discharge. There are several solutions currently available and seeing use but there is still room for further innovation.

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Re-watch key moments from the event

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Find out more about FEDCO's High Recovery RO Solutions:

BiTurbo™ high-recovery RO
High-recovery for a sustainable future
Ultra high pressure: RO for ZLD/MLD

The future of high-recovery RO

Unlocking the potential of the world's leading desalination technology

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