

Climate Technology Centre and Network (CTCN) Technical Assistance

Report of applicable desalination and resource recovery technology in Uzbekistan

**"Pre-feasibility for groundwater desalination
and resource recovery in Uzbekistan"
(Deliverable 1)**

30 April 2026

Table of Contents

Executive Summary.....	ii
1. Introduction.....	1
2. Groundwater Characteristics and Design Basis	2
3. Global Technology Review and Best Practices (Activity 1.1)	4
4. Site Investigation and Raw Water Characterization (Activity 1.2).....	6
5. Technology Screening and Comparative Evaluation (Activity 1.3)	10
6. Recommended Technology Configuration and Candidate Site Assessment (Activity 1.4)	14
7. Conclusions.....	16
Appendix A. Desalination and Resource Recovery Technologies	17
Part I. Desalination Technologies	17
Part II. Material Recovery from Brine	33
Part III. Economic and Environmental Considerations	38
References	39

Executive Summary

The Republic of Uzbekistan has increasingly recognized the need to secure sustainable groundwater resources to address growing water demand in domestic, industrial, and agricultural sectors. However, groundwater quality varies considerably across the country due to differences in hydrogeological conditions, with many regions containing highly saline groundwater that requires appropriate treatment before utilization. At the same time, concentrated brine generated during the desalination process contains valuable dissolved minerals that may be recovered as useful resources.

This report presents the results of Output 1 of the CTCN Technical Assistance project, "Pre-feasibility Study for Groundwater Desalination and Resource Recovery in Uzbekistan." The objective of this deliverable was to assess applicable desalination and resource recovery technologies and establish the technical basis for subsequent pilot system design and feasibility assessment.

A comprehensive review of commercially available and emerging desalination technologies and resource recovery processes was conducted, followed by hydrogeological investigations, groundwater monitoring data review, field surveys, and laboratory-scale experimental evaluations. Initial groundwater characterization was performed using samples collected from the Bukhara and Kashkadarya regions. Based on the preliminary findings and considering future pilot implementation, including groundwater characteristics, surrounding infrastructure, accessibility, and resource recovery potential, the assessment was subsequently focused on the Tashkent metropolitan area.

Laboratory-scale experiments were conducted using synthetic saline water prepared with commercially available sea salt to simulate representative high-salinity groundwater conditions. Hydrate-based desalination experiments demonstrated effective salt removal while producing concentrated brine suitable for subsequent resource recovery. Mineral carbonation experiments further confirmed the feasibility of recovering magnesium- and calcium-based products from concentrated brine with high removal efficiencies.

Based on the overall assessment, this study proposes an integrated desalination and resource recovery concept that combines commercially available desalination technologies, hydrate-based desalination, and mineral carbonation according to groundwater characteristics. Rather than recommending a single treatment process, the proposed concept provides a flexible process configuration that can be adapted to varying groundwater conditions expected in Uzbekistan.

Although a final pilot implementation site has not yet been determined, the hydrogeological information, field investigation, groundwater monitoring data, and

laboratory evaluation conducted in this study provide a sound technical basis for identifying potential pilot sites and developing a conceptual pilot system in the subsequent phase of the project.

The outcomes of this report will serve as the technical foundation for pilot system design, feasibility assessment, and future scale-up planning under the CTCN Technical Assistance project.

1. Introduction

1.1 Background

Uzbekistan is facing increasing challenges in securing sustainable water resources due to rapid industrial development, climate change, and the limited availability of freshwater resources. In many regions, groundwater represents an important alternative water source; however, elevated salinity and the presence of dissolved minerals significantly limit its direct utilization for drinking water, industrial processes, and agricultural applications.

At the same time, highly saline groundwater contains valuable mineral resources such as magnesium and calcium, presenting opportunities for resource recovery in addition to freshwater production. Therefore, an integrated approach that combines desalination with resource recovery can contribute not only to improving water security but also to enhancing resource efficiency and supporting carbon reduction through mineral carbonation.

This report has been prepared as part of the CTCN Technical Assistance project, "Pre-feasibility Study for Groundwater Desalination and Resource Recovery in Uzbekistan," to develop a technology assessment framework for selecting appropriate desalination and resource recovery configurations under various groundwater conditions in Uzbekistan for local conditions and to establish the technical basis for the subsequent pilot system design and feasibility assessment.

1.2 Objectives

The objective of this report is to assess applicable desalination and resource recovery technologies suitable for groundwater conditions in Uzbekistan through a systematic evaluation of technical, environmental, and economic aspects.

The assessment considers groundwater quality, particularly total dissolved solids (TDS), site characteristics, technology maturity, operational feasibility, and resource recovery potential. Based on these considerations, the report recommends an optimized process configuration and suitable pilot application strategy for the target sites.

Rather than proposing a single technology for all groundwater conditions, this assessment adopts a flexible approach in which desalination technologies are selected according to groundwater salinity. Commercially available desalination technologies are considered for relatively low-salinity groundwater, while hydrate-based desalination is evaluated as a primary treatment option for high-salinity groundwater. In both cases,

mineral carbonation is incorporated as a downstream process to recover valuable minerals and enhance overall resource utilization.

Since groundwater quality varies significantly depending on hydrogeological conditions, the selection of desalination technology should be based on site-specific groundwater characteristics rather than applying a single treatment process universally.

1.3 Scope of the Report

This report summarizes the activities carried out under Output 1 of the project and includes:

- Review of global desalination and resource recovery technologies and international best practices;
- Site investigation, groundwater sampling, and water quality analysis;
- Comparative evaluation of candidate technologies based on technical, environmental, and economic criteria;
- Recommendation of appropriate technology configurations and target sites for pilot implementation.

The outcomes of this report provide the technical foundation for the pilot system design, feasibility assessment, and scale-up planning to be conducted in the subsequent phases of the project.

2. Groundwater Characteristics and Design Basis

2.1 Hydrogeological Characteristics

Groundwater is an important water resource in Uzbekistan, supplying water for domestic, industrial, and agricultural uses in many regions. However, groundwater conditions vary considerably depending on local hydrogeological settings, resulting in significant differences in water quality and availability.

According to hydrogeological information provided by HYDROENGEO, the study area is located within the Pre-Tashkent Artesian Basin and consists of multiple aquifer systems, including modern alluvial deposits, Upper and Middle Quaternary deposits, Lower Quaternary–Upper Pliocene deposits, and deeper Miocene, Paleogene, and Upper Cretaceous formations. Groundwater mineralization and well productivity differ among these aquifers depending on geological conditions and groundwater flow characteristics.

Groundwater investigations conducted during this project confirmed that water quality varies significantly between locations, reflecting differences in aquifer characteristics and local environmental conditions. These variations were considered in the subsequent assessment of desalination and resource recovery technologies.

2.2 Groundwater Quality and Design Basis

Groundwater quality is one of the key factors influencing the applicability of desalination technologies. The hydrogeological data and field investigations indicate that groundwater salinity and chemical composition vary depending on the aquifer and site conditions. Therefore, different treatment approaches may be required according to the characteristics of the source water.

Based on the available information collected during this study, groundwater salinity, particularly the total dissolved solids (TDS) concentration, was considered one of the primary parameters in the technology assessment. In general, commercially available desalination technologies were considered for relatively low-salinity groundwater, while hydrate-based desalination was evaluated as a potential option for groundwater with higher salinity. In both cases, the concentrated brine generated during the desalination process was considered as a potential feed stream for mineral carbonation to enhance water recovery and resource utilization.

The technology assessment presented in this report was therefore conducted by considering groundwater characteristics together with technology applicability, resource recovery potential, and the overall objective of supporting future pilot-scale implementation.

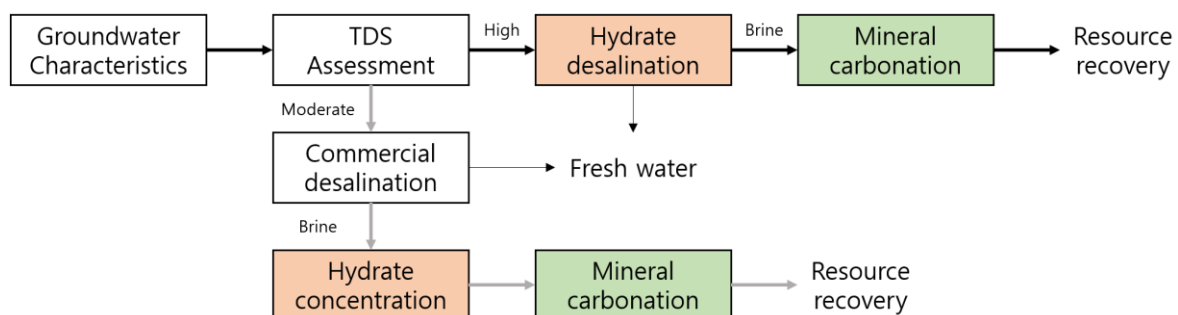


Figure 2-1. Conceptual Framework for Technology Selection

3. Global Technology Review and Best Practices

3.1 Overview

To identify desalination and resource recovery technologies applicable to groundwater conditions in Uzbekistan, a comprehensive review of commercially available and emerging technologies was conducted. The review covered desalination technologies with different separation mechanisms, as well as resource recovery technologies that can utilize concentrated brine generated during the desalination process.

The technologies were reviewed with respect to their technical characteristics, level of commercialization, operational requirements, advantages, limitations, and representative application cases. The findings of this review provided the basis for the subsequent technology assessment presented in this report.

3.2 Desalination Technologies

Desalination technologies were classified according to their separation mechanisms into membrane-based, phase-change-based, and electrochemical desalination technologies.

Membrane-based technologies, including reverse osmosis (RO), forward osmosis (FO), membrane distillation (MD), and electrodialysis (ED/EDR), are widely used depending on feed water quality and treatment objectives. Reverse osmosis is the most mature and commercially established technology, while forward osmosis and membrane distillation are primarily applied in hybrid systems or pilot-scale applications.



Figure 3-1. Lab-scale Hydrate-based Desalination System

Phase-change-based technologies include conventional thermal desalination processes, such as multi-stage flash (MSF) and multi-effect distillation (MED), as well as non-evaporative technologies such as hydrate-based desalination. Hydrate-based desalination utilizes the selective formation of gas hydrates under low-temperature and high-pressure conditions and has been investigated as a promising option for high-salinity water treatment.

Electrochemical desalination technologies, such as electrodialysis (ED/EDR) and capacitive deionization (CDI), are generally suitable for relatively low-salinity water and selective ion removal applications.

3.3 Resource Recovery Technologies

Resource recovery technologies applicable to desalination brine were also reviewed. These technologies include chemical precipitation, mineral carbonation, adsorption, and electrochemical separation processes. Particular attention was given to mineral carbonation because of its ability to recover calcium- and magnesium-based products while simultaneously utilizing carbon dioxide.

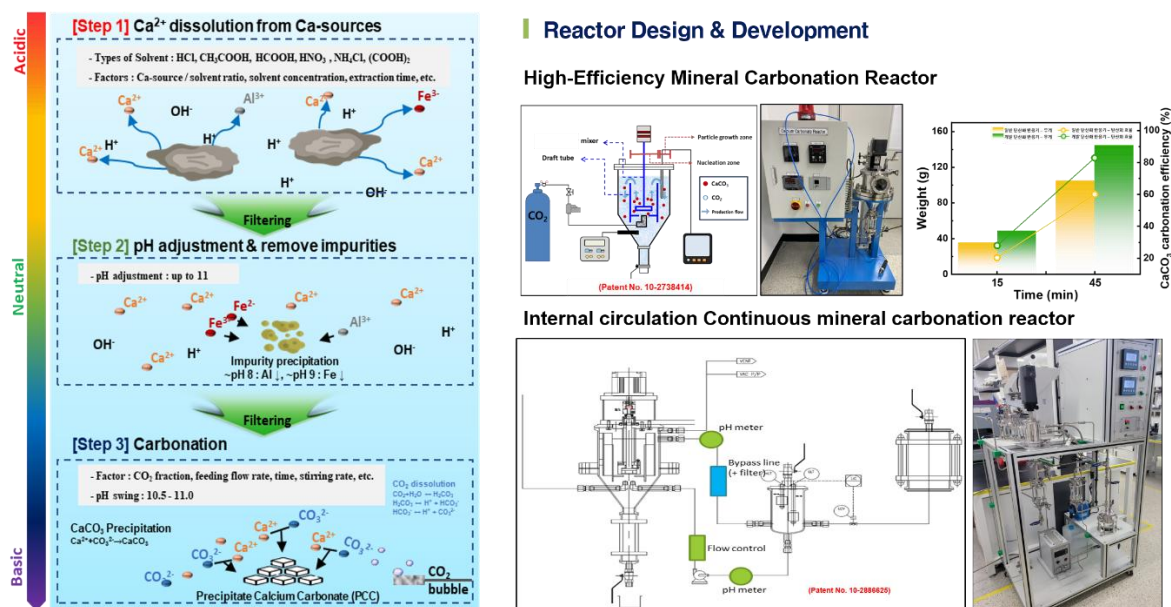


Figure 3-2. Laboratory-scale Mineral Carbonation System

The review also considered representative demonstration projects and commercial applications to evaluate the technical maturity and applicability of each technology.

3.4 Summary

The technology review confirmed that no single desalination or resource recovery technology is suitable for all groundwater conditions. Each technology has distinct advantages and limitations depending on feed water quality, operational conditions, and treatment objectives. Detailed descriptions of the reviewed technologies, including their principles, characteristics, advantages, limitations, and representative applications, are provided in Appendix A.

Therefore, the technologies reviewed in this chapter were further evaluated in subsequent chapters considering groundwater characteristics and potential pilot implementation conditions in Uzbekistan.

4. Site Investigation and Raw Water Characterization

4.1 Initial Survey and Groundwater Sampling

As originally planned, the project initially considered groundwater resources across Uzbekistan to identify potential pilot implementation sites. During the early stage of the study, groundwater samples were collected from major groundwater fields in the Bukhara and Kashkadarya regions to obtain preliminary information on groundwater quality and resource recovery potential.

Table 4-1. Preliminary Water Quality Analysis of Initial Groundwater Samples

Sample No.	pH	TOC	T-N	T-P	TDS (mg/L)
1-4	6.86	43.5	13.3	0.56	89,139
1-6	5.59	557.6	11.81	1.33	77,352
1-7	7.97	15.2	8.69	0.05	65,227
1-9	7.41	21.9	12.91	0.05	91,610
1-10	7.65	55.5	17.64	0.02	81,832
1-14	7.56	33.1	9.31	0.03	91,301
1-15	7.67	46.9	16.56	0.05	87,016
1-17	7.65	35.2	7.42	0.03	137,089
1-18	5.61	134.4	10.37	0.07	75,929

A total of 18 groundwater samples were collected from seven representative locations. The samples underwent preliminary pretreatment and were transported to Korea for laboratory analysis. Major dissolved elements were analyzed using ICP-OES, followed by screening analyses to identify groundwater sources with relatively high concentrations of recoverable minerals, including magnesium, calcium, sodium, potassium, lithium, boron, and strontium.

Based on the initial screening results, representative samples were selected for detailed analyses of pH, total organic carbon (TOC), total nitrogen (T-N), total phosphorus (T-P), and total dissolved solids (TDS). The measured TDS ranged from approximately 6.5% to 13.7%, indicating highly saline groundwater suitable for evaluating advanced desalination technologies. In addition, cation analyses of the second-round groundwater samples showed that Na, Mg, Ca, and K were the predominant dissolved constituents.

Table 4-2. Major Dissolved Elements in the Second-round Groundwater Samples

Sample No.	Li	Mg	Ca	Mn	Na	K	Al	Cr	Fe	Cu	Cd	Ni	Zn	As	Mo
2-1	0.217	474.496	475.252	0.608	3239.551	25.599	0.040	0.020	0.091	0.035	0.024	0.026	0.046	0.025	0.247
2-2	0.174	291.423	213.213	0.334	2561.973	13.515	0.027	0.013	0.023	0.029	0.022	0.024	0.036	0.032	0.322
2-3	0.369	800.611	679.752	2.799	6783.084	14.441	0.014	0.001	0.009	0.017	0.012	0.018	0.032	0.010	0.104
2-4	0.319	926.751	644.097	0.025	7538.743	14.599	0.025	0.001	0.027	0.012	0.006	0.006	0.028	0.004	0.044
2-5	0.363	719.050	491.276	0.994	5782.646	45.357	0.016	0.000	0.007	0.015	0.006	0.007	0.026	0.021	0.206
2-6	0.191	492.113	480.422	0.660	3192.858	25.545	0.018	0.000	0.009	0.010	0.003	0.008	0.020	0.021	0.214

4.2 Refinement of the Target Area

Following the preliminary investigation, the project strategy was refined to focus on the Tashkent metropolitan area rather than conducting a nationwide assessment. This decision was made after considering the overall objective of the project together with practical factors affecting future pilot implementation.

In addition to groundwater quality, factors such as industrial infrastructure, accessibility, availability of potential carbon dioxide sources for mineral carbonation, utility supply, and the potential for future demonstration and scale-up were considered. As a result, the Tashkent area was identified as the most appropriate region for conducting a pre-feasibility assessment and developing a conceptual pilot system applicable to representative groundwater conditions.

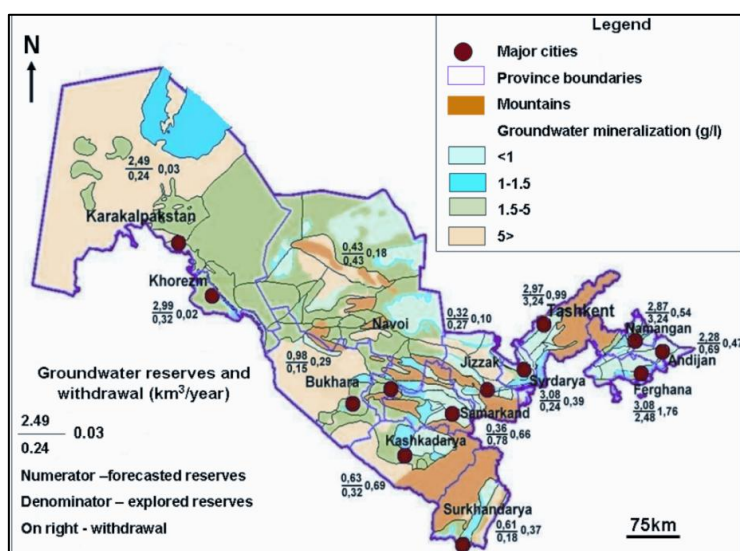


Figure 4-1. Major Hydrogeological Basins in Uzbekistan

(Cent. Eur. J. Geosci., 4(1), 2012, 67-80)

4.3 Monitoring Data Review and Field Investigation

To identify representative groundwater resources around the Tashkent area, monitoring data managed by HYDROENGEO were reviewed prior to the field survey. The centralized monitoring system provides real-time groundwater quality information and well data collected from approximately 3,000 monitoring wells throughout Uzbekistan, including more than 200 wells located in the Tashkent region.

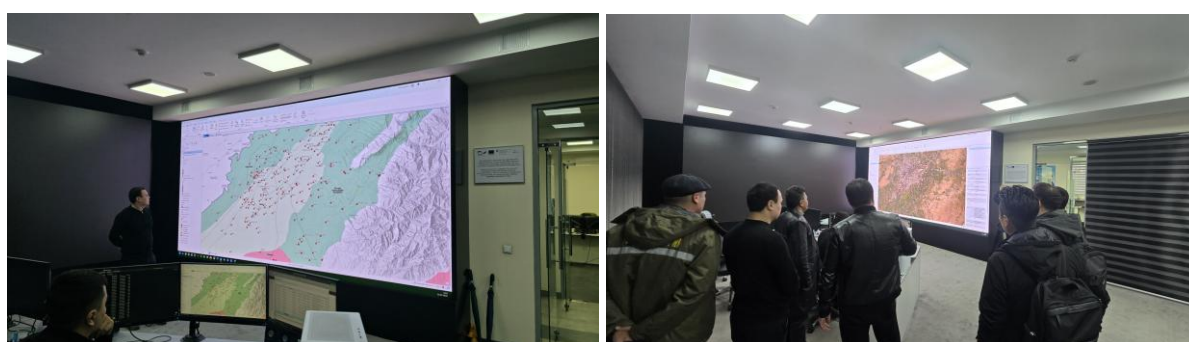


Figure 4-2. Monitoring room (HYDROENGEO, left) and Technical discussion (right)

Based on the monitoring results, a field investigation was conducted at a groundwater well located approximately 80 minutes by vehicle from the HYDROENGEO headquarters, within the Chirchik-Keles aquifer system. During the site visit, groundwater conditions, surrounding infrastructure, and potential implementation constraints were investigated.

The site is located in a semi-rural area where livestock facilities and agricultural product processing plants are present nearby. However, no major industrial facilities or significant flue gas emission sources suitable for direct carbon dioxide utilization were identified during the survey. These findings suggest that external carbon dioxide supply or transportation should be considered if mineral carbonation is selected for future pilot implementation.

Raw groundwater samples were collected for laboratory analysis and desalination testing. The information obtained through the monitoring database, field observations, and water quality analyses was subsequently used to support technology screening and conceptual pilot system design.

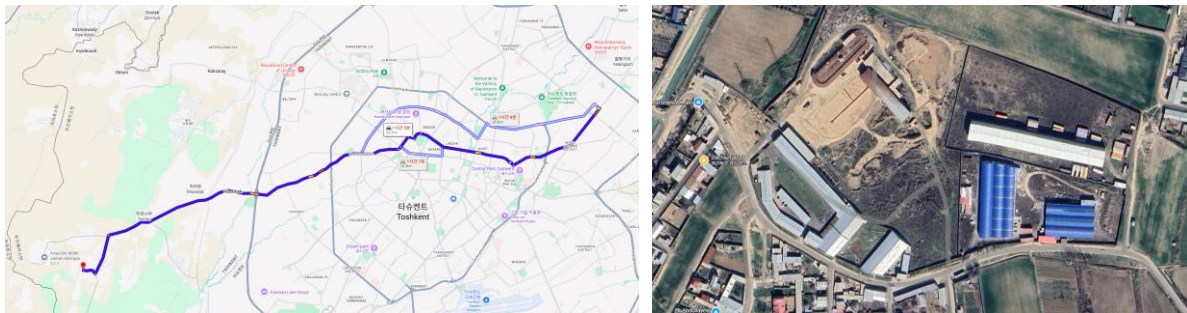


Figure 4-3. Local survey Route (left), Surrounding Site Conditions (right)



Figure 4-4. Groundwater Well Inspection and On-site Water Quality Measurement

5. Technology Screening and Comparative Evaluation

5.1 Experimental Evaluation Methodology

To experimentally evaluate the applicability of the proposed desalination and resource recovery technologies, laboratory-scale tests were performed using synthetic saline water prepared with commercially available sea salt (Natural Ocean). The synthetic water was prepared to simulate representative saline groundwater conditions expected in Uzbekistan while maintaining consistent experimental conditions for comparative evaluation.

Hydrate-based desalination experiments were conducted using an in-house hydrate formation reactor and a solid-liquid separation system developed by KITECH. The desalination performance was evaluated based on changes in major ion concentrations and total dissolved solids (TDS) before and after the hydrate formation process.

For the mineral carbonation experiments, synthetic concentrated brine representing the concentrate generated from the desalination process was prepared and treated using an internally circulating mineral carbonation reactor. The recovered solid products and the remaining liquid phase were analyzed to evaluate the recovery efficiency of target minerals.



Figure 5-1. Hydrate Formation Reactor (lab scale)



Figure 5-2. Solid-liquid Separation System (for Hydrate Recovery)



Figure 5-3. Internal Circulation Mineral Carbonation Reactor (lab scale)

5.2 Evaluation of Hydrate-based Desalination

To evaluate the applicability of hydrate-based desalination for treating highly saline groundwater in Uzbekistan, laboratory-scale desalination experiments were conducted using synthetic saline water prepared with commercially available sea salt (Natural Ocean). The synthetic saline water was formulated to simulate representative high-salinity groundwater while providing consistent feed water conditions for performance evaluation.

The experiments were performed using the in-house hydrate formation reactor and solid-liquid separation system developed by KITECH. The hydrate formation process was used to separate freshwater from the saline solution, and the desalination performance was evaluated by comparing the concentrations of major dissolved ions (Na^+ , Mg^{2+} , Ca^{2+} , K^+ , Cl^- , and SO_4^{2-}) and total dissolved solids (TDS) before and after treatment.

The experimental results showed that the TDS concentration decreased from 56,825 mg/L in the synthetic saline water to 7,991 mg/L after hydrate desalination, corresponding to an overall salt removal efficiency of 85.94%. Meanwhile, the concentrated brine reached 80,553 mg/L, representing an approximately 41% increase in concentration compared with the original feed solution.

These results demonstrate that hydrate-based desalination can effectively recover freshwater from highly saline water while simultaneously producing concentrated brine suitable for subsequent resource recovery processes.

Table 5-1. Performance of Hydrate-based Desalination

(Unit : mg/L, %)	Na^+	Mg^{2+}	Ca^{2+}	K^+	Cl^-	SO_4^{2-}	TDS
Raw conc.	16,120	1,591	432	682	33,900	4,100	56,825
Final conc.	2,461	240	78	112	4,600	500	7,991
Brine conc.	23,380	2,149	653	971	47,800	5,600	80,553
Removal efficiency	84.73	84.92	81.94	83.58	86.43	87.80	85.94

5.3 Evaluation of Mineral Carbonation

Mineral carbonation experiments were conducted to evaluate the recovery of valuable minerals from concentrated brine expected to be generated after the desalination process. Synthetic concentrated brine was prepared using commercially available sea salt (Natural Ocean) to simulate the chemical characteristics of the concentrate produced during hydrate-based desalination.

The experiments were performed using the internally circulating mineral carbonation reactor developed by KITECH. After the carbonation reaction, both the recovered solid products and the remaining liquid phase were analyzed to evaluate mineral recovery performance.

Analysis of the recovered solid products confirmed that the reaction products consisted predominantly of magnesium carbonate and calcium carbonate, indicating that the target components were successfully recovered through the carbonation process.

The composition of the remaining liquid phase after the reaction showed that 99.7% of Mg and 98.6% of Ca were removed compared with the initial synthetic concentrated brine. These results indicate that the proposed mineral carbonation process can effectively recover valuable mineral resources while significantly reducing the concentrations of dissolved divalent cations in the concentrated brine.

Table 5-2. Experimental Results of Mineral Carbonation and Mg/Ca Recovery

	Na	Ca	Mg	K	B	Remarks
Brine	17,117.1	571.54	2,137.04	821.02	4.97	Unit : mg/L
Mg carbonates	2.27	12.59	230.7	N.D	N.D	
Ca carbonates	10.05	372.23	1.44	0.02	N.D	
Wastes	25,538.94	8.03	7.53	485.83	3.01	

5.4 Overall Assessment

The experimental evaluation confirmed the technical feasibility of combining hydrate-based desalination with mineral carbonation as an integrated treatment concept for high-salinity groundwater. Hydrate-based desalination effectively reduced the salinity of the feed water while generating concentrated brine, and mineral carbonation demonstrated a high potential for recovering magnesium- and calcium-based products from the concentrated brine.

Although additional optimization will be required during the pilot-scale design stage, the experimental results provide a technical basis for applying the proposed integrated process to representative groundwater conditions in Uzbekistan.

6. Recommended Technology Configuration and Candidate Site Assessment

6.1 Recommended Technology Configuration

Based on the technology review, groundwater characterization, field investigation, and laboratory-scale experimental evaluation, an integrated desalination and resource recovery concept is proposed for groundwater conditions in Uzbekistan.

The proposed technology configuration adopts a flexible approach according to groundwater characteristics rather than relying on a single treatment process. For groundwater with relatively moderate salinity, commercially available desalination technologies may be applied as the primary freshwater production process. The concentrated brine generated from the desalination process can subsequently be treated using hydrate-based concentration to recover additional freshwater, followed by mineral carbonation for valuable mineral recovery.

For groundwater with higher salinity, hydrate-based desalination is proposed as a suitable primary treatment option. The recovered freshwater may be utilized directly as industrial water or further treated through commercially available desalination technologies to meet potable water standards, depending on the required water quality. The concentrated brine generated during the hydrate desalination process is subsequently utilized as feedwater for mineral carbonation.

This integrated process configuration is intended to maximize freshwater recovery, improve resource utilization, and provide flexibility for various groundwater conditions expected in Uzbekistan.

6.2 Candidate Site Assessment

Based on the hydrogeological information, groundwater monitoring data, field investigation, and surrounding infrastructure survey, the Tashkent metropolitan area was identified as a suitable region for further consideration during the pre-feasibility stage.

The assessment considered groundwater characteristics together with accessibility, existing infrastructure, and future implementation potential. Although a final pilot site has not yet been determined, the investigation confirmed that the region provides representative groundwater conditions for evaluating the proposed technology concept.

The proposed technology configuration is therefore intended to serve as a conceptual process applicable to potential pilot sites rather than being optimized for a specific

location. The information obtained through this study will provide the technical basis for conceptual pilot system design and feasibility assessment in the subsequent phase of the project.

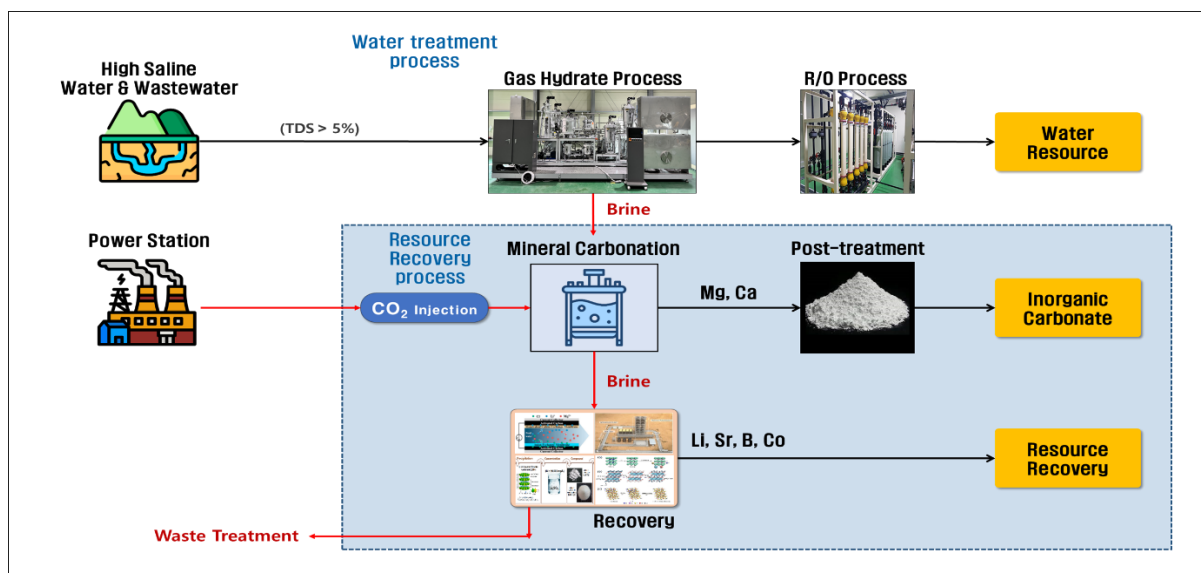


Figure 6-1. Conceptual Technology Configuration for High-salinity Groundwater

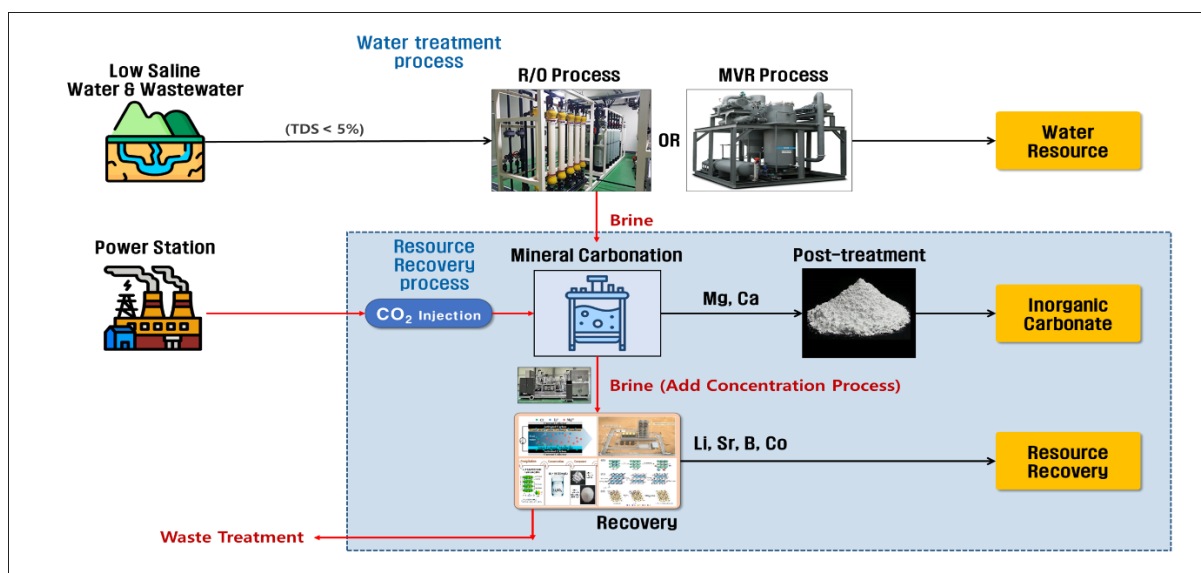


Figure 6-2. Conceptual Technology Configuration for Moderate-salinity Groundwater

7. Conclusions

This report reviewed applicable desalination and resource recovery technologies for groundwater conditions in Uzbekistan and assessed their applicability through literature review, hydrogeological investigation, field surveys, and laboratory-scale experiments.

The study confirmed that groundwater characteristics vary significantly depending on location and hydrogeological conditions, indicating that different treatment strategies may be required according to source water quality. Rather than relying on a single desalination technology, this study proposed a flexible technology configuration combining commercially available desalination technologies, hydrate-based desalination, and mineral carbonation according to groundwater characteristics.

Laboratory-scale experiments demonstrated that hydrate-based desalination effectively reduced salinity while producing concentrated brine suitable for subsequent resource recovery. Mineral carbonation experiments further confirmed the potential to recover magnesium- and calcium-based products from concentrated brine with high removal efficiencies.

Although the final pilot implementation site has not yet been determined, the hydrogeological information, monitoring data, field investigation, and laboratory evaluation conducted in this study provide a sound technical basis for identifying potential pilot sites and developing a conceptual pilot system during the subsequent phase of the project.

The outcomes of this report will be utilized as the technical foundation for pilot system design, feasibility assessment, and future scale-up planning under the CTCN Technical Assistance project.

Appendix A. Desalination and Resource Recovery Technologies

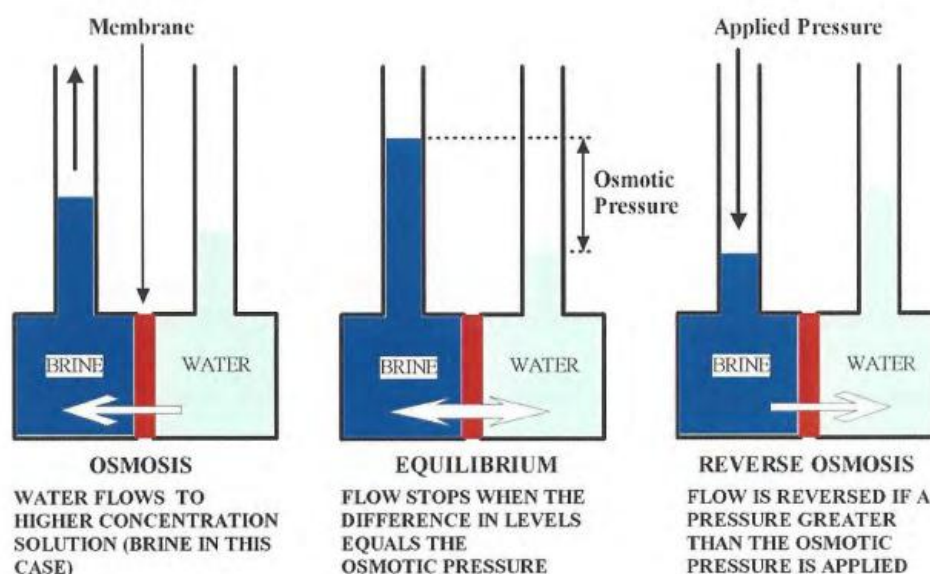
Technical overview and representative examples of desalination processes and brine-based material recovery

Part I. Desalination Technologies

1. Membrane-based Desalination

Membrane-based desalination separates water from dissolved salts using membranes that are selectively permeable to water molecules. These processes are driven by physical forces such as applied pressure, osmotic pressure gradients, or temperature differentials, and membranes currently play the central role in desalination capacity installed worldwide. Because of their favorable energy efficiency and process flexibility, membrane technologies are applied at scales ranging from large centralized plants to small distributed systems.

1.1 Reverse Osmosis (RO)



Foundation for Water Research. (2015). Desalination for water supply. Foundation for Water Research.

Characteristics

Reverse osmosis applies pressure higher than the osmotic pressure of seawater, forcing water molecules through a semi-permeable membrane while rejecting salts. Thin-film composite (TFC) polyamide membranes are the industry standard, and they can reject not only dissolved salts but also organic matter and microorganisms simultaneously. A typical RO train consists of pretreatment, high-pressure RO, energy recovery, and post-treatment stages; this standardized process architecture allows RO to be scaled from large municipal water-supply plants down to small desalination units.

Advantages

- Higher energy efficiency than thermal desalination
- High technology maturity with extensive commercial operating experience

Disadvantages

- Susceptible to membrane fouling and scaling
- Environmental burden associated with concentrate (brine) discharge

Representative Applications

• Singapore — Tuas / Tuas South / Marina East RO Plants

PUB, Singapore's national water agency, operates RO-based seawater desalination plants as a core pillar of national water supply. The Tuas South plant produces roughly 310,000 m³ of freshwater per day, using high-efficiency energy recovery devices and high-performance RO membranes to achieve stable long-term operation. This case demonstrates that RO technology has achieved sufficient reliability for large-scale urban water supply.



• Israel — Sorek Desalination Plant

Sorek is one of the largest RO facilities in the world and supplies a substantial share of Israel's total drinking-water demand. Its high-pressure RO process incorporates design measures that minimize energy consumption, making it a leading commercial example demonstrating the potential for improving RO energy efficiency.



- **Saudi Arabia — SWCC RO Plants**

The Saline Water Conversion Corporation (SWCC) of Saudi Arabia operates numerous large-scale RO plants to address severe freshwater scarcity in the Middle East. These facilities supply both drinking water and industrial water, demonstrating that RO can be applied reliably even under high-salinity seawater conditions.



- **Gijang Seawater Desalination Facility, Busan (Korea)**

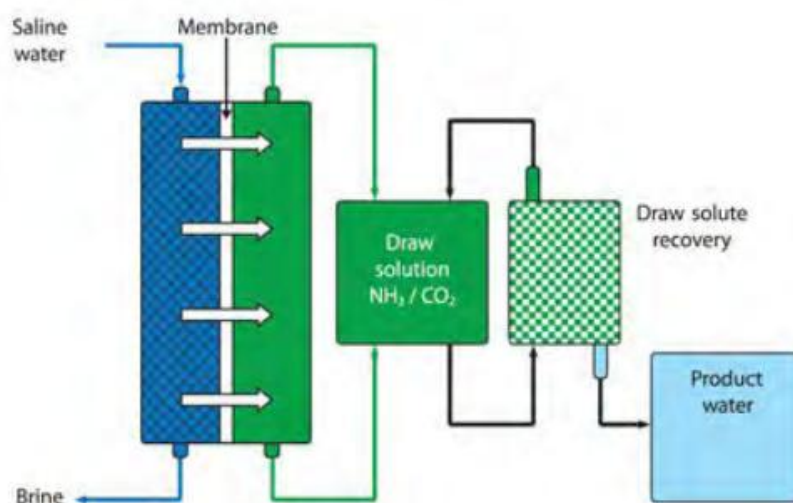
The Gijang facility was originally constructed to supply drinking water but was later converted to an industrial-water supply facility. This case illustrates that RO plants can be repurposed as demand shifts, highlighting the operational flexibility of desalination infrastructure.



- **Small-scale RO Systems for Korean Islands and Industrial Complexes**

In island communities and industrial complexes with limited power and water infrastructure, small RO systems producing tens to hundreds of cubic meters per day are installed to supply domestic or industrial water. These cases show that RO is well suited not only to large plants but also to distributed desalination systems.

1.2 Forward Osmosis (FO)



Foundation for Water Research. (2015). Desalination for water supply. Foundation for Water Research.

Characteristics

Forward osmosis is a low-pressure membrane process that uses an osmotic pressure difference as its driving force. A draw solution with high osmotic pressure draws water across the membrane, after which the draw solution is regenerated in a downstream process to recover freshwater. Because little to no hydraulic pressure is required, FO can operate relatively stably even with highly fouling or turbid feedwaters.

Advantages

- Lower membrane fouling due to low-pressure operation
- Can be used as RO pretreatment or within hybrid processes

Disadvantages

- Requires a draw-solution regeneration step
- Limited economic viability as a stand-alone desalination process

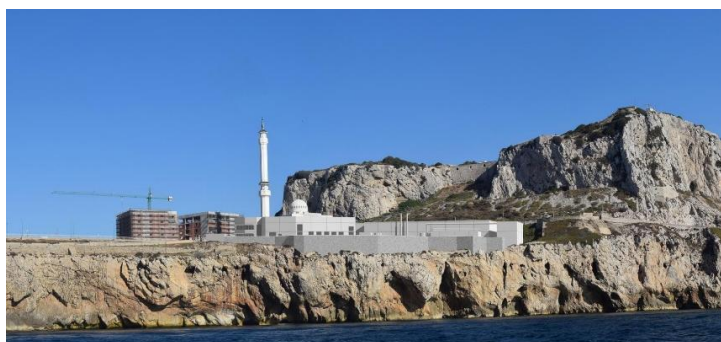
Representative Applications

• FO–RO Hybrid Pilot Plants

Hybrid systems that apply FO as a pretreatment step ahead of RO as the main process have been demonstrated at pilot scale. In these systems, heavily fouling feedwater is first treated by FO to reduce the loading on RO membranes, with the aim of lowering overall process energy consumption. This case shows that FO is more likely to be deployed as a supporting process than as a stand-alone desalination technology.

• Gibraltar — Modern Water FO Pilot Plant

Modern Water operated an 18 m³/day FO pilot plant in the British Overseas Territory of Gibraltar. This demonstration unit applied FO to seawater and brackish water to evaluate the feasibility of osmotically driven freshwater production, and it is regarded as a representative early-stage case that generated small-scale performance data for the technology.



- **FO Demonstration Studies Coupled with Industrial Wastewater Treatment**

Experimental systems that apply FO to recover water during industrial wastewater treatment, followed by a downstream process to produce freshwater, have been operated primarily by universities and research institutes. This research focuses on verifying FO process stability under highly fouling, high-salinity wastewater conditions and is regarded as a pre-commercial feasibility assessment.

- **Oman — Al Khaluf FO Pilot Plant (planned / early stage)**

Modern Water has planned and operated an FO-based desalination plant (approximately 100 m³/day) in the Al Khaluf region of Oman. This plant runs the FO process on seawater or brine to evaluate water-recovery characteristics and the feasibility of continuous operation.



1.3 Membrane Distillation (MD)

Characteristics

Membrane distillation uses a temperature difference across a hydrophobic membrane to transport water vapor while rejecting liquid brine. Because only water vapor — not dissolved salts — passes through the membrane, MD can, in principle, be applied even at very high salinities. A key feature of MD is its compatibility with low-grade heat sources such as waste heat or solar thermal energy.

Advantages

- Capable of treating high-concentration brine
- Can utilize low-grade heat sources such as waste heat or solar thermal energy

Disadvantages

- Membrane wetting and long-term stability issues
- Limited large-scale commercial deployment to date

Representative Applications

• Solar-coupled MD Demonstration Units

Small-scale MD systems using solar thermal energy as the heat source have been operated at research institutes and demonstration sites. These units have shown that freshwater can be produced using low-grade heat rather than conventional high-temperature sources, illustrating the potential of MD as a renewable-energy-coupled desalination technology.

• Qatar — MD Pilot Unit Field Test for Brine Desalination

In Qatar, an MD pilot unit was installed and operated to treat high-concentration brine, processing the concentrated reject stream from an existing thermal desalination plant and confirming freshwater production at TDS levels below 20 mg/L. This project verified the feasibility of using low-grade waste heat and solar thermal energy as regenerative heat sources while treating concentrate from local thermal power and desalination facilities.

• MD–PRO Hybrid Process Pilot (Korea)

A domestic Korean research consortium experimentally operated an MD–PRO hybrid process aimed at treating the high-concentration reject stream from RO desalination while simultaneously recovering energy. This case suggests that MD is more likely to be used to complement the limitations of existing desalination processes than as a stand-alone process.

• Maldives — Aquaver Membrane Distillation Desalination Plant

The Netherlands-based company Aquaver installed and operated the world's first commercial-scale MD-based seawater desalination plant on Gulhi Island, Maldives. The plant uses waste heat from local diesel generators as the MD heat source, providing a leading commercial example demonstrating that waste-heat-driven desalination is achievable in the field.



1.4 Pressure-Retarded Osmosis (PRO) / Salinity-Gradient Energy Recovery

Characteristics

Pressure-retarded osmosis exploits the osmotic pressure difference between two streams of different salinity — typically seawater or brine and river water or RO permeate — to generate mechanical or electrical energy rather than to produce freshwater directly. Water permeates from the low-salinity feed into a pressurized high-salinity draw stream, and the resulting volumetric flow is expanded through a turbine to generate power. Because PRO uses the same membrane-transport principles as FO, it is often discussed alongside FO and RO as a complementary technology, particularly for recovering energy from concentrated RO brine before disposal.

Advantages

- Can recover otherwise wasted osmotic energy from RO brine or estuarine mixing
- Reduces the net energy footprint of an integrated desalination facility

Disadvantages

- Achievable power density remains low compared with other renewable sources
- Membrane fouling and internal concentration polarization limit efficiency

Representative Applications

• Norway — Statkraft Tofte PRO Prototype Plant

Statkraft operated a prototype salinity-gradient power plant at Tofte, Norway, using PRO to generate electricity from the mixing of seawater and river water. Although the facility was later shut down because achieved power density fell short of commercial targets, it remains a widely cited early-stage demonstration of PRO and continues to inform current research on brine energy recovery integrated with desalination plants.

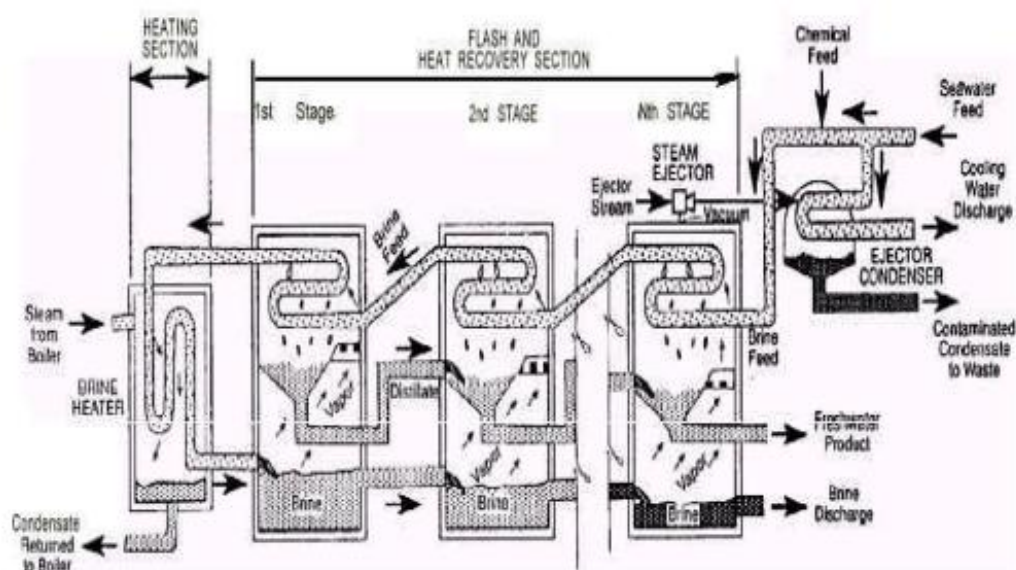
2. Phase-change-based Desalination

Phase-change-based desalination technologies separate salts and recover freshwater by exploiting the phase-change behavior of water. These technologies convert water to either a gaseous or a solid state to achieve separation and can be grouped into evaporation-based approaches, which use evaporation–condensation, and non-evaporative approaches, which rely on solid-phase (ice or hydrate) formation. Phase-change desalination generally offers high process stability and applicability to high-salinity feedwaters, and it has been deployed at scales ranging from large plants to small distributed systems.

Phase-change desalination technologies can be divided into evaporation-based phase-change desalination, which uses evaporation as the separation mechanism, and non-evaporative phase-change desalination, which relies on solid-phase formation without evaporation.

2.1 Evaporation-based Phase-change Desalination

2.1.1 Multi-Stage Flash Distillation (MSF)



Characteristics

Multi-stage flash distillation heats seawater to a high temperature and then flashes it into vapor across a series of successively lower-pressure stages. Vapor generated at each stage is condensed and collected as freshwater, and the process architecture is well suited to combined power-and-desalination plants.

Advantages

- No membranes are used, so membrane fouling is not a concern
- Stable for large-scale, long-term operation

Disadvantages

- Very high energy consumption

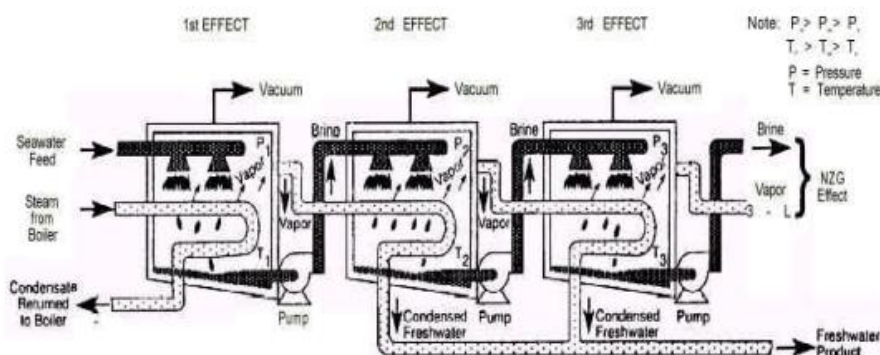
Representative Applications

• Saudi Arabia — Shoaiba and Ras Al-Khair Plants

The Shoaiba and Ras Al-Khair plants operate as combined power-and-desalination facilities, providing large-scale electricity generation together with a stable freshwater supply. Despite MSF's high energy consumption, its strength in long-term continuous operation keeps it in use in regions such as the Middle East where large-scale desalination demand persists.



2.1.2 Multi-Effect Distillation (MED)



Characteristics

Multi-effect distillation reuses the vapor generated in one evaporation stage as the heat source for the next stage, cascading heat across multiple effects. MED can operate at lower temperatures than MSF and integrates favorably with waste heat from power plants.

Advantages

- Higher thermal efficiency than MSF

Disadvantages

- Potential for heat-exchanger scaling

Representative Applications

• Power-plant Waste-heat-coupled MED Plants

Some power plants operate MED desalination systems using waste heat recovered from turbines and boilers. These cases demonstrate that MED can be applied in the field to improve the energy efficiency of thermal desalination.

• MED–RO Hybrid Process Demonstration Studies

Demonstration studies combining MED with a downstream RO process to simultaneously reduce overall thermal and electrical energy consumption have been reported. This illustrates the complementary potential of combining thermal and membrane processes.

2.1.3 Solar Still

Characteristics

A solar still is the simplest form of evaporation-based phase-change desalination, using solar radiation to naturally evaporate and condense seawater. It requires no external power supply or complex mechanical equipment.

Advantages

- No external power required

Disadvantages

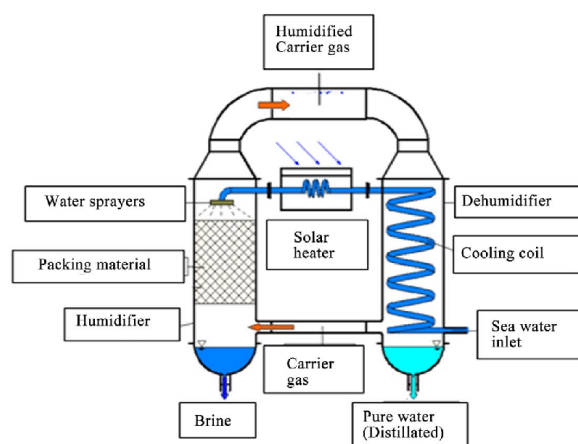
- Very low freshwater output

Representative Applications

• Educational and Emergency Solar Still Systems

Because of their simple construction and easy maintenance, solar stills are used for educational purposes and as a minimal means of securing drinking water during disaster situations. Given their limited output, they are better suited to specialized purposes than to large-scale deployment.

2.1.4 Humidification–Dehumidification Desalination (HDH)



A simple humidification–dehumidification (HDH) process.

Characteristics

HDH desalination brings air into contact with seawater to humidify it, then cools and condenses the humid air to recover freshwater. The process mimics the natural hydrological cycle and can operate at comparatively low temperature and pressure, making it compatible with low-grade heat sources.

Advantages

- Can operate at low temperature and low pressure
- Well suited to small-scale desalination

Disadvantages

- Inefficient for large-scale application

Representative Applications

• HDH Pilot Systems

Universities and research institutes have built and operated HDH pilot systems to verify the feasibility of desalination using low-temperature heat sources. These studies confirmed the technology's suitability for small-scale desalination while also identifying efficiency losses at larger scales.

• Feasibility Studies for Island Applications

Demonstration studies evaluating the applicability of HDH technology to island communities with limited power infrastructure have been conducted, and its potential as a distributed desalination system has been discussed.

• Seawater Greenhouse Project (Oman and Spain Collaborative Sites)

The Seawater Greenhouse projects implemented in Oman, Spain, and other locations are solar-driven demonstration systems that use seawater as the feed for evaporation–condensation-based desalination, supplying water for agricultural and domestic use. This project is regarded as a demonstration example showing that renewable-heat-driven evaporation–condensation systems can help address regional water scarcity.



2.1.5 Mechanical Vapor Compression (MVC)

Characteristics

Mechanical vapor compression generates freshwater by evaporating seawater and then

mechanically compressing the resulting vapor with an electrically driven compressor, which raises its temperature and pressure so that it can condense and supply the latent heat needed to evaporate additional feedwater. Because MVC uses electrical work rather than an external steam or waste-heat supply, it can operate as a self-contained, standalone unit, which makes it a common choice for marine vessels, offshore platforms, and remote or island installations that lack access to a thermal energy source.

Advantages

- Does not require an external heat source, making it well suited to standalone or remote installations
- Compact footprint relative to other thermal processes, useful where space is constrained (e.g., ships, platforms)

Disadvantages

- High electricity demand relative to membrane processes
- Mechanical wear and maintenance requirements associated with the compressor

Representative Applications

• Shipboard and Offshore Platform Desalination Units

MVC units are widely used as compact, self-contained freshwater generators aboard cargo ships, cruise ships, and offshore oil and gas platforms, where waste steam may be unavailable or unreliable and space is at a premium. This established maritime and offshore use case illustrates MVC's advantage as an independent, electrically driven desalination technology.

2.2 Non-evaporative Phase-change Desalination

2.2.1 Hydrate-Based Desalination



Characteristics

Hydrate-based desalination is a non-evaporative phase-change process that exploits the fact that gas-hydrate crystals, which form under low-temperature, high-pressure conditions, exclude salt from their crystal lattice. Because salt is separated through a liquid–solid–liquid phase change rather than evaporation, its separation mechanism is fundamentally different from that of evaporation-based phase-change desalination.

Advantages

- No membranes are used, so membrane fouling is not a concern

Disadvantages

- Process complexity is high and commercialization remains at an early stage

Representative Applications

• Hydrate Formation and Separation Experimental Studies

Laboratory-scale studies have verified the salt-exclusion characteristics of hydrate crystals formed under low-temperature, high-pressure conditions. These studies confirmed the feasibility of freshwater recovery while also evaluating process complexity and energy requirements.

• Gas-Hydrate–RO Hybrid Concept Studies

Simulation and pilot-scale studies analyzing whether combining a gas-hydrate process with RO can reduce overall energy consumption have been reported. This work currently remains at the concept-verification stage.

2.2.2 Freeze Desalination

Characteristics

When seawater or brine begins to freeze, pure water molecules form ice crystals first while dissolved solutes are continuously excluded at the growing crystal front, so that the resulting ice contains almost no salt. Freshwater is recovered by separating the pure ice fraction from the concentrated remaining liquid at the point where the two coexist, washing the ice, and then melting it in a melting tank using the condensation heat released by the refrigerant.

Advantages

- The latent heat of fusion of water is smaller than its latent heat of vaporization, so energy consumption is theoretically lower
- The separation mechanism remains effective even at high brine concentrations, which is advantageous for concentrate treatment
- No membranes are used, avoiding scaling and membrane-fouling issues
- Brine concentration and freshwater production can be achieved simultaneously, offering potential synergy with Zero Liquid Discharge (ZLD) strategies

Disadvantages

- Ice–brine separation is technically demanding, making it difficult to ensure freshwater quality
- Brine adhering to the ice surface requires an additional washing step
- Complex refrigeration and ice-making equipment make continuous-process design and scale-up difficult
- Large-scale commercial plant experience is limited and economic viability has not been well demonstrated

Representative Applications

• Experimental and Pilot Studies on Seawater and High-Concentration Brine

Numerous experimental studies have applied freeze desalination to seawater and to high-concentration brine generated by other desalination processes, verifying freshwater recovery through ice-crystal formation, separation, and melting. These studies show that freeze desalination is applicable even under high-salinity conditions, but most work remains at laboratory

or pilot scale.

• ZLD and Downstream Brine-Treatment Concept Studies

Integrated process concepts have been studied in which freeze desalination is applied as a downstream technology to further treat the concentrate produced by RO, with the aim of achieving subsequent salt recovery or full concentration toward Zero Liquid Discharge. In this context, freeze desalination is proposed as a complement to, rather than a replacement for, existing desalination processes.

3. Electrical and Electrochemical Desalination

Electrical and electrochemical desalination technologies use an electrical driving force to selectively remove ions from water, and they are generally best suited to brackish water or low-salinity feedwaters.

3.1 Electrodialysis (ED) / Electrodialysis Reversal (EDR)

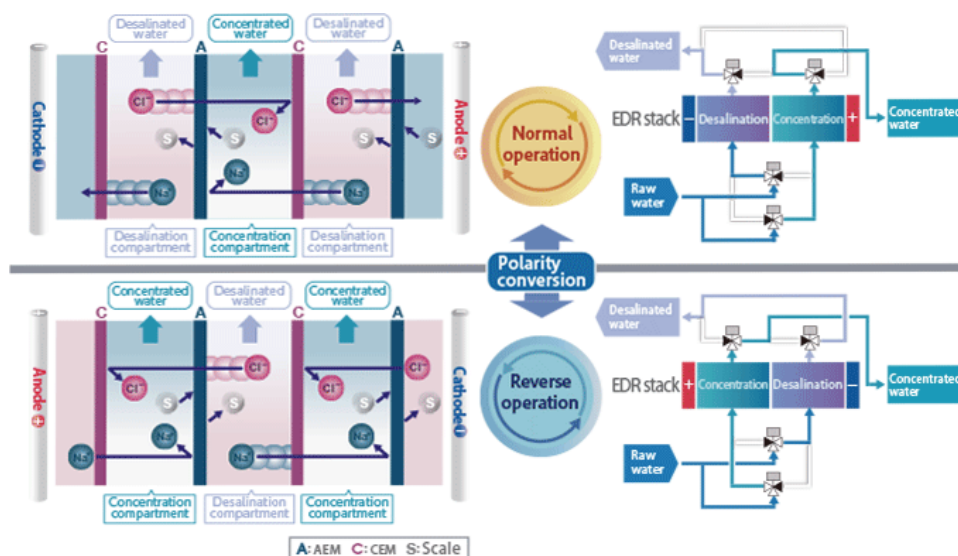


Figure 6 Principles of Electrodialysis Reversal

Characteristics

Electrodialysis moves and removes salt ions using an electric field and ion-exchange membranes. EDR mitigates membrane fouling through periodic reversal of the electrode polarity.

Advantages

- Can operate at low pressure
- Efficient for brackish water treatment

Disadvantages

- Poor economics for seawater treatment

Representative Applications

• Industrial Demineralization Facilities

ED/EDR processes are operated in industrial settings to treat process water and brackish water with relatively low salinity, showing stable performance in process-water quality control and water reuse.

- **Process-Water Reuse Systems (Korea)**

Cases of using ED/EDR to reuse process water have been reported at domestic Korean industrial water-treatment sites, with benefits noted in terms of energy consumption and maintenance.

- **USA — Brackish Water EDR Desalination Plants (Various Sites)**

In the United States, Electrodialysis Reversal (EDR) facilities are operated at multiple industrial and agricultural sites to treat relatively low-salinity brackish water. These plants mitigate membrane fouling through periodic polarity reversal, achieving stable long-term process-water quality and salt removal.



3.2 Capacitive Deionization (CDI)

Characteristics

CDI is an electro-adsorption-based desalination technology that applies a voltage across porous electrodes to adsorb ions. A membrane-enhanced variant, MCDI, has recently improved ion selectivity.

Advantages

- High energy efficiency under low-salinity conditions

Disadvantages

- Limited applicability to high-salinity seawater

Representative Applications

- **Commercial CDI Systems**

CDI units have been commercialized for small-scale desalination and water-quality improvement under low-salinity conditions and are used in batch-operation mode at some industrial and research sites.

- **Research-Institute Pilot Systems**

CDI pilot systems aimed at electrode-material development and process optimization are operated at research institutes in Korea and abroad, with ongoing research to improve technology maturity.

- **Netherlands/USA — Voltea CDI Commercial Installations**

Voltea's CDI systems have been installed commercially at numerous sites across Europe and the United States. They are applied to industrial water pretreatment and building water-quality improvement, demonstrating selective removal of specific ions in the field.



- **Europe — MCDI Pilot Systems**

European research institutes and pilot facilities have installed and operated membrane-enhanced CDI (MCDI) systems, collecting performance data on improved selectivity and continuous operation to verify the feasibility of the technology.

1.5 Comparative Summary of Desalination Technologies

The table below summarizes the technologies covered in this section for quick reference. Technology readiness levels (TRL) and energy figures are approximate and intended for relative comparison only; actual values vary with feedwater quality, plant configuration, and energy-recovery design.

Technology	Driving Force	Typical Feed Salinity	TRL (approx.)	Typical Scale
RO	Hydraulic pressure	Seawater / brackish	9 (commercial)	Small to very large
FO	Osmotic gradient	Seawater / high-fouling feeds	6–7 (pilot–early commercial)	Small–pilot
MD	Temperature difference	High-concentration brine	5–7 (pilot–early commercial)	Small–pilot
PRO	Osmotic gradient	Brine / river-water pairs	4–6 (pilot)	Small–pilot
MSF	Thermal (flashing)	Seawater	9 (commercial)	Large
MED	Thermal (multi-effect)	Seawater	9 (commercial)	Medium–large
Solar Still	Solar radiation	Seawater / brackish	9 (mature, low output)	Very small
HDH	Thermal + humidity cycle	Seawater / brackish	5–6 (pilot)	Small
MVC	Mechanical (electrical)	Seawater	9 (commercial, niche)	Small–medium
Hydrate-based	Low-temp / high-pressure phase change	Seawater / brine	3–4 (lab–early pilot)	Lab–small pilot
Freeze desalination	Freezing phase change	Seawater / high-concentration brine	3–5 (lab–pilot)	Lab–pilot
ED / EDR	Electric field	Brackish water	9 (commercial)	Small–medium
CDI / MCDI	Electro-adsorption	Low-salinity / brackish	6–8 (pilot–early commercial)	Small

Part II. Material Recovery from Brine

1. Chemical Precipitation and Crystallization-based Recovery

1.1 Hydroxide Precipitation-based Recovery

Characteristics

Hydroxide precipitation recovers metal ions by raising the pH of brine so that they precipitate as metal hydroxides. Seawater and desalination brine are rich in alkaline-earth metal ions such as Mg^{2+} and Ca^{2+} , and numerous studies have investigated their selective recovery. $Mg(OH)_2$ in particular is the most commonly cited target compound in seawater resource-recovery research.

Advantages

- Simple process that integrates readily with existing chemical processes
- Capable of large-volume recovery of an industrially useful product

Disadvantages

- Low selectivity, requiring downstream purification to remove impurities
- Large volumes of precipitated sludge, which can increase treatment cost

Representative Applications

• $Mg(OH)_2$ Recovery Studies from Seawater and Desalination Brine

Experimental and pilot studies have precipitated and recovered $Mg(OH)_2$ from seawater or desalination brine through pH adjustment. The recovered magnesium hydroxide is being evaluated for use as an industrial feedstock in neutralizing agents, flame retardants, and catalyst supports.

• Israel — Dead Sea Works $Mg(OH)_2$ Recovery Process

Dead Sea Works in Israel has long operated a process that precipitates and recovers Mg^{2+} from high-salinity brine as magnesium hydroxide. This process is a leading example of converting the Mg content abundant in seawater and brine into an industrial feedstock, demonstrating that precipitation-based metal recovery is achievable at commercial scale. The recovered $Mg(OH)_2$ is used in flame retardants, pharmaceuticals, and chemical intermediates.

1.2 Carbonation-based Recovery (Mineral Carbonation)

Characteristics

Carbonation-based recovery reacts Ca^{2+} and Mg^{2+} ions in brine with carbon dioxide to solidify them as carbonates. Because this process fixes CO_2 while simultaneously recovering a material, it has attracted attention as a seawater-based carbon capture and utilization (CCU) technology.

Advantages

- Achieves CO_2 reduction and resource recovery simultaneously
- The resulting products ($CaCO_3$, $MgCO_3$) have high industrial utility

Disadvantages

- Slow reaction kinetics requiring careful process control
- Requires optimization of CO_2 supply and reaction conditions

Representative Applications

- **Seawater-based Mineral Carbonation Studies**

Experimental studies using seawater or brine as the reaction medium to produce calcium carbonate or magnesium carbonate have been reported, and the potential use of these products as construction materials and fillers is being evaluated.

- **USA — Calera Corporation (now Fortera, Moss Landing, California)**

Calera Corporation (now Fortera) operated a pilot plant in Moss Landing, California, that used seawater and industrial effluent as the reaction medium to convert Ca^{2+} and Mg^{2+} into carbonates (CaCO_3 , MgCO_3). This process fixes CO_2 in mineral form while simultaneously recovering a solid resource, and it is regarded as an early demonstration of CCU technology based on desalination brine and seawater.

2. Adsorption and Solid-Collector-based Recovery

2.1 Black-Powder-based Adsorption Recovery

Characteristics

"Black powder" is a general term for carbon-based powdered adsorbents such as activated carbon, biochar, carbon black, and graphene-based powders. These materials are used to adsorb specific ions in brine or to serve as current collectors, and they are applied both as a stand-alone process and in combination with electrochemical processes.

Advantages

- Selectivity toward specific ions can be tuned through adsorbent composition
- Adsorbents can be regenerated and reused

Disadvantages

- Limited adsorption capacity
- Technical constraints for large-scale continuous operation

Representative Applications

- **Lithium and Boron Recovery Studies from Brine**

Experimental studies applying carbon-based adsorbents to recover lithium and boron from desalination brine have been conducted, evaluating the potential of this approach as a strategic-metal recovery technology.

- **Chile — Lithium Adsorption from Desalination Brine (R&D scale)**

In northern Chile, research has applied carbon-based and inorganic adsorbents to recover lithium from desalination-plant concentrate. This approach is evaluated as an alternative that reduces the environmental burden compared with conventional lithium mining from salt-flat brine.

2.2 Recovery of Trace and Strategic Elements (Rubidium, Cesium, Uranium)

Characteristics

Beyond the major solutes Mg, Ca, Li, and B, seawater and desalination brine also contain trace quantities of strategic elements such as rubidium, cesium, and uranium. Although present at very low concentrations, the large seawater volume processed by desalination plants means that brine represents a pre-concentrated feedstock — several times more concentrated than raw seawater —

making selective adsorption or ion-exchange recovery of these trace elements an active area of research.

Advantages

- Brine is naturally pre-concentrated relative to raw seawater, improving recovery economics
- Adds a value-recovery stream to existing desalination infrastructure at comparatively low marginal cost

Disadvantages

- Target concentrations remain extremely low, requiring highly selective sorbents
- Most work remains at laboratory scale, with limited data on long-term sorbent performance and economics

Representative Applications

• Selective Sorbent Studies for Rubidium Recovery from Desalination Brine

Laboratory studies have investigated selective sorbents capable of recovering rubidium from desalination brine, where its concentration is elevated relative to untreated seawater. This line of research is broadly consistent with the wider effort to recover trace strategic elements — including uranium and cesium — from seawater and brine, and it is viewed as a longer-term complement to the more established Mg, Ca, and Li recovery pathways described above.

3. Electrical and Electrochemical Resource Recovery

3.1 Electrodialysis-based Ion Separation

Characteristics

Electrodialysis uses an electric field and ion-exchange membranes to selectively move and separate ions in brine, enabling the concentration and recovery of salts and specific ions.

Advantages

- Relatively high ion-separation selectivity
- Can achieve brine concentration and material recovery simultaneously

Disadvantages

- Potential for increased energy consumption
- Performance can decline under high-salinity conditions

Representative Applications

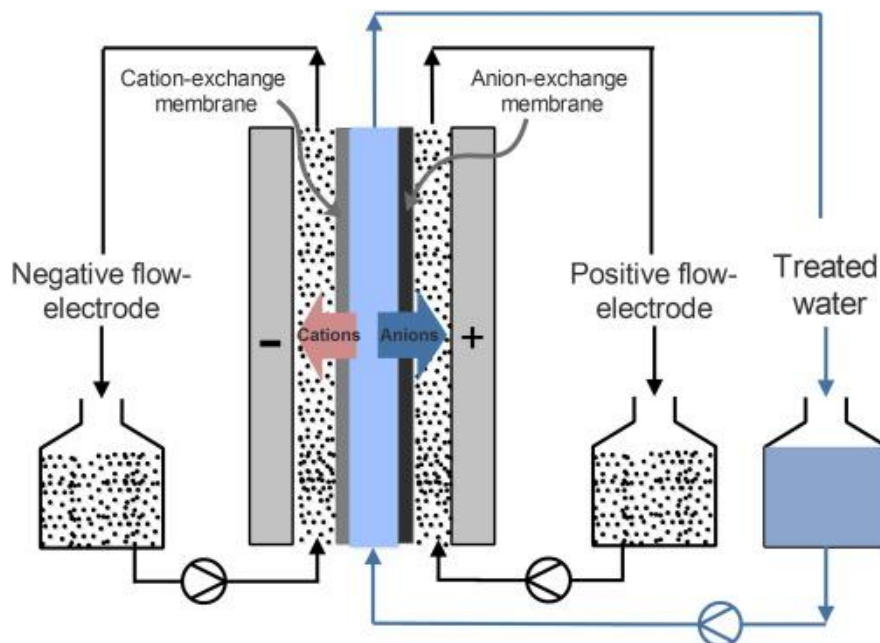
• Industrial Salt Recovery and Concentration Processes

Electrodialysis-based processes are applied in industrial settings for the purpose of salt recovery and process-water reuse.

• France — Eurodia ED Salt Recovery Systems

Eurodia supplies ED-based salt-recovery and concentration systems to industrial sites for treating industrial brine. These systems convert salt from a waste product into a reusable industrial feedstock stream.

3.2 Flow-Electrode Capacitive Deionization (FCDI)



Characteristics

Flow-electrode CDI uses carbon-based black-powder material as a slurry electrode, enabling ion adsorption and recovery even from high-salinity brine. It is being researched as an alternative that overcomes the salinity limitations of conventional fixed-electrode CDI.

Advantages

- Operable at higher brine salinities than fixed-electrode CDI
- Electrode-saturation limitations can be mitigated through slurry circulation, offering potential for continuous operation
- Electrical control allows simultaneous consideration of salt concentration and selective ion recovery

Disadvantages

- Managing the increased viscosity and stability of the slurry electrode is difficult
- Additional electrode regeneration and slurry-recovery steps increase system complexity
- Demonstrated data on energy efficiency and economics remain limited

Representative Applications

• High-Salinity Brine Treatment Pilot Studies

Pilot-scale studies have verified the feasibility of brine concentration and salt recovery, and application as a downstream technology following desalination is being discussed.

• Netherlands — Flow-Electrode CDI Pilot Plant

A flow-electrode CDI pilot system built by Dutch researchers used slurry electrodes to demonstrate continuous salt concentration and ion recovery from high-salinity brine. This plant provided field data showing that continuous operation is achievable beyond the salinity limits of conventional CDI.

4. Integrated Resource Recovery and Zero Liquid Discharge (ZLD) Strategies

Characteristics

Integrated resource-recovery strategies combine chemical precipitation, carbonation, adsorption, and electrochemical separation in a staged sequence to recover both water and solid resources from the brine generated after desalination. Recent research increasingly couples these strategies with the Zero Liquid Discharge (ZLD) concept, which aims to minimize liquid discharge.

Advantages

- Operable at higher brine salinities than fixed-electrode CDI
- Electrode-saturation limitations can be mitigated through slurry circulation, offering potential for continuous operation
- Electrical control allows simultaneous consideration of salt concentration and selective ion recovery

Disadvantages

- Managing the increased viscosity and stability of the slurry electrode is difficult
- Additional electrode regeneration and slurry-recovery steps increase system complexity
- Demonstrated data on energy efficiency and economics remain limited

Representative Applications

• Integrated Desalination–Brine–Resource Recovery Process Studies

Integrated processes that recover Mg, Ca, and salts from the brine generated after RO desalination while minimizing residual liquid are being examined at the research and pilot stage.

• Ras Al-Khair Power and Desalination Plant (Saudi Arabia)

The Ras Al-Khair Power and Desalination Plant in Saudi Arabia is a combined power-and-desalination facility that operates MSF and RO in parallel, and it serves as a site for extensive brine-treatment and resource-recovery research. Because it integrates multiple processes, this plant is a leading real-world platform for ZLD and reuse-process research.



• Al-Khafji Solar Desalination Plant (Saudi Arabia)

The Al-Khafji Solar Desalination Plant, located in eastern Saudi Arabia, is designed as a solar-powered RO facility that drives RO with PV power during daylight hours while supplementing residual energy demand from the grid in a hybrid arrangement. This plant is regarded as a leading demonstration facility for renewable-energy-coupled desalination.



5. Comparative Summary of Material Recovery Technologies

Technology	Target Species	Mechanism	TRL (approx.)
Hydroxide precipitation	Mg^{2+} , Ca^{2+}	pH-driven precipitation	9 (commercial)
Mineral carbonation	Ca^{2+} , Mg^{2+} + CO_2	Carbonate solidification	5–6 (pilot)
Black-powder adsorption	Li^+ , B	Carbon-based sorption	4–5 (lab–pilot)
Trace-element recovery (Rb, Cs, U)	Rb^+ , Cs^+ , UO_2^{2+}	Selective sorption / ion exchange	2–3 (lab)
Electrodialysis recovery	Bulk salts, specific ions	Electric-field-driven ion transport	8–9 (commercial)
Flow-electrode CDI	Ions in high-salinity brine	Slurry-electrode electro-adsorption	4–5 (pilot)
Integrated ZLD	Water + multiple solids	Staged combination of the above	5–7 (pilot–early commercial)

Part III. Economic and Environmental Considerations

Technology selection for a given site should weigh feedwater salinity, available energy sources (grid electricity, waste heat, or renewables), brine-disposal constraints, and the value of any recoverable co-products against capital and operating cost. Membrane processes (RO, ED/EDR) currently offer the lowest specific energy consumption for seawater and brackish water respectively and dominate new installed capacity, while thermal processes (MSF, MED) remain competitive chiefly where they can be co-located with power generation or industrial waste heat. Emerging processes — FO, MD, PRO, hydrate-based and freeze desalination, and flow-electrode CDI — are being pursued mainly as brine-management and energy-recovery technologies that complement RO rather than as stand-alone replacements for it, reflecting their current technology-readiness levels.

On the resource-recovery side, $Mg(OH)_2$ precipitation and mineral carbonation are the most mature pathways and are already practiced at commercial or near-commercial scale, whereas lithium, boron, and trace strategic-element recovery remain economically marginal at today's brine concentrations and would benefit from integration with existing desalination infrastructure to reduce feedstock-preparation cost. Combining desalination with staged resource recovery under a Zero Liquid Discharge framework offers the clearest path to improving both the environmental and

economic profile of large-scale seawater processing, since it converts a disposal liability (concentrated brine) into multiple marketable outputs.

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