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Revolutionizing Industrial Wastewater Management: Successful Pilot of a Low-Energy Solvent-Based Desalination Technology

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ABSTRACT

This pilot study validates a low-energy, solvent-based desalination technology for treating high-salinity industrial wastewaters, including Permian Basin produced water. The process efficiently recovers high-quality water without energy-intensive phase changes, offering a cost-effective and sustainable alternative to conventional methods. Results confirm strong water recovery, low energy use, and operational flexibility, including potential for ZLD. This approach provides a scalable solution for industries seeking energy-efficient, economically viable water treatment under increasing regulatory and sustainability pressures.

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INTRODUCTION

The management of high-salinity industrial wastewaters, particularly produced water (PW) from oil and gas operations, presents ongoing challenges. Regulatory pressures and sustainability initiatives demand treatment solutions that minimize disposal through injection and promote beneficial reuse. A range of treatment technologies have been investigated that can enable desalination of high-salinity wastewaters, however currently the only technologies that are ready for deployment are thermal-based technologies, membrane-based technologies, or solar evaporation (Shah, 2022). Thermal evaporation is energy-intensive due to the inherently high energy demand of water vaporization (Atia, 2021). As such, this approach is costly, and furthermore is often not feasible due to scaling issues (Tong, 2016). Similarly, membrane-based technologies are critically impacted by scaling issues, which significantly impacts the maximum water removal achievable and also necessitates significant chemical pretreatment of the wastewater (Foo, 2022). Solar evaporation requires excessive land use, extended treatment periods, and is only possible in a limited range of geographies. Furthermore, even where it may be feasible, the loss of the purified water to the atmosphere eliminates any possibility of beneficial reuse of the fresh water (Shah, 2022). Thus, an effective alternative technology is essential.

Solvent extraction is used extensively in a range of chemical processes (Müller, 2008). Typically, a solute of interest will be selectively extracted from an aqueous solution, and then further recovered in later steps. Extraction of water from an aqueous solution (bulk phase extraction) is significantly less common. A solvent extraction desalination pilot plant was investigated for water recovery from brackish water by Davison et al. in the 1960s (Davison, 1967). An amine solvent was used to extract water over eleven countercurrent stages, and heating enabled separation of the purified water from the solvent. Recent research has continued in this area, with various amines and other classes of solvents investigated (Foo, 2022). While there is no evaporation of water in this process, all of these approaches are nonetheless reliant on heat input to recover fresh water, with large temperature swings typically required to reduce the amount of solvent in the product water.

Aquafortus (“The Company”) has developed the ABX solvent extraction desalination process (“The Process”), which produces a concentrated brine or solid salt product by selective extraction of water from an industrial wastewater feed, however it is unique in its use of membranes for recovery of fresh water. This is enabled by a second water transfer step from the solvent (absorbent) to a membrane-compatible aqueous solution (regenerant; see Figure 1 below). Both the absorbent and regenerant may be tuned to maximize water transfer through the Process, while minimizing the passage of salts and solvent. The water is then recovered using a membrane process, providing a highly pure water product.

This paper presents laboratory data on a range of high salinity brines and the pilot-scale evaluation of this Process, designed to offer significant improvements in energy efficiency and operational reliability compared to conventional systems.

METHODS AND MATERIALS

Brines from a range of industries were either sourced from clients or prepared according to compositional analysis data. Metal analyses were carried out by ICP OES (Shimadzu ICPE-9820), and anion analysis was carried out by ion chromatography (Metrohm 930 Compact IC Flex with a Metrosep A Supp 19 - 150/4.0 column). Absorbent analysis was carried out by gas chromatography using a Shimadzu GC-2030 equipped with an HS-20 headspace sampler for partitioning investigations and an SH-Rxi-624Sil MS column. Bulk solution parameters were determined using a Metrohm 914 pH/conductivity meter, an Anton Paar DMA 1001 density meter, and a Shimadzu TOC-L analyzer.

Laboratory studies were carried out by mixing our absorbent(s) with brine samples to obtain equilibrium, followed by centrifugation, phase separation, and analysis of both phases. Based on the equilibrium results, countercurrent tests were conducted with 3-4 mixing/separating stages to determine optimum ratios for each absorbent/brine combination. Water recovery was determined by volume reduction of the brine phase, and analysis of water transfer into the absorbent, with mass balance confirmed by analysis of the final brine and suspended salt samples.

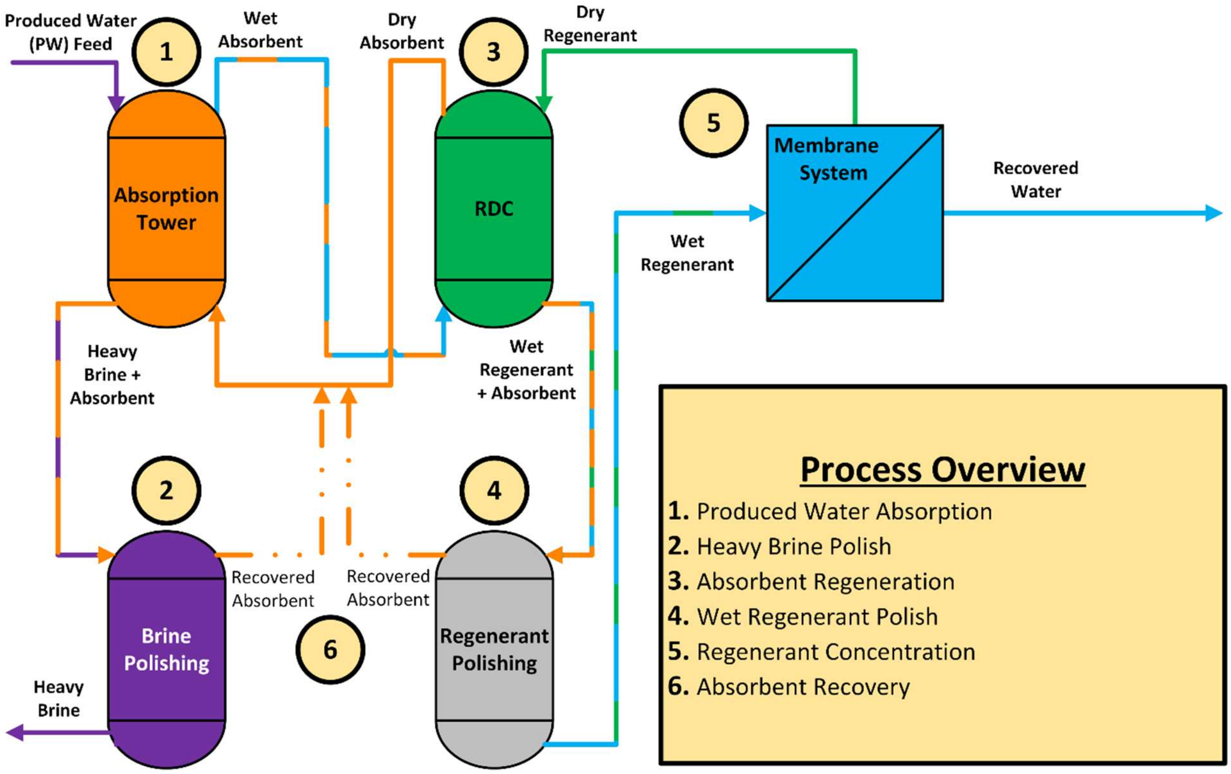
Laboratory membrane studies were carried out using a Sterlitech CF042SS crossflow setup, operating at pressures up to 160 bar.

Based on countercurrent ratios determined in the laboratory, scale-up studies were carried out to confirm and validate operating parameters.

PROCESS DESCRIPTION – Figure 1 below illustrates the Process Flow Diagram (PFD) of the pilot plant configuration. The Process utilizes a proprietary solvent-extraction method to selectively extract freshwater from produced water without thermal phase changes (Step 1). The heavy brine then goes through a polishing step to remove dissolved absorbent and is discharged from the Process (Step 2). The wet absorbent from step 1 is then mixed with the dry regenerant in an extraction column to enable water transfer from the absorbent to regenerant (Step 3, RDC = Rotating Disc Contactor). A similar polishing step is carried out to remove dissolved absorbent (Step 4), and the wet regenerant is then concentrated in a membrane step (Step 5, NF/RO process). A separate absorbent recovery step ensures that both the absorption and regeneration loops remain closed systems without the need for continuous chemical addition (Step 6).

Figure 1:

Simplified PFD



PILOT SETUP – A pilot facility was established in Colorado City, Texas, treating Permian Basin produced water.

Operational Conditions:

- Operating scale: 159 m^3/day
- Produced Water Total Dissolved Solids (TDS): approximately 120 g/L initially
- Target water recovery: optimized at approximately 40% to achieve lowest cost per m^3 desalinated.

The water recovery target of approximately 40% was established through a techno-economic analysis that considered factors such as equipment sizing, energy consumption, and overall operating costs, as well as the TDS of the feed and the non-linear increase in osmotic pressure with additional water removal. This recovery level was identified as providing the lowest cost per cubic meter of desalinated water under pilot conditions.

RESULTS AND DISCUSSION

The Process has been demonstrated with a wide range of industrial brines. For all new brines investigated in our laboratory, initial equilibration studies are carried out, which inform countercurrent water extraction experiments. Table 1 shows a representative subset of industrially relevant brines that have been treated in our laboratory using a three-stage or four-stage countercurrent extraction procedure. Brines span various produced water samples (Entries 1-4), mining brines (5-7), industrial waste brines (8-11), and a power plant wastewater (12). The water recovery chosen was based on optimized cost of treatment and does not indicate the maximum water recovery achievable with this technology. The pH of brines that have been tested spans a very wide range from highly acidic (pH = 1.7) to highly basic (pH = 11). Similarly, although the Process is typically most cost-competitive for a feed brine TDS around 120 g/L, we have demonstrated water recovery for a range of brines from moderately brackish water (10 g/L) to near-saturation (308 g/L). Based on the scaling potential of the brine, some of these investigations produced suspended solids, which could be separated and analyzed, while others produced a concentrated brine substantially free of suspended solids. It should be emphasized again that these investigations are optimized for lowest cost of treatment, rather than maximum water recovery, and full water recovery to achieve zero liquid discharge is achievable. It is also noteworthy that the nature of salt precipitation is unique in the Process, as precipitation occurs at a liquid-liquid interface at room temperature, rather than at a solid-liquid interface in both membrane and thermal-based desalination processes, which causes significant scaling effects. Whereas our earlier generation of absorbents were only commercially viable for high pH brines or those with minimal buffering capacity (absorbent C), our newest generation of absorbents (e.g. A & B) is applicable across the full pH range.

Table 1:

Representative laboratory results for treatment of a range of industrially relevant brine samples

Entry	Industry	pH	Major analytes	TDS (g/L)	Absorbent	Water recovery
1	Produced water	6.2	Cl, Na, Ca, K	117	A	40%
2	Produced water	7	Cl, Na, Ca, K	127	A	40%
3	Oil Sands produced water	7.8	Cl, Na, SO_4, Ca	50	B	72%
4	Produced water - lime pretreated	10.2	Cl, Na, Ca, K	117	C	40%
5	Mining	1.7	SO_4, Fe, Na, Al	139	A	73%
6	Mining	7	Cl, Na, SO_4, Mg	108	A	40%
7	Mining	7.2	Cl, Na, K, SO_4	308	B	30%
8	Industrial wastewater	11	SO_4, Na	45	C	80%
9	Industrial wastewater	11	SO_4, Na	45	B	80%
10	Industrial wastewater	6.9	SO_4, Na	56	A	82%
11	Industrial RO concentrate	7.4	Na, Cl, SO_4, HCO_3	10	A	94%

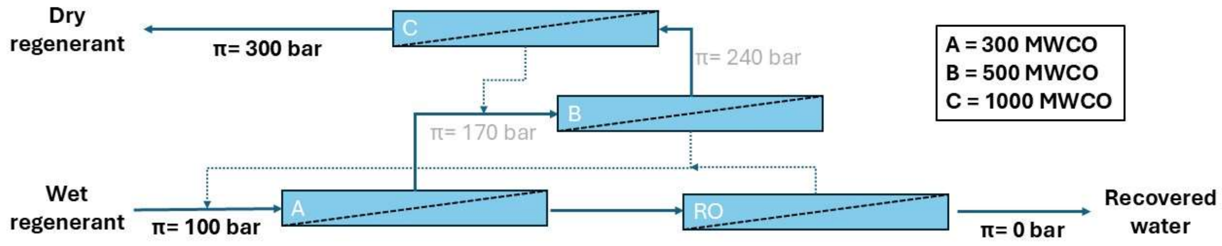
12	Flue Gas Desulfurization Wastewater	7.1	Cl, SO_4, Ca, Mg	27	B	84%

Water recovery by membrane processing

In the Process, water is transferred to the absorbent and then to the regenerant, a membrane-compatible aqueous solution (See Figure 1, above). Recovery of fresh water from the regenerant involves multiple stages of nanofiltration and reverse osmosis to give the fresh water permeate product and a highly concentrated regenerant solution that can be reused for water extraction. The regenerant salt does not cause membrane fouling even at very high osmotic pressures (>250 bar), which is critical to enable water transfer from feed brines up to and beyond their saturation point. Testing of membrane flat sheets is carried out in the laboratory, with these results used to inform membrane architecture for a continuously operating system. Representative membrane data for a regenerant salt is shown in Figure 2 below. The wet regenerant with moderately high osmotic pressure (π) is fed to membrane A (approximate molecular weight cutoff, MWCO, shown in the inset). The permeate from this membrane then proceeds to the RO stage where high purity water is recovered. The concentrate from membrane A proceeds to a series of membranes with progressively higher MWCO, eventually leaving the system at elevated osmotic pressure for reuse in the Process (Dry regenerant).

Figure 2:

Flow diagram demonstrating representative process for regenerant concentration and recovered water production over multiple membrane stages.



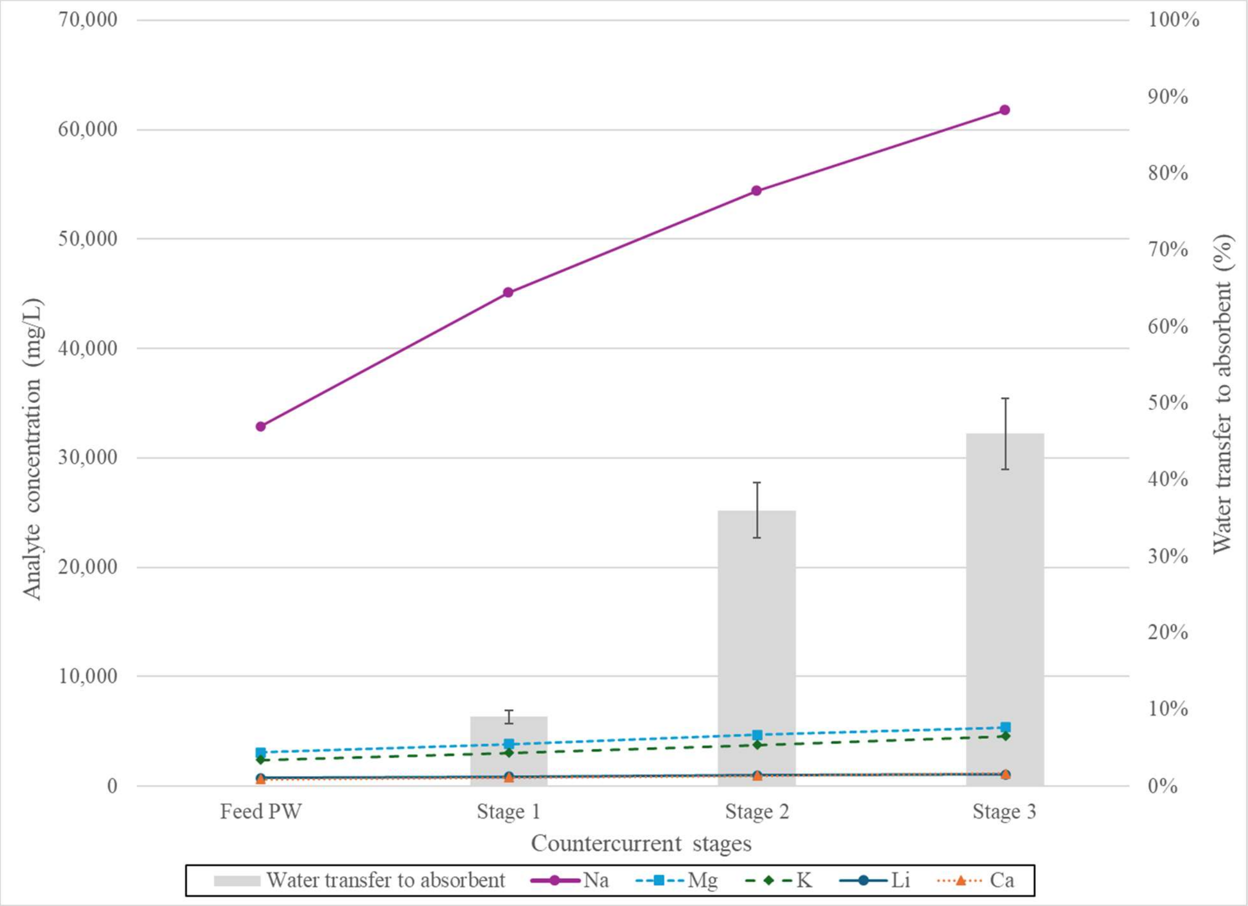
The Process described above is highly versatile for treatment of a variety of problematic wastewater streams. Below, three case studies are described, with a particular emphasis on the third case study, which details results from the Company's pilot plant in Colorado City, Texas.

Case Study 1: MLD treatment of a mining brine

A number of mining processes require volume reduction, often referred to as Minimal Liquid Discharge (MLD), from a brine to increase the concentration of the desired metal. As discussed previously, the use of evaporation ponds for this process results in the loss of this water to the environment. Water scarcity is a critical problem for many mines, so it is beneficial for the brine concentration step to be accompanied by water recovery, enabling this water to be reused in the mining process. A neutral mining brine (Table 1, Entry 6) was investigated for treatment to enable recovery of valuable metals in the brine and fresh water. A three-stage countercurrent process was chosen to give approximately 40% water recovery, with minimal salt precipitation. Figure 3 below shows the increase in salt concentration across the three stages of a countercurrent process. The increase in the concentration of all salts is in agreement with the cumulative transfer of water into the absorbent across the countercurrent stages, demonstrating full recovery of water in the absorbent and excellent salt rejection of all cations present in the brine.

Figure 3:

Concentration of metals in brine and transfer of water to absorbent across countercurrent extraction stages

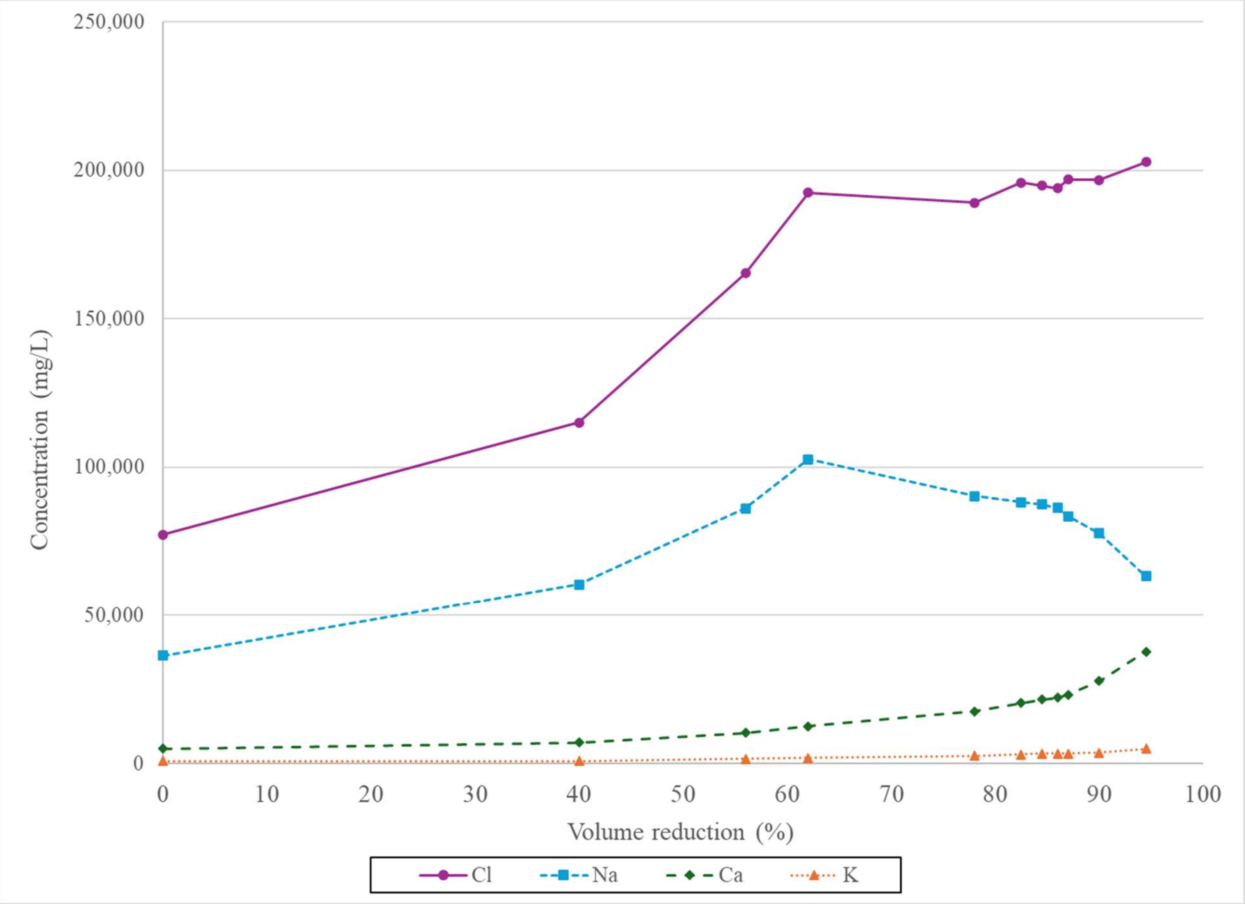


Case Study 2: ZLD treatment of produced water

The Oil and Gas industry is under pressure to reduce its reliance on brine injection into disposal wells following a string of significant seismic events that have been linked to the disposal of produced water (Pollyea, 2019). While MLD treatment of produced water is the most cost-effective option, the Process has also been demonstrated for Zero Liquid Discharge (ZLD) treatment (95% water recovery) for produced water. When volume reduction is driven further than the precipitation point of a major salt species, significant changes in brine chemistry occur. A representative depiction of brine composition change with increasing water recovery from a produced water sample (see Table 1; Entry 2) is shown in Figure 4. Minimal salt precipitation occurs until sodium chloride reaches its saturation point at about 60% water recovery. At this stage the sodium concentration begins to decrease and chloride concentration plateaus while the concentration of calcium continues to increase. Above 95% water recovery, the dominance of calcium chloride significantly increases the osmotic pressure of the brine, which greatly increases the energy cost of water recovery.

Figure 4:

Concentration of major brine analytes during ZLD treatment of a produced water



Case Study 3: Pilot scale demonstration of the Process using produced water

WATER RECOVERY AND QUALITY – The pilot consistently achieved freshwater recoveries of approximately 40%, with produced water TDS reduced from ~120 g/L to a permeate TDS consistently below 100 mg/L. Salt rejection remained uniform across all ions, with no selective precipitation observed (see Figure 5).

Table 2:

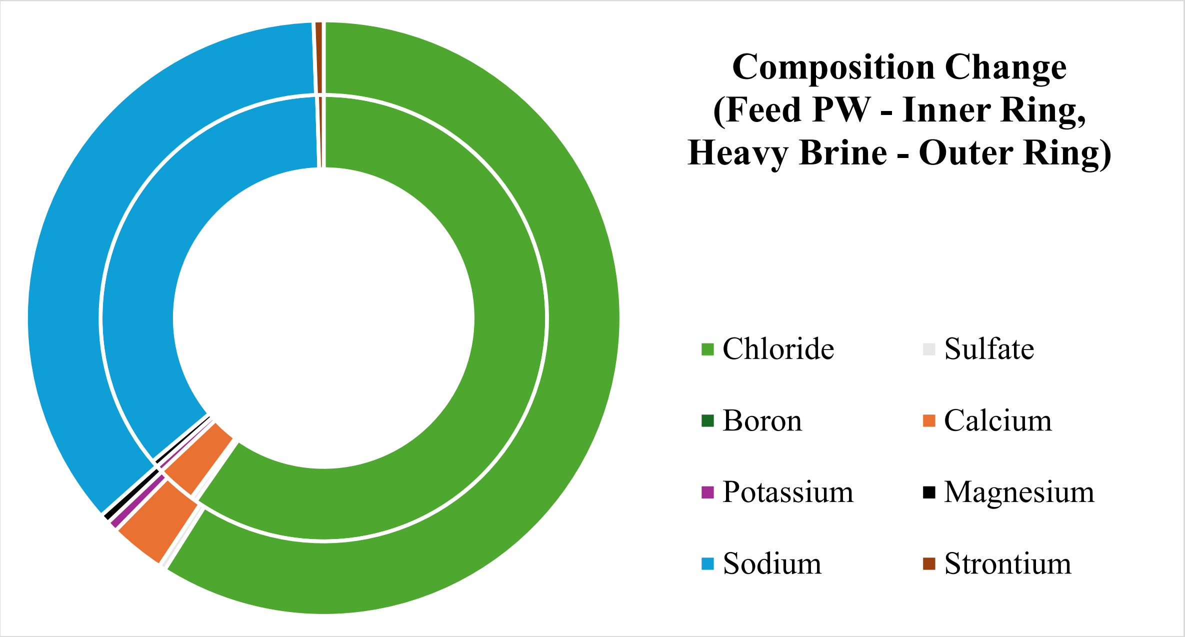
Water Quality Results

Concentration (mg/L)	Cl	SO_4	B	Ca	K	Mg	Na	Sr
Recycled PW Feed	73,500	440	40	5,440	560	590	43,800	600
Brine @ 40%* Water Recovery	115,200	700	60	5,870	1,170	1,020	70,370	1,070
Final RO Permeate	34	3	<0.25	1	22	<2.5	9	<0.25

* Concentration limited by customer request; not a technology limitation

Figure 5:

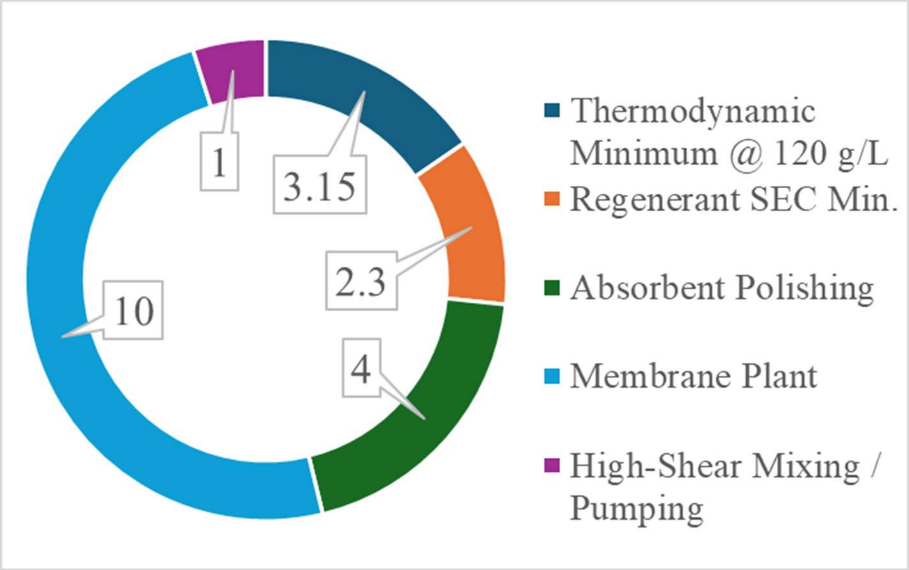
Water Quality Composition Change



ENERGY CONSUMPTION – Specific energy consumption was measured at 20.45 kWh/m³ under current conditions. While initially predicted at 10.5 kWh/m³, optimization opportunities were identified to further reduce energy consumption closer to this lower benchmark, highlighting potential future improvements (Figure 6).

Figure 6:

Energy Consumption of ABX pilot system (kWh/m^3 desalinated)



KEY PERFORMANCE INDICATORS - The pilot established the following Key Performance Indicators (KPIs) to evaluate Process viability:

- Product water quality: TDS <100 mg/L
- Energy efficiency: significantly lower compared to thermal methods
- Operational robustness and reliability, demonstrated through continuous pilot operation.

ADVANTAGES OF THE PROCESS –

- Non-thermal: avoids high-energy phase transitions
- No fouling or scaling due to bulk-phase extraction
- Minimal pretreatment and chemical requirements
- Operational flexibility to adjust water recovery by controlling solvent flows.

CURRENT LIMITATIONS AND FUTURE IMPROVEMENTS – The current pilot system, originally designed for ZLD, operated below optimal conditions. Further energy optimization and refinement of operating parameters are required to fully realize the projected performance advantages.

CONCLUSIONS

Laboratory studies have demonstrated the versatility of the Process through the desalination of a broad range of brines with pH ranging from 1.7 to 11, and TDS ranging from 10 g/L to 308 g/L. The ability to tune the Process to any desired level of water recovery without the necessity for thermal treatment of the brine was highlighted by three case studies.

The pilot-scale evaluation demonstrates that this solvent-based desalination Process is a technically viable and economically attractive alternative to conventional high-energy treatment methods. The ability to produce high-quality freshwater while significantly reducing energy use and operational complexity positions this technology favorably for widespread commercial implementation in industrial wastewater management, particularly within the oil and gas sector.

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