RECLAMATION

Managing Water in the West

Concentrate Management Toolbox: Instructions and Case Studies

Research and Development Office
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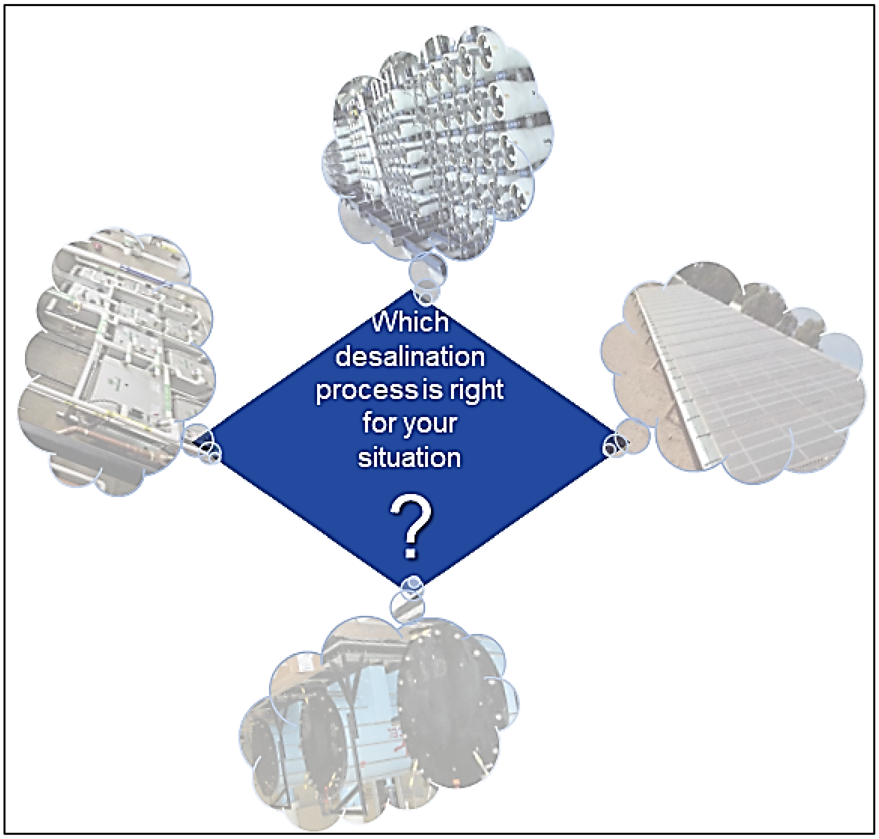

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The Concentrate Management Toolbox is a planning level tool to assist with concentrate management technology identification and selection. The Toolbox addresses the challenge of accurately evaluating concentrate management technologies, their readiness, and their applicability to be used.

The Toolbox is an Excel spreadsheet that can help planners screen technologies based on the Bureau of Reclamation's technology assessments and weights that users provide. Because many of the technology assessments and scores are subjective, we encourage users to review the scores in the Toolbox before conducting analyses. In some cases, a user may have a unique application or prior experience with a technology that warrants a different assessment and score than the default provided in the Toolbox. Customizing the Toolbox entries will result in more accurate results. Desktop studies and pilot testing are recommended for cost estimation and performance testing of the technologies that the Toolbox results suggest for particular uses.

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Concentrate Management Toolbox: Instructions and Case Studies

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Acronyms and Abbreviations

%	percent
°	degrees
°C	degrees Celsius
AGMD	air gap membrane distillation
BC	brine crystallizer
CAPEX	capital expenses
CDI	capacitive deionization
DCMD	direct contact membrane distillation
DWI	deep well injection
ED	electrodialysis
EDM	electrodialysis metathesis
EDR	electrodialysis reversal
EMWD	Eastern Municipal Water District
EPA	United States Environmental Protection Agency
FO	forward osmosis
ft	feet
ft^{t2}	square feet
GE	General Electric
GP	gypsum precipitation
gpd	gallons per day
gpm	gallons per minute
HDH	humidification-dehumidification
HEED®	high efficiency electrodialysis
kWh	kilowatthours
kWh/m^3	kilowatthour per cubic meter
L/h	liters per hour
LCC	life-cycle costs
m^3	cubic meters
m^3/d	cubic meters per day
MCDI	membrane capacitive deionization
MD	membrane distillation

MED	multi-effect distillation
MF	microfiltration
mg/L	milligrams per liter
mgd	million gallons per day
MLD	minimal liquid discharge
MSF	multi-stage flash distillation
MVC	mechanical vapor compression
NTMWD	North Texas Municipal Water District
O&M	operation and maintenance
OM&R	operation, maintenance, and repair
OPEX	operating expenses
ppm	parts per million
R&D	Research and Development
Reclamation	Bureau of Reclamation
RO	reverse osmosis
S&T	Science and Technology
SCADA	supervisory control and data acquisition
SPARRO	slurry precipitation and recycle reverse osmosis
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved solids
Toolbox	Concentrate Management Toolbox
TRL	technology readiness level
UF	ultrafiltration
USDW	underground source of drinking water
VC	vapor compression
VMD	vacuum membrane distillation
VOC	volatile organic constituents
WAIV™	wind aided intensified evaporation
ZLD	zero liquid discharge

Executive Summary

This Reclamation Science and Technology (S&T) Program research project developed a Concentrate Management Toolbox (Toolbox) that enables water planners and treatment professionals to:

1. Determine what concentrate management methods are available to treat, manage, and reduce the volume of concentrate generated from desalination plants; and

2. Compare different concentrate management methods using a defined set of criteria to help identify candidate technologies for a given application.

Initially, we developed technology evaluation criteria that were used to score various concentrate management technologies. Next, the technologies and scores were used to develop the Toolbox, which was designed to inventory and categorize existing technologies and identify practical and economical strategies for concentrate management for a wide spectrum of water treatment situations. We then developed a framework for collecting information from users to define project-specific needs, analyze the technology inventory relative to these needs, and identify a candidate list of technologies for the user's project. The Toolbox is an Excel spreadsheet [Toolbox], available on request from the authors.

This document accomplishes the following:

- Explains the factors to consider for managing concentrate when planning a desalination project, whether it be for an add-on feature to an existing plant or for a new plant

- Guides users through a series of screening questions to determine which concentrate management technologies are appropriate for their application

- Guides users through a series of evaluation (weighting and prioritizing) questions to determine which technologies best suit their priorities

- Presents suitable technologies, ranked in order of likely best fit, for the user's project

We successfully demonstrated the Toolbox in two case studies: North Texas Municipal Water District (NTMWD) in Texas and Eastern Municipal Water District (EMWD) in California.

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1. Project Purpose and Need

As the need for fresh water increases, the Bureau of Reclamation's (Reclamation) mission to deliver water in the Western United States will become more difficult to fulfill with conventional fresh water supplies. Desalination technologies have the potential to treat currently unusable water supplies to help meet future demands; however, governmental, municipal, and industrial water treatment all face increasing challenges in disposing the concentrate stream (what is left over from the water treatment process) cost-effectively and sustainably.

Thousands of documents have been published that present a myriad of concentrate management technologies, from technology development studies to regional assessments and review documents. Researchers and consultants have documented the "success" of these technologies, however, what researchers consider successful may still not be acceptable for an entity interested in implementing the technology at full scale.

Evaluating new technologies at the research and development stage, as well as newer technologies that have achieved some degree of commercial success, is challenging because:

- Obtaining full-scale costs of technologies in development is difficult.
- Companies frequently use overly optimistic marketing projections/ statements of performance, cost, and range of applications when hoping to obtain funding and strategic partners to enhance development and commercialization efforts.

Moreover, a large number of concentrate treatment technologies are becoming available for full-scale use as entities are increasingly interested in commercializing technology to solve concentrate issues. Because of the vast number of options for managing concentrate, water planners are often overwhelmed when determining which technology is the best for their situation. Water treatment planners developing existing or new desalination facilities must spend time and resources evaluating these technologies and companies, which drives up the already high cost of desalination.

Water planners can now more rapidly assess potential concentrate management options for their water/wastewater treatment situation with the Concentrate Management Toolbox (Toolbox).

To develop the Toolbox, we asked:

1. What methods are available to treat, manage, and reduce the volume of concentrate generated by inland desalination of brackish water?

2. How can different concentrate management methods be compared? Which criteria should be used to compare different methods, and how might these criteria differ by user?

3. What are the applications, markets, and cost drivers for concentrate management technologies?

We then conducted case studies using the Toolbox to answer:

1. How do factors impacting the selection of concentrate management options differ among various locations and projects?

2. How can criteria be applied to a specific project to assess the factors which determine the most suitable concentrate management methods for each inland desalination application?

3. Based on the results of the criteria evaluation, what methods are best suited to reduce and manage concentrate generated from desalination plants?

2. Concentrate Management Overview

Inland desalination requires management and disposal of concentrate generated from desalination plants. In seawater desalination for coastal locations, the concentrate stream is typically discharged into the ocean. Inland areas not having access to this discharge body must focus on handling, treating, and managing their concentrate streams. Further treatment of concentrate streams, termed "high recovery processes" can produce additional usable water from the concentrate, which reduces its volume.

As more and more technologies become available for treating concentrate, water treatment planners developing new desalination facilities and expanding existing facilities must spend time and resources evaluating these technologies. water treatment planners are often overwhelmed when considering which technology is the best for their situation Because of the vast number of options for managing concentrate,.

Technological, financial, environmental, and regulatory issues associated with concentrate management constrain wider implementation of inland brackish desalination. Traditional concentrate management methods include surface water discharge, discharge to a sanitary sewer, deep well injection (DWI), evaporation ponds, and land application. Traditional approaches to concentrate management are often unsustainable and do not make efficient use of the water contained in the concentrate.

There are three primary options for the management of concentrate. These include the following:

- **Disposal.** Concentrate can be disposed of through evaporation ponds, land application, surface discharge, sewer discharge, and DWI.
- **Beneficial use.** Concentrate can be used directly for beneficial use or in passive concentrate management strategies, such as halophyte irrigation, industrial reuse, or treatment wetlands.
- **High recovery processing involving treatment.** Concentrate can be treated to produce beneficial byproducts plus additional usable water both of which reduce the volume for disposal.

The conventional technical approach to concentrate management involves a desalination step, typically a reverse osmosis (RO) system, followed by thermal-evaporative systems, such as a concentrator and a crystallizer. The high capital expenses (CAPEX) and operating expenses (OPEX) associated with commercial high recovery systems limit high recovery systems almost entirely to industrial situations driven by regulatory pressures. To date, the only documented implementation of conventional higher recovery systems in utility systems has been one zero liquid discharge system (ZLD) (using RO followed by thermal evaporation) used to supply drinking water to a prison in Tracy, California (Mickley, 2020).

Emerging high recovery approaches include volume reduction and ZLD technologies. Many of these methods have already been commercialized, and many more are in the development stages. High recovery processing is important because of the need to extract more water from concentrate to meet the growing demand for fresh water supplies. It is also important from an environmental standpoint to reduce impacts from concentrate discharges and disposal.

An additional option to manage concentrate is to use a post-treatment process to treat the concentrate from the primary desalination process:

- **High recovery processing using secondary treatment.** Post-treatment can include minimal liquid discharge (MLD) and ZLD processes. Concentrate can be fed directly from the primary desalination process to the secondary desalination process, or it can undergo intermediate treatment prior to secondary desalination.

Intermediate treatment typically consists of chemical treatment to remove or reduce the concentration of scale-forming salts, such as calcium carbonate or calcium sulfate. Intermediate treatment processes include ion exchange, lime softening, pellet softening, and other methods of chemical precipitation (see figure 1). High recovery processing to extract more water from concentrates addresses the Nation’s need to meet the growing demand for fresh water supplies and reduces environmental impacts from concentrate disposal.

Concentrate management strategies can be employed at different stages within a water/wastewater treatment process after the primary desalination step and can involve multiple processing steps. The process that generates fresh water and produces concentrate as a byproduct is called the primary desalination process. Figure 1 shows these different concentrate management strategies and how they fit into an overall desalination process.

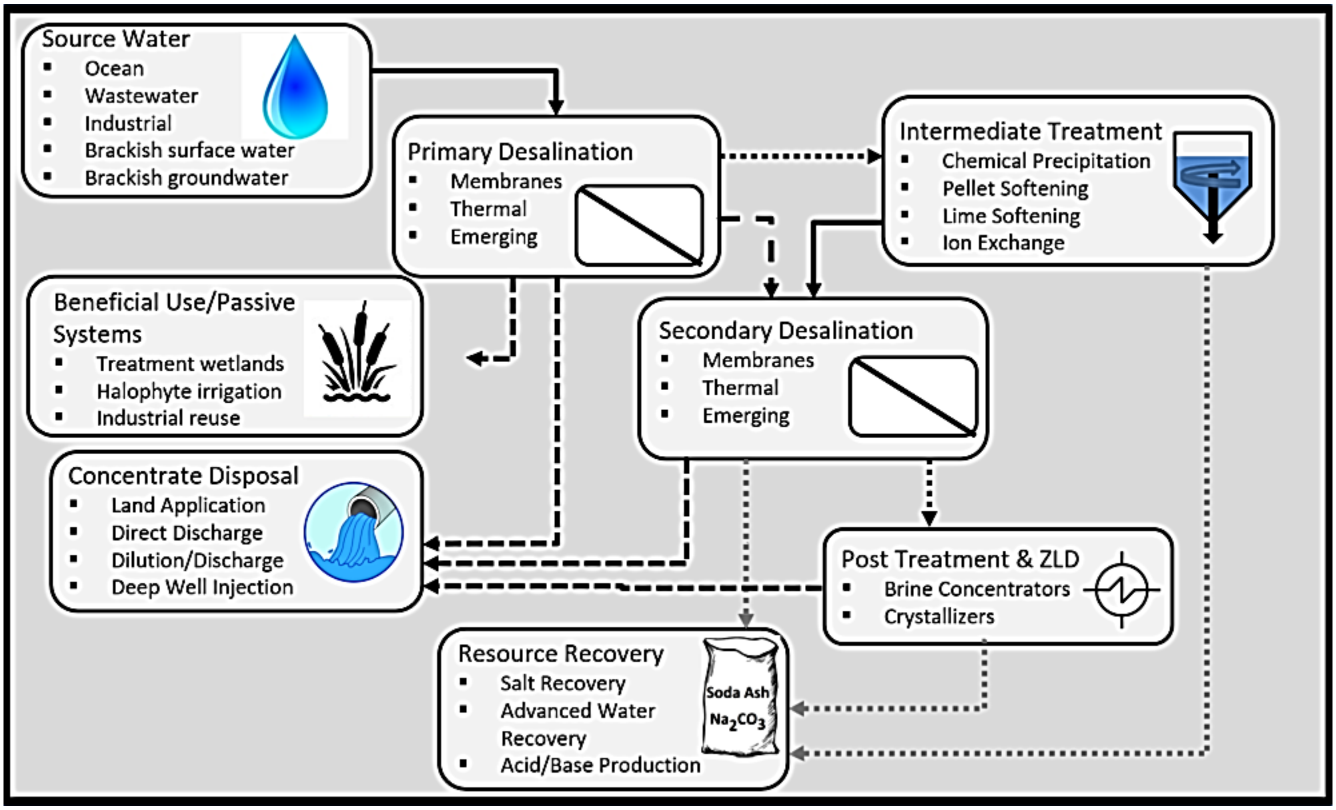


Figure 1. General framework for concentrate management.

3. Toolbox Overview

The Concentrate Management Toolbox is a planning level tool designed to compare concentrate management technologies based on the needs of the end user. This Toolbox helps water treatment planners identify and select processes for managing concentrate from new and existing desalination plants.

Water treatment planners grapple with a lack of technical information on performance and cost over a wide spectrum of water treatment situations; therefore, desktop studies and pilot testing are recommended for cost estimation and performance testing of the recommended technologies.

Companies often use overly optimistic marketing projections/statements of performance, cost, and range of applications, hoping to obtain funding and strategic partners to enhance development, commercialization and/or implementation efforts. Moreover, there is no standard way that companies provide information about their technologies, so water treatment planners do not have consistent ways to compare technologies. This Toolbox will help water planners survey, assess and compare specific technologies.

The Toolbox addresses the challenge of accurately evaluating concentrate management technologies, their readiness, and their applicability to different water management situations by using a predefined set of criteria to compare technologies according to the needs of the user.

This Reclamation Science and Technology Program (S&T) research project used this information to assess overall technologies, examine challenges for high recovery processes, and develop a practical toolbox for water treatment planners to plan the best approach for concentrate management. To develop the list of concentrate management approaches, methods, and technologies used in this Toolbox, we: a) assessed many conventional, widely accepted, best available, newer, and/or promising concentrate management technologies), and b) conducted literature reviews and industry research. We used a common set of criteria to review, assess, and evaluate each concentrate management practice. This common set of criteria allows for comparison of concentrate management technologies in a systematic fashion.

The Concentrate Management Toolbox provides an updatable and customizable inventory of existing technologies and identifies practical and economical strategies for concentrate management for various water treatment situations. Water treatment planners can use this to more rapidly assess concentrate management options—thus lowering implementation costs.

The Toolbox has two main inputs: (1) technology assessment sheets and (2) user inputs. First, each technology is evaluated using a technology assessment sheet based on a preselected set of criteria. All the assessment sheets are incorporated into the Toolbox. Next, users input the screening criteria and weighting criteria. The Toolbox then provides results by listing which technologies could meet the user's needs and a ranked score based on the user's priorities.

Assessment sheets evaluate various concentrate management technologies based on the predefined criteria chosen according to the end user's needs for concentrate management technologies. They represent what a water treatment planner would use to evaluate a technology, its performance, and other evaluation criteria. The completed assessment sheets are provided in appendix A.

Some portions of the assessment sheets contain subjective scoring based on analysis of available literature and authors' expertise. Concentrate management technologies are continually improving and changing. This Toolbox is a snapshot of the assessed technologies at the time of publication and is designed so that the user can modify or update scores for technologies included in the Toolbox or add new technologies to the Toolbox. This will allow the user to adapt the Toolbox to their specific needs and ensure that it is relevant and timely for future applications.

Users can change a technology assessment's constraints and capabilities scores. we encourage users to review the scores in the Toolbox before conducting analyses Because many of the technology assessment scores involve a level of subjectivity. In some cases, a user may have a unique application or prior experience with a technology that warrants a different score than the default provided in the Toolbox.

The scores are a snapshot from the state of the industry in 2016-2018. As new or existing technologies are developed, the technology scores can and should change to reflect changes to the technology.

The technologies assessed for this Toolbox were selected to represent the best available technologies today to manage concentrate along with promising technologies that are in different stages of development and commercialization.

These technologies are not assessed individually without publicly available experience or information because there is often not enough literature and/or information available on various proprietary technologies,. This lack of information on proprietary technologies was discovered as individual assessment sheets were developed for a couple of proprietary technologies that the authors had working knowledge of. The Toolbox does contain the developed assessment sheets on those proprietary technologies, but additional proprietary assessment sheets were not developed.

4. Criteria Development

Concentrate management technology studies in the published literature have either presented test results or qualitative descriptions of the benefits and limitations of concentrate management technologies. Many site-specific desktop and pilot studies have been completed that test one or, at best, a few technologies. In addition, study results are often presented in a way that makes it difficult to compare results across studies or to predict how a technology would perform in another application. To the best of our knowledge, no other studies have compared concentrate management technologies for a specific desalination project based on a predefined set of design and operational criteria selected by the user to fit his or her individual concentrate management needs.

Many criteria were initially considered to assess the technologies. Experts from consulting firms, municipalities, and academia helped us narrow these criteria down to 7 screening constraints (Technology Use Constraints) and 15 capabilities for weighting priorities (Technology Capabilities). By means of these criteria, each concentrate management approach can be evaluated and scored. The 7 technology use constraints can be used to determine suitability of a technology for a given application, and the 15 technology capability criteria can be used to rank technologies for a given application.

4.1. Technology Use Constraints as Screening Criteria

Technology use constraints are used to identify technologies that do not meet the user's requirements for a particular water treatment situation. The constraints are used to assess technologies, summarize the user's needs, and screen technologies that are not a good fit for the user. Technologies that fail to meet the minimum user requirements for this category are determined unviable for the user's application. The technology use constraints are listed in table 1.

4.2. Technology Capabilities

Technology capability criteria are used to determine the most promising technologies for a given water treatment application. Technology assessments shown in tables 1 and 2 rate each technology's capability on a 0 to 3 scale.

Table 1. Technology Use Constraints (Screening Criteria) for Evaluating Technologies

Constraints	Definition	Assessment Consideration	
		Yes	No
Technology readiness (TRL)	Assessment of technology readiness based on a 1-9 scale, where 1 represents a concept and 9 represents a fully developed, commercialized technology with large implementation. Please see TRL definitions in the Toolbox spreadsheet for further information.	Numerical value range between 1 and 9	
Flexibility	Capability of the technology to accommodate a wide range of feed water qualities and to handle an upset in water quality without failure or reduced product water quality.	Technology is flexible and capable of treating and/or dealing with varying feed water qualities.	Technology is not flexible and not capable of treating and/or dealing with varying feed water qualities.
Scalability	The ease at which a process can be redesigned and modified to account for a change in flowrate.	Technology is scalable and can be redesigned and/or modified based on changing flowrates.	Technology is not scalable and cannot be redesigned and/or modified based on changing flowrates.
Environmental constraints	Environmental considerations that impact the applicability of this technology; for example, requirements for high evaporation rates, high solar insolation, and/or large land area.	Environmental constraints do not pose limitations to technology.	Environmental constraints pose limitations to technology.
Process residuals	Volume and/or quality of final residual from technology.	There are no constraints associated with residuals from the concentrate process	There are constraints associated with residuals from the concentrate process.
Land area availability	Land area required by technology and its related auxiliary equipment.	Land area is not a constraint.	There are constraints associated with land area availability.
Feed water quality limitations	Feed water constituent that would impose treatment limitations such as high scaling tendency, organic content, etc.	There are no feed water limitations such as scaling tendency, organic content, etc.	Feed water is very difficult to treat due to either one or more constituents.

Table 2. Technology Capability Scoring Approach

Capability	Definition	Assessment Score			
		3	2	1	0
Technology readiness level (TRL)	How ready the technology is for use in full-scale systems. Please see TRL definitions in the Toolbox spreadsheet for further information.	1 to 9			
Produces additional “usable” water	The technology(ies) produce a new, usable water source from the concentrate.	Desalinated water can be captured for reuse.			Concentrate volume is reduced, but desalinated water is not captured.
If water is produced, anticipated water quality (salinity)	Level of salinity in water after the concentrate treatment process.	Produced water has a salinity of < 500 mg/L TDS.	Produced water has a salinity of 500 to 1,000 mg/L TDS.	Produced water has a salinity of 1,000 to 2,000 mg/L TDS.	Produced water has a salinity of > 2,000 mg/L TDS.
Overall process recovery (concentrate volume minimization)	The amount of process recovery following primary desalination plus concentrate treatment.	ZLD maximum recovery is achieved.	Near ZLD residual, very high recovery is achieved.	Increased overall system recovery is achieved.	No additional recovery is achieved.
Residual waste disposal	The level of effort, cost, and general level of complexity associated with the minimization, disposal, and management of any waste produced by a concentrate technology.	ZLD solid phase waste easily passes TCLP, and the landfill is easily accessed.	Solid phase waste passes TCLP, levels of liquid waste are moderate, and disposal is not considered to be problematic.	Selection of disposal option is unlikely in most regions or cases.	The cost of disposal is prohibitively high due to volume, concentrated toxic compounds, etc.

Table 2. Technology Capability Scoring Approach

Capability	Definition	Assessment Score			
		3	2	1	0
Limitations to large-scale utilization	The number of limitations that must be overcome for large-scale use (operational, design, construction, or OM&R challenges)	No limitations to overcome.	Some limitations to overcome to scale up system.	Many limitations to overcome to scale up system.	Too many limitations to overcome to scale up system.
Hardness removal	Degree of selective removal of multi-valet cations	All hardness is removed.	Most hardness is removed.	Some hardness is removed.	No hardness is removed.
Heavy metals removal	Degree of heavy metal removal	All heavy metals are removed.	Most heavy metals are removed.	Some heavy metals are removed.	No heavy metals are removed.
Organic contaminant removal	Degree of removal or degradation of organic compounds	All organics are removed.	Most organics are removed.	Some organics are removed.	No organics are removed.
Radionuclide removal	Degree of radionuclide removal	All radionuclide is removed.	Most radionuclide is removed.	Some radionuclide is removed.	No radionuclide is removed.
Chemical demand	The amount of chemical additives necessary to ensure proper operation of concentrate management system	No or little chemical additives are required.	Moderate chemical additives are required.	High chemical additives are required, and less chemically intensive options exist. (This technology is selected when chemical use is not the primary criterion.)	Chemical needs are considered prohibitive under most circumstances.
Energy demand	The amount of energy required by a concentrate management process in addition to what is locally available in the form of insolation, heat, wind, etc.	Energy demand is low.	Energy demand is moderate.	Energy demand is high, and more energy efficient options usually exist. (This technology is selected when energy demand is not the primary criterion.)	Energy demand is considered prohibitive under most circumstances or when co-located to capture waste heat or energy.

Table 2. Technology Capability Scoring Approach

Capability	Definition	Assessment Score			
		3	2	1	0
Labor requirements	The amount of system complexity and operator oversight necessary to operate a concentrate management process.	System complexity is low, and little or no operator oversight is required. This process may be easily automated.	System complexity is moderate, and a trained operator must be onsite at all times.	System complexity is high, and a top level (A) operator must be onsite at all times.	System complexity is considered prohibitive and only practical if a top level (A) operator is onsite at all times during operation and dedicated only to the concentrate treatment system.
Reliability	The ability of the technology to produce target water quality consistently with minimal shutdown or failure.	System operates with very few shutdowns while producing target water quality over long periods of time.	System experiences some issues with continuous, steady state operation.	System experiences significant issues with maintaining steady state operation.	Previous testing and demonstration reveal the system has difficulty maintaining sustained, steady state operation and producing consistent water quality.
Value added	Additional benefits not included in earlier criteria (e.g., habitat restoration or resource recovery)	High added benefits.	Moderate added benefits.	Low added benefits.	No added benefits.

Note: mg/L = milligrams per liter, TCLP = toxicity characteristic leaching procedure, TDS = total dissolved solids, OM&R = operation, maintenance, and repair.

5. Technology Evaluation and Assessment Sheets

As discussed previously in Chapter 4, “Criteria Development,” the concentrate management technology criteria were first narrowed down for weighting priorities into 7 technology use constraints and 11 technology capabilities. These constraints and capabilities were then used to compare and evaluate potential water concentrate technologies to determine which technologies could meet a specific user’s requirements for a particular water treatment situation, while screening out technologies that failed to meet the user’s requirements. The evaluation of concentrate management technologies, using the criteria described in chapter 4 was supplemented by information obtained from published studies, as well as the expertise of the authors and contributors to this project.

Following the technology evaluations, the results were summarized on technology assessment sheets, which are open sourced documents that can be modified and/or updated by the users. Individual assessment sheets were created for each potential concentrate management technology. Each assessment sheet contains the following sections:

- Technology Description
- Constraints
- Capabilities
- Research Needs – gathered from literature
- References

In the assessment sheets, each concentration management technology is described by the same criteria that were required and weighed by the user. The individual assessment sheets were then grouped into technology categories based on Mickley’s work (Mickley, 2020) and were assessed for use in the Toolbox. Table 3 lists the assessment sheets contained within each technology category.

Table 3. List of Assessment Sheets Developed by Technology Category

Technology Category	Assessment Sheet
RO based high recovery processes	Dual stage RO precipitation
Electrolytic processes	AquaSel
	EDR with gypsum precipitation
	EDM
	HEED®
	ED
	ED with SPARRO
	CDI
FO processes	FO
MD processes	MD
	MD – air gap
	MD – direct contact
	MD – sweep gas
	MD – multi-effect vacuum
	Pervaporation
Evaporative processes	WAIV™
	BC
	MED
	MSF
	VC
	HDH
MISC processes	Direct solar vapor generation
	Solvent extraction
Traditional concentrate management solutions	DWI

Note: BC = brine crystallizer, CDI = capacitive deionization DWI = deep well injection, ED = electrodialysis, EDM = electrodialysis metathesis, EDR = electrodialysis reversal, FO = forward osmosis, HDH = humidification-dehumidification, HEED® = High Efficiency Electrodialysis, MD = membrane distillation, MED = multi-effect distillation, MSF = multi-stage flash distillation, SPARRO = slurry precipitation and recycle reverse osmosis, WAIV™ = wind aided intensified evaporation , VC = vapor compression.

6. Concentrate Management Toolbox

The Excel-based Toolbox contains several tabs as described in the following sections:

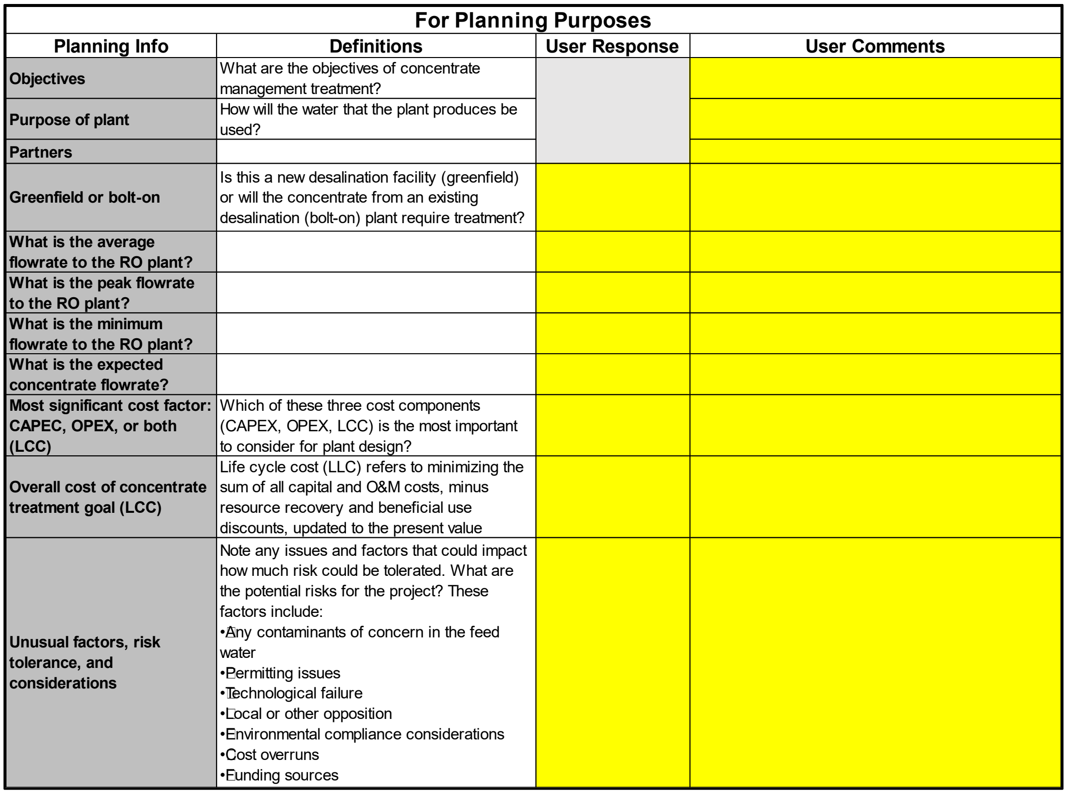
- **Toolbox Instructions.** Brief guidance on toolbox use
- **Planning Description.** Background information for user's concentrate management needs
- **User Input.** User and site-specific requirements and preferences
- **Toolbox Results.** Screened and prioritized list of recommended technologies based on technology evaluations and end user needs
- **Technology List.** List of technologies currently in the Toolbox that have been assessed
- **Assessment Sheet Criteria.** Definitions of the various criteria used in the assessment of technologies
- **Technology Readiness Levels Definitions.** Definitions of the technology's readiness and readiness to be used in full-scale plants

6.1. Toolbox Tab No. 1: Toolbox Instructions

Toolbox Tab No. 1: Toolbox Instructions describes the purpose of the Toolbox, provides steps for users on how to use the Toolbox, and describes the sheets contained in it. The following sections in this report provide more detailed instruction for using the Toolbox.

6.2. Toolbox Tab No. 2: Planning Description

Toolbox Tab No. 2: Planning Description provides a convenient place for information about the planned concentrate management technology use. This information is not factored into the Toolbox results. It also helps users provide a basis for their input into the screening and weighting analysis. Users can describe the need for concentrate management in the user response fields shown in figure 2. This section describes the various items contained in the planning description.



For Planning Purposes			
Planning Info	**Definitions**	**User Response**	**User Comments**
Objectives	What are the objectives of concentrate management treatment?		
Purpose of plant	How will the water that the plant produces be used?		
Partners			
Greenfield or bolt-on	Is this a new desalination facility (greenfield) or will the concentrate from an existing desalination (bolt-on) plant require treatment?		
What is the average flowrate to the RO plant?			
What is the peak flowrate to the RO plant?			
What is the minimum flowrate to the RO plant?			
What is the expected concentrate flowrate?			
Most significant cost factor: CAPEC, OPEX, or both (LCC)	Which of these three cost components (CAPEX, OPEX, LCC) is the most important to consider for plant design?		
Overall cost of concentrate treatment goal (LCC)	Life cycle cost (LCC) refers to minimizing the sum of all capital and O&M costs, minus resource recovery and beneficial use discounts, updated to the present value		
Unusual factors, risk tolerance, and considerations	Note any issues and factors that could impact how much risk could be tolerated. What are the potential risks for the project? These factors include: •Any contaminants of concern in the feed water •Permitting issues •Technological failure •Local or other opposition •Environmental compliance considerations •Cost overruns •Funding sources		

Figure 2. Screenshot of Toolbox Tab No. 2: Planning Description. Yellow fields are for user responses and comments.

6.2.1. Plant Description

The planning description page is set up in tabular format. Four columns appear across the top: (1) “Planning Information,” (2) “Definitions,” (3) “User Response,” and (4) “User Comments.” Numbered rows on the left side of the table list specific planning items that should be considered during the planning stage. Assistance is provided below to help the user fill out necessary planning information for the plant. Describe the plant in the yellow highlighted cells.

6.2.2. Greenfield or Bolt-On

Select one of the two following descriptions:

- **Greenfield.** Will the concentrate management technology be integrated into a new primary desalination facility?

  or

- **Bolt-on.** Will the concentrate management technology be added to existing systems by treating the waste stream of the primary desalination system?

6.2.3. Flowrates

Some concentrate management technologies in development have not been tested at higher flowrates; however, as these technologies further develop, they will likely be capable of treating larger volumes of water. Knowing the volume of water that will need treatment is important to screen out concentrate management technologies that have not been tested at higher flowrates and to help determine weighted priorities.

Answer the following questions for plant flowrates:

- What is the average flowrate to the desalination plant?
- What is the peak flowrate to the desalination plant?
- What is the minimum flowrate to the desalination plant?
- What is the expected concentrate flowrate?

6.2.4. Costs

It is very difficult to assess technology costs because a wide spectrum of information is available, which varies greatly. Costs found in literature vary based on site-specific treatment and the cost of prototype units, as opposed to full-scale systems. Also, operation and maintenance costs can vary greatly for one technology based on operation, site, etc. For these reasons, while costs are generally discussed in the assessment sheet, the Toolbox does not rank costs. Costs are, however, a vital decision factor, so a user should determine cost priorities and perform a cost benefit analysis that is specific to their situation after ranking other factors using this Toolbox.

Answer the following question to specify the most significant cost component for the desalination plant:

- Which of these three cost components is the most important to consider for plant design: capital (CAPEX), operation and maintenance (OPEX), or lifecycle cost (LCC)?

When addressing this question, keep in mind that LCC combines both CAPEX and OPEX, minus resource recovery and beneficial use discounts, updated to the present value. Minimizing LCC means minimizing the sum of all CAPEX and OPEX costs.

Examine and answer the following questions to determine life-cycle cost (LCC) goal:

- What is the funding source? Are there more funds available up front (making OPEX more important) or after the plant is built (making CAPEX more important)?

- Are there other factors that may make CAPEX higher (e.g., permitting requirements, nearby buildings, needs for infrastructure, remote location, noise and traffic considerations, architectural and landscaping concerns)?

- Are there other factors that may make OPEX costs higher (e.g., energy and/or labor costs, remote location, environmental protection considerations, source water)?

6.2.5. Unusual Factors, Risk Tolerance, and Considerations

Note any issues and factors that could impact how much risk could be tolerated. What are the potential risks for the project? These factors include:

- Any contaminants of concern in the feed water
- Permitting issues
- Technological failure
- Local or other opposition
- Environmental compliance considerations
- Cost overruns
- Funding sources

6.2.6. Water Quality

Knowing the water quality is critical to understanding the volume and constituents in concentrate and finding the right concentrate treatment technology:

- Provide feed water quality
- Provide concentrate water quality
- Provide target product water quality

6.3. Toolbox Tab No. 3—User Input

Toolbox Tab No. 3: User Input enables the user to enter site-specific requirements and preferences (technology use constraints), as well as technology weighting and priority criteria (technology capabilities). Technology use constraints are used as screening criteria to determine whether or not a particular concentrate management technology is suitable for a given application. Technology capabilities are screening criteria used to establish the importance, or priority, of each selection factor to determine the most promising technologies for a given application.

6.3.1. Technology Use Constraints (Screening Analysis)

Under Toolbox Tab No. 3: User Input, on the "Technology Use Constraints" table, the user can enter site-specific requirements and preferences (see figure 3). These technology use constraints use minimum requirements as screening criteria to help determine suitability of a technology for a given application. There are seven technology use constraints used to screen/flag technologies. Table 4 lists the seven constraints and summarizes the user input evaluation approach for each of them.

Table 4. Technology Use Constraints (Screening Analysis)

Constraint	Definition	Evaluation Approach
Technology Readiness Level	What is the minimum acceptable Technology Readiness Level (TRL)? Please see TRL definitions for further information. Choose between 1 to 9	1 to 9
Flexibility	Is flexibility of technology to treat varying feed water quality or capability to handle system upset important?	Yes/No
Scalability	Is scalability, i.e. redesign and/or modification of technology to treat varying feed water quantity important?	Yes/No
Environmental constraints	Are there any environmental considerations that impact the applicability of a technology? For example, requirements for high evaporation rates, high solar insolation, and/or large land area.	Yes/No
Process residuals	Are there any final residuals that have any quality or quantity concerns that might limit technologies? i.e., permits available for discharge to deep wells, or surface water, can also include normal landfill of solids	Yes/No
Land area availability	Is land area limited for concentrate discharge/management?	Yes/No
Feed water quality limitations	Are there any feed water constituents that would impose treatment limitations such as high scaling tendency, organic content, or etc.?	Yes/No

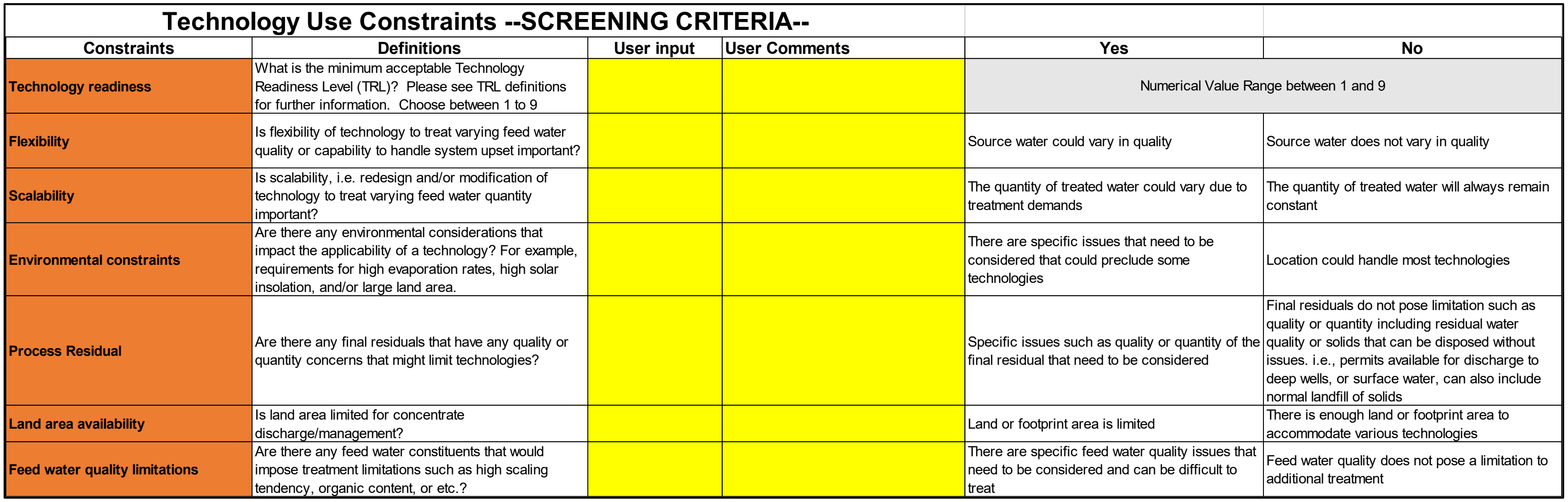
As mentioned above, the screening constraints are used to match suitable technologies to the user's needs. For example, if the user needs a flexible system, only technologies that are flexible will be returned as suitable—and all technologies that are inflexible will be flagged as unsuitable. However, if the user has a constraint, technology that is incapable of meeting the constraint would be flagged as unsuitable technology for the user. If a user does not indicate the need for a flexible system, then both flexible and inflexible technologies would be presented as suitable. Both descriptions for a user's or a technology's constraints are provided in the subsection below.

Except for the technology readiness constraint (TRL), which is evaluated on a 1 to 9 scale, the remainder of the technology use constraints are assessed and answered by means of a "Yes" or "No" approach. For example, if a technology assessment results in a "Yes" answer for a particular constraint, this means a constraint (or limitation) exists that could potentially make the technology unsuitable for meeting the user's needs. This constraint may involve the user's site, water quality constituents, or some other factor.

Conversely, if a technology assessment results in a "No" answer for a particular constraint, the technology is free from limitations and can meet the user's needs (see the matrix in table 5). All flagged and/or screened technologies will be scored and ranked for the user's consideration.

Table 5. Technology Use Constraint (Screening Analysis) Answer Matrix

User	Technology	Result
Yes, this is a constraint and, the user needs this factor.	Yes, the technology can handle this factor.	Yes, the technology is suitable.
Yes, this is a constraint, and the user needs this factor	**No,** the technology cannot handle this factor.	No, the technology is not suitable.
No, this is not a constraint, and the user does not need this factor.	Yes, the technology can handle this factor . or No, the technology cannot handle this factor.	Yes, the technology is suitable.



Technology Use Constraints --SCREENING CRITERIA--

Constraints	Definitions	User input	User Comments	Yes	No
Technology readiness	What is the minimum acceptable Technology Readiness Level (TRL)? Please see TRL definitions for further information. Choose between 1 to 9			Numerical Value Range between 1 and 9	
Flexibility	Is flexibility of technology to treat varying feed water quality or capability to handle system upset important?			Source water could vary in quality	Source water does not vary in quality
Scalability	Is scalability, i.e. redesign and/or modification of technology to treat varying feed water quantity important?			The quantity of treated water could vary due to treatment demands	The quantity of treated water will always remain constant
Environmental constraints	Are there any environmental considerations that impact the applicability of a technology? For example, requirements for high evaporation rates, high solar insolation, and/or large land area.			There are specific issues that need to be considered that could preclude some technologies	Location could handle most technologies
Process Residual	Are there any final residuals that have any quality or quantity concerns that might limit technologies?			Specific issues such as quality or quantity of the final residual that need to be considered	Final residuals do not pose limitation such as quality or quantity including residual water quality or solids that can be disposed without issues. i.e., permits available for discharge to deep wells, or surface water, can also include normal landfill of solids
Land area availability	Is land area limited for concentrate discharge/management?			Land or footprint area is limited	There is enough land or footprint area to accommodate various technologies
Feed water quality limitations	Are there any feed water constituents that would impose treatment limitations such as high scaling tendency, organic content, or etc.?			There are specific feed water quality issues that need to be considered and can be difficult to treat	Feed water quality does not pose a limitation to additional treatment

Figure 3. Screenshot of Toolbox Tab No. 2: User Input, "Technology Use Constraints" page. Yellow fields are for user input and comments

Table 6. Technology Readiness Level (TRL)

Technology Readiness Level	Definition
Concept Development Bench Scale Testing: 1-4	
1	***Transition from scientific research to applied research.*** Basic principles are observed and reported (idea development). Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
2	***Applied research.*** Technology concept and/or application formulated (theoretical understanding). Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
3	***Proof of concept validation.*** Analytical and experimental critical function and/or characteristic proof of concept (bench scale). Active research and development is initiated with analytical and laboratory studies.
4	***Bench scale***. Component/subsystem validation in laboratory environment. Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
Pilot and Demonstration Testing: 5-7	
5	***Pilot testing components.*** System/subsystem/component validation in relevant environment. Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
6	***Pilot testing systems.*** System/subsystem model or prototyping demonstration in a relevant environment. Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
7	***Demonstration testing.*** System prototyping demonstration in an operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
Full Scale: 8-9	
8	***End of system development.*** Actual system is evaluated through test and demonstration in an operational environment. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and validation completed.
9	***Full scale use.*** Technology has been used successfully at full scale. Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed.

To assist users in filling out required areas of the Technology Use Constraints page, a detailed set of questions has been developed. Each question is presented and discussed below.

6.3.1.1 Technology Readiness

What is the minimum acceptable Technology Readiness Level (TRL)?

Assessment of technology readiness is based on a 1-9 scale, defined in table 6. Consider:

- What are the risks of failure? Municipalities may require a higher level of technological readiness as bondholders and others may have a low risk tolerance.

- Are there any potential benefits for employing and developing lower TRL level technologies?

- Does the project purpose encourage using less mature technologies?

Note any considerations that might influence the risk tolerance decision for the concentrate management system's technological readiness in Toolbox Tab No. 2: Planning Description.

6.3.1.2 Flexibility

Is flexibility of technology to treat varying feed water quality or capability to handle system upsets important?

Does the system need to be flexible enough to accommodate a wide range of feed water qualities and/or handle an upset in water quality without failure or reduced product water quality?

Answering "Yes" indicates that the source water could vary in quality, and flexibility is needed. Explain this under Toolbox Tab No. 2: Planning Description. Also see Section 6.2.6, "Water Quality."

Answering "No" indicates that the source water does not vary in quality.

Consider:

- What is the source of your feed water?

- What influences are there on the feed water? If this is a surface water source, could the quality ever change due to additional precipitation, changes in runoff quality, etc.? If this is a groundwater source, could the quality ever change due to groundwater intrusion, groundwater depletions, etc.?

- Are there any other events that could influence the concentrate quality (such as an issue in the primary desalination treatment)?

Technology assessment sheets have been developed to identify the flexibility of the technology to accommodate a wide range of feed water qualities and to handle an upset in water quality without failure or reduced product water quality.

A “Yes” answer indicates the technology is flexible and can treat and/or deal with varying feed water qualities. A “No” answer indicates the technology is inflexible and incapable of treating and/or dealing with varying feedwater qualities.

6.3.1.3 Scalability

Is scalability, i.e. re-design and/or modification of technology to treat varying feed water quantity important?

Do you need to be able to change the amount of concentrate being treated in the future? Can the process be easily re-designed and modified to account for a change in flowrate?

Answering “Yes” indicates that the quantity of treated water could vary due to treatment demands. Explain this on the Toolbox Tab No. 2: Planning Description.

Answering “No” indicates that the quantity of treated water will always remain constant.

Consider:

- What is the source of your feedwater and will it vary?
- What influences are there on the feedwater? If this is a surface water source, could the quantity ever change due to supply and demand?
- Are there any other events that could influence the concentrate quantity?

Technology assessment sheets have been developed to identify the scalability of the technology to the ease at which a process can be redesigned and modified to account for a change in flowrate.

A “Yes” answer indicates technology is scalable and can be redesigned and/or modified based on changing flowrates. A “No” answer indicates technology is not scalable and cannot be redesigned and/or modified based on changing flowrates.

6.3.1.4 Environmental Constraints

Are there any environmental considerations that impact the applicability of a technology? For example, requirements for high evaporation rates, and/or high solar insolation.

A “Yes” answer means specific issues exist that could preclude some technologies and they need to be considered . These issues should be noted in Toolbox Tab No. 2: Planning Description. Also see Section 6.2.5, “Unusual Factors, Risk Tolerance, and Considerations.”

A “No” answer means that the selected location could handle most technologies. Consider constraints such as:

- High and intense sunlight (i.e., high solar insolation)
- Land restrictions other than available land area (e.g., terrain, elevations)
- High evaporation rates

Technology assessment sheets have been developed to identify the environmental considerations that impact the applicability of the technology; Examples include requirements for high evaporation rates, high solar insolation, and/or large land area.

A “Yes” answer indicates environmental constraints do not pose limitations to technology. A “No” answer indicates environmental constraints pose limitations to technology.

6.3.1.5 Process Residuals

Are there any final residuals that have any quality or quantity concerns that might limit technologies?

Does the volume and/or quality of final residuals pose additional limitations for concentrate process residuals?

A “Yes” answer means that specific issues exist, such as quality or quantity of the final residual, that need to be considered. These issues should be noted in Toolbox Tab No. 2: Planning Description.

A “No” answer means that final residuals do not pose limitations such as quality or quantity, including residual water quality or solids that can be disposed of without issues (i.e., permits available for discharge to deep wells, or surface water, can also include normal landfill of solids).
Consider:

- Quality—are there any contaminants or salts that require special handling, such as any radioactive materials or other hazardous materials? See Section 6.2.6., “Water Quality.”

- Quantity—Is the amount of concentrate large enough or could a contaminant concentration level become high enough in the final residual to pose a concern? See quantity descriptions in Section 6.2.3, “Flowrates.”

A “Yes” answer indicates there are no constraints associated with residuals from the concentrate process.

A “No” answer indicates there are constraints associated with residuals from the concentrate process.

6.3.1.6 Land Area/Footprint Requirements

Is land area limited for concentrate discharge/management?

Can your footprint handle larger equipment? Is the technology and its related auxiliary equipment free from land or footprint requirements? Is there land available for expansion of components or for final residual disposal using an evaporation pond?

A “Yes” answer indicates that the land or footprint area is limited. Specific information should be included in Toolbox Tab No. 2: Planning Description. Also see Section 6.2.5, “Unusual Factors, Risk Tolerance, and Considerations.”

A “No” answer indicates there is enough land or footprint area to accommodate various technologies.

Consider

- Land area - is land available for expansion?
- Land area - is land available for evaporation ponds, if needed?

Technology assessment sheets have been developed to identify land area required by technology and its related auxiliary equipment.

A “Yes” indicates land area is not a constraint.

A “No” indicates constraints associated with land area availability.

6.3.1.7 Feed Water Quality Limitations

Are there any feed water constituents that would impose treatment limitations such as high scaling tendency, organic content, or etc.?

Would the technology have limitation in treating most constituents in the feedwater?

A “Yes” answer means that specific feed water quality issues exist that need to be considered and that can be difficult to treat. These issues should be noted in Toolbox Tab No. 2: Planning Description. Also see Section 6.2.6, “Water Quality.”

A “No” answer means that feed water quality does not pose a limitation to additional treatment.

Consider:

- What are the contaminants in the feed water?
- What special handling or considerations might any of these contaminants require?
- Are there any risks of different contaminants in the feedwater in the future?

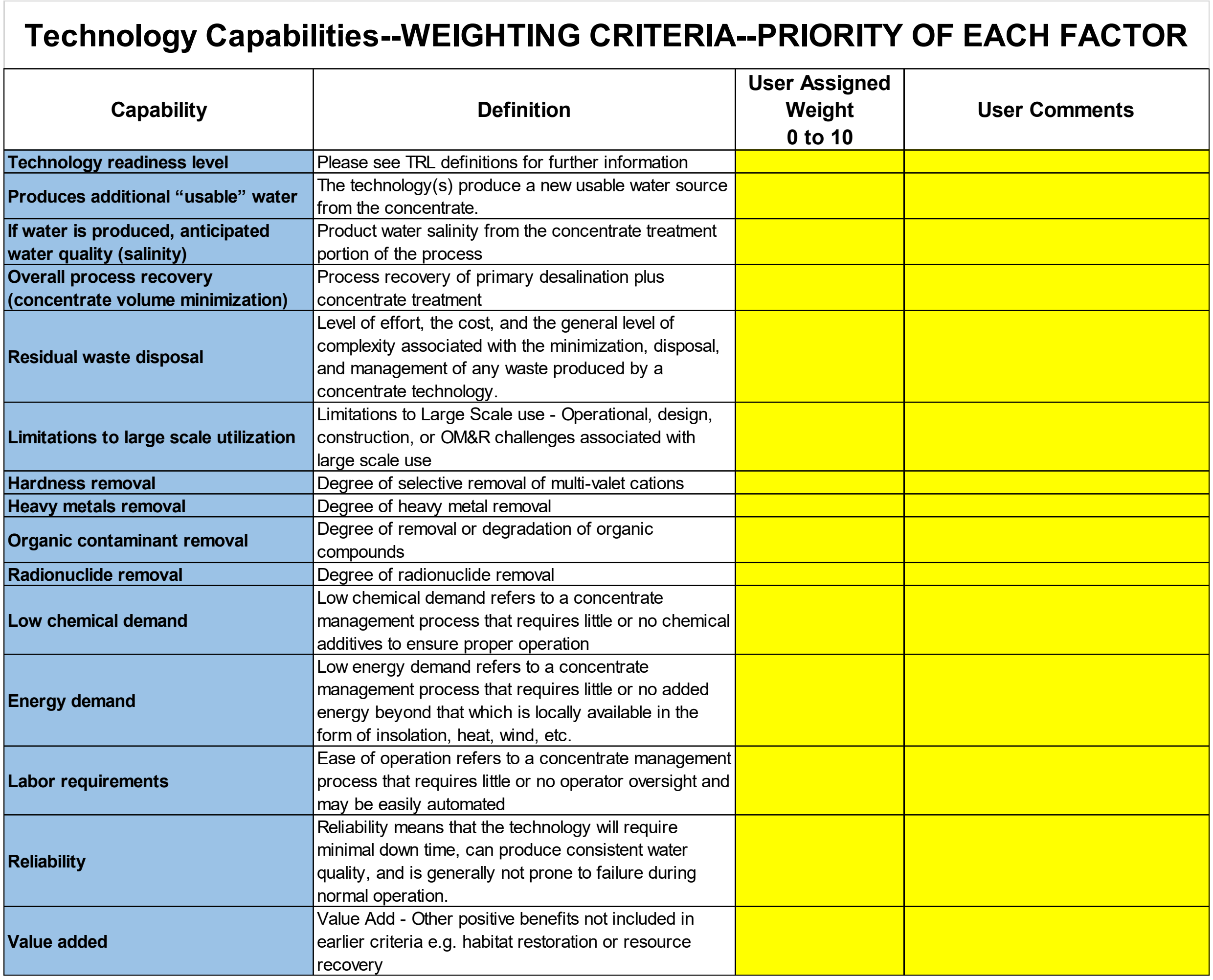
Technology assessment sheets have been developed to identify limitations to the use of the technology by feed water constituent such as high scaling tendency, organic content, or etc.

A “Yes” answer indicates no feed water limitations such as scaling tendency, organic content, or etc.

A “No” answer indicates feed water is very difficult to treat due to either one or more constituents.

6.3.2. Technology Capabilities (Weighting Criteria – Priority of Each Factor)

Assessing technology capabilities by conducting a screening analysis helps establish the importance, or priorities, of each selection factor. These selection factors are then used as weighting criteria to determine the most promising technologies for a given application. Users rate the importance of each capability and assign a weight on a 0 to 10 scale (0 as a nonpriority and 10 as a very high priority) (see figure 4).



Technology Capabilities--WEIGHTING CRITERIA--PRIORITY OF EACH FACTOR

Capability	Definition	User Assigned Weight 0 to 10	User Comments
Technology readiness level	Please see TRL definitions for further information		
Produces additional "usable" water	The technology(s) produce a new usable water source from the concentrate.		
If water is produced, anticipated water quality (salinity)	Product water salinity from the concentrate treatment portion of the process		
Overall process recovery (concentrate volume minimization)	Process recovery of primary desalination plus concentrate treatment		
Residual waste disposal	Level of effort, the cost, and the general level of complexity associated with the minimization, disposal, and management of any waste produced by a concentrate technology.		
Limitations to large scale utilization	Limitations to Large Scale use - Operational, design, construction, or OM&R challenges associated with large scale use		
Hardness removal	Degree of selective removal of multi-valet cations		
Heavy metals removal	Degree of heavy metal removal		
Organic contaminant removal	Degree of removal or degradation of organic compounds		
Radionuclide removal	Degree of radionuclide removal		
Low chemical demand	Low chemical demand refers to a concentrate management process that requires little or no chemical additives to ensure proper operation		
Energy demand	Low energy demand refers to a concentrate management process that requires little or no added energy beyond that which is locally available in the form of insolation, heat, wind, etc.		
Labor requirements	Ease of operation refers to a concentrate management process that requires little or no operator oversight and may be easily automated		
Reliability	Reliability means that the technology will require minimal down time, can produce consistent water quality, and is generally not prone to failure during normal operation.		
Value added	Value Add - Other positive benefits not included in earlier criteria e.g. habitat restoration or resource recovery		

Figure 4. Screenshot of Toolbox Tab No. 2: User Input, "Technological Capabilities" page, showing technology capability criteria for evaluating their importance (priority). Yellow fields are for user assigned weights and comments.

Technology assessments rate each technology's capability on a 0 – 3 scale for each capability criteria. Technology scores are calculated as:

Technology Score = User's Capability Weight * Technology Assessment Score

It is possible to have equal weights for the technology capabilities. For example, a municipality relying on the water treatment plant as its main water supply might weigh both reliability and the amount of produced water with level 10 ratings. This would increase the scores for those technologies that scored high in their technology assessment for both reliability and the amount of produced water.

The 15 capabilities used to score and rank technologies are described below, and each capability is discussed separately in the sections that follow:

- Technology readiness level
- Cost (LCC)
- Produces additional “usable” water
- If water is produced, anticipated water quality (salinity)
- Overall process recovery (concentrate volume minimization)
- Residual waste disposal
- Limitations to large scale utilization
- Hardness removal
- Heavy metals removal
- Organic contaminant removal
- Radionuclide removal
- Low chemical demand
- Energy demand
- Labor requirements
- Reliability
- Value added

6.3.2.1 Technology Readiness Level

Rate the importance of the technological readiness and assign a weight from 0 to 10.

Consider:

- Are you willing to consider technologies that are in a pilot or concept scale?

- What is the level of risk you are willing to take if the technology fails?

- Do you have an interest in using your project to advance new technology and further research?

Technology readiness levels are defined in table 6 2.

6.3.2.2 Produces Additional “Usable” Water

Rate how important it is for a chosen concentrate management technology to obtain as much usable water as possible from the feedwater (i.e., how important it is to produce additional “usable” water from the concentrate). Assign a weight from 0 to 10.

Consider:

- **Water needs**. Is generating a higher volume of usable water and a lesser volume of concentrate worth the potential added costs?

- **Water supply.** Are there limited water supplies, which would increase the importance of generating additional usable water from the concentrate? Is the raw water supply a significant cost?
- **Disposal.** Are the costs and efforts needed to dispose of the concentrate higher for larger concentrate amounts (for example, concentrate must be transported long distances), which would increase the importance of limiting the amount of final concentrate that needs to be disposed of? Or are the costs and efforts the same for higher volumes (for example, there is a DWI nearby), which would decrease the importance?

Table 7 describes the technology scores for the "produces additional 'usable' water" capability.

Table 7. Technology Scores for Produces Additional Water Capability (a Yes/No Criteria)

Score	Description
3	**Yes.** Treated water can be captured for reuse.
0	**No.** Concentrate volume reduced; however, treated water is not captured.

6.3.2.3 Quality of Product Water

Rank how important it is for a chosen concentrate management technology to produce high-quality water from the concentrate water treated. Assign a weight from 0 to 10.

Consider:

- **Project objectives.** What is the end use for the treated water, and what water quality objectives does that treated water need to meet?
- **Distribution system.** What water quality is needed to protect the distribution system?

Table 8 describes the technology scores for the "If water is produced, the anticipated water quality (salinity)" capability.

Table 8. Technology Scores for Anticipated Water Quality (Salinity) of Produced Water Capability

Score	Description
3	< 500 mg/L TDS
2	500 to 1,000 mg/L TDS
1	1,000 to 2,000 mg/L TDS
0	> 2,000 mg/L TDS

6.3.2.4 Overall Process Recovery

Rank how important it is for a chosen concentrate management technology system (both primary and concentrate) to produce as little concentrate volume as possible as an end product. The goal is to minimize the volume of concentrate generated. Assign a weight from 0 to 10.

Consider:

- **The ease and cost of concentrate disposal.** The actual disposal method is not as important as the costs and considerations for that disposal. For example, it may be important to minimize the amount of the final concentrate if the concentrate must be transported over long distances. Conversely, if a deep injection well is nearby, volumes of final concentrate may not be as important.
- **Other limits on volumes** of final concentrate, such as:
    - Permit requirements
    - Land application considerations
    - Evaporation pond disposal considerations

Table 9 describes the technology scores for the "overall process recovery (amount of volume minimization" capability, based on the amount of discharge.

Table 9. Technology Scores for Overall Process Recovery Capability

Score	Description
3	ZLD, maximum recovery
2	MLD, very high recovery
1	Increased overall system recovery
0	No additional recovery

6.3.2.5 Residual Waste Disposal

Rank how important it is that waste disposal be easy (how important is it for your project to minimize the level of effort, cost, and complexity associated with minimizing, disposing of, and managing any waste produced by a chosen concentrate management technology)? This is similar to the overall process recovery capability considerations, but it focuses more on any special constituents or issues that might arise. Assign a weight from 0 to 10.

Consider:

- Site factors such as ease of access to disposal site (such as a landfill).
- Constituents within the final concentrate such as toxic compounds (e.g., radionuclides), which, when concentrated, require hazardous material disposal and permitting.
- Disposal methods. For example, higher recovery rates can reduce the volume of concentrate; therefore, reducing the size of follow-on, cost-intensive evaporative steps.

Table 10 describes the technology scores for the "residual waste disposal" capability.

Table 10. Technology Scores for Residual Waste Disposal Capability

Score	Description
3	ZLD. Solid phase waste easily passes the TCLP. Easy access to landfill.
2	Solid phase wastes pass TCLP. Moderate levels of liquid waste. Disposal not considered problematic
1	Disposal option unlikely to be selected in most regions or cases
0	The cost of disposal Is prohibitively high due to volume, concentrated toxic compounds, etc.

6.3.2.6 Limitations for Large-Scale Use

Rank how important it is for a chosen concentrate management technology to be able to scale up or to address any limitations the site may have for large-scale use such as operational, design, construction, or OM&R challenges. Assign a weight from 0 to 10.

Consider:

- **Future water needs.** Will there be population growth? Will future needs grow? Do you anticipate needing to expand or scale up the water treatment system to meet these future needs?
- **Current water supplies.** Will current supplies decrease in the future? Will there be a need for additional supplies in addition to conservation efforts?
- **Future updates.** Will the water treatment system need to be updated to address any other concerns with future feedwater quality or quantity?

- **Future challenges.** Are there issues that would pose a challenge for large-scale use? Are there enough available land, capital costs, and operating costs and resources for a larger footprint plant?

Table 11 describes the technology scores for the limitations to large-scale use capability.

Table 11. Technology Scores for Limitations to Large-Scale Utilization Capability

Score	Description
3	None
2	Some limitations to overcome to scale up system
1	Many limitations to overcome to scale up system
0	Too many limitations to overcome to scale up system

6.3.2.7 Hardness Removal

Rank how important it is for a chosen concentrate management technology to remove chemicals from the concentrate that cause "hard water" (e.g., bicarbonates, chlorides, and sulfates). Assign a weight from 0 to 10.

Consider:

- Feedwater quality constituents
- Product water quality objectives
- Need for technology to remove multi-valent cations

Table 12 describes the technology scores for the hardness removal capability.

Table 12. Technology Scores for Hardness Removal Capability

Score	Description
3	Majority of hardness removed
2	Most hardness removed
1	Some hardness removed
0	No hardness removed

6.3.2.8 Heavy Metals Removal

Rank how important it is for a chosen concentrate management technology to remove heavy metals from the concentrate (i.e., metals with relatively high densities such as iron, copper, tin, zin, cadmium, mercury, and lead). Assign a weight from 0 to 10.

Consider:

- Feedwater quality constituents
- Product water quality objectives
- Need for technology to remove heavy metals

Table 13 describes the technology scores for the heavy metals removal capability.

Table 13. Technology Scores for Heavy Metals Removal Capability

Score	Description
3	Majority of heavy metals removed
2	Most heavy metals removed
1	Some heavy metals removed
0	No heavy metals removed

6.3.2.9 Organic Contaminant Removal

Rank how important it is for a chosen concentrate management technology to remove or degrade organic compounds from the concentrate. Assign a weight from 0 to 10.

Consider:

- Feedwater quality constituents
- Product water quality objectives
- Need for technology to remove organic contaminants

Table 14 describes the technology scores for the organic contaminant removal capability.

Table 14. Technology Scores for Organic Contaminant Removal Capability

Score	Description
3	Majority of organics removed
2	Most organics removed
1	Some organics removed
0	No organics removed

6.3.2.10 Radionuclide Removal

Rank how important it is for a chosen concentrate management technology to remove radionuclides from the concentrate. Assign a weight from 0 to 10.

Consider:

- Feedwater quality constituents
- Product water quality objectives
- Need for technology to remove radionuclides

Table 15 describes the technology rating criteria for radionuclide removal.

Table 15. Technology Scores for Radionuclide Removal Capability

Score	Description
3	Majority of radionuclides removed
2	Most radionuclides removed
1	Some radionuclides removed
0	No radionuclides removed

6.3.2.11 Low Chemical Demand

Rank how important it is for a chosen concentrate management technology to add as few chemicals as possible during operations. Assign a weight from 0 to 10.

Consider:

- **Chemical's final destination.** Chemicals added in the process may end up in the product water or the final concentrate.

- **Chemical disposal.** Consider the ease of handling the chemicals in the final concentrate.

- **Requirements to lower operating costs.** Lower chemical use may lower operating costs.

- **Transportation.** Can chemicals be transported to your plant? Safety concerns, such as transporting chemicals over mountain passes during the winter or over populated roads or areas, may limit chemical use.

- **Storage and handling.** Does the plant have the space, operating expertise, security requirements, etc., to store and handle large amounts of chemicals?

Table 16 describes the technology scores rating criteria for the "low chemical demand" capability, based on the amount of chemicals that the technology requires.

Table 16.   Technology Scores for Low Chemical Demand Capability

Score	Description
3	Technologies with low or no chemical requirements.
2	Chemical use is moderate.
1	Chemical use is high, and other less chemically intensive options exist. This technology is selected when chemical use is not the primary criterion.
0	Chemical needs are considered to be prohibitive under most circumstances.

6.3.2.12   Energy Demand

Rank how important it is for the chosen technology to use as little energy as possible during operations. Low energy demand refers to a concentrate management process that requires little or no added energy beyond that which is locally available in the form of solar energy, heat, wind, etc. Assign a weight from 0 to 10.

Consider:

- Requirements to lower operating costs
- Energy availability and cost
- Lowering carbon or energy footprint

Table 17 describes the technology scores for the low energy demand capability, based on the amount of energy the technology requires.

Table 17. Technology Scores for Energy Demand Capability

Score	Description
3	Technologies with low energy requirements.
2	Energy demand is moderate.
1	Energy demand is high, and more energy efficient options usually exist. This technology is selected when energy demand is not the primary criterion.
0	Energy demand is considered to be prohibitive under most circumstances, or this technology is only feasible when co-located to capture waste heat or energy.

6.3.2.13 Labor Requirements

Rank how important it is for the chosen technology to require as little operator oversight as possible during operations. Ease of operation refers to a concentrate management process that requires little or no operator oversight and may be easily automated. Assign a weight from 0 to 10.

Consider:

- Requirements to lower operating costs; labor rates can be costly.
- Availability of skilled labor in the area.

Table 18 describes the technology scores for the labor requirement capability, based on the amount of skilled labor the technology requires.

Table 18. Technology Scores for Labor Requirements Capability

Score	Description
3	System complexity is low, and little or no operator oversight is required. This process may be easily automated.
2	System complexity is moderate, requiring a trained operator onsite at all times.
1	System complexity is high, requiring a top level (A) operator to be onsite at all times.
0	System complexity is considered prohibitive; only practical if a top level (A) operator is present during operation and dedicated only to the concentrate treatment system.

6.3.2.14 Reliability

Rank how important it is for the technology to be as reliable as possible during operation. Reliability means that the technology will require minimal down time, can produce consistent water quality, and is generally not prone to failure during normal operation. Assign a weight from 0 to 10.

Consider:

- **Project objectives.** A municipality with limited backup supplies that depends on the product water might rate reliability high, whereas reliability might not be as important for a plant treating stored water from a mine to release downstream.

- **Need for consistent** water quality and water quantity.

- **Risks to the water supply** for scheduled and unscheduled downtime. For example, what would happen if the plant had scheduled downtime for a few days every quarter or unscheduled outage for a few weeks?

- **Requirements to lower operating costs.** The lower the reliability, the more potential for higher repair and operating costs.

Table 19 provides the technology scores for the reliability capability, based on general overall reliability ratings. Note that reliability ratings for technology types are subjective and based on past experience and anecdotal evidence of long-term system performance and steady-state operation.

Table 19. Technology Scores for Reliability Capability

Score	Description
3	System has been shown to operate with very few shutdowns while producing target water quality over long periods of time.
2	System experiences some issues with continuous, steady-state operation.
1	System experiences significant issues with maintaining steady-state operation.
0	Previous testing and demonstration have shown that sustained, steady-state operation producing consistent water quality is difficult to achieve.

6.3.2.15 Value Added

Rank how important it is for a chosen technology to have other positive benefits not included in earlier criteria (e.g., habitat restoration or resource recovery). Assign a weight from 0 to 10. The technology assessment sheets in Chapter 7, “Case Studies,” discuss specific benefits.

Consider:

- Potential uses for the waste stream
- Proximity to potential benefits such as habitat restoration

Table 20 describes the technology score for the value added capability.

Table 20. Technology Scores for Value Added Capability

Score	Description
3	High value added
2	Moderate value added
1	Low value added
0	No value added

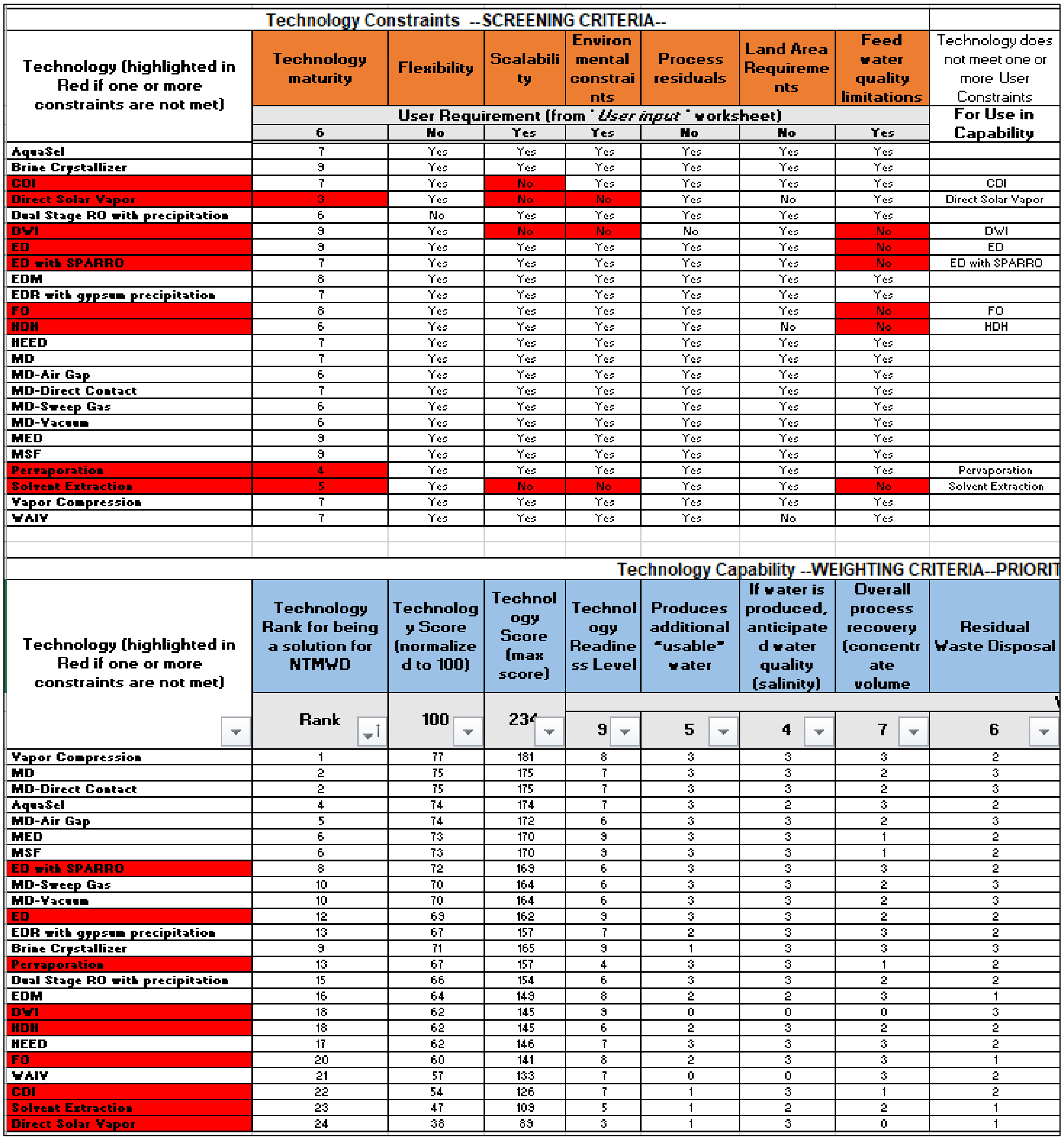
6.4. Toolbox Tab No. 4: Toolbox Results

Toolbox Tab No. 4: "Toolbox Results" contains two tables that correspond to the constraints and capabilities of each technology (see figure 5). These constraints and capabilities were previously described in the assessment sheets and were defined by the user input. A description of the two tables in figure 5 follows.

- **Technology Constraints** (figure 5 - top) are used to screen technologies that do not meet the user's constraints. All technologies which do not meet the minimum criteria desired are flagged in red, allowing the user to quickly identify which technologies are not anticipated to meet their needs.
- **Technology Capabilities** (figure 5 - bottom) provide scores from technology assessment sheets and the technology capability weights provided by the user. Each water treatment technology is assigned a final score based on these assessments and weights. The technology is then ranked according to the score, and a list is provided of recommended technologies that best meet the user's needs.

  The light gray row (weight) contains the users' input on the importance (or priority) of each factor. Three columns at the beginning provide, rank and scores for each concentrate technology. Note that technologies that do not meet the user's constraints are still shown in this table for reference, along with the technology, which is highlighted in red.

    - **Technology Scores** are derived by multiplying each technology's criteria evaluation (on a 1 to 3 scale, as defined by the assessment sheets) by the criteria weight (on a scale of 1 to 10, as defined by the user).
    - **Technology Scores are normalized** to 100 to provide an easier frame of reference.
    - **Technology Rank** shows the technologies in their ranked order based on the evaluation score.



Technology Constraints --SCREENING CRITERIA--

Technology (highlighted in Red if one or more constraints are not met)	Technology maturity	Flexibility	Scalability	Environmental constraints	Process residuals	Land Area Requirements	Feed water quality limitations	Technology does not meet one or more User Constraints
	User Requirement (from '*User input*' worksheet)							For Use in Capability
	6	No	Yes	Yes	No	No	Yes	
AquaSel	7	Yes	Yes	Yes	Yes	Yes	Yes	
Brine Crystallizer	9	Yes	Yes	Yes	Yes	Yes	Yes	
CDI	7	Yes	No	Yes	Yes	Yes	Yes	CDI
Direct Solar Vapor	3	Yes	No	No	Yes	No	Yes	Direct Solar Vapor
Dual Stage RO with precipitation	6	No	Yes	Yes	Yes	Yes	Yes	
DWI	9	Yes	No	No	No	Yes	No	DWI
ED	9	Yes	Yes	Yes	Yes	Yes	No	ED
ED with SPARRO	7	Yes	Yes	Yes	Yes	Yes	No	ED with SPARRO
EDM	8	Yes	Yes	Yes	Yes	Yes	Yes	
EDR with gypsum precipitation	7	Yes	Yes	Yes	Yes	Yes	Yes	
FO	8	Yes	Yes	Yes	Yes	Yes	No	FO
HDH	6	Yes	Yes	Yes	Yes	No	No	HDH
HEED	7	Yes	Yes	Yes	Yes	Yes	Yes	
MD	7	Yes	Yes	Yes	Yes	Yes	Yes	
MD-Air Gap	6	Yes	Yes	Yes	Yes	Yes	Yes	
MD-Direct Contact	7	Yes	Yes	Yes	Yes	Yes	Yes	
MD-Sweep Gas	6	Yes	Yes	Yes	Yes	Yes	Yes	
MD-Vacuum	6	Yes	Yes	Yes	Yes	Yes	Yes	
MED	9	Yes	Yes	Yes	Yes	Yes	Yes	
MSF	9	Yes	Yes	Yes	Yes	Yes	Yes	
Pervaporation	4	Yes	Yes	Yes	Yes	Yes	Yes	Pervaporation
Solvent Extraction	5	Yes	No	No	Yes	Yes	No	Solvent Extraction
Vapor Compression	7	Yes	Yes	Yes	Yes	Yes	Yes	
WAIV	7	Yes	Yes	Yes	Yes	No	Yes	

Technology Capability --WEIGHTING CRITERIA--PRIORIT

Technology (highlighted in Red if one or more constraints are not met)	Technology Rank for being a solution for NTMWD	Technology Score (normalized to 100)	Technology Score (max score)	Technology Readiness Level	Produces additional "usable" water	If water is produced, anticipated water quality (salinity)	Overall process recovery (concentrate volume	Residual Waste Disposal
	Rank	100	234	9	5	4	7	6
Vapor Compression	1	77	181	8	3	3	3	2
MD	2	75	175	7	3	3	2	3
MD-Direct Contact	2	75	175	7	3	3	2	3
AquaSel	4	74	174	7	3	2	3	2
MD-Air Gap	5	74	172	6	3	3	2	3
MED	6	73	170	9	3	3	1	2
MSF	6	73	170	9	3	3	1	2
ED with SPARRO	8	72	169	6	3	3	3	2
MD-Sweep Gas	10	70	164	6	3	3	2	3
MD-Vacuum	10	70	164	6	3	3	2	3
ED	12	69	162	9	3	3	2	2
EDR with gypsum precipitation	13	67	157	7	2	3	3	2
Brine Crystallizer	9	71	165	9	1	3	3	3
Pervaporation	13	67	157	4	3	3	1	2
Dual Stage RO with precipitation	15	66	154	6	3	3	2	2
EDM	16	64	149	8	2	2	3	1
DWI	18	62	145	9	0	0	0	3
HDH	18	62	145	6	2	3	2	2
HEED	17	62	146	7	3	3	3	2
FO	20	60	141	8	2	3	3	1
WAIV	21	57	133	7	0	0	3	2
CDI	22	54	126	7	1	3	1	2
Solvent Extraction	23	47	109	5	1	2	2	1
Direct Solar Vapor	24	38	89	3	1	3	0	1

Figure 5. Screenshot of Toolbox Tab No. 5: Toolbox Results. Technologies that are unsuitable for the user are flagged in red

6.5. Other Toolbox Tabs

The Toolbox also contains the follow additional tabs:

- **Technology List.** A list of technologies currently in the Toolbox that have been assessed (see Chapter 5, "Technology Evaluation and Assessment Sheets" for more information).

- **Assessment Sheet Criteria.** Definitions of the various criteria used in the assessment of technologies (see Chapter 4, "Criteria Development," for more information).

- **Technology Readiness Levels Definitions.** Definitions of the technology's readiness and readiness to be used in full-scale plants (see Section 6.3.1.1, "Technology Readiness," for more information).

7. Case Studies

7.1. Eastern Municipal Water District

7.1.1. Introduction/Description/Background

Eastern Municipal Water District (EMWD) in California is planning to expand its primary desalination and will require management of the additional concentrate. EMWD is inland in a metropolitan area and currently disposes its concentrate into a pipeline, which eventually discharges into the ocean. It is interested in an alternative to the pipeline and is considering reducing the volume of its concentrate to reduce the cost of concentrate management, plan for future expansion, and, ultimately, be able to provide water to its customers at an affordable price. Traditional concentrate disposal options for EMWD are either not possible or are limited; thus, EMWD is investigating high recovery process alternatives to manage the concentrate generated from its expanding desalination plant.

7.1.2. Planning Description

EMWD's planning description (table 21) is an example case study.

Table 21. Planning Description for EMWD

Planning Information	Definitions	User Response	User Comments
Objectives	What are the objectives of concentrate management treatment?		Reduce concentrate volume
Purpose of plant	How will the water that the plant produces be used?		Provide treated water to the community
Partners			NA
Greenfield or bolt-on	Is this a new desalination facility (greenfield), or will the concentrate from an existing desalination (bolt-on) plant require treatment?	Greenfield or bolt-on	Could add a concentrate technology to a desalination process or could develop an integrated desalination/ concentration reduction process; therefore, no technologies eliminated based on this response.
What is the average flowrate to the RO plant?		10 mgd	
What is the peak flowrate to the RO plant?		15 mgd	

Table 21. Planning Description for EMWD

Planning Information	Definitions	User Response	User Comments
What is the minimum flowrate to the RO plant?		7.5 mgd	
What is the expected concentrate flowrate?		2.5 mgd	
Most significant cost factor: CAPEC, OPEX, or both (LCC)	Which of these three cost components (CAPEX, OPEX, LCC) is the most important to consider for plant design?	LCC	The municipality is interested in a low-cost option to treat concentrate.
Overall cost of concentrate treatment goal (LCC)	LCC refers to minimizing the sum of all capital and O&M costs, minus resource recovery and beneficial use discounts, updated to the present value	$2.00/1,000 gallons	
Unusual factors, risk tolerance, and considerations	Note any issues and factors that could impact how much risk could be tolerated. What are the potential risks for the project? These factors include: • Any contaminants of concern in the feed water • Permitting issues • Technological failure • Local or other opposition • Environmental compliance considerations • Cost overruns • Funding sources	NA	

Note: NA = not applicable, mgd = million gallons per day.

7.1.3. Technology Use Constraints (Screening Analysis)

EMWD provided input for technology use constraints, as shown in table 22. EMWD is interested in technologies that can reduce concentrate volume and have been at least pilot tested successfully in the field. This interest correlates to a TRL of 5 or above for technologies that have shown pilot testing with real waters. Technologies that have not been successful at piloting or are only at a concept or lab scale were not considered for this case study because the development cycle for such technologies would be beyond their needs for a concentrate treatment plant.

Table 22. Technology Use Constraints for EMWD

Constraints	Definitions	User input	User Comments
Technology readiness	What is the minimum acceptable Technology Readiness Level (TRL)? Assign a score from 1 to 9. (Please see TRL definitions in the toolbox for further information.)	5	Interested in technologies that show promise -- not tied to proven technologies or the TRL classifications.
Flexibility	Is flexibility of technology to treat varying feed water quality or capability to handle system upset important?	No	System flexibility not a requirement, since feed water is pretty consistent, will not eliminate technologies based on flexibility requirement.
Scalability	Is scalability, i.e., redesign and/or modification of technology to treat varying feed water quantity important?	Yes	Systems that can be easily adapted to increased flowrates will be targeted.
Environmental constraints	Are there any environmental considerations that impact the applicability of a technology? For example, requirements for high evaporation rates, high solar insolation, and/or large land area.	No	No significant environmental constraints have been identified.
Process residual	Are there any final residuals that have any quality or quantity concerns that might limit technologies?	Yes	Chemical composition of final residual could pose risk of deposition in brine pipeline
Land area availability	Is land area limited for concentrate discharge/ management?	No	There is enough land or footprint area to accommodate various technologies
Feed water quality limitations	Are there any feed water constituents that would impose treatment limitations such as high scaling tendency, organic content, etc.?	Yes	High sulfate, silica and calcium content in the concentrate that requires technologies capable of handling higher scaling tendency of this concentrate

Other constraints that limit technologies for EMWD are:

- **Flexibility.** EMWD's feedwater quality fluctuates as wells come online and go offline due to various reasons; therefore, EMWD needs a flexible technology to handle its concentrate.

- **Scalability.** EMWD is also expecting growth to meet their future water treatment needs, thus generating more concentrate and needing technologies that can be scaled easily.

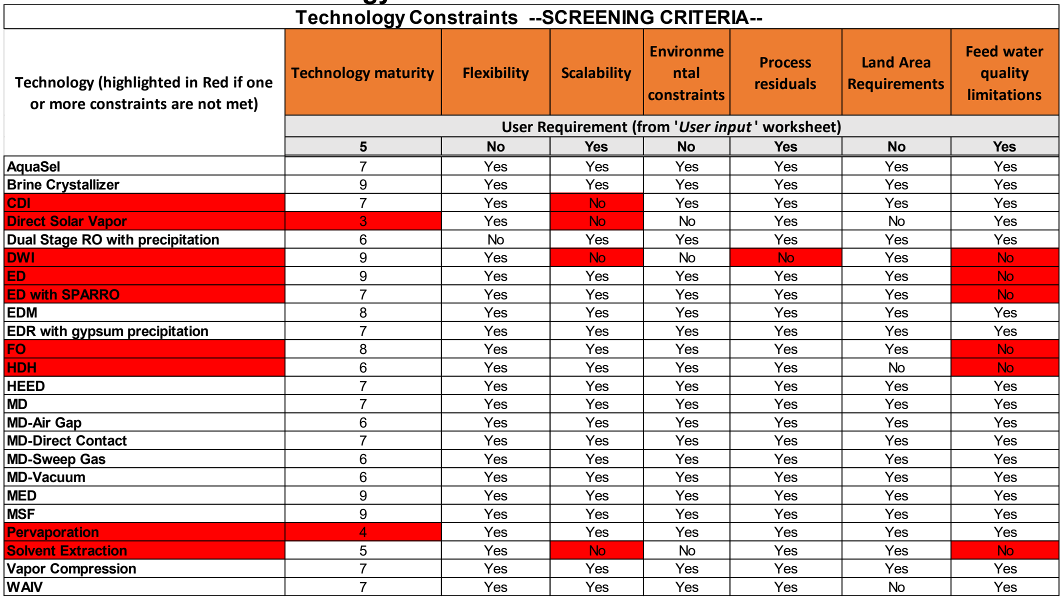
- **Land area availability.** Location is in a metropolitan area, and land availability is limited.

- **Feed water quality**. EMWD's feedwater contains excess amounts of Si, Ca, and SO_4 in quantities that, when concentrated by a primary desalination process, will be at or beyond saturation limits for SiO_2 and $CaSO_4$. As a result, concentrate technologies to be considered will need to handle SiO_2 and $CaSO_4$ beyond their saturation limits.

Table 23 displays the Toolbox technology constraint results, based on the technology use constraints shown in table 22. Technologies that do not meet EMWD's minimum requirements for constraints are flagged in red and can be identified quickly. Those technologies will, however, be scored and ranked in the "Technology Capabilities" section and possible evaluation if they are deemed of interest to EMWD.

In table 23, an example of a technology that does not meet the minimum requirements is Direct Solar Vapor. It does not meet the following technology constraints: TRL, scalability, and land area. (To learn more about the specific technologies and why they do not meet the requirements, please see the assessment sheets for specific technologies in appendix A.)

Table 23. Toolbox Technology Constraint Results for EMWD



Technology Constraints --SCREENING CRITERIA--

Technology (highlighted in Red if one or more constraints are not met)	Technology maturity	Flexibility	Scalability	Environmental constraints	Process residuals	Land Area Requirements	Feed water quality limitations
	User Requirement (from '*User input*' worksheet)						
	5	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**
AquaSel	7	Yes	Yes	Yes	Yes	Yes	Yes
Brine Crystallizer	9	Yes	Yes	Yes	Yes	Yes	Yes
CDI	7	Yes	No	Yes	Yes	Yes	Yes
Direct Solar Vapor	3	Yes	No	No	Yes	No	Yes
Dual Stage RO with precipitation	6	No	Yes	Yes	Yes	Yes	Yes
DWI	9	Yes	No	No	No	Yes	No
ED	9	Yes	Yes	Yes	Yes	Yes	No
ED with SPARRO	7	Yes	Yes	Yes	Yes	Yes	No
EDM	8	Yes	Yes	Yes	Yes	Yes	Yes
EDR with gypsum precipitation	7	Yes	Yes	Yes	Yes	Yes	Yes
FO	8	Yes	Yes	Yes	Yes	Yes	No
HDH	6	Yes	Yes	Yes	Yes	No	No
HEED	7	Yes	Yes	Yes	Yes	Yes	Yes
MD	7	Yes	Yes	Yes	Yes	Yes	Yes
MD-Air Gap	6	Yes	Yes	Yes	Yes	Yes	Yes
MD-Direct Contact	7	Yes	Yes	Yes	Yes	Yes	Yes
MD-Sweep Gas	6	Yes	Yes	Yes	Yes	Yes	Yes
MD-Vacuum	6	Yes	Yes	Yes	Yes	Yes	Yes
MED	9	Yes	Yes	Yes	Yes	Yes	Yes
MSF	9	Yes	Yes	Yes	Yes	Yes	Yes
Pervaporation	4	Yes	Yes	Yes	Yes	Yes	Yes
Solvent Extraction	5	Yes	No	No	Yes	Yes	No
Vapor Compression	7	Yes	Yes	Yes	Yes	Yes	Yes
WAIV	7	Yes	Yes	Yes	Yes	No	Yes

7.1.4. Technology Capabilities (Weighting Analysis)

EMWD assigned a weight for each technology capability based on its importance (priority) and its requirement for that capability and notes as listed in table 24. Scores are calculated based on the weights and scores and a technology can be compared against these other technologies based on the total score.

Table 24. Technology Capabilities for EMWD

Capability	Definition	User Assigned Weight 0 to 10	User Comments
Technology readiness level	Please see TRL definitions for further information.	7	Promising and mature technologies are of interest
Produces additional “usable” water	The technology(s) produce a new usable water source from the concentrate.	8	Producing additional usable water is relatively important nearly as important as reducing the volume of concentrate
If water is produced, anticipated water quality (salinity)	Product water salinity from the concentrate treatment portion of the process.	8	If additional water is recovered, it would be great if it is low in TDS and does not require additional treatment
Overall process recovery (concentrate volume minimization)	Process recovery of primary desalination plus concentrate treatment.	9	High recovery is important due to concentrate volume reduction

Table 24. Technology Capabilities for EMWD

Capability	Definition	User Assigned Weight 0 to 10	User Comments
Residual waste disposal	Level of effort, the cost, and the general level of complexity associated with the minimization, disposal, and management of any waste produced by a concentrate technology.	7	Anticipate residual waste would require additional treatment
Limitations to large scale utilization	Limitations to large-scale use (operational, design, construction, or OM&R challenges associated with large-scale use).	8	Large scale use is desirable
Hardness removal	Degree of selective removal of multi-valet cations.	6	
Heavy metals removal	Degree of heavy metal removal.	1	No heavy metals in feed
Organic contaminant removal	Degree of removal or degradation of organic compounds.	1	No organic contaminants in feed
Radionuclide removal	Degree of radionuclide removal.	1	
Low chemical demand	Low chemical demand refers to a concentrate management process that requires little or no chemical additives to ensure proper operation.	6	chemicals add to O&M cost, thus it would be good to have technologies with low chemical demand, but not a requirement
Energy demand	Low energy demand refers to a concentrate management process that requires little or no added energy beyond that which is locally available in the form of insolation, heat, wind, etc.	7	Lowering energy cost of treatment is important
Labor requirements	Ease of operation refers to a concentrate management process that requires little or no operator oversight and may be easily automated.	7	Lower O&M cost associated with labor is favored
Reliability	Reliability means that the technology will require minimal down time, can produce consistent water quality, and is generally not prone to failure during normal operation.	9	The system must be reliable
Value added	Value added refers to other positive benefits not included in earlier criteria (e.g., habitat restoration or resource recovery).	3	N/A

Table 25 summarizes the Toolbox technology capability results for EMWD and ranks the best fit technologies for its concentrate management needs. The Toolbox recommended that technologies require further pilot testing to determine which technology is most suitable for meeting EMWD's concentrate management needs. Further pilot testing will provide EMWD with performance and cost data for those tested technologies based on EMWD's site, feed, and other conditions.

Table 25. Toolbox Technology Capabilities Results for EMWD

Technology (highlighted in Red if one or more constraints are not met)	Technology Rank for being a solution	Technology Score (normalized to 100)	Technology Score (max score)
	Rank	100	262
Vapor Compression	1	79	208
MD	2	78	203
MD-Direct Contact	2	78	203
MD-Air Gap	4	77	201
AquaSel	5	76	199
ED with SPARRO	6	74	193
MD-Sweep Gas	7	73	192
MD-Vacuum	7	73	192
MED	9	72	189
MSF	9	72	189
ED	11	72	188
Brine Crystallizer	12	71	185
EDR with gypsum precipitation	13	70	182
Pervaporation	13	70	182
Dual Stage RO with precipitation	15	67	176
HEED	16	67	175
HDH	17	65	171
EDM	18	64	167
FO	19	60	157
WAIV	20	56	146
DWI	21	55	144
CDI	22	54	142
Solvent Extraction	23	48	125
Direct Solar Vapor	24	38	100

7.2. North Texas Municipal Water District

7.2.1. Introduction/Description/Background

North Texas Municipal Water District (NTMWD) in Texas is considering brackish water desalination as an alternative water supply. NTMWD is located inland, has concentrate disposal restrictions, and is interested in reducing the volume of its concentrate to reduce the cost of concentrate management.

7.2.2. Planning Description

NTMWD's planning description is displayed in table 26.

Table 26. Planning Description for NTMWD

Planning Information	Definitions	User Response	User Comments
Objectives	What are the objectives of concentrate management treatment?		Reduce concentrate volume.
Purpose of plant	How will the water that the plant produces be used?		Provide treated water to the community.
Partners			NA.
Greenfield or bolt-on	Is this a new desalination facility (greenfield) or will the concentrate from an existing desalination (bolt-on) plant require treatment?	Greenfield or bolt-on	Could add a concentrate technology to a desalination process or could develop an integrated desalination/concentration reduction process; therefore, no technologies eliminated based on this response.
What is the average flowrate to the RO plant?		10 mgd	
What is the peak flowrate to the RO plant?		15 mgd	
What is the minimum flowrate to the RO plant?		7.5 mgd	
What is the expected concentrate flowrate?		2.5	
Most significant cost factor: CAPEX, OPEX, or both (LCC)	Which of these three cost components (CAPEX, OPEX, LCC) is the most important to consider for plant design?	LCC	The municipality is interested in a low-cost option to treat concentrate.

Table 26. Planning Description for NTMWD

Planning Information	Definitions	User Response	User Comments
Overall cost of concentrate treatment goal (LCC)	LLC refers to minimizing the sum of all capital and O&M costs, minus resource recovery and beneficial use discounts, updated to the present value	$2.00/1,000 gallons	
Unusual factors, risk tolerance, and considerations	Note any issues and factors that could impact how much risk could be tolerated. What are the potential risks for the project? These factors include: • Any contaminants of concern in the feed water • Permitting issues • Technological failure • Local or other opposition • Environmental compliance considerations • Cost overruns • Funding sources	NA	

7.2.3. Technology Use Constraints (Screening Analysis)

NTMWD provided input for technology use constraints, which are shown in table 27. Of note, NTMWD is interested in technologies that show promise. This correlates to a TRL of 6 or above for technologies that have shown successful pilot testing with real waters. Technologies that have not been successful at piloting or are only at a concept or lab scale are not considered.

Other constraints that limit technologies for NTMWD are:

- **Scalability.** NTMWD is expecting growth for its water treatment needs, thus generating more concentrate and needing technologies that can be scaled up easily to manage this increased volume.

- **Environmental constraints.** NTMWD's climate has variable evaporation rates, which removes evaporation ponds and other evaporative technologies that require a higher degree of environmental evaporation.

- **Feed water quality limitations.** NTMWD's feedwater contains Ca and SO_4, among other sparingly soluble salts in quantities that, when concentrated by a primary desalination process, will be at or beyond saturation limits for $CaSO_4$. As a result. the concentrate technologies to be considered will need to handle $CaSO_4$ beyond its saturation limit.

Table 27. Technology Use Constraints for NTMWD

Constraints	Definitions	User input	User Comments
Technology readiness	What is the minimum acceptable Technology Readiness Level (TRL)? Assign a score from 1 to 9. (Please see TRL definitions in the toolbox for further information.)	6	Interested in technologies that show promise – not tied to proven technologies or the TRL classifications.
Flexibility	Is flexibility of technology to treat varying feed water quality or capability to handle system upset important?	Yes	System flexibility is a requirement because feed water has seasonal variability.
Scalability	Is scalability, i.e., redesign and/or modification of technology to treat varying feed water quantity important?	Yes	Systems that can be easily adapted to increased flowrates will be targeted.
Environmental constraints	Are there any environmental considerations that impact the applicability of a technology? For example, requirements for high evaporation rates, high solar insolation, and/or large land area.	Yes	Evaporative technologies are not preferred because the local climate limits evaporation rates.
Process residual	Are there any final residuals that have any quality or quantity concerns that might limit technologies?	No	Open to alternative in concentrate treatment. There is no specific quality or quantity issue that would cause a technology limitation associated with the process residual.
Land area availability	Is land area limited for concentrate discharge/ management?	No	The treatment facility site is in a rural area with the potential to acquire additional land, if needed. Technologies will not be eliminated based on land requirements.
Feed water quality limitations	Are there any feed water constituents that would impose treatment limitations such as high scaling tendency, organic content, etc.?	Yes	The sulfate and calcium content in the concentrate is anticipated to necessitate technologies capable of handling the scaling potential of the concentrate.

Table 28 displays the Toolbox technology constraint results, based on the technology use constraints shown in table 27. Technologies that do not meet NTMWD's minimum requirements for constraints are flagged in red and can be identified quickly. These technologies will, however, be scored and ranked in the "Technology Capabilities" section and possible evaluation if deemed of interest to NTMWD.

Table 28. Toolbox Technology Constraint Results for NTMWD

Technology (highlighted in Red if one or more constraints are not met)	Technology Constraints --SCREENING CRITERIA-- Technology maturity	Flexibility	Scalability	Environmental constraints	Process residuals	Land Area Requirements	Feed water quality limitations
	User Requirement (from '*User input*' worksheet)						
	6	No	Yes	Yes	No	No	Yes
AquaSel	7	Yes	Yes	Yes	Yes	Yes	Yes
Brine Crystallizer	9	Yes	Yes	Yes	Yes	Yes	Yes
CDI	7	Yes	No	Yes	Yes	Yes	Yes
Direct Solar Vapor	3	Yes	No	No	Yes	No	Yes
Dual Stage RO with precipitation	6	No	Yes	Yes	Yes	Yes	Yes
DWI	9	Yes	No	No	No	Yes	No
ED	9	Yes	Yes	Yes	Yes	Yes	No
ED with SPARRO	7	Yes	Yes	Yes	Yes	Yes	No
EDM	8	Yes	Yes	Yes	Yes	Yes	Yes
EDR with gypsum precipitation	7	Yes	Yes	Yes	Yes	Yes	Yes
FO	8	Yes	Yes	Yes	Yes	Yes	No
HDH	6	Yes	Yes	Yes	Yes	No	No
HEED	7	Yes	Yes	Yes	Yes	Yes	Yes
MD	7	Yes	Yes	Yes	Yes	Yes	Yes
MD-Air Gap	6	Yes	Yes	Yes	Yes	Yes	Yes
MD-Direct Contact	7	Yes	Yes	Yes	Yes	Yes	Yes
MD-Sweep Gas	6	Yes	Yes	Yes	Yes	Yes	Yes
MD-Vacuum	6	Yes	Yes	Yes	Yes	Yes	Yes
MED	9	Yes	Yes	Yes	Yes	Yes	Yes
MSF	9	Yes	Yes	Yes	Yes	Yes	Yes
Pervaporation	4	Yes	Yes	Yes	Yes	Yes	Yes
Solvent Extraction	5	Yes	No	No	Yes	Yes	No
Vapor Compression	7	Yes	Yes	Yes	Yes	Yes	Yes
WAIV	7	Yes	Yes	Yes	Yes	No	Yes

In table 28, an example of a technology that does not meet NTMWD's minimum requirements is Direct Solar Vapor. It does not meet the following technology constraints: TRL, scalability, and environmental constraints. (To learn more about the technologies and why they do not meet the requirements, please see the assessment sheets for specific technologies in appendix A.)

7.2.4 Technology Capabilities (Weighting Analysis)

These criteria are used to determine the most promising technologies for a given water treatment situation. Each technology is assessed for its capability, and a subjective score has been given to each technology based on available literature and experience on the available technology. NTMWD determined a weight for each capability based on the importance and its requirement for that capability (table 29). Scores were calculated based on the weights and scores, and a technology can be compared against these other technologies based on the total score.

More info on technology capabilities can be found in Section 6.2, "Technology Capabilities (Weighting Criteria – Priority of Each Factor." All technology assessments can be found in Chapter 7, "Case Studies."

Table 29. Technology Capabilities for NTMWD

Capability	Definition	User Assigned Weight 0 to 10	User Comments
Technology readiness level	Please see TRL definitions for further information.	9	Promising and mature technologies are of interest.
Produces additional “usable” water	The technology(s) produce a new usable water source from the concentrate.	5	Producing additional usable water is relatively important, but it is not as important as reducing the volume of concentrate.
If water is produced, anticipated water quality (salinity)	Product water salinity from the concentrate treatment portion of the process.	4	It is preferred that the product water be low in TDS and not require additional treatment; however, the additional water could be returned to the head of the treatment train for treatment if the product water quality is not sufficient.
Overall process recovery (concentrate volume minimization)	Process recovery of primary desalination plus concentrate treatment.	8	High recovery is important because the concentrate volume needs to be reduced.
Residual waste disposal	Level of effort, the cost, and the general level of complexity associated with the minimization, disposal, and management of any waste produced by a concentrate technology.	6	
Limitations to large scale utilization	Limitations to large-scale use (operational, design, construction, or OM&R challenges associated with large-scale use).	9	Requires large-scale treatment to treat the anticipated concentrate volume,
Hardness removal	Degree of selective removal of multi-valet cations.	4	
Heavy metals removal	Degree of heavy metal removal.	0	
Organic contaminant removal	Degree of removal or degradation of organic compounds.	3	
Radionuclide removal	Degree of radionuclide removal.	5	

Table 29. Technology Capabilities for NTMWD

Capability	Definition	User Assigned Weight 0 to 10	User Comments
Low chemical demand	Low chemical demand refers to a concentrate management process that requires little or no chemical additives to ensure proper operation.	4	Since chemicals add to O&M cost, it would be beneficial to have technologies with low chemical demand, but low chemical demand is not a high priority.
Energy demand	Low energy demand refers to a concentrate management process that requires little or no added energy beyond that which is locally available in the form of insolation, heat, wind, etc.	7	Technologies with low energy demand are preferred to reduce O&M costs.
Labor requirements	Ease of operation refers to a concentrate management process that requires little or no operator oversight and may be easily automated.	6	Technologies with lower labor requirements are preferred to reduce O&M costs.
Reliability	Reliability means that the technology will require minimal down time, can produce consistent water quality, and is generally not prone to failure during normal operation.	8	The system must be reliable.
Value added	Value added refers to other positive benefits not included in earlier criteria (e.g., habitat restoration or resource recovery).	3	Additional benefits would be good but are not necessary.

Table 30 demonstrates the Toolbox technology capabilities results for NTMWD and ranks the best fit technologies for its concentrate management needs. The Toolbox recommended that technologies require further pilot testing to determine which technology most suitable for meeting NTMWD's concentrate management needs. Further pilot testing will provide NTMWD with performance and cost data for those tested technologies based on NTMWD's site, feed, and other conditions.

Table 30. Toolbox Technology Capabilities Results for NTMWD

Technology (highlighted in Red if one or more constraints are not met)	Technology Rank for being a solution for NTMWD	Technology Score (normalized to 100)	Technology Score (max score)
	Rank	100	234
Vapor Compression	1	77	181
MD	2	75	175
MD-Direct Contact	2	75	175
AquaSel	4	74	174
MD-Air Gap	5	74	172
MED	6	73	170
MSF	6	73	170
ED with SPARRO	8	72	169
Brine Crystallizer	9	71	165
MD-Sweep Gas	10	70	164
MD-Vacuum	10	70	164
ED	12	69	162
EDR with gypsum precipitation	13	67	157
Pervaporation	13	67	157
Dual Stage RO with precipitation	15	66	154
EDM	16	64	149
HEED	17	62	146
HDH	18	62	145
DWI	18	62	145
FO	20	60	141
WAIV	21	57	133
CDI	22	54	126
Solvent Extraction	23	47	109
Direct Solar Vapor	24	38	89

8. Conclusion

The Toolbox is a compilation of all of the assessment sheets. It can be used for guidance or a planning level tool. It is an open sourced Excel spreadsheet. Users can modify and update technology constraints and criteria scores and weights to reflect their subjective expertise on the technology and need or applicability for the various criteria.

The user can input technology use constraints and technology capability criteria into the Toolbox to be screened. The user assigns a weight to each technology capability criteria based on its importance (priority) for the user's water management needs. Capability scores and weights are used to assign a final score to each technology. The Toolbox then quickly identifies water management technologies that do not meet the user's minimum requirements or desires for the technology, as well as the best treatment technologies for the planner to investigate further.

Appendix A

Concentrate Management Toolbox Assessment Sheets

Appendix A

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A1 Reverse Osmosis Based High Recovery Processes

A1.1 Dual Stage Reverse Osmosis Precipitation

A1.1.1 Technology Description

Dual stage reverse osmosis (RO) with precipitation can overcome scaling-induced limits that hinder conventional RO recovery by precipitating sparingly soluble salts from the primary concentrate stream and then recovering additional water in a second RO unit.

Figure A-1 is a schematic showing the general process for dual-stage RO precipitation. It consists of three steps: (1) a primary RO unit, (2) a chemical precipitation unit, and (3) a secondary RO unit. The primary RO unit concentrates the feed to a point just below the threshold of membrane scaling. The subsequent method to precipitate salts is highly dependent on the chemical makeup of the feed water but has been demonstrated with chemical precipitation and seeding. Further process recovery may be achieved by recycling a portion of the secondary RO concentrate to the precipitation step. The process results in three outputs: (1) permeate, (2) a concentrate stream, and (3) a solids stream. Disposal of the concentrate stream and solids stream may pose a challenge in some environments, but the dual-stage RO precipitation produces less volumes of waste than the traditional single stage RO.

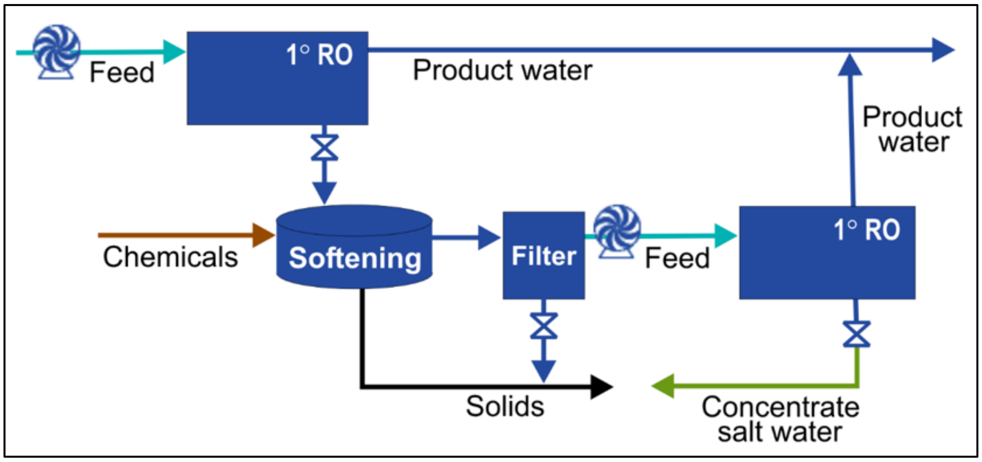

Figure A-1. Schematic of dual-stage RO with precipitation process (based on Colorado School of Mines, n.d.).

A1.1.2 Technology Constraints

Table A-1 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-1. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Currently has only been demonstrated at the pilot scale. Pilot scale studies have been conducted and have covered a variety of precipitation processes.	6	Gabelich et al., 2007 McCool et al., 2012 Sanciolo et al., 2012 Rahardianto et al., 2010
Flexibility	Process has low flexibility to adjust to changing conditions without intervention. Changes in feed chemistry may require recalculation of precipitation process if chemicals are added.	No	Gabelich et al., 2007
Scalability	Precipitation process may be limited by tank size, residence time, chemical feed, and storage requirements, as well as by solids handling and disposal.	Yes	
Environmental constraints	Outputs of process are high concentrated liquid and solids streams, which may pose site-specific disposal challenges depending on feed water constituents.	Yes	
Process residual	Process residuals are high TDS liquid stream and solids stream. Disposal of residuals may vary based on location and feed water constituents. Process may require chemical addition for precipitation, adding to solids.	Yes	McCool et al., 2012 Sanciolo et al., 2012 Rahardianto et al., 2010
Land area availability	Process footprint does not require large land availability.	Yes	
Feed water quality limitations	Process may require chemical addition for precipitation, adding to solids. Other feed water limitations could be sparingly soluble salts, organics, and oxidants present in the process stream.	Yes	McCool et al., 2012 Sanciolo et al., 2012 Rahardianto et al,. 2010

Note: TDS = total dissolved solids.

A1.1.3 Technology Capability

Table A-2 describes the technology capabilities based on available literature, experience, and interpretation of available criteria information. Scores are used to compare technologies.

Table A-2. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Currently has only been demonstrated at the pilot scale. Pilot scale studies have been conducted and have covered a variety of precipitation processes.	6	Gabelich et al., 2007 McCool et al., 2012 Sanciolo et al., 2012 Rahardianto et al., 2010
Produces additional “usable” water	Yes, process produces additional usable water (1° and 2° RO permeate).	3	
If water is produced, anticipated water quality (salinity)	High produced water quality, consistent with RO process: 2° RO.	3	Gabelich et al., 2007
Overall process recovery (concentrate volume minimization)	Up to 95% recovery demonstrated at pilot scale (1° RO at 83%, 2° RO at 68%). Up to 98% recovery is possible (estimate is based on thermodynamic models). Actual recovery depends on application.	2	Gabelich et al., 2007
Residual waste disposal	Process residuals are a high-TDS liquid stream and solids stream. Disposal of residuals may vary based on location. Process may require adding chemicals for precipitation, which adds to the solids stream. Some applications may be able to recycle seed crystals to reduce chemical demand or recycle the secondary RO concentrate.	2	McCool et al., 2012 Sanciolo et al., 2012 Rahardianto et al., 2010
Limitations to large scale utilization	Large footprint (secondary RO unit, process equipment, chemical storage for precipitation). Certain applications may have large chemical demand (cost). Disposal of sludge from precipitation step.	2	
Hardness removal	High hardness removal.	3	Gabelich et al., 2007
Heavy metals removal	High removal of metals.	3	Gabelich et al., 2007 Gabelich et al., 2010
Organic contaminant removal	Moderate to low removal of organics reported in precipitation phase.	1	Gabelich et al., 2007
Radionuclide removal	High removal of radionuclides.	3	
Low chemical demand	Chemicals required at multiple process stages:	1	McCool et al., 2012

Table A-2. Technology Capabilities

Capability	Assessment	Score	References
	○ Pretreatment for primary RO (antiscalant, pH adjustment) ○ Pretreatment for secondary RO (antiscalant, pH adjustment) ○ Precipitation step may be driven by chemical process (pH adjustment, seed crystals, etc.), may require antiscalant scavenging ○ Chemical cleaning ○ Product water may require pH adjustment, remineralization, etc. Exact chemical use depends on specific applications and precipitation methods.		
Energy demand	Energy costs would be higher than an integrated two-stage RO system of similar size.	1	
Labor requirements	High labor requirements for precipitation step. Online chemistry adjustments may be required to feed water to precipitation or precipitation process to achieve demineralization.	1	Gabelich et al., 2007
Reliability	RO systems are reliable. Precipitation technology reliability depends on specific technology selected, operating parameters, and source water.	2	
Value added	Beneficial byproducts can be generated but could require additional processing to increase purity level.	1	

Note: ° = degree, % = percent

A1.1.4 Life-Cycle Costs

Capital costs are a significant cost factor (two RO units, precipitation unit, multiple pumps, etc.). This process may require a development period to optimize precipitation process for the feed water. Also, chemical costs during operation may be a significant cost factor depending on application and water quality.

A1.1.5 Research Needs

Application-specific research is necessary because chemical treatment may be required in excess of stoichiometric relationships, which increases costs. Seeding, however, may prove problematic in the presence of antiscalants. Long-term performance and cost data for systems treating varying feed water are necessary to better understand this process.

A1.1.6 References

Colorado School of Mines Advanced Water Technology Center, and Dual Reverse Osmosis with Chemical Precipitation, September 2018, http://aqwatec.mines.edu/produced_water/treat/docs/Dual_RO_with_chemical_precipitaiton.pdf.

Gabelich, C.J., M.D. Williams, A. Rahardianto, J.C. Franklin, and Y. Cohen, 2007. High-Recovery Reverse Osmosis Desalination Using Intermediate Chemical Demineralization. Journal of Membrane Science, 301(1):131-141, September 2007, DOI: 10.1016/j.memsci.2007.06.007.

Gabelich, C.J., P. Xu, and Y. Cohen, 2010. Concentrate Treatment for Inland Desalting. Sustainability Science and Engineering, 2: 295-236. https://doi.org/10.1016/S1871-2711(09)00210-4.

McCool, B.C., A. Rahardianto, and Y. Cohen, 2012. Antiscalant Removal in Accelerated Desupersaturation of RO Concentrate via Chemically-Enhanced Seeded Precipitation (CESP). Wagter Res., 46: 4261-4271. https://www.ncbi.nlm.nih.gov/pubmed/22673342.

Rahardianto, A., B.C. McCool, and Y. Cohen, 2010. Accelerated Desupersaturation of Reverse Osmosis Concentrate by Chemically-Enhanced Seeded Precipitation. Desalination, 264: 256-267. https://doi.org/10.1016/j.desal.2010.06.018.

Sanciolo, P., E. Ostarcevic, P. Atherton, G. Leslie, T. Fane, Y. Cohen, M. Payne, and S. Gray, 2012. Enhancement of Reverse Osmosis Water Recovery Using Interstage Calcium Precipitiation. Desalination, 295: 43-52. https://doi.org/10.1016/j.desal.2012.03.015.

Subramani, A., and J.G. Jacangelo, 2014. Treatment Technologies for Reverse Osmosis Concentrate Volume Minimization: A Review. Separation and Purification Technology, 122: 472-489. DOI: 10.1016/j.seppur.2013.12.004.

A2 Electrolytic Processes

A2.1 AquaSel^{TM}

A.2.1.1 Technology Description

General Electric's (GE)'s AquaSel^{TM} is a nonthermal technology that combines a membrane desalination unit with a concentration unit to reduce concentrate stream volumes. AquaSel^{TM} treats concentrate streams from municipal and industrial desalination plants. In a pilot study, AquaSel^{TM} had an overall recovery of 95% in 1,000 hours of operation (Bureau of Reclamation [Reclamation], 2016). This process can produce additional usable water that is otherwise trapped in concentrate streams and can reduce the volume of concentrate that requires disposal.

The AquaSel™ technology consists of an electrodialysis reversal (EDR) unit and a precipitator. The RO concentrate feeds the EDR unit. The diluate from the EDR process can be used as product water or be returned as feed to the primary RO, depending on the quality. The concentrate from the EDR process is fed to the precipitator from the precipitator Decant (i.e., the layer that does not have the precipitate), is filtered, and is then returned to the EDR unit. Solid salt and some liquid waste exit the precipitator as residuals requiring disposal. Figure A-2 is a schematic that shows this process.

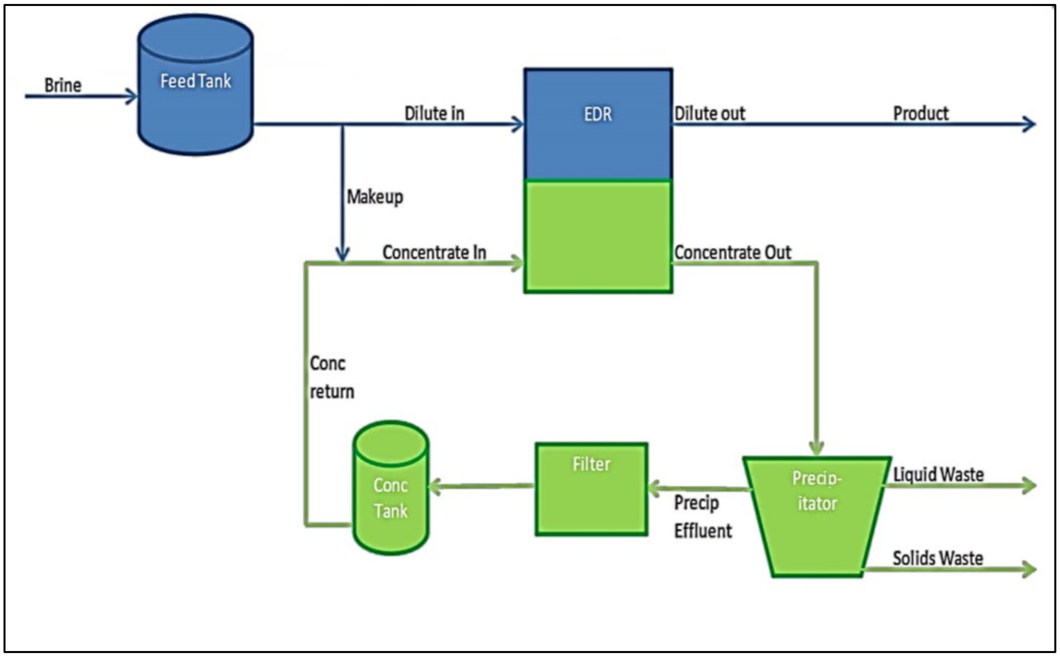

Figure A-2. Schematic diagram of AquaSel (based on GE, 2013).

A2.1.2 Technology Use Constraints (Screening Criteria)

Table A-3 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-3. Technology Use Constraints

Constraint	Assessment	Score	References[1]
Technology readiness level	Industrial applications of AquaSel have been pilot tested, and plans for demonstration sized testing were underway in August 2016.	7	GE, 2013
Flexibility	AquaSel is expected to be able to treat a wide range of TDS because of the flexibility of EDR to treat a wide range of water quality.	Yes	
Scalability	AquaSel is highly modular; both the membrane unit and the concentration unit can be sized to appropriate needs.	Yes	
Environmental constraints	This technology is not impacted by environmental conditions.	Yes	
Process residual	Final concentrate volume can be small and no chemicals are added; therefore, there are minimal residuals or complications with ultimate disposal.	Yes	
Land area availability	System is compact compared to other concentrate management technologies.	Yes	
Feed water quality limitations	Volatile organic constituents (VOC) are not removed or retained; however, VOCs are typically not a major concern for municipal drinking water concentrate. Removing scale-forming constituents could be necessary for long-term stable operation.	Yes	

[1] This is an example of a proprietary technology; authors have had expertise with the technology, but very little literature is currently available as reference material.

A2.1.3 Technology Capability (Weighing Criteria)

Table A-4 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A2.1.4 Life-Cycle Costs

High capital cost is expected due to desalination and concentrator equipment. Operational complexity, energy requirements, and other operation and maintenance (O&M) costs are also significant.

Table A-4. Technology Capabilities

Capability	Assessment	Score	References[1]
Technology readiness level	Industrial applications for AquaSel have been pilot tested, and plans for demonstration sized testing were underway in August 2016.	7	
Produces additional "usable" water	Treated water from AquaSel can be used as new water supply and/or be returned to headwater of an existing plant to augment plant feed water.	3	
If water is produced, anticipated water quality (salinity)	"Usable" produced water from AquaSel requires additional treatment to reduce TDS. The effluent for AquaSel will mostly be composed of monovalent ions, which can easily be treated further by the desalination plant (bolt-on configuration) or by a polishing step (greenfield configuration).	2	
Overall process recovery (concentrate volume minimization)	AquaSel will reduce concentrate by 10 to 50 times of the feed water, or the equivalent of 90 to 98% overall system recovery.	3	
Residual waste disposal	High recovery and low chemical use.	2	
Limitations to large-scale utilization	Technology can be scaled up.	3	
Hardness removal	Very high rejection of hardness.	3	
Heavy metals removal	Very high rejection of heavy metals.	3	
Organic contaminant removal	ED does not remove uncharged organics.	1	
Radionuclide removal	Moderate rejection, but this is costly and complex.	2	EDR removal: EPA, 2015
Low chemical demand	Increases the concentration of constituents above the saturation limit to cause precipitation, rather than by adding chemicals.	3	
Energy demand	The EDR component of the process is energy intensive.	2	
Labor requirements	Difficult to assess due to limited number of full-scale installations, but system complication could require intermediate to advanced operator skills.	1	
Reliability	Difficult to assess due to limited number of full-scale installations. The precipitator component of the process is less known; however, EDR is a proven technology.	1	
Value added	Produces salt pellets that could be used beneficially based on feed water constituents.	2	

[1] This is an example of a proprietary technology; authors have had expertise with the technology, but very little literature is currently available as reference material.

Note: ED = electrodialysis, EPA = U.S. Environmental Protection Agency.

A2.1.5 Research Needs

AquaSel technology can benefit from pilot and demonstration sized testing to help water treatment plant designers gain additional information about the performance and cost of the system.

A2.1.6 References

This is an example of a proprietary technology; authors have had expertise with the technology, but very little literature is currently available as reference material. It is difficult to find literature and publications on proprietary technologies that are still in development and are not quite in full-scale production and wide use in the industry.

EPA, 2015. Radionuclides in Drinking Water. U.S. Environmental Protection Agency. https://cfpub.epa.gov/safewater/radionuclides/radionuclides.cfm?action=Rad_Electrodialysis

GE, 2013. GE Pilots New AquaSel Technology at Coca-Cola Plant: Solution for Near Zero Liquid Discharge. General Electric, June 2013. https://www.ge.com/in/sites/default/files/IndiaWaterCocaCola.pdf.

Reclamation, 2016. Desalination and Water Purification Research and Development Report No. 195, AquaSel Technology Pilot-Scale Demonstration Menifee Desalter. Bureau of Reclamation. https://www.usbr.gov/research/dwpr/reportpdfs/report195.pdf.

A2.2 Electrodialysis Reversal with Gypsum Precipitation

A2.2.1 Technology Description

Electrodialysis reversal with gypsum precipitation (GP) can be used to reduce the volume of RO concentrate and could produce a fresh water stream and a marketable solid gypsum. Testing GP was reported in the literature using both ED and EDR. This document considers EDR, rather than ED, implemented in combination with GP.

In this EDR with GP process, RO concentrate is fed to an EDR unit and produces a low TDS product water that can either be combined with the product water from the primary RO or be combined with the feed to the RO (Oren et al., 2010), as well as a further concentrated brine stream at or near saturation of the sparingly soluble salt, gypsum (figure A-3). The EDR brine is pumped to a seeded gypsum precipitator for solids recovery. The precipitator decantant is recovered and pumped through a filter and then fed back to the EDR unit for further concentration. Coupling GP with EDR allows the removal of calcium sulfate from the recirculating EDR brine stream, thus increasing EDR recovery. The process takes advantage of gypsum's tendency to exist as a stable, oversaturated solution that precipitates in the presence of gypsum seeds (Korngold et al., 2009). This process has been demonstrated on concentrate from brackish water RO at the pilot scale. Oren et al. (2010) also proposed using EDR with GP in combination with Wind-Aided Intensified eVaporation (WAIV™) to treat the brine blowdown from the EDR.

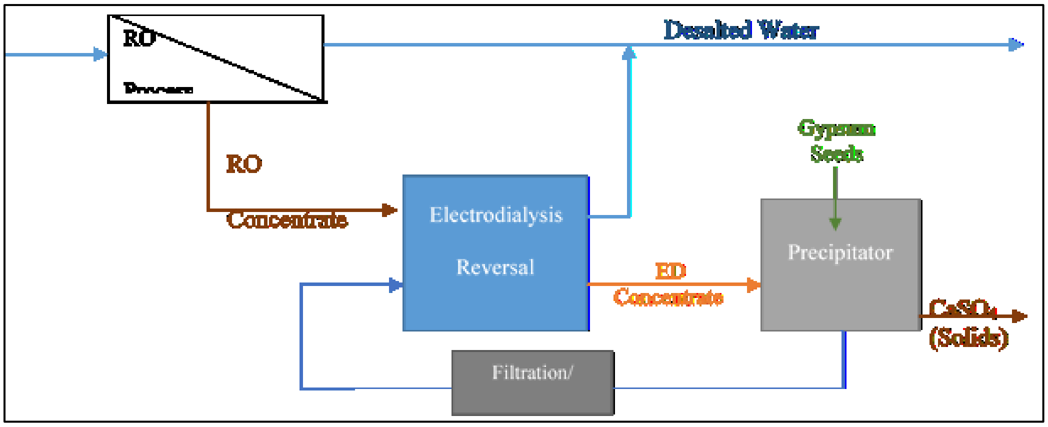

Figure A-3. EDR with GP process schematic (based on Korngold et al., 2009).

A2.2.2 Technology Constraints

Table A-5 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-5. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	The process has been demonstrated at the pilot scale. The largest flow documented was 500 L/h (ED unit) / 120 L/h (precipitator) (2009).	7	Korngold et al., 2009
Flexibility	This process should be able to handle minor changes in concentrate water quality without upset when EDR diluate is combined with RO feed. Minor water quality changes can be handled with operational changes.	Yes	Korngold et al., 2009
Scalability	ED/EDR is scalable by adding stacks and can be designed for a variety of flowrates. A change in the process flowrate may impact the residence time in the GP process, which could be problematic; this portion of the process is not considered as scalable as the EDR.	Yes	
Environmental constraints	This technology is not impacted by environmental conditions.	Yes	
Process residual	Precipitated salt and the precipitator brine stream present minimal complications with ultimate disposal, unless the feed water contains hazardous constituents when concentrated to high levels.	Yes	Korngold et al., 2009
Land area availability	This process does not require a significant amount of land area compared to other technologies.	Yes	Pérez-González et al., 2012
Feed water quality limitations	Silica concentration is not a limiting constituent as it is with many other technologies; however, to produce a pure gypsum product, the silica must remain below saturation in the ED/EDR brine to prevent co-precipitation with gypsum (product fouling) or ED/EDR unit fouling. Pretreatment to reduce the silica concentration may be required.	Yes	Korngold et al., 2009 Pérez-González et al., 2012

Note: L/h = liters per hour.

A2.2.3 Technology Capability

Table A-6 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-6. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	The process has been demonstrated at the pilot scale. The largest flow documented was 500 L/h (ED unit) / 120 L/h (precipitator) (2009).	7	Korngold et al., 2005 Korngold et al., 2009
Produces additional "usable" water	EDR diluate can be used to either increase feed to the primary desalination unit or, if the EDR diluate quality is acceptable, it can be used to augment the fresh water production from the primary RO.	2	Oren et al., 2010
If water is produced, anticipated water quality (salinity)	<500 ppm.	3	Korngold et al., 2009
Overall process recovery (concentrate volume minimization)	Brine concentrated from 2% to 20%. Overall process recovery: 97 to 98% (RO-ED-GP). Pilot scale process has demonstrated high overall process recovery at over 97%.	3	Korngold et al., 2009
Residual waste disposal	This process produces a brine from the GP system and solid gypsum. The brine would require final disposal; however, the gypsum could potentially be a sellable product.	2	Korngold et al., 2009
Limitations to large-scale utilization	To date, this has only been tested at the pilot scale. The largest flow documented was 400 to 500 L/h (RO concentrate to ED unit) / 120 L/h (ED concentrate to precipitator). Large-scale implementation may be complicated by the complexity of operating and maintaining the large number of unit operations. The size of crystallizer/settling tank increases with increases in scale, causing increased and prohibitive settling times. This may be overcome by adding UF or MF after crystallization to promote separation.	2	Oren et al., 2010
Hardness removal	High (based on ED).	3	Korngold et al., 2009

Table A-6. Technology Capabilities

Capability	Assessment	Score	References
Heavy metals removal	High (based on ED).	3	
Organic contaminant removal	Uncharged species remain in EDR diluate stream in ED; therefore, not removed.	1	
Radionuclide removal	Moderate (based on ED).	2	Montana et al., 2013
Low chemical demand	Chemical addition may be required for pH adjustment and scale inhibition. Addition of gypsum crystals may be necessary to induce precipitation. May require treatment to remove or defunctionalize antiscalants to promote GP.	2	Korngold et al., 2009
Energy demand	Energy ranged from 1.5 to 7 kWh/m^3 during pilot process (brine concentration: 200 g/L). Energy demand of standalone ED unit: 1-7 kWh/m^3. Energy demand proportional to ED feed concentration. Continuous gypsum removal minimizes ED unit energy consumption per unit water recovered by lowering TDS. Energy demand of gypsum precipitation unit is unknown.	2	Korngold et al., 2009 Pérez-González et al., 2012 Oren et al., 2010
Labor requirements	Intermediate to advanced operator skill required.	1	
Reliability	Process has not been demonstrated on full scale; therefore, the long-term reliability in unknown.	1	
Value added	Gypsum produced may be marketable.	1	Korngold et al., 2009

Note: ppm = parts per million, kWh/m^3 = kilowatthours per cubic meter, UF = ultrafiltration, MF = microfiltration.

A2.2.4 Life-Cycle Cost

Costs were assumed to be similar to EDR and chemical precipitation as cited in Subramani and Jacangelo (2014):

- ED capital: ~\$23,070 per m^3/hr; O&M: ~\$0.07 per m^3
- GP: Unknown, likely low

A2.2.5 Research Needs

A better understanding of the following topics is necessary for this technology. Further research in these areas could be beneficial:

- Energy use of GP unit
- Cost of technology and ways to reduce the cost
- Long-term operation of the GP

A2.2.6 References

Korngold, E., L. Aronov, N. Belayev, and K. Kock, 2005. Electrodialysis with Brine Solutions Oversaturated with Calcium Sulfate. Desalination, 172(1): 63-75. http://doi.org/10.1016/j.desal.2004.06.197.

Korngold, E., L. Aronov, and N. Daltrophe, 2009. Electrodialysis of Brine Solutions Discharged from an RO Plant. Desalination, 242(1-3): 215-227. http://doi.org/10.1016/j.desal.2008.04.008.

Montana, M., A. Camacho, I. Serrano, R. Devesa, L. Matia, and I. Valles, 2013. Removal of Radionuclides in Drinking Water by Membrane Treatment Using Ultrafiltration, Reverse Osmosis and Electrodialysis Reversal. Journal of Environmental Radioactivity, 125: 86-92. DOI: 10.1016/j.jenvrad.2013.01.010.

Oren, Y., E. Korngold, N. Daltrophe, 2010. Pilot Studies on High Recovery BWRO-EDR for Near Zero Liquid Discharge Approach. Desalination, 261(3): 321-330. http://doi.org/10.1016/J.DESAL.2010.06.010.

Pérez-González, A., A.M. Urtiaga, R. Ibáñez, and I. Ortiz, 2012. State of the Art and Review on the Treatment Technologies of Water Reverse Osmosis Concentrates. Water Research, 46(2): 267-283. http://doi.org/10.1016/j.watres.2011.10.046.

Subramani, A. and J.G. Jacangelo, 2014. Treatment Technologies for Reverse Osmosis Concentrate Volume Minimization: A Review. Separation and Purification Technology, 122: 472-489. https://www.researchgate.net/publication/274175545_Treatment_technologies_for_reverse_osmosis_concentrate_volume_minimization_A_review.

Zhang, Y., K. Ghyselbrecht, and B. Meesschaert, 2011. Electrodialysis on RO Concentrate to Improve Water Recovery in Wastewater Reclamation. Journal of Membrane Science, 278 (1-2): 101-110. www.vliz.be/imisdocs/publications/292298.pdf.

A2.3 Electrodialysis Metathesis

A2.3.1 Technology Description

Electrodialysis metathesis (EDM) is an electrical membrane process that desalinates a saline stream by moving ions from the saline stream through anion and cation membranes into two separate streams containing more soluble ion pairs. The vast majority of research and testing on EDM for concentrate has used this technology as a component in the zero discharge desalination process (Davis, 2006).

EDM consists of two concentrating streams and two diluting streams, each separated by a membrane. The set of four streams and four membranes is called a quad. Typical EDM units consist of 100 or more quads. In EDM, a feed water stream rich in calcium sulfate is separated into a calcium-chloride-rich stream and a sodium-sulfate-rich stream, leaving behind a fresh diluate stream (figure A-4).

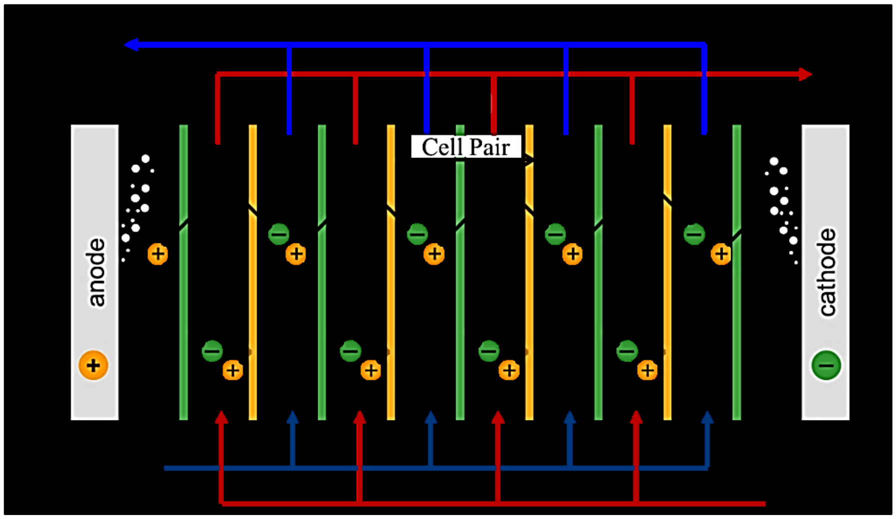

Figure A-4. Schematic diagram of EDM (based on Capelle and Davis, 2014).

A2.3.2 Technology Constraints

Table A-7 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-7. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Technology has been tested at the bench, pilot, and demonstration scale; however, there are no permanent installations for desalination concentrate treatment, and no commercial vendors have been identified.	8	Capelle and Davis, 2014 Bond et al., 2011
Flexibility	System can be operated at different set points to produce different diluate water quality and to handle different salinity product water.	Yes	
Scalability	Stacks can be added and taken offline to account for variations in feed water flowrate.	Yes	
Environmental constraints	Sodium chloride solution is needed to make process work. Without a recycle loop for sodium chloride solution, there may be significant environmental impacts to supply and dispose of spent sodium chloride.	Yes	
Process residual	Produces a diluted NaCl process stream. If this stream is not recycled, it could be a potential source of residuals that could impede the use of this technology.	Yes	
Land area availability	EDM is compact and does not require as much land area to implement as other concentrate management technologies.	Yes	
Feed water quality limitations	Calcium carbonate can cause scaling in the EDM stack but can be controlled by adjusting the pH.	Yes	

A2.3.3 Technology Capability

Table A-8 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A2.3.4 Life-Cycle Costs

Costs from Bond et al. (2011) are for EDM crystallizer and are in 2011 dollars:

- TDS < 1,500 milligrams per liter (mg/L): \$0.64 to \$0.90 per m^3 treated
- TDS = 5,300 mg/L: \$4.20 per m^3 treated
- TDS = 28,000 mg/L: \$11.21 per m^3 treated

A2.3.5 Research Needs

Research needs for using EDM for concentrate volume reduction include:

- Salt requirement reduction or salt recycle

- Improved system integration and system controls (supervisory control and data acquisition [SCADA]) to reduce unplanned system downtime or malfunction

Table A-8. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Technology has been tested at the bench, pilot, and demonstration scale; however, there are no permanent installations for desalination concentrate treatment, and no commercial vendors have been identified.	8	Capelle and Davis, 2014 Bond et al., 2011
Produces additional "usable" water	Diluate water can be used to augment primary desalination feed or be used for nonpotable applications where higher salinity is acceptable.	2	
If water is produced, anticipated water quality (salinity)	Lower quality.	2	
Overall process recovery (concentrate volume minimization)	Recovery when used in a process with other technologies can produce overall process recoveries of 99.8%.	3	Capelle and Davis, 2014
Residual waste disposal	Large amounts of sodium chloride are produced by this process.	1	
Limitations to large-scale utilization	EDM is modular; therefore, stacks could be added to reach the desired process flowrate.	2	
Hardness removal	89%	3	Biagini et al., 2012
Heavy metals removal	Unknown, but anticipated to be relatively high because these are charged species.	3	
Organic contaminant removal	Does not remove uncharged species to a high degree	1	
Radionuclide removal	Not well documented, likely some removal	2	
Low chemical demand	Antiscalant is needed to control calcium carbonate scaling, if NaCl not recycled, then significant amount of NaCl is required	1	
Energy demand	Energy demand of EDM is similar to that of the primary desalination process.	2	
Labor requirements	Largely unknown since this technology hasn't been used.	1	
Reliability	Unknown.	1	
Value added	Could be used to produce relatively pure salt by-products	2	

A2.3.6 References

Biagini, B., 2012. Zero Discharge Desalination Testing at Brackish Groundwater National Desalination Research Facility (BGNDRF). International Mine Water Association Annual Conference.

Bond, R., B. Batchelor, T. Davis, and B. Klayman, 2011. Zero Liquid Discharge Desalination of Brackish Water with an Innovative Form of Electrodialysis: Electrodialysis Metathesis. Florida Water Resources Journal, July 2011. https://www.fwrj.com/techarticles/0711%20tech1.pdf.

Capelle, M., and T. Davis, 2014. Zero Discharge Desalination Testing at BGNDRF.

Davis, T.A., 2006. Desalination and Water Purification Research and Development Zero Discharge Seawater Desalination: Integrating the Production of Freshwater, Salt, Magnesium, and Bromine, Denver. https://www.usbr.gov/research/dwpr/reportpdfs/report111.pdf.

A2.4 High Efficiency Electrodialysis (HEED®)

A2.4.1 Technology Description

High Efficiency Electrodialysis (HEED®) is a patented pending technology, developed by the EET Corporation, that uses a split-cell ED design connected through patented gaskets that allow for increased hydraulic and electrical staging within a single unit. Figure A-5 illustrates the flow configurations within a HEED® stack, which can be operated in a series or parallel configuration. In a series configuration, voltage can be independently adjusted for each pass of fluid to optimize the electric potential. In parallel configuration, multiple streams can be treated at the same time. HEED® has been used to treat industrial waste waters, including blowdown from cooling towers and laundry water (EET Corporation, n.d.).

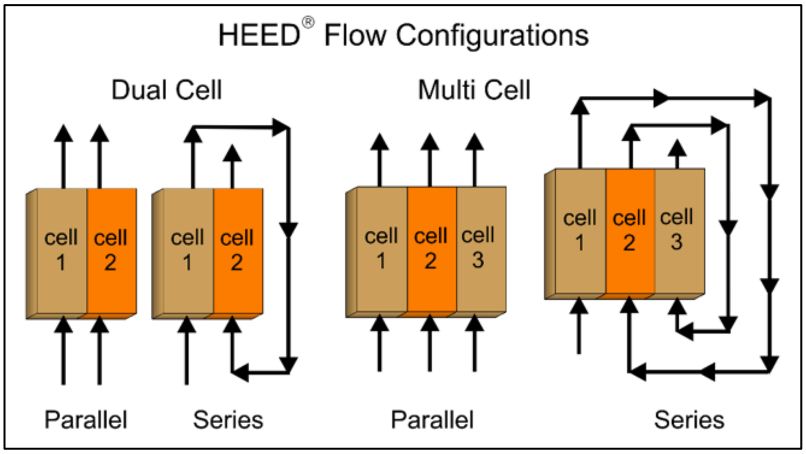

Figure A-5. HEED® flow configurations (based on EET Corporation, n.d.).

A2.4.2 Technology Constraints

Table A-9 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

A2.4.3 Technology Capability

Table A-10 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-9. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Commercially available technology at flows ranging from ~500 mgd to 1.3 mgd.	7	EET Corporation, n.d.
Flexibility	Able to treat feed water with salinity ranging from 100 to 20,000 ppm. System can adapt to changing mineral content of feed water or desired produced water quality.	Yes	EET Corporation, n.d.
Scalability	Scalable through the addition of modular stacks in series or parallel	Yes	EET Corporation, n.d.
Environmental constraints	This technology is not impacted by environmental conditions.	Yes	
Process residual	High TDS concentrate stream produced, and ultimate disposal will depend on feed water quality.	Yes	
Land area availability	Low land area requirements: ~70 ft^2 per 100,000+ gpd system	Yes	EET Corporation, n.d.
Feed water quality limitations	Suspended solids removed through cartridge or multimedia filtration (prior to entering HEED® system). EDR process does not remove silica or other uncharged components. Energy requirements increase with increasing feed TDS.	Yes	EET Corporation, n.d.

Note: ft^2 = square feet, gpd = gallons per day.

Table A-10. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Commercially available technology at flows ranging from ~500 gpd to 1.3 mgd.	7	EET Corporation, n.d.
Produces additional "usable" water	Yes.	3	
If water is produced, anticipated water quality (salinity)	Demonstrated to 2 ppm (98% salt removal).	3	EET Corporation, n.d.
Overall process recovery (concentrate volume minimization)	>98%, assuming 80% initial RO recovery (though tested at lower TDS).	3	Schmidt and Sferrazza, 2009.
Residual waste disposal	High TDS stream (reduced flow from concentrate).	2	EET Corporation, n.d.
Limitations to large-scale utilization	Cost of systems could be a limitation to large-scale use.	1	

Table A-10. Technology Capabilities

Capability	Assessment	Score	References
Hardness removal	Yes (tested on used engine coolant).	3	Schmidt, 2002
Heavy metals removal	Yes (tested on used engine coolant).	3	Schmidt, 2002
Organic contaminant removal	Not reported, but expected to be low based on traditional EDR processes.	1	
Radionuclide removal	Not reported, but expected to be low based on traditional EDR processes.	2	
Low chemical demand	Chemical demand is low. pH adjustment and/or antiscaling treatment may be necessary depending on application. Chemicals may be required for cleaning.	2	
Energy demand	May use less energy than traditional EDR, but this marginal difference decreases with increasing influent TDS. Current use efficiency decreases with decreasing outlet TDS.	1	
Labor requirements	Applications may require increased upfront labor for optimization of hydraulic and electric staging. Operating the system can also be complex and subject to feed water quality changes, thus requiring skilled labor for operation and maintenance.	1	
Reliability	Not reported.	1	
Value added	Unknown.	1	

A2.4.4 Research Needs

Additional testing with various feed water qualities is necessary to understand long-term performance of HEED®.

A2.4.5 References

EET Corporation, n.d. Originally at [http://www. EET Corporation.com/lts/heednew.htm](http://www.EETCorporation.com/lts/heednew.htm). No longer available.

Schmidt, E., and A. Sferrazza, 2009. U.S. Patent No. EP 1476247 B1. Fiscal Year 2018 Budget Justification. U.S. Patent and Trademark Office, Washington, DC. https://www.uspto.gov/sites/default/files/documents/fy18pbr.pdf.

Schmidt, E., 2002. Recycling Used Engine Coolant; What Every Recycler Needs to Know. Presented at the NORA 2002 Annual Recycling Conference and Trade Show, Dallas, Texas.

A2.5 Electrodialysis

A2.5.1 Technology Description

Electrodialysis is widely used to reduce the salt concentration of feed water. The electrochemically driven process uses selective membranes and an applied voltage to remove charged species from water; however, process recovery is limited by membrane scaling as sparingly soluble salts reach saturation in the concentrated stream.

In an ED process (figure A-6), a feed solution and a draw solution pass through alternating channels. Positively charged species are pulled toward the cathode, diffusing from the feed through a cation-exchange membrane to the draw solution. Similarly, negatively charged species move from the feed toward the anode through an anion exchange membrane. Uncharged species, such as organic compounds, remain in the feed solution. When treating RO concentrate, the RO concentrate is supplied as a feed to the ED unit to produce a usable water stream (the diluate) and a further concentrated brine stream (the concentrate). The concentrated brine stream can be recycled through the unit as the draw solution to supply a medium for ions transferring from the feed solution. An additional byproduct of ED is gas, which is generated at the electrodes.

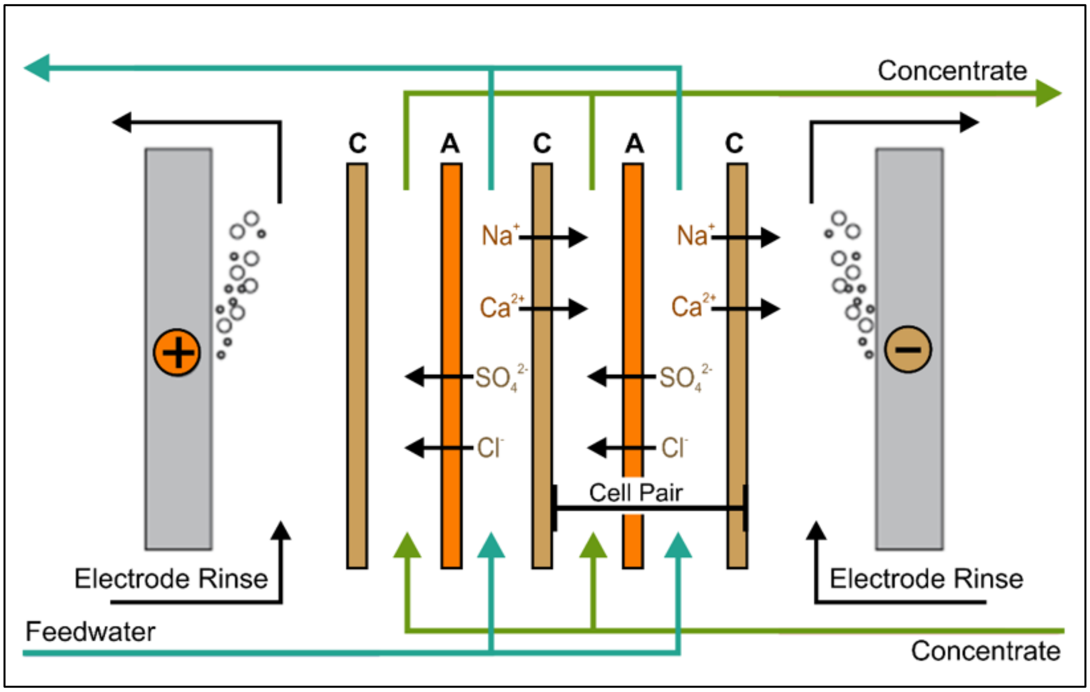

Figure A-6. Schematic of ED process (based on of the University of Texas at El Paso, n.d.).

A2.5.2 Technology Constraints

Table A-11 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-11. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Full-scale ED processes exist as a primary desalination step. Pilot scale processes have been developed for concentrate management.	9	Meesschaert et al., 2010
Flexibility	Energy requirements for ED increase with increasing feed salinity. ED is more feasible for applications with low to moderate feed salinity, but it can treat higher salinity waters.	Yes	Subramani and Jacangelo, 2014
Scalability	ED is scalable by adding ED stacks and can be designed for a range of flowrates.	Yes	
Environmental constraints	No environmental constraints.	Yes	
Process residual	EDM is compact and does not require as much land area as other concentrate management technologies.	Yes	
Land area availability	Low land area requirements.	Yes	Pérez-González et al., 2012
Feed water quality limitations	ED does not remove organic or uncharged species. Feed water with high scaling potential requires pretreatment.	No	

A2.5.3 Technology Capability

Table A-12 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-12. Technology Capabilities

Capability	Assessment	Assessment Score	References
Technology readiness level	Full-scale ED processes exist as a primary desalination step. Pilot scale processes have been developed for concentrate management.	9	Meesschaert et al., 2010
Produces additional "usable" water	ED produces additional water from RO concentrate.	3	
If water is produced, anticipated water quality (salinity)	Water quality treated with ED is low in TDS and most contaminants.	3	Zhang et al., 2012
Overall process recovery (concentrate volume minimization)	High water quality can be achieved with ED, depending on feedwater constituents.	2	Subramani and Jacangelo, 2014
Residual waste disposal	Moderate volume of liquid waste compared to RO input. ED discharge accounts for 2.5% of initial RO feed. Near zero liquid discharge (ZLD) is possible.	2	Zhang et al., 2012
Limitations to large-scale utilization	Membranes prone to scaling. Feed water may require chemical pretreatment to mitigate scaling potential.	2	
Hardness removal	High removal of charged species.	3	
Heavy metals removal	High removal of charged species.	3	
Organic contaminant removal	Uncharged species are not removed.	1	Duranceau and Taylor, 2012
Radionuclide removal	High removal of charged species.	2	
Low chemical demand	Pretreatment chemicals may be added to reduce scaling.	2	
Energy demand	7 to 8 kWh/m^3 for RO concentrate treatment. Energy demand increases with increasing salinity of feed.	1	Subramani and Jacangelo, 2014
Labor requirements	Moderate-high system complexity, considering chemical additions to reduce scaling potential .	1	
Reliability	ED processes for primary desalination are considered reliable. Complexity of ED to treat a concentrate stream needs additional testing.	2	Watson et al., 2003
Value added	ED can treat waters with higher silica content than RO because uncharged particles move freely about the feed channel in bulk; however, saturation limits can be reached and cause scaling. Silica tolerance depends on feedwater.	1	

A2.5.4 References

Duranceau, S.J., and J.S. Taylor, 2010. Chapter 11, "Membrane Processes," in Water Quality and Treatment (6th edition). J.K. Edzwald (ed.), New York, NY: McGraw-Hill; p. 11-1 to 11-106.

Joo, S.H., and B. Tansel, 2015. Novel Technologies for Reverse Osmosis Concentrate Treatment: A Review. Journal of Environmental Management, 150: 322-335. 10.1016/j.jenvman.2014.10.027.

McGovern, R.K., A.M. Weiner, L. Sun, C.G. Chambers, S.M. Zubair, and J.H. Lienhard, 2014. On the Cost of Electrodialysis for the Desalination of High Salinity Feeds. Applied Energy, 136 : 649-661, December 2014. https://doi.org/10.1016/j.apenergy.2014.09.050.

Meesschaert, B., Y. Zhang, K. Ghyselbrecht, E. Van Houtte, L. Pinoy, and B. Van der Bruggen, 2010. Pilot Scale Study on Salt Removal by Electrodialysis from RO Concentrate with High Scaling Potential. Presented at IWA World Water Congress and Exhibition 2010, Montreal, Canada, 2010.

Morillo, J., J. Usero, D. Rosado, H.E. Bakouri, A. Riaza, and F.J. Bernaola, 2014. Comparative Study of Brine Management Technologies for Desalination Plants. Desalination, 336: 32-49. doi.org/10.1016/j.desal.2013.12.038

Pérez-González, A., A.M. Urtiaga, R. Ibáñez, and I. Ortiz, 2012. State of the Art and Review on the Treatment Technologies of Water Reverse Osmosis Concentrates. Water Research, 46(2): 267-283. https://www.ncbi.nlm.nih.gov/pubmed/22119366.

Subramani, A., and J.G. Jacangelo, 2014. Treatment Technologies for Reverse Osmosis Concentrate Volume Minimization: A Review. Separation and Purification Technology, 122: 472-489. doi:10.1016/j.seppur.2013.12.004.

University of Texas – El Paso, n.d. Electrodialysis schematic.

Watson, I.C., O.J. Morin, and L. Henthorne, 2003. Desalting Handbook for Planners (third edition). Bureau of Reclamation, Denver, Colorado. https://www.usbr.gov/research/dwpr/reportpdfs/report072.pdf.

Zhang, Y., K. Ghyselbrecht, B. Meesschaert, L. Pinoy, and B. Van der Bruggen, 2011. Electrodialysis on RO Concentrate to Improve Water Recovery in Wastewater Reclamation. Journal of Membrane Science, 378 (1-2): 101-110. doi:10.1016/j.memsci.2010.10.036.

Zhang, Y., K. Ghyselbrecht, R. Vanherpe, B. Meesschaert, L Pinoy, and B. Van der Bruggen, 2012. RO Concentrate Minimization by Electrodialysis: Techno-Economic Analysis and Environmental Concerns. Journal of Environmental Management, 107: 28-36. doi:10.1016/j.jenvman.2012.04.020.

A2.6 Electrodialysis Reversal with Slurry Precipitation and Recycle Reverse Osmosis

A2.6.1 Technology Description

Electrodialysis reversal is widely used to reduce the salt concentration of a feed water (figure A-7). The electrochemically driven process uses selective membranes and an applied voltage to remove charged species from water; however, process recovery is limited by membrane scaling as sparingly soluble salts reach saturation in the concentrated stream. The slurry precipitation and recycle reverse osmosis (SPARRO) process uses seed crystals comprised of a sparingly soluble salt to promote controlled precipitation (figure A-8). SPARRO has been proposed for use in the mining and municipal water treatment industry. Adding a SPARRO to EDR addresses scaling limitations by precipitating sparingly soluble salts from the EDR concentrate stream and recycling them back to the EDR process for additional treatment if needed. Adding the SPARRO process also increases the percent recovery and quality of the EDR product stream.

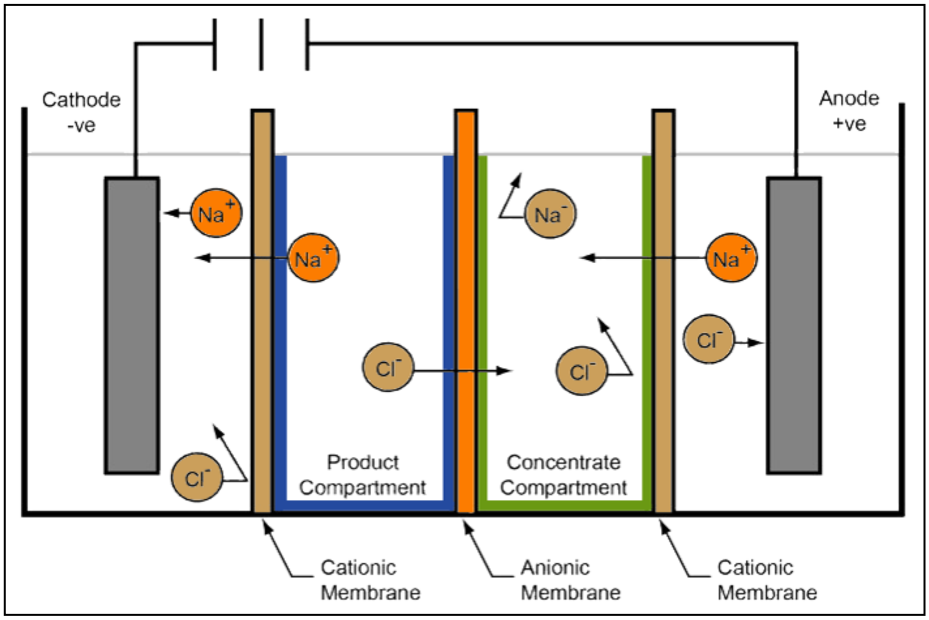

Figure A-7. ED/EDR schematic.

In a combined EDR/SPARRO process (figure A-9), RO concentrate is fed to the EDR unit. The highly concentrated EDR blowdown is then supplied to the SPARRO unit for salt precipitation and recycled back to the EDR unit, replacing makeup water that would otherwise come from EDR feed water. Combining EDR and SPARRO overcomes limitations inherent in both processes. The SPARRO process requires a large footprint to accommodate tubular RO membranes to prevent clogging with seed crystals. The SPARRO process treats only EDR blowdown; therefore, the flow is significantly smaller than the initial RO concentrate, which reduces the land area requirement.

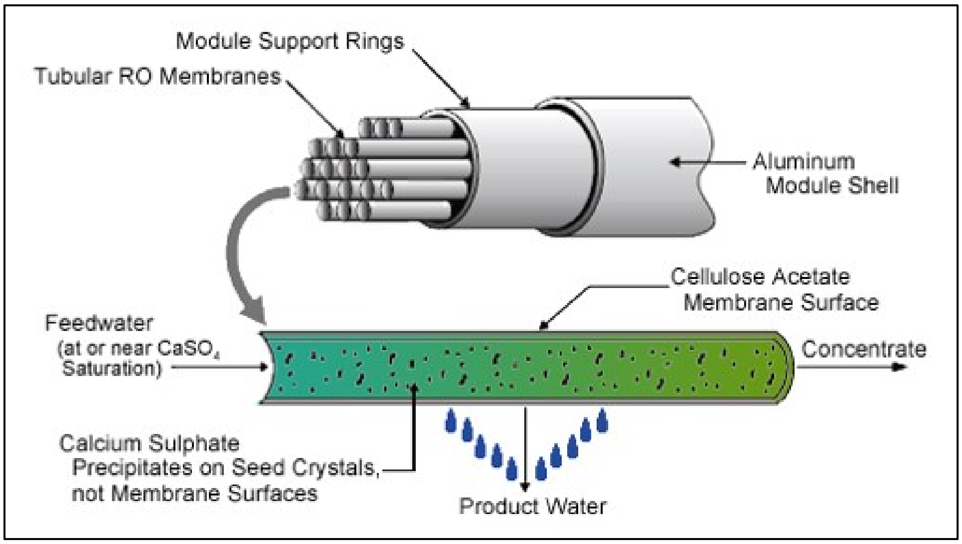

Figure A-8. Conceptual illustration of SPARRO process.

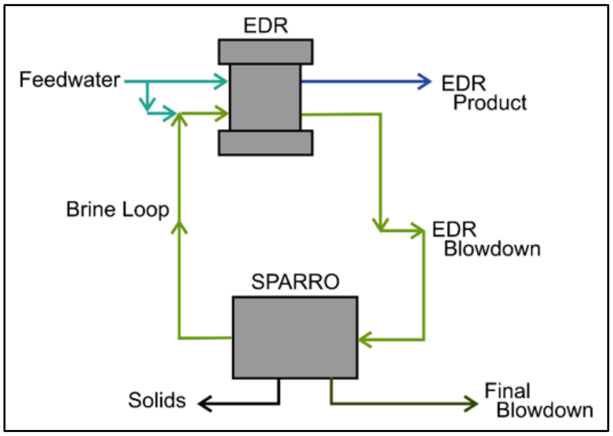

Figure A-9. ED and SPARRO combined process for concentrate management.

A2.6.2 Technology Constraints

Table A-13 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-13. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Technology has been demonstrated at the pilot scale. (Reclamation sponsored a study in Corona, California, with 200 hours of EDR/SPARRO operating time.)	6	Reclamation, 2013
Flexibility	EDR/SPARRO is able to cover a wide range of waters; however, certain applications may be more cost effective than others with salt recovery.	Yes	Reclamation, 2009
Scalability	Limited scalability. Recovery may be limited within a system by SPARRO system sizing. Recovery can be improved through recycle of SPARRO blowdown.	Yes	Reclamation, 2009
Environmental constraints	Process residuals consist of a high-TDS liquid stream and a solids stream. Disposal of residuals may vary based on location and feed water constituents.	Yes	Reclamation, 2009
Process residual	Process results in reduced concentrate volume. Final residual includes solids that require handling.	Yes	
Land area availability	Land area requirement is larger than the typical RO process for the SPARRO. The RO membranes are tubular and not spiral-wound membrane elements, so they require a larger footprint. In general, however, land requirement is not a constraint for this technology.	Yes	Reclamation, 2009
Feed water quality limitations	High concentration of sparingly soluble salts in feed water may result in scaling in the SPARRO unit. Feed water could pose a constraint on the system. Pretreatment may be required.	No	Reclamation, 2013

A2.6.3 Technology Capability

Table A-14 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A2.6.4 Life-Cycle Costs

Costs are expected to be high because the technology has not been demonstrated at full scale. Also, using tubular RO requires additional processing (Le and Nunes, 2016; Reclamation, 2013).

Table A-14. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Technology has been demonstrated at the pilot scale. (Reclamation sponsored a study in Corona, California, with 200 hours of EDR/SPARRO operating time.)	6	Reclamation, 2013
Produces additional “usable” water	Additional usable water produced.	3	
If water is produced, anticipated water quality (salinity)	RO and EDR produced waters are low in TDS and other constituents.	3	
Overall process recovery (concentrate volume minimization)	Overall process recovery can be as high 96 to 98%.	3	Reclamation, 2013
Residual waste disposal	Process residuals are high-TDS liquid and solids stream. Disposal of residuals varies based on location.	2	
Limitations to large-scale utilization	Costs, including O&M, can pose a limitation to large-scale use.	2	Reclamation, 2013
Hardness removal	High (based on ED and RO).	3	
Heavy metals removal	High (based on ED and RO).	3	
Organic contaminant removal	Uncharged species remain in EDR diluate stream and are not removed. Organics can be removed in RO, but they can also cause organic fouling on RO membranes.	2	
Radionuclide removal	High (based on ED and RO).	3	
Low chemical demand	Chemical demand is low, but demands depend on the specific feed water. EDR/SPARRO has limited material inputs. Some chemical pretreatment may be necessary for pH adjustment.	2	
Energy demand	Energy demand for process is lower than with thermal technologies used for concentrate minimization.	2	Reclamation, 2009
Labor requirements	Process has high labor requirements (complex operation of SPARRO unit).	1	Reclamation, 2009
Reliability	Reliability is currently unknown due to limited technology readiness.	1	
Value added	Certain applications may allow for recovery of salts (e.g., high-quality gypsum).	2	Reclamation, 2009

A2.6.5 Research Needs

Research needs are:

- Investigate precipitation process to be designed to produce a value-added product.
- Investigate applicability of technology to treat various sparingly soluble salts .

A2.6.6 References

Juby, G.J.G.. 1992. Membrane Desalination of Service Water from Gold-Mines. Journal of the South African Institute of Mining and Metallurgy, 92(3): 65-69. https://journals.co.za/content/saimm/92/3/AJA0038223X_2168.

Juby, G.J.G., C.F. Schutte, and J. Van Leeuwen, 1996. Desalination of Calcium Sulphate Scaling Mine Water – Design and Operation of the SPARRO Process. Water SA, 22(2): 161-172.

Juby, G.J.G., and C.F. Schutte, 2000. Membrane Life in a Seeded-Slurry Reverse Osmosis System. Water SA, 26(2): 239-248. http://www.wrc.org.za/wp-content/uploads/mdocs/WaterSA_2000_02_1171.pdf.

Le, N.L., and S.P. Nunes, 2016. Materials and Membrane Technologies for Water and Energy Sustainability. Sustainable Materials and Technologies, 7: 1-28. https://core.ac.uk/download/pdf/81155118.pdf

Pulles, W., G.J.G. Juby, and R.W. Busby, 1992. Development of the Slurry Precipitation and Recycle Reverse Osmosis (SPARRO) Technology for Desalinating Scaling Mine Waters. Water Science and Technology, 25(10): 177-192.

Reclamation, 2008. Evaluation and Selection of Available Processes for a Zero-Liquid Discharge System for the Perris, California, Ground Water Basin. Desalination and Water Purification Research and Development Program Report No. 149. Bureau of Reclamation, Denver, Colorado, April 2008. https://www.usbr.gov/research/dwpr/reportpdfs/report149.pdf.

Reclamation, 2009. Treatment of Concentrate, Desalination and Water Purification Research and Development Program Report No. 155. Bureau of Reclamation, October 2009. https://www.usbr.gov/research/dwpr/reportpdfs/report155.pdf.

Reclamation, 2013. Increasing Recovery of Inland Desalters by Combining EDR and SPARRO Technologies to Treat Concentrate. Desalination and Water Purification Research and Development Program Report No. 172. Bureau of Reclamation, Denver, Colorado, December 2013. https://www.usbr.gov/research/dwpr/reportpdfs/report172.pdf.

A2.7 Capacitive Deionization

A2.7.1 Technology Description

Capacitive Deionization (CDI) is a low-pressure desalination process that uses electricity to separate ions from an aqueous solution. Electric potential is applied to porous electrodes, and a membrane can be used to keep the separated ions from flowing back into the main center feed channel when the polarity of the electrodes is reversed to discharge the removed ions. As figure A-10a illustrates, saline feed water enters the center channel, and ions with the opposing charge are attracted to the opposing electrode. Pure water leaves the center channel. To move the ions away from the electrodes to regenerate (figure A-10b), the charge on the electrodes is reversed, and ions are released into the center channel and discharged in a typical CDI process. In a membrane CDI (MCDI), a membrane barrier keeps the discharged ions away from the center channel, and they are flushed out of the system. MCDI requires less flush water to remove the ions from the CDI module.

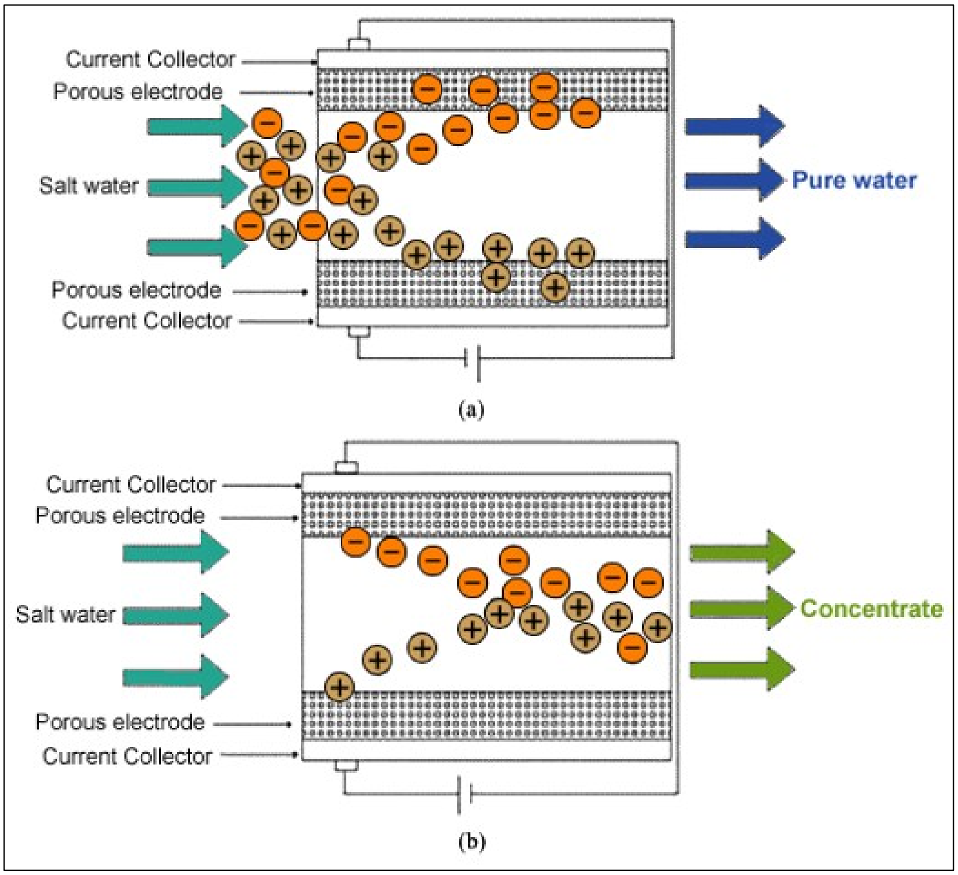

Figure A-10. (a) CDI purification, and (b) CDI regeneration.

A2.7.2 Technology Constraints

Table A-15 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-15. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Technology has been commercialized for containerized systems and point of use. Largest CDI units demonstrated for desalination are up 1,000 m^3/d or 300,000 gpd.	7	Voltea, 2018 AlMarzooqi et al., 2014
Flexibility	System can treat lower TDS water with a wide range of ionic content. Can only treat lower TDS water with low organics. Organics should be removed prior to CDI. Additional treatment is needed to remove organics.	Yes	AlMarzooqi et al., 2014 Tao et al., 2011
Scalability	CDI can only realistically treat a limited amount of water because it must be lower in TDS for feed to CDI. Large municipal scale systems have not yet been developed, and CDI development and use have been centered on point of use and small-scale systems.	No	Voltea, 2018
Environmental constraints	Managing concentrated brine can be a constraint based on the feed water quality.	Yes	AlMarzooqi et al., 2014
Process residual	Concentrated brines are generated if CDI is used for high recovery; however, because CDI operates at lower salinities, concentrate TDS levels are not as high as with other concentrating technologies.	Yes	Tao et al., 2011 AlMarzooqi et al., 2014
Land area availability	CDI footprint is not a constraint.	Yes	
Feed water quality limitations	Organics can cause fouling on electrode surfaces and must be minimized prior to CDI feed. A MCDI configuration can minimize scaling issues relative to ionic scaling. Silica scaling can be problematic.	Yes	Zhang et al., 2013 Mossad and Zou, 2013 Tao et al., 2011 AlMarzooqi et al., 2014

m^3/d = cubic meters per day.

A2.7.3 Technology Capability

Table A-16 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-16. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Technology commercialized for containerized systems and point of use. Largest CDI units demonstrated for desalination are up 1,000 m^3/d or 300,000 gpd	7	Voltea, 2018 AlMarzooqi et al., 2014
Produces additional "usable" water	Only efficient to desalinate lower TDS waters.	1	Zhang et al., 2013 Mossad and Zou, 2013 AlMarzooqi et al., 2014
If eater is produced, anticipated eater quality (salinity)	Produced water is high quality with ionic content removed.	3	Mossad and Zou., 2013 AlMarzooqi et al., 2014
Overall process recovery (concentrate volume minimization)	At lower TDS feeds to CDI, overall process recovery can be high, but CDI is most efficient at TDS of ~2,000 mg/L or below.	1	AlMarzooqi et al., 2014 Zhang et al., 2013 Mossad and Zou, 2013
Residual waste disposal	Concentrated brines must be disposed of if CDI is used for high recovery; however, because CDI operates at lower salinities, the concentrated TDS is not as high as with other concentrating technologies.	2	Tao et al., 2011 AlMarzooqi et al., 2014
Limitations to large-scale utilization	Limited operation to lower TDS feeds, flowrate, recovery, and presence of organics are limitations to large scale adoption.	1	AlMarzooqi et al., 2014 Zhang et al., 2013 Mossad and Zou, 2013
Hardness removal	Can preferentially remove divalents such as calcium, magnesium, and sulfate.	2	Tang et al., 2017
Heavy metals removal		1	
Organic contaminant removal	Organics cause fouling, lowered TDS removal, and increased power requirements.	0	Zhang et al., 2013 Mossad and Zou, 2013
Radionuclide removal	Charged radionuclides can be removed with CDI.	2	
Low chemical demand	System does not require many chemicals for operation.	2	AlMarzooqi et al., 2014
Energy demand	Energy requirements for CDI are lower than other membrane technologies	2	AlMarzooqi et al., 2014
Labor requirements		1	AlMarzooqi et al., 2014
Reliability	Not enough large-scale testing has taken place to understand reliability of CDI.	1	
Value added	Softening of waters at no additional salt input	2	

A2.7.4 Research Needs

- Efficient electrode development at a low cost for desalination at higher concentrated salinity.
- Long term pilot testing to demonstrate scalability, reliability and life-cycle cost (LCC)
- Modeling of CDI electrosorption process.
- Better understanding of electrode fouling due to organic carbon presence in water.
- Due to "softening" capabilities of CDI, higher selectivity, and affinity of removal of divalent ions to monovalent ions, CDI should be studied as an interstage process for high recovery (lowering concentrate volumes) processes.

A2.7.5 References

AlMarzooqi, F.A., A.A. Ghaferi, I. Saadat, and N. Hilal, 2014. Application of Capacitive Deionisation in Water Desalination: A Review. Desalination, 342: 3-15, ISSN 0011-9164. https://doi.org/10.1016/j.desal.2014.02.031.

Anderson, M.A., A.L. Cudero, and J. Palma, 2010. Capacitive Deionization as an Electrochemical Means of Saving Energy and Delivering Clean Water – Comparison to Present Desalination Practices: Will It Compete? Electrochimica Acta, 55(12).

Biesheuvel, P.M., and A. van der Wal, 2010. Membrane Capacitive Deionization. Journal of Membrane Science, 346(2): 256-262, ISSN 0376-7388, doi: https://doi.org/10.1016/j.memsci.2009.09.043.

Dursun, D., S. Ozkul, R. Yuksel, and H.E. Unalan, 2017. Enhancing Capacitive Deionization Technology as an Effective Method for Water Treatment Using Commercially Available Graphene. Water Science and Technology, 75(3): 643-649, doi: https://dx.doi.org/10.2166/wst.2016.544

Mossad, M., and L. Zou, 2013. Study of Fouling and Scaling in Capacitive Deionisation by Using Dissolved Organic and Inorganic Salts. Journal of Hazardous Materials, 244-245: 387-393, ISSN 0304-3894, https://doi.org/10.1016/j.jhazmat.2012.11.062

Oren, Y., 2008. Capacitive Deionization (CDI) for Desalination and Water Treatment – Past, Present and Future (A Review). Desalination, 228(1-3).

Porada, S., R. Zhao, A. van der Wal, V. Presser, and P.M. Biesheuvel, 2013. Review on the Science and Technology of Water Desalination by Capacitive Deionization. Progress in Materials Science, 58(8): 1388-1442, ISSN 0079-6425, doi: https://doi.org/10.1016/j.pmatsci.2013.03.005.

Suss, M.E., S. Porada, X. Sun, P.M. Biesheuvel, J. Yoon, and V. Presser, 2015. Water Desalination via Capacitive Deionization: What is it and What Can We Expect from it? Energy & Environmental Science.

Tang, W., D. He, C. Zhang, and T.D. Waite, 2017. Optimization of Sulfate Removal from Brackish Water by Membrane Capacitive Deionization (MCDI). Water Research, 121: 302-310. http://dx.doi.org/10.1016/j.watres.2017.05.046.

Tao, G., B. Viswanath, K. Kekre, Y.L. Lee, H.Y. Ng, S.L. Ong, and H. Seah, 2011. RO Brine Treatment and Recovery by Biological Activated Carbon and Capacitive Deionization Process. Water Science and Technology, 64(1): 77-82, doi: http://dx.doi.org/10.2166/wst.2011.604.

Voltea, 2018. Voltea's CAPDI Technology Product & Systems Catalog. Farmer's Branch, Texas, http://voltea.com/wp-content/uploads/2018/03/Voltea-Product-And-Systems-Catalog-UPDATE-1.2018LR.pdf

Welgemoed, T.J., and C.F. Schutte, 2005. Capacitive Deionization Technology™: An Alternative Desalination Solution. Desalination, 183(1-3): 327-340, ISSN 0011-9164, doi: https://doi.org/10.1016/j.desal.2005.02.054.

Zhang, W., M. Mossad, and L. Zou, 2013. A Study of the Long-Term Operation of Capacitive Deionisation in Inland Brackish Water Desalination. Desalination, 320: 80-85, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2013.04.010.

A3 Forward Osmosis Processes

A3.1 Forward Osmosis

A3.1.1 Technology Description

Forward osmosis (FO) can be used to reduce the volume of a saline water source. FO works by drawing pure water across a semi-permeable membrane. Typically, the process is used to extract pure water from a saline source, thereby reducing volume of the saline source and producing fresh water. Unlike RO, FO uses a concentration gradient, rather than the application of hydraulic pressure to produce clean water.

FO uses a draw solution with a high osmotic pressure to essentially pull clean water across a semi-permeable membrane, thereby concentrating the original feed solution (figure A-11). Clean water can be produced from RO concentrate using a FO draw solution, such as sulfur dioxide or ammonium bicarbonate. The draw solution is diluted by water from the RO concentrate (feed); the osmotic agent used to make the draw solution must then be removed by distillation or other means. The recovered osmotic agent can be reused in the FO process.

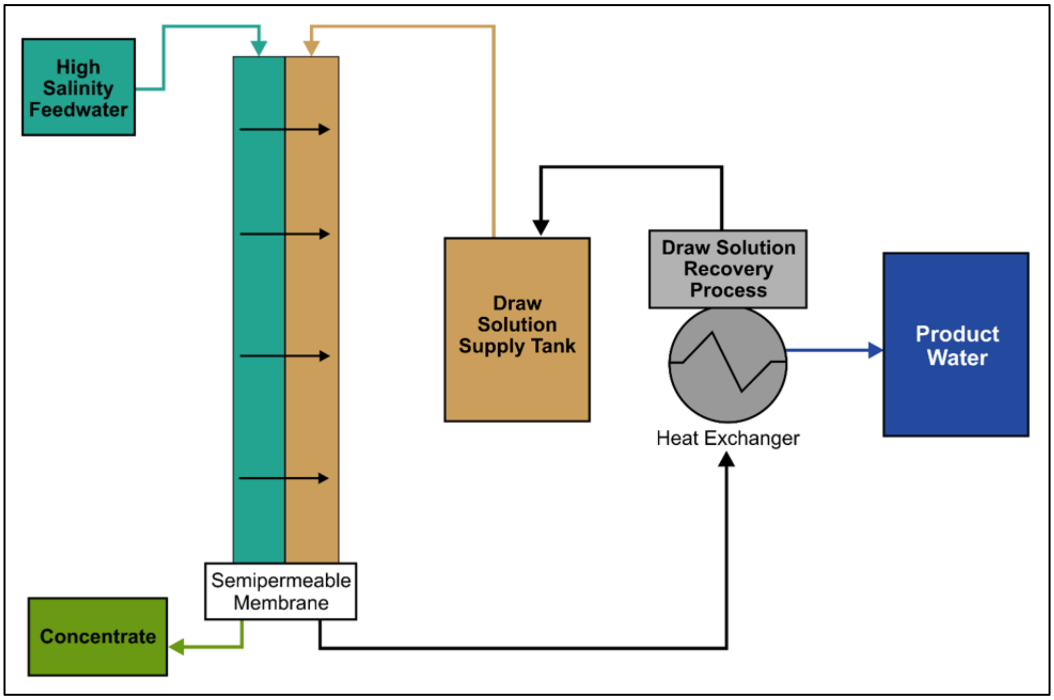

Figure A-11. FO process schematic.

A3.1.2 Technology Constraints

Table A-17 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-17. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Commercial systems exist (e.g., HTI Green Machine and Oasys Membrane Water Concentrator). Few deployments exist; they are primarily in industrial water treatment (e.g., oil and gas and cooling tower blowdown).	8	Coday et al., 2014 Subramani and Jacangelo, 2014
Flexibility	Changing feed water quality (salinity) will reduce the driving force, thereby reducing the flux of FO; however, the system will tolerate these changes without significant upset.	Yes	
Scalability	Like other membrane technologies, FO is modular, and more units can be added or taken offline to accommodate changing process flows.	Yes	
Environmental constraints	No environmental constraints.	Yes	
Process residual	A concentrate stream (more concentrated than the original feed with smaller volume) is produced from the FO process, which requires further treatment/disposal.	Yes	
Land area availability	FO requires a small to moderate amount of land area near the RO facility.	Yes	
Feed water quality limitations	The feed water must have a lower osmotic pressure than the draw solution; this can be problematic for more highly saline concentrate streams. Highly saline concentrates would require very concentrated draw solutions.	No	

A3.1.3 Technology Capability

Table A-18 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-18. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Commercial systems exist (e.g., HTI Green Machine and Oasys Membrane Water Concentrator). Few deployments exist; they are primarily in industrial water treatment (e.g., oil and gas and cooling tower blowdown).	8	Coday et al., 2014 Subramani and Jacangelo 2014
Produces additional "usable" water	FO produces additional water of high quality; water flux/productivity is lower than with other technologies such as RO.	2	
If water is produced, anticipated water quality (salinity)	Similar to RO permeate. Higher boron rejection than with RO.	3	
Overall process recovery (concentrate volume minimization)	98% if the primary RO recovers 80%.	3	Coday et al., 2014
Residual waste disposal	Concentrate will require disposal.	1	
Limitations to large-scale utilization	Low flux rates are the primary limiting factor. They require a large membrane area.	1	
Hardness removal	High	3	
Heavy metals removal	High	3	
Organic contaminant removal	Medium-high	2	
Radionuclide removal	High	3	
Low chemical demand	Additional chemicals are needed to generate the draw solution.	0	
Energy demand	Reported energy requirements for cooling tower blowdown water treatment: 90 kWh/m^3 (thermal).	2	Oasys Water, 2018
Labor requirements	Similar to RO, but with slightly more membrane area due to lower fluxes; also need to support draw solution recovery process.	1	
Reliability	Similar to RO.	1	
Value added	None.	0	

A3.1.4 Life-Cycle Costs

There are lower operating costs due to low energy requirements; however, there are high capital costs for membranes and probably high equipment costs for draw solution recovery.

A3.1.5 Research Needs

The following are research needs that could increase the use of FO for concentrate treatment:

- Operational and/or membrane property improvements to reduce fouling
- Higher membrane packing density or improved membrane flux to reduce the required footprint/membrane area
- Better understanding of process cost to allow utilities to weigh benefits of investing in this technology
- Improved draw solution and recovery methods.

A3.1.6 References

Coday, B., P. Xu, E.G. Beaudry, J. Herron et al., 2014. The Sweet Spot of Forward Osmosis: Treatment of Produced Water, Drilling Wastewater, and Other Complex and Difficult Liquid Streams. Desalination, Volume 333, Issue 1, January 15, p. 23-35. https://doi.org/10.1016/j.desal.2013.11.014.

Garcia-Castello, E.M., J.R. McCutcheon, and M. Elimelech, 2009. Performance Evaluation of Sucrose Concentration Using Forward Osmosis. Journal of Membrane Science, Volume 338, Issues 1–2, August 10, p. 61-66. http://doi.org/10.1016/j.memsci.2009.04.011.

Hancock, N.T., and T.Y. Cath, 2009. Solute Coupled Diffusion in Osmotically Driven Membrane \Processes. Environmental Science and Technology, 43(17): 6769-6775, http://doi.org/10.1021/es901132x.

Hancock, N.T., P. Xu, D.M. Heil, C. Bellona, and T.Y. Cath, 2011. Comprehensive Bench- and Pilot-Scale Investigation of Trace Organic Compounds Rejection by Forward Osmosis. Environmental Science and Technology, 45(19): 8483-8490, http://doi.org/10.1021/es201654k.

Martinetti, C.R., A.E. Childress, and T.Y. Cath, 2009. High Recovery of Concentrated RO Brines Using Forward Osmosis and Membrane Distillation. Journal of Membrane Science, 331(1-2): 31-39, http://doi.org/10.1016/j.memsci.2009.01.003.

McCutcheon, J.R, R.L. McGinnis, and M. Elimelech, 2006. Desalination by Ammonia–Carbon Dioxide Forward Osmosis: Influence of Draw and Feed Solution Concentrations on Process Performance. Journal of Membrane Science, Volume 278, Issues 1–2, July 5, p. 114-123.

Oasys Water, 2018. Company Web Site. Retrieved from http://oasyswater.com/. May 9, 2018.

Pérez-González, A., A.M. Urtiaga, R. Ibáñez, and I. Ortiz, 2012. State of the Art and Review on the Treatment Technologies of Water Reverse Osmosis Concentrates. Water Research, 46(2): 267-283. http://doi.org/10.1016/j.watres.2011.10.046.

Sponsor, S., R. Now, and L. News, 2015. Oasys Forward Osmosis Concentrates in China, 1–2.

Subramani, A., and J.G. Jacangelo, 2014. Treatment Technologies for Reverse Osmosis Concentrate Volume Minimization: A Review. Separation and Purification Technology, 122(10): 472-489. http://doi.org/10.1016/j.seppur.2013.12.004.

A4. Membrane Distillation Processes

A4.1 Membrane Distillation

A4.1.1 Technology Description

Membrane distillation (MD) uses membranes and a vapor pressure driving force to produce distillate. MD increases water production and uses less energy than traditional thermal distillation. It can be used as a primary desalination method; however, because distillate 49 production is less dependent on feed water salinity than conventional membrane desalination, it may be best suited to secondary desalination specifically tailored to concentrate desalination.

In MD, water vapor condenses on the permeate side of the membrane. There are various configurations that condense this vapor. Figure 12 shows the basic process for MD's various configurations: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and sweeping gas membrane distillation (SGMD). Each of these configurations has its own assessment sheet.

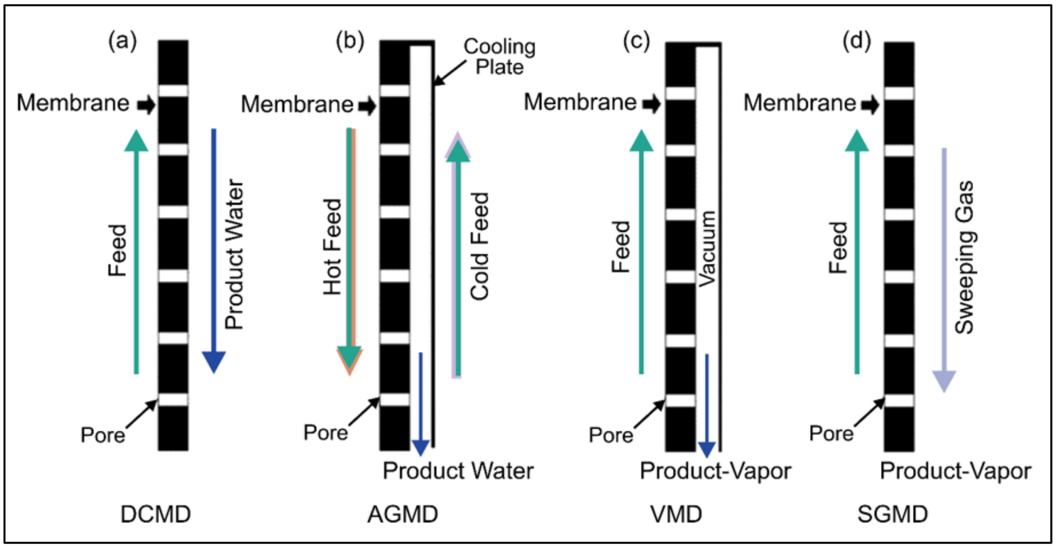

Figure A-12. Schematic diagram of MD configurations (based on Camacho et al., 2013).

A4.1.2 Technology Constraints

Table A-19 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-19. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	There is a known installation of a small-scale seawater MD treatment system for a municipal application in Maldives (with capacity less than 2 gpm); however, very few full-scale commercial vendors exist for this technology, and it has not been used for concentrate management at a full scale.	7	Aquaver, 2014
Flexibility	MD can treat a wide range of TDS.	Yes	
Scalability	From market research, largest single unit commercially available is ~ 8 gpm; therefore, multiple units would be necessary to meet higher demands.	Yes	
Environmental constraints	Availability of waste heat or economic capture of solar/geothermal energy greatly improves process economics.	Yes	
Process residual	Concentrated brine and spent cleaning chemicals.	Yes	
Land area availability	Incorporating solar thermal energy may require large land areas. Packing density of system is relatively low.	Yes	
Feed water quality limitations	Volatile constituents are not removed or retained; however, this is typically not a major concern for municipal drinking water concentrate. Scale-forming constituents could be problematic for sustained operations.	Yes	Warsinger et al., 2015

Note: gpm = gallons per minute.

A4.1.3 Technology Capability

Table A-20 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A4.1.4 Life-Cycle Costs

There are limited cost data for various MD configurations. Capital cost would be high because low production efficiency requires more membranes. Operating costs would be lower due to vapor pressure driving force (Wang and Chung, 2015).

Table A-20. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	There is a known installation of a small-scale seawater MD treatment system for a municipal application in Maldives (with a capacity less than 2 gpm); however, very few full-scale commercial vendors exist for this technology, and it has not been used for concentrate management at a full scale.	7	Aquaver, 2014
Produces additional "usable" water	< 1 mg/L.	3	Adham et al., 2013
If water is produced, anticipated water quality (salinity)	80%.	2	Camacho et al., 2013 Martinetti et al., 2009
Overall process recovery (concentrate volume minimization)	RO-MD = 89% overall recovery.	2	Camacho et al., 2013
Residual waste disposal	Final concentrate volume can be small. Because no chemicals are added, there are minimal residuals.	3	
Limitations to large-scale utilization	The process has low flux; therefore, MD requires more membrane area. Waste heat availability can increase cost. Because this is not in widespread use, potential issues for large-scale use are not well researched.	1	
Hardness removal	Very high rejection of all salts.	3	
Heavy metals removal	Very high rejection of heavy metals.	3	
Organic contaminant removal	Volatile compounds will not be rejected, and MD may have higher passage of compounds with neutral charges.	1	
Radionuclide removal	Very high rejection of radionuclides.	3	
Low chemical demand	Antiscalants may be used, although literature is inconclusive regarding their effectiveness.	3	Warsinger et al., 2015
Energy demand	Waste heat or solar thermal heat can be used to offset grid-supplied energy.	2	
Labor requirements	Difficult to assess due to limited number of full-scale installations.	2	
Reliability	Difficult to assess due to limited number of full-scale installations.	2	
Value added	Waste heat uses an otherwise unusable resource to produce fresh water	1	

A4.1.5 Research Needs

Development of MD technologies would benefit from research in:

- Development of new and improved membranes
- Improved module design
- Development of protocols for choosing the best available technologies and operating conditions
- More accurate modeling to understand how process performance can impact costs at full scale-installations (Drioli et al., 2015).

A4.1.6 References

Adham, S., A. Hussain, J.M. Matar, R. Dores, and A. Janson, 2013. Application of Membrane Distillation for Desalting Brines from Thermal Desalination Plants. Desalination, 314: 101-08. http://doi.org/10.1016/j.desal.2013.01.003.

Aquaver, 2014. Desalination Plant Powered by Waste Heat Opens in Maldives. EIP Water. European Innovation Partnerships on Water, https://www.eip-water.eu/desalination-plant-powered-waste-heat-opens-maldives.

Camacho, L.M., L. Dumee, and J. Zhang, 2013. Advances in Membrane Distillation for Water Desalination and Purification Applications. Water, 5(1): 94-196. https://doi.org/10.3390/w5010094.

Drioli, E., A. Ali, and F. Macedonio, 2015. Membrane Distillation: Recent Developments and Perspectives. Desalination, 356: 56-84, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2014.10.028.

Martinetti, C.R., A.E. Childress, and T.Y. Cath, 2009. High Recovery of Concentrated RO Brines Using Forward Osmosis and Membrane Distillation. Journal of Membrane Science, 331(1-2): 31-39, ISSN 0376-7388, https://doi.org/10.1016/j.memsci.2009.01.003.

Wang, P., and T-S. Chung, 2015. Recent Advances in Membrane Distillation Processes: Membrane Development, Configuration Design and Application Exploring. Journal of Membrane Science, 474: 39-56, https://doi.org/10.1016/j.memsci.2014.09.016.

Warsinger, D.M., J. Swaminathan, E. Guillen-Burrieza, H.A. Arafat, and J.H. Lienhard, 2015. Scaling and Fouling in Membrane Distillation for Desalination Applications: A Review. Desalination, 356: 294-313. https://doi.org/10.1016/j.desal.2014.06.031.

A4.2 Air Gap Membrane Distillation

A4.2.1 Technology Description

Membrane distillation uses membranes and a vapor pressure driving force to produce distillate. MD increases water production and uses less energy than traditional thermal distillation. It can be used as a primary desalination method; however, because distillate production is less dependent on feed water salinity than conventional membrane desalination, it may be best suited to secondary desalination specifically tailored to concentrate desalination.

In MD, water vapor condenses on the permeate side of the membrane. There are various configurations that condense this vapor. In the AGMD configuration (figure A-13), there is an air gap between the permeate side of the membrane and the cooling surface. The water vapor going through the membrane must also travel through the airgap and condense on the cool surface, forming a liquid permeate.

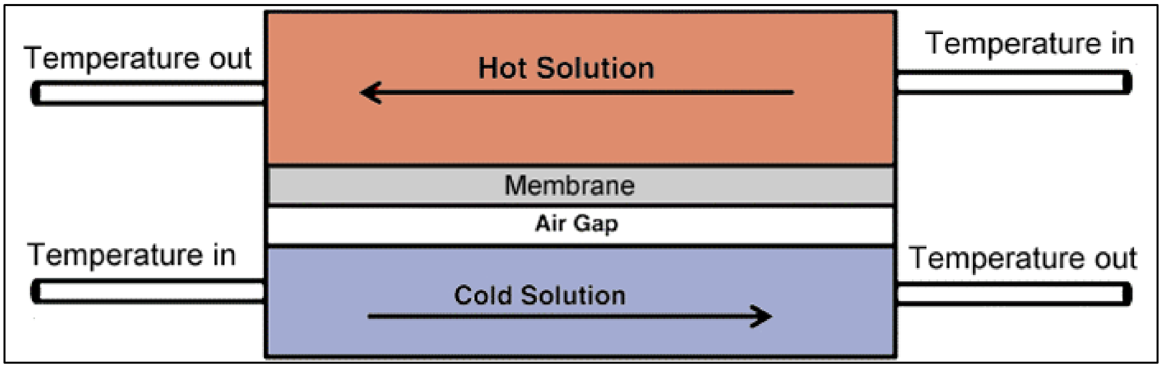

Figure A-13. AGMD configuration (based on Alkhudhiri et al., 2012).

A4.2.2 Technology Constraints

Table A-21 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-21. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	AGMD currently has small-scale installations and testing has been done on them.	6	Alkhudhiri et al., 2012 Thomas et al., 2017 Mickley, 2020
Flexibility	AGMD can treat a wide variety of TDS.	Yes	
Scalability	The largest single unit commercially available is ~ 8 gpm; therefore, multiple units would be necessary to meet higher demands. System is scalable.	Yes	
Environmental constraints	Availability of waste heat or economic capture of solar/geothermal energy improves process economics.	Yes	
Process residual	Concentrated brine and spent cleaning chemicals.	Yes	
Land area availability	Incorporating solar thermal energy may require a large land area. The packing density of the system is relatively low. The footprint of the AGMD process itself is low and comparable to other membrane treatment systems.	Yes	
Feed water quality limitations	Volatile constituents are not removed or retained; however, this is typically not a major concern for municipal drinking water concentrate. Scale-forming constituents could be problematic for sustained operations.	Yes	Warsinger et al., 2015

A4.2.3 Technology Capability

Table A-22 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A4.2.4 Life-Cycle Costs

There are limited cost data for various MD configurations. AGMD would have higher capital cost due to low production efficiency and lower operating cost due to vapor pressure driving force. More process equipment is required for AGMD than for DCMD (Saffarini et al., 2012; Meindersma et al., 2006).

Table A-22. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	AGMD currently has small scale installations and testing has done on them.	6	Alkhudhiri et al., 2012 Thomas et al., 2017 Mickley, 2020
Produces additional "usable" water	Distillate can be used as a new water supply.	3	
If water is produced, anticipated water quality (salinity)	Water quality of condensed water vapor is low in TDS.	3	Adham et al., 2013 Pangarkar and Sane, 2011
Overall process recovery (concentrate volume minimization)	Higher than 90% overall recovery is achievable by using MD to treat concentrate for most feed water qualities.	2	Camacho et al., 2013
Residual waste disposal	Final concentrate volume can be small, but it contains the feed constituents. This small volume may require additional handling steps, but this is not a limitation of the process.	3	
Limitations to large-scale utilization	As the process has low flux, DCMD requires more membrane area than other membrane processes to treat the same quantity of water. Waste heat availability can increase cost. As this is not in widespread use, potential issues for large-scale use are not well researched.	1	
Hardness removal	High rejection of salts.	3	Pangarkar and Sane, 2011
Heavy metals removal	High rejection of heavy metals.	3	
Organic contaminant removal	Volatile compounds will not be rejected, and more compounds with a neutral charge may be passed.	1	Alkhudhiri et al., 2012
Radionuclide removal	High rejection of radionuclides.	3	
Low chemical demand	Antiscalants may be used.	3	Warsinger et al., 2015
Energy demand	Waste heat or solar thermal heat can be used to offset grid supplied energy usage.	2	Alsaadi et al., 2013
Labor requirements	Difficult to assess due to limited number of full-scale installations.	2	Alsaadi et al., 2013
Reliability	Difficult to assess due to limited number of full-scale installations. Additional process equipment is needed when comparing AGMD to DCMD.	1	Alsaadi et al., 2013
Value added	Waste heat utilization can reduce cost of MD treatment	1	

A4.2.5 Research Needs

Development of MD technologies and all various configurations will benefit from the following areas of research:

- Development of new and improved membranes with higher fluxes and lower fouling
- Improved module design
- Development of protocols for choosing the best available technologies and operating conditions
- More accurate modeling to understand how process performance can impact costs at full-scale installations (Drioli et al., 2015).

A4.2.6 References

Adham, Samer & Hussain, Altaf & Minier-Matar, Joel & Dores, Raul & Janson, Arnold. (2013). Application of Membrane Distillation for desalting brines from thermal desalination plants. Desalination. 314. 101–108. 10.1016/j.desal.2013.01.003.

Alkhudhiri, A., N. Darwish, and N. Hilal, 2012. Membrane Distillation: A Comprehensive Review. Desalination, 287: 2-18, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2011.08.027.

Alsaadi, A.S., N. Ghaffour, and J.-D. Li, 2013. Modeling of Air-Gap Membrane Distillation Process: A Theoretical and Experimental Study. Journal of Membrane Science, 445:53-65, https://www.sciencedirect.com/science/article/pii/S0376738813004705.

Camacho, Lucy & Ludovic, Dumée & Zhang, Jianhua & Li, Jun-de & Duke, Mikel & Gomez, Juan & Gray, Steve. (2013). Advances in Membrane Distillation for Water Desalination and Purification Applications. Water. 5. 94-196.

Drioli, E., A. Ali, and F. Macedonio, 2015. Membrane Distillation: Recent Developments and Perspectives. Desalination, 356: 56-84, ISSN 0011-9164. https://doi.org/10.1016/j.desal.2014.10.028.

Meindersma, G.W., C.M. Guijt, and A.B. de Haan, 2006. Desalination and Water Recycling by Air Gap Membrane Distillation. Desalination, 187:291-301, https://doi.org/10.1016/j.desal.2005.04.088.

Mickley, 2020. Report 208 (in publication). Mickley and Associates, Lafayette, Colorado.

Pangarkar, B.L., and M.G. Sane, 2011. Performance of Air Gap Membrane Distillation for Desalination of Ground Water and Seawater. International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 5:177-181, https://www.semanticscholar.org/paper/Performance-of-Air-Gap-Membrane-Distillation-for-of-Pangarkar-Sane/62d08d459b135c49275919350214afd2cf2bd5ae.

Pramanik, B.K., K. Thangavadivel, and L. Shu, 2016. A Critical Review of Membrane Crystallization for the Purification of Water and Recovery of Minerals. Reviews in Environmental Science and Bio/Technology, 15: 411-439, https://doi.org/10.1007/s11157-016-9403-0.

Ruiz Salm´on, I., and P. Luis, 2018. Membrane Crystallization via Membrane Distillation. Chemical Engineering and Processing, 123: 258-271, https://doi.org/10.1016/j.cep.2017.11.017.

Saffarini, R.B., E.K. Summers, H.A. Arafat, and J.H. Lienhard, 2012. Economic Evaluation of Stand-Alone Solar Powered Membrane Distillation Systems. Desalination, 299:55-62, https://doi.org/10.1016/j.desal.2012.05.017.

Thomas, N., M.O. Mavukkandy, S. Loutatidou, and H.A. Arafat, 2017. Membrane Distillation Research & Implementation: Lessons from the Past Five Decades. Separation and Purification Technology, 189:108-127, https://app.dimensions.ai/details/publication/pub.1090940325.

Warsinger, D.M., J. Swaminathan, E. Guillen Burrieza, H.A. Arafat, and J.H. Lienhard, 2015. Scaling and Fouling in Membrane Distillation for Desalination Applications: A Review. Desalination, 356: 294-313, https://doi.org/10.1016/j.desal.2014.06.031.

A4.3 Direct Contact Membrane Distillation

A4.3.1 Technology Description

Membrane distillation uses membranes and a vapor pressure driving force to produce distillate. MD increases water production and uses less energy than traditional thermal distillation. It can be used as a primary desalination method; however, because distillate production is less dependent on feed water salinity than conventional membrane desalination, it may be best suited to secondary desalination specifically tailored to concentrate desalination.

In MD, water vapor condenses on the permeate side of the membrane. There are various configurations that condense this vapor. In the DCMD configuration, a cooler liquid is in direct contact with the membrane on the distillate side of the membrane. This results in water vapor going through the membrane and condensing in the cold solution. Figure A-14 shows this process.

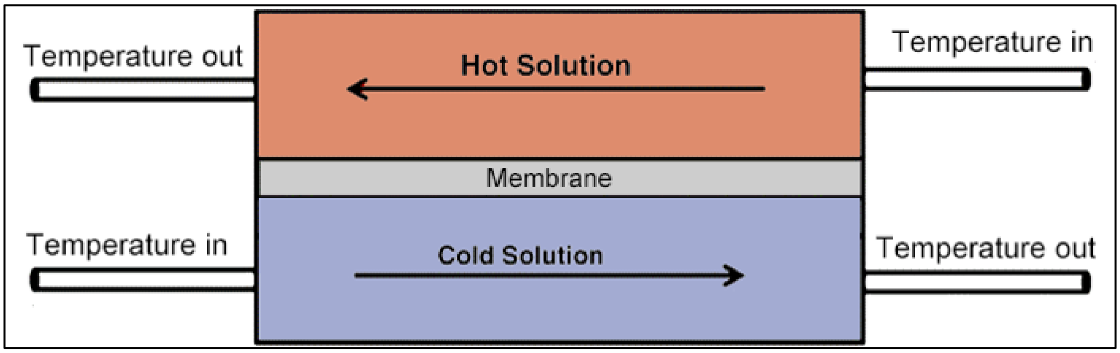

Figure A-14. DCMD configuration (based on Alkhudhiri et al., 2012).

A4.3.2 Technology Constraints

Table A-23 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

A4.3.3 Technology Capability

Table A-24 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-23. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	DCMD is currently the most mature configuration of MD.	7	Alkhudhiri et al., 2012 Thomas et al., 2017 Mickley, 2020
Flexibility	MD can treat a wide range of TDS.	Yes	
Scalability	From market research, the largest single unit commercially available is ~ 8 gpm; therefore, multiple units would be necessary to meet higher demands. System is scalable.	Yes	
Environmental constraints	Availability of waste heat or economic capture of solar/geothermal energy improves process economics.	Yes	
Process residual	Concentrated brine and spent cleaning chemicals	Yes	
Land area availability	Incorporating solar thermal energy may require a large land area. Packing density of the system is relatively low. The footprint of the MD process itself is low and comparable to other membrane treatment systems.	Yes	
Feed water quality limitations	Volatile constituents are not removed or retained; however, this is typically not a major concern for municipal drinking water concentrate. Scale-forming constituents could be problematic for sustained operations.	Yes	Warsinger et al., 2015

Table A-24. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	DCMD is currently the most mature configuration of MD.	7	Alkhudhiri et al., 2012 Thomas et al., 2017 Mickley, 2020
Produces additional “usable” water	Distillate can be used as new water supply.	3	
If water is produced, anticipated water quality (salinity)	Water quality of condensed water vapor is low in TDS.	3	Adham et al., 2013
Overall process recovery (concentrate volume minimization)	MD can recover more than 90% overall recovery for most feed water qualities.	2	Camacho et al. 2013

Table A-24. Technology Capabilities

Capability	Assessment	Score	References
Residual waste disposal	Final concentrate volume can be small, but it contains the feed constituents. This small volume may require additional handling steps, but this is not a limitation of the process.	3	
Limitations to large-scale utilization	As the process has low flux, DCMD requires more membrane area than other membrane processes to treat the same quantity of water. Waste heat availability can increase cost. As this is not in widespread use, potential issues for large-scale use are not well researched.	1	
Hardness removal	High rejection of salts.	3	
Heavy metals removal	High rejection of heavy metals.	3	
Organic contaminant removal	Volatile compounds will not be rejected, and DCMD may have higher passage of compounds with neutral charges.	1	
Radionuclide removal	High rejection of radionuclides.	3	
Low chemical demand	Antiscalants may be used.	3	Warsinger et al., 2015
Energy demand	Waste heat or solar thermal heat can be used to offset grid-supplied energy.	2	
Labor requirements	Difficult to assess due to limited number of full-scale installations.	2	
Reliability	Difficult to assess due to limited number of full-scale installations.	2	
Value added	Using waste heat can reduce the cost of MD treatment.	1	

A4.3.4 Life-Cycle Costs

There are limited cost data for various MD configurations. Capital cost would be high because low production efficiency requires more membranes. Operating costs would be lower due to vapor pressure driving force.

A4.3.5 Research Needs

Development of MD technologies and all various configurations would benefit from the following areas of research:

- Development of new and improved membranes with higher fluxes and lower fouling

- Improved module design
- Development of protocols for choosing the best available technologies and operating conditions
- More accurate modeling to understand how process performance can impact costs at full scale installations (Drioli et al., 2015)

A4.3.6 References

Adham, S., A. Hussain, J.M. Matar, R. Dores, and A. Janson, 2013. Application of Membrane Distillation for Desalting Brines from Thermal Desalination Plants. Desalination, 314: 101-08. http://doi.org/10.1016/j.desal.2013.01.003.

Alkhudhiri, A., N. Darwish, and N. Hilal, 2012. Membrane Distillation: A Comprehensive Review. Desalination, 287: 2-18, ISSN 0011-9164. https://doi.org/10.1016/j.desal.2011.08.027.

Camacho, L.M., L. Dumee, and J. Zhang, 2013. Advances in Membrane Distillation for Water Desalination and Purification Applications. Water, 5(1): 94-196. https://doi.org/10.3390/w5010094.

Drioli, E., A. Ali, and F. Macedonio, 2015. Membrane Distillation: Recent Developments and Perspectives. Desalination, 356: 56-84, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2014.10.028.

Mickley, 2020. Report 208 (in publication). Mickley and Associates, Lafayette, Colorado.

Pramanik, B.K., K. Thangavadivel, L. Shu, and V. Jegatheesan, 2016. A Critical Review of Membrane Crystallization for the Purification of Water and Recovery of Minerals. Reviews in Environmental Science and Bio/Technology, 15: 411, https://doi.org/10.1007/s11157-016-9403-0.

Ruiz Salm´on, I., and P. Luis, 2018. Membrane Crystallization via Membrane Distillation. Chemical Engineering and Processing, 123: 258-271, https://doi.org/10.1016/j.cep.2017.11.017.

Thomas, N., M.O. Mavukkandy, S. Loutatidou, and H.A. Arafat, 2017. Membrane Distillation Research and Implementation: Lessons from the Past Five Decades. Separation and Purification Technology, 189: 108-127, https://doi.org/10.1016/j.seppur.2017.07.069.

Warsinger, D.M., J. Swaminathan, E. Guillen-Burrieza, H.A. Arafat, and J.H. Lienhard, 2015. Scaling and Fouling in Membrane Distillation for Desalination Applications: A Review. Desalination, 356: 294-313, https://doi.org/10.1016/j.desal.2014.06.031.

A4.4 Sweep Gas Membrane Distillation

A4.4.1 Technology Description

Membrane distillation uses membranes and a vapor pressure driving force to produce distillate. MD increases water production and uses less energy than traditional thermal distillation. It can be used as a primary desalination method; however, because distillate production is less dependent on feed water salinity than conventional membrane desalination, it may be best suited to secondary desalination specifically tailored to concentrate desalination.

In MD, water vapor condenses on the permeate side of the membrane (figure A-15). There are various configurations that condense this vapor. In the SGMD configuration (figure A-15), a cooler sweep gas flows through the permeate side of the membrane and captures the water vapor. The resulting gas stream is condensed outside the MD module, producing a liquid permeate stream.

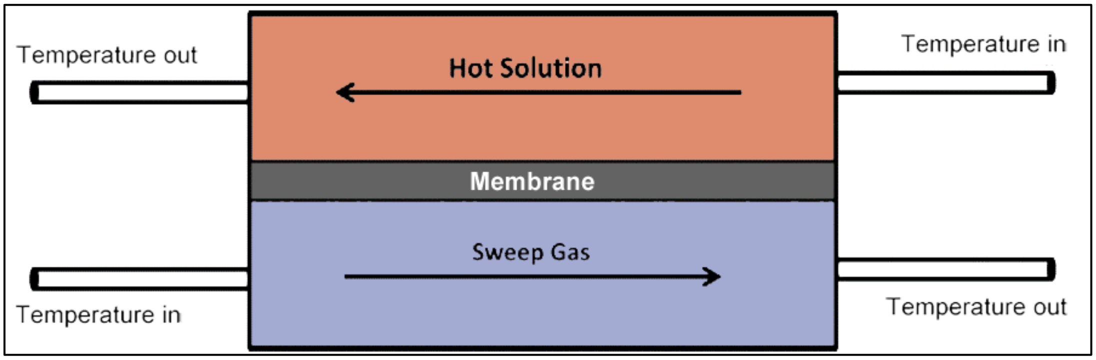

Figure A-15. SGMD configuration (based on Alkhudhiri et al., 2012).

A4.4.2 Technology Constraints

Table A-25 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

A4.4.3 Technology Capability

Table A-26 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-25. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	SGMD currently has limited small-scale installations, and testing has taken place for water/concentrate treatment.	5	Alkhudhiri et al., 2012 Thomas et al., 2017 Mickley, 2020
Flexibility	MD can treat a wide range of TDS.	Yes	
Scalability	From market research, the largest single unit that is commercially available is ~ 8 gpm; therefore, multiple units would be necessary to meet higher demands. System is scalable.	Yes	
Environmental constraints	Availability of waste heat or economic capture of solar/geothermal energy improves process economics.	Yes	
Process residual	Concentrated brine and spent cleaning chemicals.	Yes	
Land area availability	Incorporating solar thermal energy may require a large land area. Packing density of the system is relatively low. The footprint of the MD process itself is low and comparable to other membrane treatment systems.	Yes	
Feed water quality limitations	Volatile constituents are not removed or retained; however, this is typically not a major concern for municipal drinking water concentrate. Scale-forming constituents could be problematic for sustained operations.	Yes	Warsinger et al., 2015

Table A-26. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	SGMD currently has limited small-scale installations and testing has taken place for water/concentrate treatment.	5	Alkhudhiri et al., 2012 Thomas et al., 2017 Mickley, 2020
Produces additional “usable” water	Distillate can be used as new water supply.	3	
If water is produced, anticipated water quality (salinity)	Water quality of condensed water vapor is low in TDS.	3	Adham et al., 2013
Overall process recovery (concentrate volume minimization)	Higher than 90% overall recovery is achievable by using MD to treat concentrate for most feed water qualities.	2	Camacho et al., 2013
Residual waste disposal	Final concentrate volume can be small, but it contains the feed constituents. This small	3	

Table A-26. Technology Capabilities

Capability	Assessment	Score	References
	volume may require additional handling steps, but this is not a limitation of the process.		
Limitations to large-scale utilization	As the process has low flux, SGMD requires more membrane area than other membrane processes to treat the same quantity of water. Waste heat availability can increase cost. As this is not in widespread use, potential issues for large-scale use are not well researched.	1	
Hardness removal	High rejection of salts.	3	
Heavy metals removal	High rejection of heavy metals.	3	
Organic contaminant removal	Volatile compounds will not be rejected, and SGMD may have higher passage of compounds with neutral charges.	1	
Radionuclide removal	High rejection of radionuclides.	3	
Low chemical demand	Antiscalants may be used.	3	Warsinger et al., 2015
Energy demand	Waste heat or solar thermal heat can be used to offset grid-supplied energy.	2	
Labor requirements	Difficult to assess due to limited number of full-scale installations.	2	
Reliability	Difficult to assess due to limited number of full-scale installations.	1	
Value added	Waste heat use can reduce the cost of MD treatment.	1	

A4.4.4 Life-Cycle Costs

There are limited cost data for various MD configurations. Capital cost would be high because low production efficiency requires more membranes. Operating costs would be lower due to vapor pressure driving force. More process equipment is needed for SGMD than for DCMD (Meindersma et al., 2006; Saffarini et al., 2012).

A4.4.5 Research Needs

Development of MD technologies and all various configurations would benefit from the following areas of research:

- Development of new and improved membranes with higher fluxes and lower fouling
- Improved module design

- Development of protocols for choosing the best available technologies and operating conditions
- More accurate modeling to understand how process performance can impact costs at full-scale installations (Drioli et al., 2015)

A4.4.6 References

Adham, Samer & Hussain, Altaf & Minier-Matar, Joel & Dores, Raul & Janson, Arnold. (2013). Application of Membrane Distillation for desalting brines from thermal desalination plants. Desalination. 314. 101–108. 10.1016/j.desal.2013.01.003.

Alkhudhiri, A., N. Darwish, and N. Hilal, 2012. Membrane Distillation: A Comprehensive Review. Desalination, 287: 2-18, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2011.08.027.

Alsaadi, A.S., N. Ghaffour, and J.-D. Li, 2013. Modeling of Air-Gap Membrane Distillation Process: A Theoretical and Experimental Study. Journal of Membrane Science, 445:53-65, https://www.sciencedirect.com/science/article/pii/S0376738813004705.

Camacho, Lucy & Ludovic, Dumée & Zhang, Jianhua & Li, Jun-de & Duke, Mikel & Gomez, Juan & Gray, Steve. (2013). Advances in Membrane Distillation for Water Desalination and Purification Applications. Water. 5. 94-196.

Drioli, E., A. Ali, and F. Macedonio, 2015. Membrane Distillation: Recent Developments and Perspectives. Desalination, 356: 56-84, ISSN 0011-9164. https://doi.org/10.1016/j.desal.2014.10.028.

Meindersma, G.W., C.M. Guijt, and A.B. de Haan, 2006. Desalination and Water Recycling by Air Gap Membrane Distillation. Desalination, 187: 291-301, https://doi.org/10.1016/j.desal.2005.04.088.

Mickley, 2020. Report 208 (in publication). Mickley and Associates, Lafayette, Colorado.

Pangarkar, B.L., and M.G. Sane, 2011. Performance of Air Gap Membrane Distillation for Desalination of Ground Water and Seawater. International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering, 5: 177-181. https://www.semanticscholar.org/paper/Performance-of-Air-Gap-Membrane-Distillation-for-of-Pangarkar-Sane/62d08d459b135c49275919350214afd2cf2bd5ae.

Pramanik, B.K., K. Thangavadivel, L. Shu, and V. Jegatheesan, 2016. A Critical Review of Membrane Crystallization for the Purification of Water and Recovery of Minerals. Reviews in Environmental Science and Bio/Technology, 15: 411, https://doi.org/10.1007/s11157-016-9403-0.

Ruiz Salm´on, I., and P. Luis, 2018. Membrane Crystallization via Membrane Distillation. Chemical Engineering and Processing – Process Intensification, 123: 258-271, https://doi.org/10.1016/j.cep.2017.11.017.

Saffarini, R.B., E.K. Summers, H.A. Arafat, and J.H. Lienhard, 2012. Economic Evaluation of Stand-Alone Solar Powered Membrane Distillation Systems. Desalination, 299: 55-62, https://doi.org/10.1016/j.desal.2012.05.017.

Thomas, N., M.O. Mavukkandy, S. Loutatidou, and H.A. Arafat, 2017. Membrane Distillation Research and Implementation: Lessons from the Past Five Decades. Separation and Purification Technology, 189: 108-127, https://doi.org/10.1016/j.seppur.2017.07.069.

Warsinger, D.M., J. Swaminathan, E. Guillen-Burrieza, H.A. Arafat, and J.H. Lienhard, 2015. Scaling and Fouling in Membrane Distillation for Desalination Applications: A Review. Desalination, 356: 294 – 313. https://doi.org/10.1016/j.desal.2014.06.031.

A4.5 Vacuum Membrane Distillation

A4.5.1 Technology Description

Membrane distillation uses membranes and a vapor pressure driving force to produce distillate. MD increases water production and uses less energy than traditional thermal distillation. It can be used as a primary desalination method; however, because distillate production is less dependent on feed water salinity than conventional membrane desalination, it may be best suited to secondary desalination specifically tailored to concentrate desalination.

In MD, water vapor condenses on the permeate side of the membrane (figure A-16). There are various configurations that condense this vapor. In the VMD configuration, a vacuum draws and condenses the water vapor across the membrane and into the permeate side of the membrane.

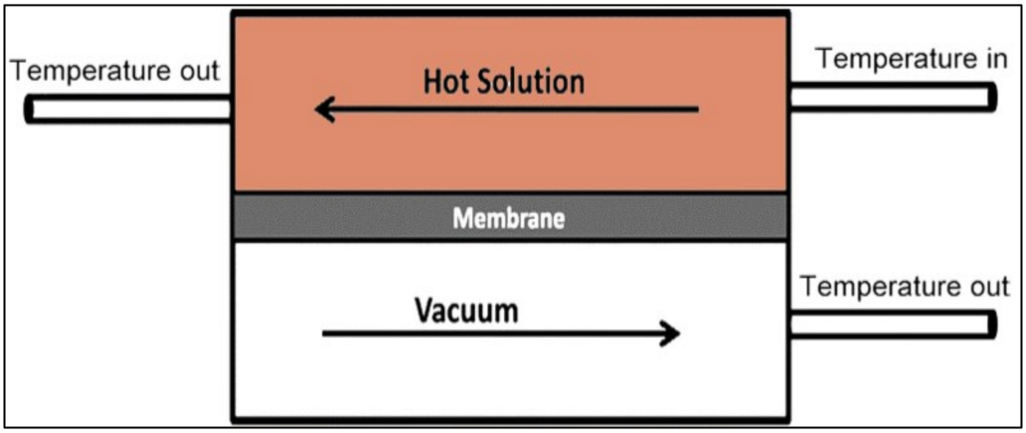

Figure A-16. VMD configuration (based on Alkhudhiri et al., 2012).

A4.5.2 Technology Constraints

Table A-27 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

A4.5.3 Technology Capability

Table A-28 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-27. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	VMD currently has small-scale installations and testing done on them.	6	Alkhudhiri et al. 2012 Thomas et al. 2017 Mickley 2020
Flexibility	MD can treat a wide range of TDS.	Yes	
Scalability	From market research, the largest single unit commercially available is ~ 175 gpm; therefore, multiple units would be necessary to meet higher demands. System is scalable.	Yes	
Environmental constraints	Availability of waste heat or economic capture of solar/geothermal energy improves process economics.	Yes	
Process residual	Concentrated brine and spent cleaning chemicals.	Yes	
Land area availability	Incorporating solar thermal energy may require a large land area. Packing density of the system is relatively low. The footprint of the MD process itself is low and comparable to other membrane treatment systems.	Yes	
Feed water quality limitations	Volatile constituents are not removed or retained; however, this is typically not a major concern for municipal drinking water concentrate. Scale-forming constituents could be problematic for sustained operations.	Yes	Warsinger et al. 2015

Table A-28. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	VMD currently has small-scale installations, and testing has been performed on them.	6	Alkhudhiri et al., 2012 Thomas et al., 2017 Mickley, 2020
Produces additional “usable” water	Distillate can be used as a new water supply.	3	
If water is produced, anticipated water quality (salinity)	Water quality of condensed water vapor is low in TDS.	3	Adham et al., 2013
Overall process recovery (concentrate volume minimization)	Higher than 90% overall recovery is achievable by using MD to treat concentrate for most feed water qualities.	2	Camacho et al., 2013

Table A-28. Technology Capabilities

Capability	Assessment	Score	References
Residual waste disposal	Final concentrate volume can be small, but it contains the feed constituents. This small volume may require additional handling steps, but this is not a limitation of the process.	3	
Limitations to large-scale utilization	As the process has low flux, VMD requires more membrane area than other membrane processes to treat the same quantity of water. Waste heat availability can increase cost. As this is not in widespread use, potential issues for large-scale use are not well researched.	1	
Hardness removal	High rejection of salts.	3	
Heavy metals removal	High rejection of heavy metals.	3	
Organic contaminant removal	Volatile compounds will not be rejected, and more compounds with a neutral charge may be passed.	1	
Radionuclide removal	High rejection of radionuclides.	3	
Low chemical demand	Antiscalants may be used.	3	Warsinger et al., 2015
Energy demand	Waste heat or solar thermal heat can be used to offset grid supplied energy usage.	2	
Labor requirements	Difficult to assess due to limited number of full-scale installations.	2	
Reliability	Difficult to assess due to limited number of full-scale installations.	1	
Value added	Waste heat use can reduce cost of MD treatment.	1	

A4.5.4 Life-Cycle Costs

There are limited cost data for various MD configurations. AGMD would have higher capital cost due to low production efficiency and lower operating cost due to vapor pressure driving force. More process equipment is required for VMD than for DCMD.

A4.5.5 Research Needs

Development of MD technologies and all various configurations would benefit from the following areas of research:

- Development of new and improved membranes with higher fluxes and lower fouling

- Improved module design
- Development of protocols for choosing the best available technologies and operating conditions
- More accurate modeling to understand how process performance can impact costs at full scale installations (Drioli et al., 2015)

A4.5.6 References

Adham, S., A. Hussain, J.M. Matar, R. Dores, and A. Janson, 2013. Application of Membrane Distillation for Desalting Brines from Thermal Desalination Plants. Desalination, 314: 101-08, http://doi.org/10.1016/j.desal.2013.01.003.

Alkhudhiri, A., N. Darwish, and N. Hilal, 2012. Membrane Distillation: A Comprehensive Review. Desalination, 287: 2-18, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2011.08.027.

Camacho, L.M., L. Dumee, and J. Zhang, 2013. Advances in Membrane Distillation for Water Desalination and Purification Applications. Water, 5(1): 94-196, https://doi.org/10.3390/w5010094.

Drioli, E., A. Ali, and F. Macedonio, 2015. Membrane Distillation: Recent Developments and Perspectives. Desalination, 356: 56-84, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2014.10.028.

Pramanik, B.K., K. Thangavadivel, L. Shu, and V. Jegatheesan, 2016. A Critical Review of Membrane Crystallization for the Purification of Water and Recovery of Minerals. Reviews in Environmental Science and Bio/Technology, 15: 411, https://doi.org/10.1007/s11157-016-9403-0.

Ruiz Salm´on, I., and P. Luis, 2018. Membrane Crystallization via Membrane Distillation. Chemical Engineering and Processing, 123: 258-271, https://doi.org/10.1016/j.cep.2017.11.017.

Thomas, N., M.O. Mavukkandy, S. Loutatidou, and H.A. Arafat, 2017. Membrane Distillation Research and Implementation: Lessons from the Past Five Decades. Separation and Purification Technology, 189: 108-127, https://doi.org/10.1016/j.seppur.2017.07.069.

Mickley, 2020. Report 208 (in publication). Mickley and Associates, Lafayette, Colorado.

Warsinger, D.M., J. Swaminathan, E. Guillen-Burrieza, H.A. Arafat, and J.H. Lienhard, 2015. Scaling and Fouling in Membrane Distillation for Desalination Applications: A Review. Desalination, 356: 294-313, https://doi.org/10.1016/j.desal.2014.06.031.

A4.6 Pervaporation

A4.6.1 Technology Description

Pervaporation combines membrane permeation with evaporation and can be used to selectively separate volatile solution components. Because pervaporation can separate water from a saline feed stream, it can be used for concentrate management. The partial pressure and membrane permeability of each component in the solution drives the separation.

Pervaporation involves permeation through a selective membrane barrier, followed by the evaporation of the permeate to separate solution components (figure A-17). Pervaporation uses a hydrophilic, nonporous membrane to produce clean water from a concentrate stream. The driving force for water flux is a partial pressure gradient achieved through applied vacuum, temperature gradient, a carrier gas, or a combination of the aforementioned (Mallenvialle et al., 1996; Wang et al., 2016). Pervaporation has been reported to have high salinity rejection, due to the low vapor pressure and membrane permeability of salt, and high VOC rejection from low membrane permeability (Wang et al., 2016).

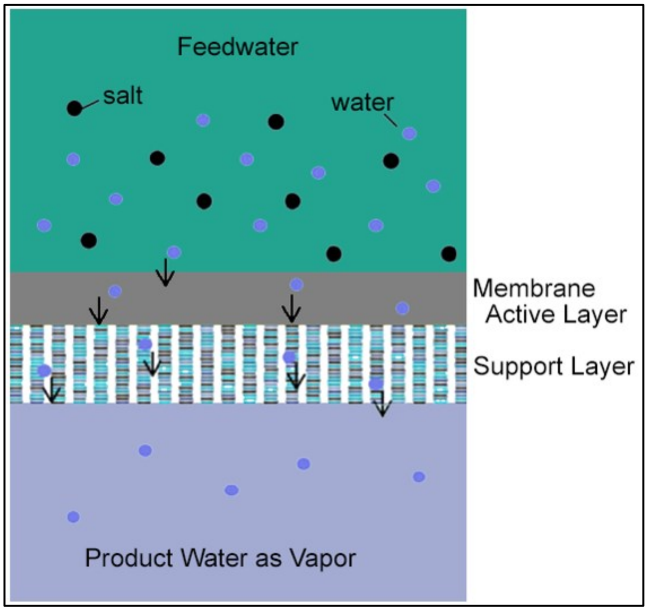

Figure A-17. Schematic diagram of pervaporation separation process (based on Wang et al., 2016).

A4.6.2 Technology Constraints

Table A-29 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-29. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Pervaporation has typically been used for industrial applications because certain components in the feed solution preferentially permeate through a dense or molecular-sieving, porous membrane and evaporate downstream. Although the industrial applications used to remove volatile species from wastewater have shown promise, application for the extraction of water from saline solutions is not well documented.	4	Mallenvialle et al., 1996 Xie,et al., 2011 Wang et al., 2016
Flexibility	Pervaporation can treat highly concentrated salt solutions and does not require much adjustment of driving force.	Yes	Xie et al., 2011 Wang et al., 2016
Scalability	The system can be modular. Additional units can increase the quantity of water treated.	Yes	
Environmental constraints	Low-grade waste heat and/or solar heating of pervaporation feed improves flux.	Yes	Wang et al., 2016
Process residual	Concentrated residual could pose final disposal issues, depending on the level of concentration of feed constituents that are considered hazardous.	Yes	
Land area availability	Membrane-based systems do not require large land areas.	Yes	Khan et al., 2013
Feed water quality limitations	Scale-forming feedwater constituents (specifically, sparingly soluble salts) can pose limitations on pervaporation.	Yes	

A4.6.3 Technology Capability

Table A-30 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A4.6.4 Life-Cycle Costs

Cost data are limited since technology is in a commercialization state. The cost is considered comparable to MD. There are reduced costs from vapor pressure driving force relative to MD, and there are increased costs from low membrane flux relative to other membrane technologies (Khan et al., 2013).

Table A-30. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Pervaporation has typically been used for industrial applications because certain components in the feed solution preferentially permeate through a dense or molecular-sieving porous membrane and evaporate downstream. Although the industrial applications used to remove volatile species from wastewater have shown promise, application for the extraction of water from saline solutions is not well documented.	4	Mallenvialle et al., 1996 Xie et al., 2011b Wang et al., 2016
Cost (LCC)			
Produces additional “usable” water	Yes, pervaporation produces additional usable water from concentrate.	3	
If water is produced, anticipated water quality (salinity)	Produced water quality will be low in TDS and other feed constituents because the membrane barrier and vaporized water will provide purified water.	3	Wang et al., 2016
Overall process recovery (concentrate volume minimization)	At 20 degrees Celsius (°C), the salt concentration has negligible effect on water flux, while at higher temperatures the influence becomes significant; hence recovery is impacted by temperature, as well as membrane type and salt chemistry.	1	Xie et al., 2011b
Residual waste disposal	No chemicals are added, and there is a small final concentrate volume, but VOCs are included in the final waste stream. This can be a problem if radium is present in the feed water (saline wells, for example).	2	
Limitations to large-scale utilization	Low flux is a limiting factor, and it may require large membrane surface area and waste heat availability.	1	Wang et al., 2016
Hardness removal	High hardness removal.	3	
Heavy metals removal	High metals removal.	3	
Organic contaminant removal	High. Water-selective hydrophilic membranes prevent passage of VOC, despite partial pressure driving force.	3	Wang et al., 2016
Radionuclide removal	High radionuclide removal.	3	
Low chemical demand	Chemical addition is low. Antiscalants may be used.	3	

Table A-30. Technology Capabilities

Capability	Assessment	Score	References
Energy demand	Increased feed stream temperature improves flux but low grade heat or solar thermal can be used if available. Energy consumption is not highly dependent on feed salinity. Pervaporation requires energy to condense the water vapor that permeates the membrane.	2	Xie et al., 2011a Wang et al., 2016 Xie et al., 2011b
Labor requirements	Difficult to assess based on the limited industrial application of pervaporate for desalination.	2	Gude, 2018
Reliability	Difficult to assess based on the limited industrial application of pervaporation for desalination.	2	Gude, 2018
Value added	Lower energy demand (partial pressure driving force) and potential if waste heat is used.	1	Wang et al., 2016

A4.6.5 References

Basile, A., A. Figoli, and M. Khayet, 2015. Pervaporation, Vapour Permeation and Membrane Distillation: Principles and Applications, https://www.sciencedirect.com/book/9781782422464/pervaporation-vapour-permeation-and-membrane-distillation.

Gude, G., 2018. Emerging Technologies for Sustainable Desalination Handbook (first edition). Veera Gnaneswar Gude (ed.), Elsevier Books, https://www.elsevier.com/books/emerging-technologies-for-sustainable-desalination-handbook/gude/978-0-12-815818-0.

Khan, S., M. Usman, N. Gull, M.T.Z. Butt, and T. Jamil, 2013. An Overview on Pervaporation (an Advanced Separation Technique). Journal of Quality and Technology Management, IX(I): 155-161, http://pu.edu.pk/images/journal/iqtm/PDF-FILES/08-Pervaporation%20(Dr%20Taqi%20Butt)_v_ix_issue1_june2013.pdf.

Mallenvialle, J., P.E. Odendaal, and M.R. Wiesner (eds.), 1996. Water Treatment Membrane Processes. American Water Works Association Research Foundation, https://www.worldcat.org/title/water-treatment-membrane-processes/oclc/473703801.

Wang, Q., N. Li, B. Bolto, M. Hoang, and Z. Xie, 2016. Desalination by Pervaporation: A Review. Desalination, 387: 46-60, http://doi.org/10.1016/j.desal.2016.02.036

Xie, Z., M. Hoang, T. Duong, D. Ng, B. Dao, and S. Gray, 2011a. Sol-Gel Derived Poly(Vinyl Alcohol)/Maleic Acid/Silica Hybrid Membrane for Desalination by Pervaporation. Journal of Membrane Science, 383(1-2): 96-103, http://doi.org/10.1016/j.memsci.2011.08.036.

Xie, Z., D. Ng, M. Hoang, T. Duong, and S. Gray, 2011b. Separation of Aqueous Salt Solution by Pervaporation through Hybrid Organic-Inorganic Membrane: Effect of Operating Conditions. Desalination, 273(1): 220-225, http://doi.org/10.1016/j.desal.2010.10.026.

A5 Evaporative Processes

A5.1 Wind Aided Intensified Evaporation

A5.1.1 Technology Description

Wind aided intensified evaporation is an enhanced evaporation process that uses wind energy and vertical wetted surfaces to increase the effective surface area and evaporative capacity to reduce land area requirements for evaporation. The WAIV™ process can be used to reduce the volume of desalination concentrate (figure A-18).

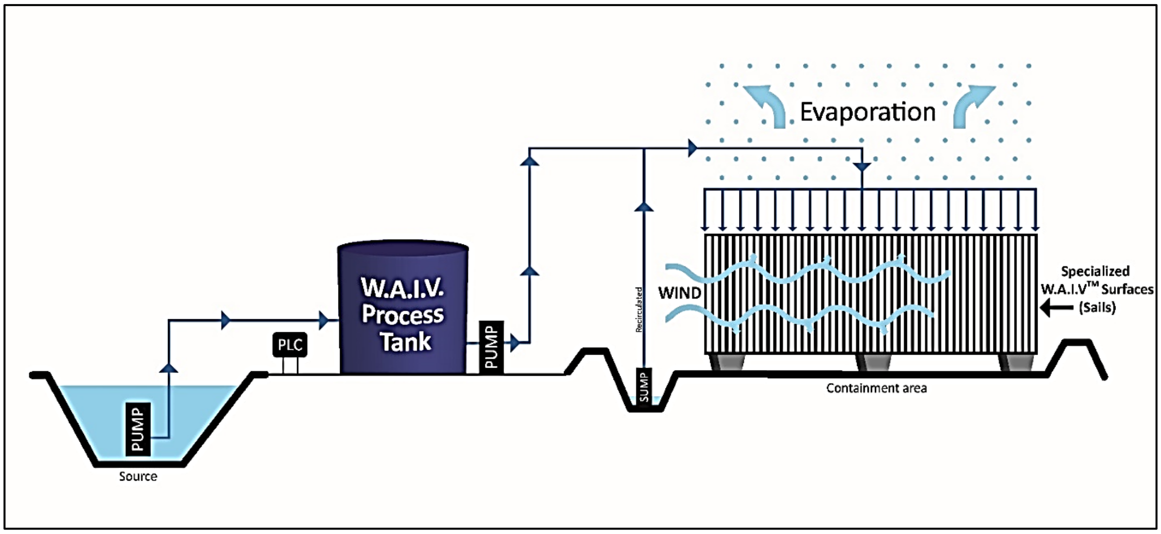

Figure A-18. WAIV™ process flow diagram (based on Clear Creek Environmental Solutions, n.d.).

A5.1.2 Technology Constraints

Table A-31 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

A5.1.3 Technology Capability

Table A-32 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-31. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Technology is commercially available, and patent protection exists. Demonstration units exist in Israel, Australia, and Mexico, and the technology has been demonstrated on RO concentrate and RO/ED concentrate.	7	Katzir et al., 2010 Leachate, n.d.
Flexibility	The system can handle varying concentrate water quality and salinity.	Yes	Leachate, n.d.
Scalability	The system is modular. Individual units are reported to treat 2,500 to 5,000 gpd, and additional units can be added, as necessary, to meet flow requirements.	Yes	Leachate, n.d.
Environmental constraints	The evaporation rate from the WAIV^{TM} unit is correlated to localized pan evaporation rates. Units will perform best in areas with low relative humidity, high wind speed, high temperatures, and low precipitation.	Yes	
Process residual	This technology removes water from concentrate; therefore, a smaller volume of more highly concentrated water remains as a residual, requiring final disposal. Used process textiles are also a process residual.	Yes	Gilron et al., 2003
Land area availability	The unit requires land area. Depending on the volume of concentrate requiring disposal, the land area requirement can become a constraint. A unit with a 1,625 ft^2 (65-ft by 25-ft) footprint (2,500 to 5,000 gpd) provides 62,000 ft^2 of wetted surface area.	No	Leachate, n.d.
Feed water quality limitations	WAIV^{TM} can treat a wide range of water types (RO concentrate, landfill leachate, produced water, and industrial wastewater); therefore, it can be considered highly flexible. The evaporation rate decreases as salinity increases, but the process is still effective. High TDS feeds may require periodic textile flushing with lower TDS water to remove solids and prevent flow path/evaporative surface area restrictions.	Yes	Gilron et al., 2003 Macedonio et al., 2011

A5.1.4 Life-Cycle Costs

Available cost data are limited and site specific. See Katzir et al. (2010) and Macedonio et al. (2011).

A5.1.5 Research Needs

Long term testing of WAIV™ on concentrate is needed to better understand maintenance and replacement requirements for this technology, along with a better understanding of textile material for longer durability, more reliability, lower costs, and higher evaporation rates.

Table A-32. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Technology is commercially available, and patent protection exists. Demonstration units exist in Israel, Australia, and Mexico, and the technology has been demonstrated on RO concentrate and RO/ED concentrate.	7	Katzir et al., 2010 Leachate, n.d.
Produces additional “usable” water	No water is captured in this evaporative process.	0	
If water is produced, anticipated water quality (salinity)	No water is produced.	0	
Overall process recovery (concentrate volume minimization)	When incorporated into a treatment train, overall process recovery can achieve near or zero liquid discharge.	3	Macedonio et al., 2011
Residual waste disposal	Residual solids will require disposal or further treatment (e.g., crystallization). Used WAIV^{TM} textile surfaces will require disposal.	2	Gilron et al., 2003 Macedonio et al., 2011
Limitations to large-scale utilization	Land area and operational requirements, as well as final WAIV^{TM} concentrate disposal, may limit more large-scale use. Current systems treat 5,000 gpd per unit or up to 20,000 gpd per installment.	1	Leachate, n.d.
Hardness removal	Not applicable.	0	
Heavy metals removal	Not applicable.	0	
Organic contaminant removal	Organics should be removed before WAIV^{TM} treatment. Volatile organics cause air emissions if not removed prior to WAIV^{TM}.	0	
Radionuclide removal	Not applicable. Could be problematic in WAIV^{TM} concentrate if not removed with pretreatment.	0	
Low chemical demand	No chemicals required. Low TDS water may be required for flushing.	3	Gilron et al., 2003 Macedonio et al., 2011
Energy demand	Energy requirements are lower than for other concentrate management technologies.	3	
Labor requirements	There are low labor requirements during operation. Periodic replacement of WAIV^{TM} evaporative sheets and maintenance of other process equipment are required. Periodic cleaning or flushing of textiles to remove solids buildup may be required.	3	

Table A-32. Technology Capabilities

Capability	Assessment	Score	References
Reliability	Life of textiles is 5 to 7 years for groundwater applications. Some textiles may be damaged by system shutdown and resultant crystallization, causing rigidity, which results in reduced water uptake and evaporation.	2	Macedonio et al., 2011 U.S. Department of Energy, 2015
Value added	There is a potential for salt recovery from textile sheets.	1	Katzir et al., 2010 Macedonio et al., 2011

A5.1.6 References

Clear Creek Environmental Solutions, n.d. Company Web Site, October 2017, https://www.ccenv.us/.

Gilron, J., Y. Folkman, R. Savliev, M. Waisman, and O. Kedem, 2003. WAIV – Wind Aided Intensified Evaporation for Reduction of Desalination Brine Volume. Desalination, 158(1-3): 205-214, https://doi.org/10.1016/S0011-9164(03)00453-3.

Katzir, L., Y. Volkmann, N. Daltrophe, and E. Korngold, 2010. WAIV – Wind Aided Intensified Evaporation for Brine Volume Reduction and Generating Mineral Byproducts. Desalination and Water Treatment, 13(1-3): 63-73, https://doi.org/10.5004/dwt.2010.772.

Kedem, A., J. Gilron, and O. Kedem, 2007. U.S. Patent No. US 7,166,188 B2. USPTO Patent Full-Text and Image Database, U.S. Patent and Trademark Office, Washington DC.

Leachate, 2017. WAIV™ Evaporation System. Leachate Management Specialists, LLC, https://www.leachate.us/waiv/, accessed March 20, 2017.

Macedonio, F., L. Katzir, N. Geisma, S. Simone, E. Drioli, and J. Gilron, 2011. Wind-Aided Intensified eVaporation (WAIV) and Membrane Crystallizer (MCr) Integrated Brackish Water Desalination Process: Advantages and Drawbacks. Desalination, 273(1): 127-135, https://doi.org/10.1016/j.desal.2010.12.002.

U.S. Department of Energy, 2015. Alternatives Analysis of Contaminated Groundwater Treatment Technologies. Tuba City, Arizona, Disposal Site, February 2015, p. 23, Energy.gov, Office of Legacy Management, https://www.lm.doe.gov/Tuba/S12161_AltAnalysis.pdf.

A5.2 Brine Crystallizer

A5.2.1 Technology Description

Brine crystallizer (BC) evaporates water from a concentrate or brine stream. This is typically the final step in a ZLD process due to the large energy requirement for its operation. Typical energy requirement for BCs range from 190 to 265 kilowatt hours (kWh) per 1,000 gallons (50 to 70 kWh/m^3) (Tiezheng and Elimelech, 2016). They do, however, produce a solid discharge and additional treated water, which can be beneficial.

There are several configurations for BCs. One configuration is the vapor compression crystallizer (figure 1). Brine is introduced to the system in the crystallizer chamber, mixed with the recirculating brine, and pumped to the heat exchanger—typically a shell and tube. The brine is heated using the heat from the vapor compressor in the heat exchanger. The heated brine is sent into the BC chamber, where it evaporates, and salt crystals form after the water evaporates. The crystals are removed through a centrifuge and are purged from the system. The vapor from the crystallizer chamber is compressed in a compressor, and it is used to heat the brine recirculating in the system. A stream of pure water and solid mixed salts are generated (constituents depend on the feed water quality) (figure A-19).

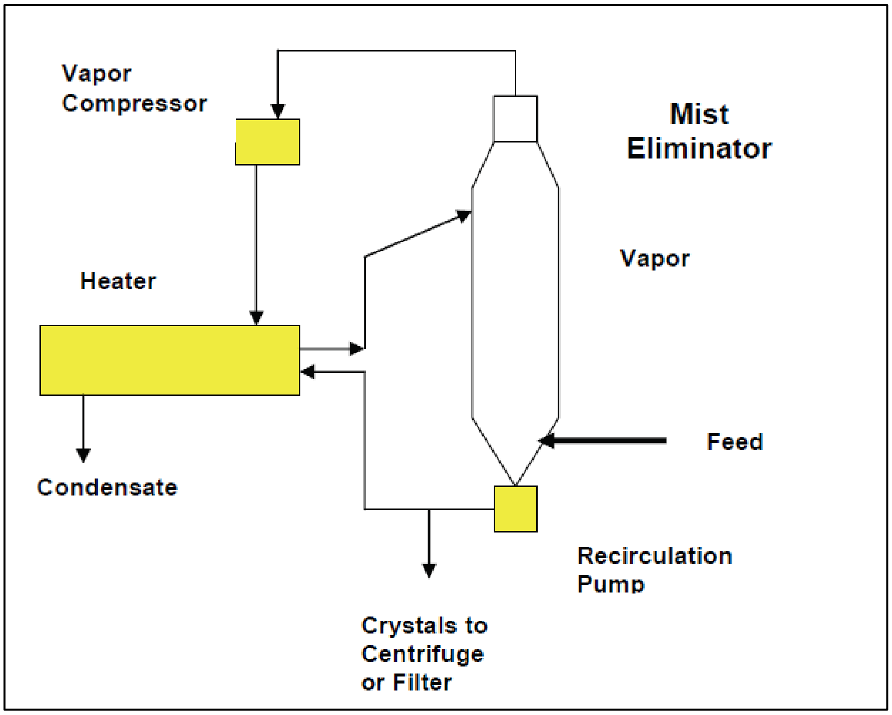

Figure A-19. Vapor compression crystallizer (based on Mickley, 2006).

A5.2.2 Technology Constraints

Table A-33 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-33. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Technology is employed at full scale.	9	Mickley, 2006 Burbano and Brandhuber, 2012
Flexibility	Can treat various feed water quality.	Yes	Mickley, 2006 Burbano and Brandhuber, 2012
Scalability	Systems are scalable. However, typically smaller scale (lower flowrate) systems are used rather than larger systems due to high energy needs. Other separation technologies are typically employed upstream of BC to cost-effectively reduce the volume of concentrate, and BC is used as a final step to get to ZLD.	Yes	Mickley, 2006
Environmental constraints	High energy requirement. Typical energy requirement for BCs range from 190 kWh/1,000 gallons to 265 kWh/1,000 gallons (50 to 70 kWh/m^3).	Yes	Tiezheng and Elimelech, 2016
Process residual	Solid mixed salts are generated from the system.	Yes	Bostjancic and Ludlum, 2013 Mickley, 2006
Land area availability	Land requirement is not a constraint to BC use.	Yes	
Feed water quality limitations	Can treat various feed water quality	Yes	Bostjancic and Lundlum, 2013

A5.2.3 Technology Capability

Table A-34 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-34. Technology Capabilities

Capability	Assessment	Score	References
Technology Readiness Level	Technology is employed at full scale.	9	Mickley, 2006 Burbano and Brandhuber, 2012
Produces Additional "Usable" Water	Vapor is condensed and is available as usable water. The amount of water is limited since the feed solution is highly concentrated and is the final step in the treatment train due to cost of BC treatment.	1	Mickley, 2006
If Water is Produced, Anticipated Water Quality (salinity)	Vapor is generated and is very high quality (low salinity).	3	Mickley, 2006
Overall Process Recovery (concentrate volume minimization)	As this is the final step in a ZLD process and generates pure water and solid salt, there is a very high recovery.	3	Tiezheng and Elimelech, 2016 Mickley, 2006 Burbano and Brandhuber, 2012
Residual Waste Disposal	Residual waste is typically a mixed salt.	3	Bostjancic and Ludlum, 2013
Limitations to Large Scale Utilization	High capital costs and energy requirements limit large scale use.	1	Tiezheng and Elimelech, 2016 Mickley, 2006
Hardness Removal	Vapor is generated and is high quality.	3	Mickley, 2006
Heavy Metals Removal	Vapor is generated and is high quality.	3	Mickley, 2006
Organic Contaminant Removal	Vapor is generated and is high quality.	3	Mickley, 2006
Radionuclide Removal	Vapor is generated and is high quality.	3	Mickley, 2006
Low Chemical Demand	Low levels to no chemicals are needed in most situations where BC is used.	3	Mickley, 2006
Energy Demand	Energy requirements are about three times that of other thermal desalination systems such as VC, MED or MSF.	0	Tiezheng and Elimelech, 2016 Burbano and Brandhuber, 2012
Labor Requirements	Labor requirement is moderate.	1	
Reliability	System operation is moderate.	2	
Value Added	Most viable ZLD solution is currently as the final step in a treatment train	2	Mickley, 2006

Note: VC = vapor compression.

A5.2.4 Life-Cycle Costs

Brine crystallizer has more costs other concentrate management technologies. It is the final step after all other technologies have reduced the volume of concentrate and solid disposal is needed (Tiezheng and Elimelech, 2016; Burbano and Brandhuber, 2012).

A5.2.5 Research Needs

The biggest challenge of BC is the huge energy requirement (50 – 70 kWh/m^3). Consider research to reduce the volume of brine entering the BC or the application of using hybrid BC systems (MD coupled with BC).

A5.2.6 References

Bostjancic, J., and R. Ludlum, 2013. Getting to Zero Discharge: How to Recycle That Last Bit of Really Bad Wastewater; Suez's Water Technologies and Solutions. https://www.suezwatertechnologies.com/kcpguest/documents/Technical%20Papers_Cust/Americas/English/TP1041EN.pdf

Burbano, A., and P. Brandhuber, 2012. Demonstration of Membrane Zero Liquid Discharge for Drinking Water Systems – A Literature Review. WERF5T10a, Water Environment Research Foundation, Alexandria, Virginia.

Farahbod, F., D. Mowla, M.R. Jafari Nasr, and M. Soltanieh, 2012. Experimental Study of Forced Circulation Evaporator in Zero Discharge Desalination Process. Desalination, 285, 2012.

Kim, D.H., 2011. A Review of Desalting Process Techniques and Economic Analysis of the Recovery of Salts from Retentates. Desalination, 270(1-8), El Sevier Publications, https://www.deepdyve.com/lp/elsevier/a-review-of-desalting-process-techniques-and-economic-analysis-of-the-Te7Uh9BvjU

Mickley, M., 2006. Membrane Concentrate Disposal: Practices and Regulation (Second Edition). U.S. Department of the Interior, Bureau of Reclamation, Desalination and Water Purification Report 123.

Mickley, M., 2008. Survey of High-Recovery and Zero Liquid Discharge Technologies for Water Utilities. WRF-02-006a, WateReuse Foundation, Alexandria, Virginia.

Sharon, H., and K.S. Reddy, 2015. A Review of Solar Energy Driven Desalination Technologies. Renewable and Sustainable Energy Reviews, 41.

Tiezheng, T., and M. Elimelech, 2016. The Global Rise of Zero Liquid Discharge for Wastewater Management: Drivers, Technologies, and Future Directions. Environmental Science and Technology, 50(13): 6846-6855, 10.1021/acs.est.6b01000.

A5.3 Multiple-Effect Distillation

A5.3.1 Technology Description

Multiple-effect distillation is a thermal process that separates a solution by vaporization of volatile components. It can be used to treat concentrate or raw water. The process produces a new water source from what was otherwise unusable water or a concentrated brine. MED requires thermal input to initiate the process in the first effect, but it can use low-pressure steam or low-grade waste heat from an external thermal processes (e.g., power generation).

In MED, a series of evaporator effects produces water at progressively slightly lower pressures (figure A-20). Because water boils at lower temperatures as pressure decreases, the water vapor of the first evaporator effect serves as the heating medium for the second evaporator effect, and so on. The more effects, the higher the performance ratio. From a thermodynamic and heat transfer point of view, typically the power consumption of an MED plant is lower than that of a multistage flash (MSF) plant. Some MED plants operate with a top brine temperature in the first effect of about 70 °C to reduce the potential for scaling of the brine/seawater (Khawaji et al., 2008).

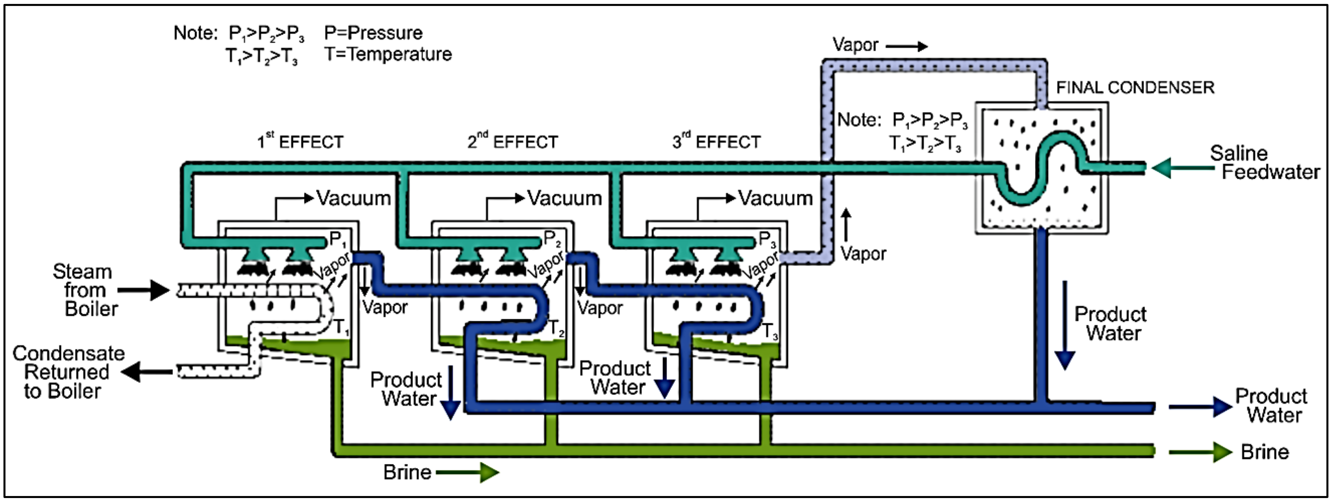

Figure A-20. Schematic of MED process (based on Buros, 2000).

A5.3.2 Technology Constraints

Table A-35 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-35. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	MED is used at full scale for primary distillation. MED process is the oldest desalination method. Horizontal MED plants have been operating for decades	9	Khawaji et al., 2008
Flexibility	Able to handle range of incoming feed concentrations.	Yes	Ophir and Lokiec, 2013
Scalability	Able to accommodate feed rate variation. Difficult to scale down to small sizes due to complexity and large numbers of parts required. Normally, the number of effects ranges from 4 to 21. Two units in Sharjah, United Arab Emirates, have a capacity of 22,700 m^3/d each.	Yes	Ophir and Lokiec, 2013 Khawaji et al., 2008
Environmental constraints	None.	Yes	
Process residual	MED can achieve near ZLD.	Yes	
Land area availability	Land area requirements are not limitations to the process.	Yes	
Feed water quality limitations	Removal of silica and other high scaling potential compounds. Removal of heavy metals to prevent corrosion.	Yes	Subramani and Jacangelo, 2014 Watson et al., 2003

A5.3.3 Technology Capability

Table A-36 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A5.3.4 Life-Cycle Costs

Capital costs are high, and O&M costs are low, compared to other desalting technologies. The cost is competitive with other distillation processes. Although the capital costs are high, decreasing water cost with increasing volume (Watson et al., 2003).

Table A-36. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	MED is used at full scale for primary distillation. MED process is the oldest desalination method. Horizontal MED plants have been operating for decades.	9	Khawaji et al., 2008
Produces additional “usable” water	Additional usable water is produced.	3	
If water is produced, anticipated water quality (salinity)	0.5 to 25 mg/L.	3	Watson et al., 2003
Overall process recovery (concentrate volume minimization)	MED as a concentrate treatment option that is combined with other desalination processes to increase overall process recovery. (RO+MED, assuming 80% RO recovery).	1	Subramani and Jacangelo, 2014
Residual waste disposal	Highly concentrated brine (up to 106,000 mg/L). Some applications may allow for near ZLD, or ZLD after precipitation.	2	Watson et al., 2003
Limitations to large-scale utilization	Vessel sizing can limit plant scale. Ideal for coupling with powerplants because steam can be used efficiently at pressure as low as 0.35 bar abs or less. The total number of effects is limited by the total temperature range available and the minimum allowable temperature difference between one effect and the next effect. The decreased temperature in the first effect (70 °C) reduces the potential of scaling; however, additional heat from the tube will be needed.	2	Khawaji et al., 2008
Hardness removal	Yes.	3	
Heavy metals removal	Yes, but they should be removed before the process to prevent corrosion.	3	
Organic contaminant removal	VOCs can be removed by venting.	3	
Radionuclide removal	Yes.	3	
Low chemical demand	Chemicals are needed to reduce scaling potential of the feed water. Chemical demand can be reduced by operational parameters such as pressure or temperature, but it is unlikely to be eliminated due to high incoming TDS concentration.	2	Buros, 1990 Watson et al., 2003
Energy demand	High energy demand (steam). Thermal efficiency depends on the number of stages. Reported up to 9.9 kg/MJ,	1	Subramani and Jacangelo, 2014 Buros, 1990

Table A-36. Technology Capabilities

Capability	Assessment	Score	References
	configuration dependent. Operates at low temperature (< 70 °C) and at low concentration (< 1.5) to avoid corrosion and scaling. Incompatible with higher temperature heat sources due to scaling issues during spray evaporation. Low electrical consumption (less than 1.0 kWh/m^3) compared to other thermal processes such as MSF or membrane processes (RO).		Watson et al., 2003 Warsinger et al., 2015 Giwa et al., 2017
Labor requirements	Moderate labor requirements; depends on number of effects.	2	
Reliability	High reliability during steady-state operation.	2	
Value added	Some applications can use low-grade waste heat and low-pressure steam. Note that MED can be combined with RO and MD and crystallization methods for zero discharge applications.	1	Ophir and Lokiec, 2013 Perez-Gonzalez et al., 2012 Heijman et al., 2009 Giwa et al., 2017

A5.3.5 Research Needs

- Corrosion resistance/inhibition
- Fouling reduction
- Coating development
- Increased heat transfer efficiency

A5.3.6 References

Al-Shammiri, M., and M. Safar, 1999. Multi-Effect Distillation Plants: State of the Art. Desalination, 126(1-3): 45-59, https://doi.org/10.1016/S0011-9164(99)00154-X.

Buros, O.K., 1990. The Desalting ABCs. Topsfield, Massachusetts: International Desalination Association.

Buros, O. K., 2000. The ABCs of Desalting (second edition). https://water.ca.gov/LegacyFiles/pubs/surfacewater/abcs_of_desalting/abcs_of_desalting.pdf.

Giwa, A, V. Dufour, F. Al Marzooqi, M. Al Kaabi, and S.W. Hasan, 2017. Brine Management Methods: Recent Innovations and Current Status. Desalination, 407(1): 1-23, https://doi.org/10.1016/j.desal.2016.12.008.

Heijman, S.G.H., H. Guo, S. Li, J.C. Van Dijk, and L.P. Wessels, 2009. Zero Liquid Discharge: Heading for 99% Recovery in Nanofiltration and Reverse Osmosis. Desalination, 236(1): 357-362, https://doi.org/10.1016/j.desal.2007.10.087.

Khawaji A.D., I.K. Kutubkhanah, and J-M Wie, et al., 2008. Advances in Seawater Desalination Technologies. Desalination, 221(1-3): 47-69, https://doi.org/10.1016/j.desal.2007.01.067.

Ophir, A., and F. Lokiec, 2013. Review of MED Fundamentals and Costing. http://www.ide-tech.com/wp-content/uploads/2013/09/Review-of-MED-Fundamentals-and-Costing.pdf.

Pérez-González, A., A.M. Urtiaga, R. Ibáñez, and I. Ortiz, 2012. State of the Art and Review on the Treatment Technologies of Water Reverse Osmosis concentrates. Water Research, 46(2): 267-283, https://doi.org/10.1016/j.watres.2011.10.046.

Subramani, A., and J.G. Jacangelo, 2014. Treatment Technologies for Reverse Osmosis Concentrate Volume Minimization: A Review. Separation and Purification Technology, 122: 472-489, https://doi.org/10.1016/j.seppur.2013.12.004.

Watson, I.C., O.J. Morin, and L. Henthorne, 2003. Desalting Handbook for Planners (third edition). Bureau of Reclamation, Denver, Colorado, https://www.usbr.gov/research/dwpr/reportpdfs/report072.pdf.

Warsinger, D.M., K.H. Mistry, K.G. Nayar, H.W. Chung, Hyung Won, and J.H. Lienhard, 2015. Entropy Generation of Desalination Powered by Variable Temperature Waste Heat. Entropy, pp. 7530-7566. doi:10.3390/e17117530

A5.4 Multi-Stage Flash Distillation

A5.4.1 Technology Description

Multi-stage flash distillation is a thermal process using sudden evaporation, or flashing, to separate components of a solution (i.e., separating water from salt for concentrate management). The process consists of multiple stages, each operated at a successively lower pressure and temperature to allow heat recovery through vapor condensation. The entire feed is heated to the flash temperature of the first chamber, then flows through all stages of the process. Within each stage, a small amount of feed, proportional to the temperature difference from the prior stage, is flashed to a vapor (figure A-21).

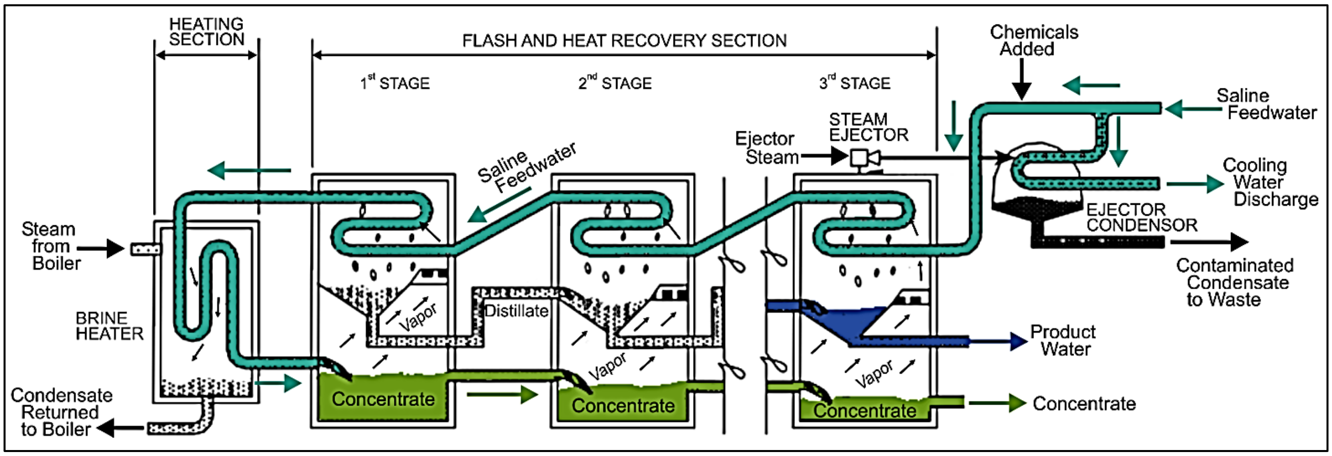

Figure A-21. MSF diagram.

The MSF distillation process can be applied to treat membrane desalination process concentrate and produce an additional water source. A hybrid RO/MSF process has been studied at the pilot scale (Hamed et al., 2009), and MSF is the leading thermal process, by installed capacity, for primary desalination worldwide (Gleick et al., 2006). MSF distillation requires an external heat source to heat the feed to the operating conditions of the first stage and is inherently thermodynamically inefficient. Some process configurations can use brine recycle, low grade waste heat, or low temperature steam to reduce O&M costs. Use of MSF to treat RO concentrate represents a significant cost savings from the reduced size of process equipment (smaller flow) and reduced energy needs (lower water content) compared to use as a primary desalination process.

A5.4.2 Technology Constraints

Table A-37 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-37. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Full-scale, widely used for primary desalination. The technology is the second most commonly used technology for desalting (RO processes are the first). Pilot study (MSF: 20 m^3/d) conducted using RO concentrate and raw seawater (make-up) in MSF unit (2009).	9	Hamed et al., 2009 Al-Karaghouli and Kazmerski, 2013
Flexibility	Able to accommodate changes in feed water composition and salinity.	Yes	
Scalability	Individual units have limited scalability. Additional units can be added to meet influent flowrates.	Yes	
Environmental constraints	Disposal of brine may be limited or may require secondary crystallization process. Output brine stream may be at elevated temperatures. Discharge is 10–15 °C warmer than ambient temperatures; TDS increase by 15–20%.	Yes	Sommariva et al., 2004
Process residual	Highly concentrated brine. Brine may contain antiscalants or other chemicals from pretreatment. Condensate from steam ejector.	Yes	
Land area availability	Land area is not a limiting factor in MSF use.	Yes	
Feed water quality limitations	Incoming concentrations of sparingly soluble salts (i.e., gypsum) may limit operating temperature and, thus, affect process efficiency and recovery. In MSF processes, scaling usually happens at the orifices of the flash chambers and inside the tubes of the heat exchangers and the brine heaters.	Yes	Buros, 1990 Turek, 2003 Zhao et al., 2018

A5.4.3 Technology Capability

Table A-38 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-38. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Full-scale, widely used for primary desalination. The technology is the second most commonly used technology for desalting (RO processes are the first). Pilot study (MSF: 20 m^3/d) conducted using RO concentrate and raw seawater (make-up) in MSF unit (2009).	9	Hamed et al., 2009 Al-Karaghouli and Kazmerski, 2013
Produces additional "usable" water	Desalinated water can be collected for reuse.	3	
If water is produced, anticipated water quality (salinity)	2–10 mg/L TDS	3	Khawaji et al., 2008
Overall process recovery (concentrate volume minimization)	Overall: 82.4% MSF recovery: 68% SWRO recovery: 45%	1	Hamed et al., 2009
Residual waste disposal	Achieves highly concentrated brine (or slurry) stream (may be fed to ZLD process). When heating with fossil fuels, airborne emissions (NO_x, SO_x, CO_2) from plant operation are high. Emissions could be reduced through the use of waste heat.	2	Raluy et al., 2006
Limitations to large-scale utilization	High capital costs and high O&M costs (energy, chemical addition).	2	
Hardness removal	High.	3	Jeppesen et al., 2009
Heavy metals removal	High.	3	
Organic contaminant removal	High.	3	
Radionuclide removal	High.	3	
Low chemical demand	Chemical demand is necessary to decrease scaling potential for feed water.	2	Buros, 1990
Energy demand	High energy demand, thermodynamically inefficient process. Potential for waste heat use. Performance ratios for modern MSF	1	Khawaji et al., 2008

Table A-38. Technology Capabilities

Capability	Assessment	Score	References
	plants for primary desalination are 6.5-10.5 pounds of produced water per 1,000 British thermal unit heat input.		
Labor Requirements	Operator involvement may be required for scale control.	2	Buros, 1990
Reliability	Reliability has improved recently with advances in automation, improved construction materials, and scale controls.	2	Buros, 1990 Khawaji et al., 2008 Jeppesen et al., 2009
Value added	MSF may produce brine stream with a high concentration of salts and low water content that can be used in ZLD precipitation process with salt recovery.	1	Turek, 2003 Jeppesen et al., 2009

A5.4.4 Life-Cycle Costs

Operating costs for theoretical UF-NF-RO-MSF system ~ \$0.90 to \$1.50/m^3. Electrical (stand alone or co-generation) cost is 3.5 to 5.0 kWh/m^3. Stand-alone thermal cost is between 69 and 83 kWh/m^3. Co-generation thermal cost is 44 to 47 kWh/m^3. (Jeppesen et al., 2009; Mezher et al., 2011; Khawaji et al., 2008)

A5.4.5 Research Needs

- Corrosion resistance/inhibition
- Scaling reduction
- Coating development to avoid corrosion and reduce heat loss
- Increase heat transfer efficiency
- Solar hybrid systems

A5.4.6 References

Al-Karaghouli, A., and L.K. Kazmerski, 2013. Energy Consumption, MSF, and Water Production Cost of Conventional and Renewable-Energy-Powered Desalination Processes. Renewable and Sustainable Energy Reviews, 24: 343-356, https://doi.org/10.1016/j.rser.2012.12.064.

Bandi C.S., R. Uppaluri, and A. Kumar, 2016. Global Optimization of MSF Seawater Desalination Processes. Desalination, 394: 30-43, https://doi.org/10.1016/j.desal.2016.04.012.

Buros, O.K., 1990. The Desalting ABCs. Topsfield, Massachusetts: International Desalination Association.

El-Ghonemy A.M.K., 2017. Performance Test of a Sea Water Multi-Stage Flash Distillation Plant: Case Study. Alexandria Engineering Journal, 57(4): 2401-2413, December 2018, https://doi.org/10.1016/j.aej.2017.08.019.

Fath, H., A. Sadik, and M. Toufic, 2013. Present and Future Trend in the Production and Energy Consumption of Desalinated Water in GCC Countries. International Journal of Thermal and Environmental Engineering, 5(2): 155-165, http://iasks.org/wp-content/uploads/pdf/ijtee201305020155165.pdf.

Gleick, P.H, G.H. Wolff, H. Cooley et al., 2006. The World's Water 2006-2007: The Biennial Report on Freshwater Resources. Island Press, ISBN 1-59726-108-8, Washington, DC.

Hamed, O.H, A.M. Hassan, K. Al-Shail, and M. Farooque, 2009. Performance Analysis of a Trihybrid NF/RO/MSF Desalination Plant. Desalination and Water Treatment, 1(1-3): 215-222, January 2009, ISSN: 1944-3994. https://doi.org/10.5004/dwt.2009.113.

International Atomic Energy Agency (IAEA), 2000. Introduction of Nuclear Desalination. Technical Reports Series No. 400, Vienna, Austria, https://www.iaea.org/publications/5925/introduction-of-nuclear-desalination.

Jeppesen, T., L. Shu, G. Keir, and V. Jegatheesan, 2009. Metal Recovery from Reverse Osmosis Concentrate. Journal of Cleaner Production, 17(7): 703-707, https://doi.org/10.1016/j.jclepro.2008.11.013.

Khawaji A.D., I.K. Kutubkhanah, and J-M Wie et al., 2008. Advances in Seawater Desalination Technologies. Desalination, 221(1-3): 47-69, https://doi.org/10.1016/j.desal.2007.01.067.

Khoshrou I., and M.R. Jafari Nasr, 2017. New Opportunities in Mass and Energy Consumption of the Multi-Stage Flash Distillation Type of Brackish Water Desalination Process. Solar Energy, 153: 115-125.

Mezher, T., H. Fath, Z. Abbas, and A. Khaled, 2011. Techno-Economic Assessment and Environmental Impacts of Desalination Technologies. Desalination, 266: 263-273, https://doi.org/10.1016/j.desal.2010.08.035.

Morin, O. 1993. Design and Operating Comparison of MSF and MED Systems. Desalination, 93(1-3): 69-109, https://doi.org/10.1016/0011-9164(93)80097-7.

Raluy, G., L. Serra, and J. Uche, 2006. Life Cycle Assessment of MSF, MED, and RO Desalination Technologies. Energy, 31(13): 2025-2036, doi: 10.1016/j.energy.2006.02.005.

Sommariva, C., H. Hogg, and K. Callister, 2004. Environmental Impact of Seawater Desalination: Relations Between Improvement in Efficiency and Environmental Impact. Desalination, 167: 439-444. https://doi.org/10.1016/j.desal.2004.06.159.

Turek, M., 2003. Seawater Desalination and Salt Production in a Hybrid Membrane-Thermal Process. Desalination, 153(1-3): 173-177, https://doi.org/10.1016/S0011-9164(02)01123-2.

Wade N.M., 2000. Distillation Plant Development and Cost Update. Desalination: 3-12, https://doi.org/10.1016/S0011-9164(01)00159-X.

Watson, I.C., O.J. Morin, and L. Henthorne, 2003. Desalting Handbook for Planners (third edition). Bureau of Reclamation, Denver, Colorado, https://www.usbr.gov/research/dwpr/reportpdfs/report072.pdf.

Zhao, J., M. Wang, H.M.S Lababidi, H. Al-Adwani, and K.K. Gleason, 2018. A Review of Heterogeneous Nucleation of Calcium Carbonate and Control Strategies for Scale Formation in Multi-Stage Flash (MSF) Desalination Plants. Desalination, 442: 75-88, https://doi.org/10.1016/j.desal.2018.05.008.

A5.5 Vapor Compression

A5.5.1 Technology Description

Vapor compression can be used to reduce the volume of concentrate from membrane processes and produce a useable, high-purity water stream. The process can also be used as a primary desalination step, but VC is considered more cost effective for higher salinity feed waters (e.g., seawater, brackish water concentrate, or brine) than membrane processes; furthermore, vapor compression can achieve minimal liquid discharge and is more often used as a brine concentration step prior to crystallization or discharge to evaporations ponds.

VC produces water by compressing the generated vapor and uses energy generated in theVC to evaporate the water (figure A-22). The vapor is compressed either through a mechanical (a compressor) or a thermal (high-pressure steam) process. Because VC is a thermal-based evaporation process, it is thus limited thermodynamically. Mechanical systems are most commonly used in practical applications for seawater desalination or brine concentration because they are able to achieve higher efficiencies than other thermal systems such MED or MSF. Thermal systems are commonly used if a low-cost, high-pressure steam source is readily available. Compressing the vapor raises the pressure of the vapor, thereby increasing the temperature at which the vapor will condense and making it possible to recover the condensation's heat back into the same unit.

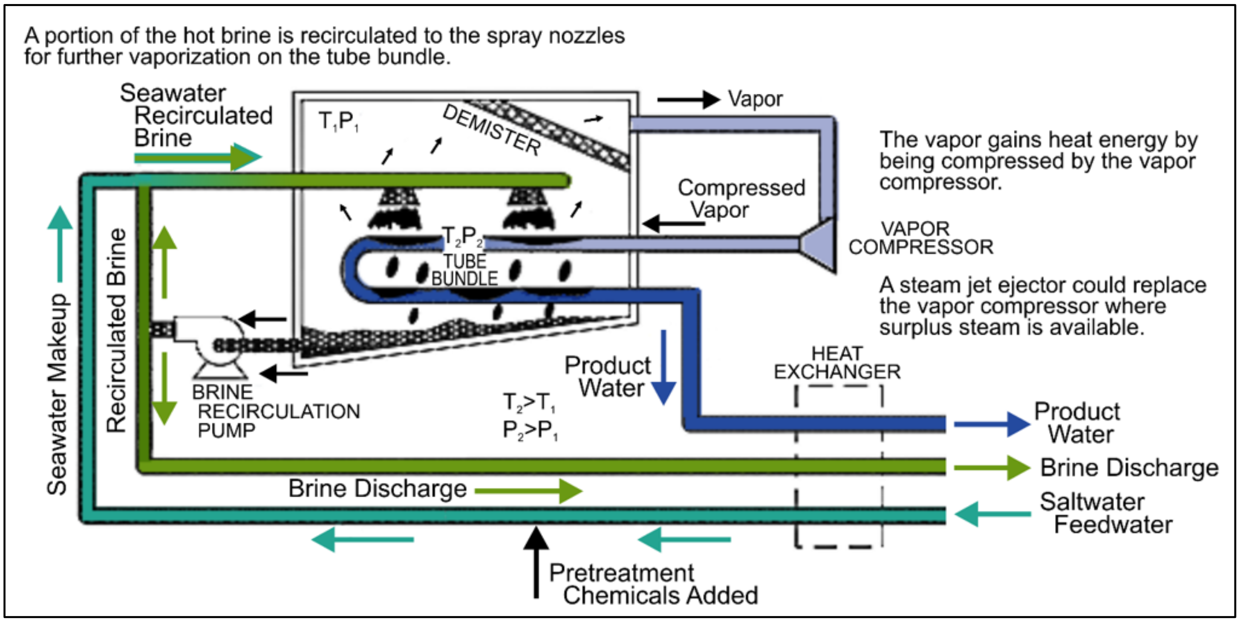

Figure A-22. Mechanical vapor compression (MVC) (based on Buros, 2000). Note that the process for thermal VC is almost identical, replacing the vapor compressor with a high-pressure steam stream.

VC systems can achieve MLD to prevent scaling and limit energy use. Some systems employ multiple effects to recycling high temperature outputs from through stages and improve efficiency, but the capital costs associated with larger units are generally prohibitive.

A5.5.2 Technology Constraints

Table A-39 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-39. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Full-scale applications exist for concentration management. The VC process has also been implemented at large scales for primary desalination. MVC has been reported to have the highest thermodynamic efficiency of the desalination technologies for treatment of salt-saturated brines. Other thermally driven processes, such as flash evaporation and distillation, are able to process brine solutions but at lower thermodynamic efficiencies than MVC.	8	Veza, 1995 Vane, 2017
Flexibility	Highly flexible VC can be used to treat a wide range of feed waters. A noticeable decrease in specific power consumption and specific heat transfer area at elevated values of MVC inlet temperatures has been reported.	Yes	Mickley, 2006 Ettouney et al., 1999
Scalability	Individual units have limited scalability. Additional units can be added to meet influent flowrates.	Yes	Buros, 1990
Environmental constraints	Process output is a concentrated brine solution. Disposal of brine may be limited or may require secondary crystallization process.	Yes	
Process residual	Process residuals are highly concentrated brine. Highly concentrated brine presents a disposal challenge. May require secondary crystallization process to achieve ZLD.	Yes	
Land area availability	Low land area requirement for VC unit. Low flow units may be skid mounted. Some VC configurations may require a tall tower profile.	Yes	Mickley, 2006 Reclamation, 2009
Feed water quality limitations	Incoming chemistry (salt content) may limit recovery to prevent scaling. Due to the prominent energy conservation performance, single-stage MVC thermal system has been widely used in many fields when the final mass concentration of the concentrated solution is less than 6% (Alasfour and Abdulrahim, 2011).	Yes	Mickley, 2006 Alasfour and Abdulrahim, 2011

A5.5.3 Technology Capability

Table A-40 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-40. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Full-scale applications exist for concentration management. The VC process has also been implemented at large scales for primary desalination. MVC has been reported to have the highest thermodynamic efficiency of the desalination technologies for treatment of salt-saturated brines. Other thermally driven processes, such as flash evaporation and distillation, are able to process brine solutions but at lower thermodynamic efficiencies than MVC.	8	Veza, 1995 Vane, 2017
Produces additional "usable" water	Desalinated water can be collected for reuse.	3	
If Water is produced, anticipated water quality (salinity)	Less than 10 mg/L TDS.	3	Mickley, 2006
Overall process recovery (concentrate volume minimization)	Near ZLD. 40:1 concentrate volume minimization. Primary desalination (~85%+) and concentrate treatment (~90%+) yield 98.5%+ yield.	3	Mickley, 2006
Residual waste disposal	Process produces saturated or highly concentrated brine stream that requires disposal.	2	
Limitations to large-scale utilization	High capital costs.	1	
Hardness removal	High hardness removal.	3	
Heavy metals removal	High heavy metal removal.	3	
Organic contaminant removal	High for non-volatile species.	2	
Radionuclide removal	High radionuclide removal.	3	
Low chemical demand	Chemical demand is low.	2	
Energy demand	Energy demand ranges from 7-25 kWh/m^3 . 60-100 kWh/1,000 gallons feed water. Theoretical least work: 6.7 kJ/kg feed. Actual work: 78.8 kJ/kg feed (one effect system, feed: 35 g/kg TDS, output at saturation). A detailed economic study revealed that an MVC system operating at high operating	1	Subramani and Jacangelo, 2014 Buros, 1990 Mickley, 2006 Chung et al., 2017 Lara and Holtzapple, 2007

Table A-40. Technology Capabilities

Capability	Assessment	Score	References
	temperature of 172 °C can deliver the following advantages: low compression work and small heat transfer area.		
Labor requirements	Low labor requirements – simplistic operation.	2	Buros, 1990 Mickley, 2006
Reliability	High reliability.	3	Buros, 1990
Value added	Produced water may be used for high-purity applications.	2	Mickley, 2006

A5.5.4 Life-Cycle Costs

Operation and maintenance costs per unit of produced water can be reduced by adding a second (or more) effect, but additional capital costs often limit these additions and result in only marginal improvements to efficiency (Chung et al., 2017).

A5.5.5 Research Needs

Research focus areas for VC are:

- Using renewable energy technology to reduce operating costs of VC process
- Processes or process improvements to reduce energy requirements of VC
- Coupling of MVC with other technologies such as wind power.

A5.5.6 References

Alasfour, F.N., and H.K. Abdulrahim, 2011. The Effect of Stage Temperature Drop on MVC Thermal Performance. Desalination, 265: 213-221, https://doi.org/10.1016/j.desal.2010.07.054.

Buros, O.K., 1990. The Desalting ABCs. Topsfield, Massachusetts: International Desalination Association.

Chung, H.W., K.G. Nayar, J. Swaminathan, K.M. Chehayeb, and J.H. Leinehard, 2017. Thermodynamic Analysis of Brine Management Methods: Zero-Discharge Desalination and Salinity-Gradient Power Production. Desalination, 404: 291-303, https://doi.org/10.1016/j.desal.2016.11.022.

Ettouney, H., H. El-Dessouky, and Y. Al-Roumi, 1999. Analysis of Mechanical Vapor Compression Desalination Process. International Journal of Energy Research, 23: 431-451, https://doi.org/10.1002/(SICI)1099-114X(199904)23:5<431::AID-ER491>3.0.CO;2-S.

Hasbani, N., 1985. An Evaluation of Brine Recycling and Wastewater Reclamation by R/O and Vapor Compression. Desalination, 56: 37-46, https://doi.org/10.1016/0011-9164(85)85013-X.

Lara J.R., and M.T. Holtzapple, 2007. An Advanced Vapor-Compression Desalination System. IDAWC/MP07-175.

Mabrouk, A.A., A.S. Nafey, and H.E.S. Fath, 2007. Analysis of a New Design of a Multi-Stage Flash Mechanical Vapor Compression Desalination Process. Desalination, 204: 482-500, https://doi.org/10.1016/j.desal.2006.02.046.

Mickley, M.C., 2006. Membrane Concentrate Disposal: Practice and Regulation. Desalination and Water Purification Research and Development Program Report No. 123, Second Edition, April 2006 (Agreement No. 98-FC-81-0054). Prepared for the U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Water Treatment Engineering and Research Group. https://www.usbr.gov/research/dwpr/reportpdfs/report123.pdf.

Reclamation, 2009. Brine-Concentrate Treatment and Disposal Options Report, Southern California Regional Brine-Concentrate Management Study – Phase I. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, http://s3-us-west-2.amazonaws.com/ucldc-nuxeo-ref-media/69c012ec-cae3-4b58-a56a-3a712960a918.

Subramani, A., and J.G. Jacangelo, 2014. Treatment Technologies for Reverse Osmosis Concentrate Volume Minimization: A Review. Separation and Purification Technology, 122: 472-489, https://doi.org/10.1016/j.seppur.2013.12.004.

Vane, L.M., 2017. Water Recovery from Brines and Salt-Saturated Solutions: Operability and Thermodynamic Efficiency Considerations for Desalination Technologies. Journal of Chemical Technology and Biotechnology, 92(10): 2506-2518, https://doi.org/10.1002/jctb.5225.

Veza, J.M., 1995. Mechanical Vapour Compression Desalination Plants – A Case Study. Desalination, 101(1): 1-10, https://doi.org/10.1016/0011-9164(95)00002-J.

Watson, I.C., O.J. Morin, and L. Henthorne, 2003. Desalting Handbook for Planners (third edition). Bureau of Reclamation, Denver, Colorado, https://www.usbr.gov/research/dwpr/reportpdfs/report072.pdf.

A5.6 Humidification-Dehumidification

A5.6.1 Technology Description

Humidification-dehumidification (HDH) desalinates concentrate by mimicking the natural water cycle's ability to desalinate seawater into rainwater. The HDH process uses a humidifier, dehumidifier, and heater to manipulate the saline feed water into fresh water (figure A-23). The feedwater is heated by the heater and enters into the humidifier, where the dry air coming from the dehumidifier is humidified. The moist air moves into the dehumidifier and condenses on the cool surface opposite of the entering cool feed. This produces the fresh water. An HDH system can be configured in different ways to treat concentrate. Variations of these systems include losed air open water, closed water open air, air heated, water heated, natural circulation, and forced circulation systems (figure A-24).

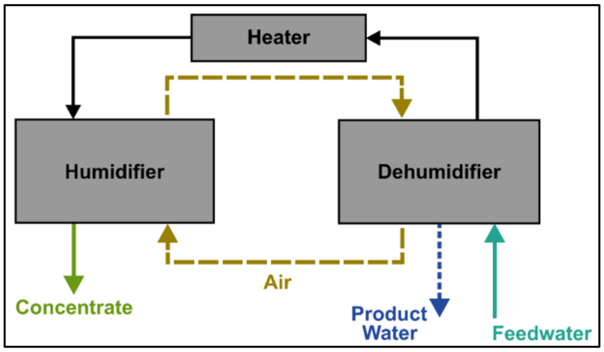

Figure A-23. Simple schematic of a typical HDH system (Lienhard, n.d.).

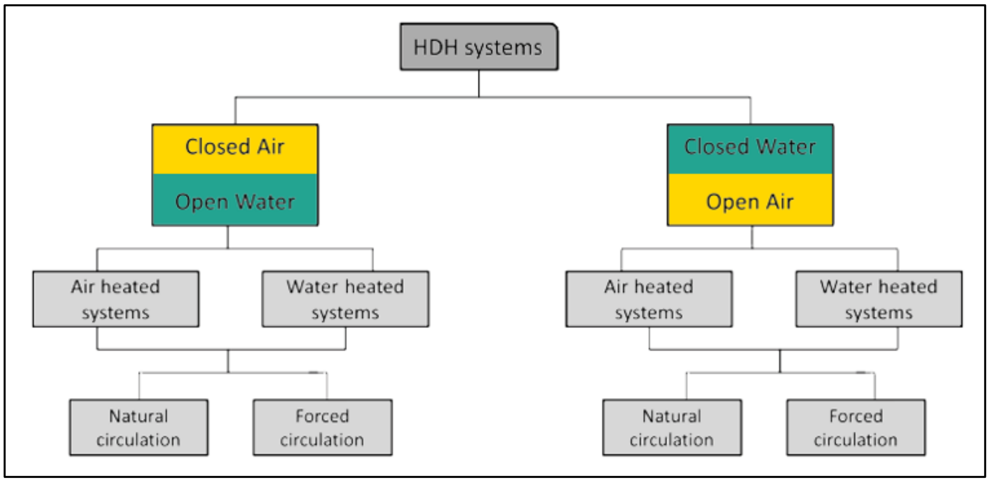

Figure A-24. Variations of HDH configurations (Narayan and Lienhard, 2014).

A5.6.2 Technology Constraints

Table A-41 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-41. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Has been tested at bench and pilot scales.	6	
Flexibility	System can be configured to accommodate varying feed water compositions.	Yes	Narayan and Lienhard, 2014
Scalability	Can be configured for a variety of flowrates.	Yes	
Environmental constraints	No environmental constraints.	Yes	
Process residual	Because the concentrate volume is reduced by removing fresh water, feed water constituents can concentrate to high levels and could reach hazardous levels.	Yes	
Land area availability	Useful for small-scale deployment. Requires large footprint for larger scale uses.	No	Lienhard et al., 2012
Feed water quality limitations	Useful for varying and difficult feed water qualities but has limited use for feed waters containing volatile compounds and radionuclides.	No	Narayan and Lienhard, 2014

A5.6.3 Technology Capability

Table A-42 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A5.6.4 Life-Cycle Costs

HDH uses relatively inexpensive components. Thermal energy input can be costly for heating feed. Estimates are about \$4.91 per m^3 (Lienhard et al., 2012; Narayan and Lienhard, 2014).

Table A-42. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Has been tested at bench and pilot scales.	6	
Produces additional "usable" water	Additional water produced is usable.	2	
If water is produced, anticipated water quality (salinity)	High-quality produced water.	3	Li, 2009
Overall process recovery (concentrate volume minimization)	Up to 90% recovery when brine is recirculated.	2	Narayan and Lienhard, 2014
Residual waste disposal	Because the concentrate volume is reduced by removing fresh water, feed water constituents can concentrate to high levels and could reach hazardous levels.	2	
Limitations to large-scale utilization	Can be configured to the size needed, but costs for thermal energy will increase with increasing size.	1	
Hardness removal	High hardness removal.	3	Li, 2009
Heavy metals removal	High heavy metals removal.	3	Li, 2009
Organic contaminant removal	Up to 95% total organic compounds removal.	3	Li, 2009
Radionuclide removal	Likely to be high removal.	2	
Low chemical demand	No chemicals needed.	3	
Energy demand	Thermal energy requirements are higher than for other technologies.	1	Lienhard et al., 2012
Labor requirements	Minimal labor requirements (can be done by nontechnical laborers).	2	Narayan and Lienhard, 2014
Reliability	Difficult to assess because no full-scale implementations have been completed.	1	
Value added	Using waste heat to heat the feed water may provide value by reducing energy the requirement.	1	

A5.6.5 References

Deniz, E., and S. Cinar, 2016. Energy, Exergy, Economic and Environmental (4E) Analysis of a Solar Desalination System with Humidification-Dehumidification. Energy Conversion and Management, 126:12-19, 2016, DOI: 10.1016/j.enconman.2016.07.064.

Hamed, M.H., A.E. Kabeel, Z.M. Omara, and S.W. Sharshir, 2015. Mathematical and Experimental Investigation of a Solar Humidification-Dehumidification Desalination unit. Desalination, 358:9-17, 2015, https://doi.org/10.1016/j.desal.2014.12.005.

Kabeel, A.E., M.H. Hamed, Z.M. Omara, S.W. Sharshir, 2013. Water Desalination Using a Humidification-Dehumidification Technique – A Detailed Review. Natural Resources, 4:286-305, DOI: 10.4236/nr.2013.43036.

Li, X., 2009. Experimental Analysis of Produced Water Desalination by a Humidification-Dehumidification Process. Master's Thesis, New Mexico Institute of Mining and Technology, http://www.prrc.nmt.edu/publications/media/pdf/thesis/Li%20X%20Thesis%20experimental%20analysis.pdf.

Lienhard, J.H., A. Bilton, M.A. Antar, G. Zaragoza, and J. Blanco, 2012. Solar Desalination. Chapter 9 in Annual Review of Heat Transfer, Vol. 15, New York: Begell House, Inc., http://web.mit.edu/lienhard/www/papers/reviews/Solar_Desalination_AnnRevHeatTransfer-Vol15-2012-4659.pdf.

Lienhard J.H., n.d. HDH Desalination. Lienhard Research Group, http://lienhard.scripts.mit.edu/research/?page_id=1475.

Narayan, G.P., and J.H. Lienhard, 2014. Humidification Dehumidification Desalination. Desalination: Water from Water. Chapter 9 (J. Kucera, ed.), pp. 425-427, Wiley-Scrivener, Salem, Massachusetts. http://web.mit.edu/lienhard/www/papers/reviews/HDH-Desalination-chapter-2014.pdf.

Narayan, G.P., M.H. Sharqawy, E.K. Summers, J.H. Lienhard, S.M. Zubair, and M.A. Antar, 2010. The Potential of Solar-Driven Humidification-Dehumidification Desalination for Small-Scale Decentralized Water Production. Renewable and Sustainable Energy Reviews, 14(4):1187-1201. https://www.sciencedirect.com/science/article/pii/S1364032109002767.

Sharshir, S.W., G. Peng, and N. Yang, 2016. A Hybrid Desalination System Using Humidification-Dehumidification and Solar Stills Integrated with Evacuated Solar Water Heater. Energy Conversion and Management, 124:287-296, 2016, DOI: 10.1016/j.enconman.2016.07.028.

Zubair, M.I., F.A. Al-Sulaiman, and M.A. Antar, 2017. Performance and Cost Assessment of a Solar Driven Humidification Dehumidification Desalination System. Energy Conversion and Management, 132:28-39, 2017, DOI: 10.1016/j.enconman.2016.10.005.

A6 Miscellaneous Processes

A6.1 Direct Solar Vapor

A6.1.1 Technology Description

Direct solar vapor technology uses a gel, a membrane, or some other material in mesh-like cover over the feed water's surface to help evaporate saline waters. Recent research has been focused on using double-layer carbon nanomaterial to localize heat for water evaporation (figure A-25). The carbon disk is hydrophilic and porous. The top layer (exfoliated graphite) absorbs heat, and the bottom layer (carbon foam) insulates; thus, 97% of the irradiated solar power is absorbed within the top layer (Ghasemi et al., 2014).

This material captures more of the solar energy than water would uptake on its own. The solar-to-steam conversion is as high as 85% using a graphite/carbon form, double-layer nanoporous material (Ghasemi et al., 2014). Latent heat of water vaporization is lowered in the mesh material, thus allowing for more evaporation under the same solar energy availability compared to nonmesh water vaporization.

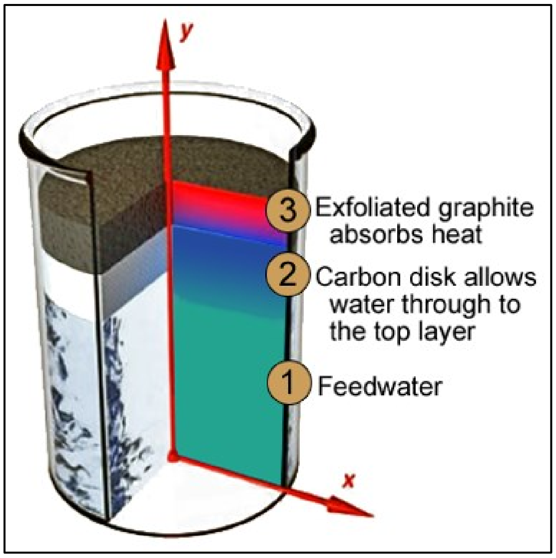

Figure A-25. Direct solar vapor process (Ghasemi et al., 2014).

A6.1.2 Technology Constraints

Table A-43 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-43. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	To date, some lab and pilot testing has been conducted. More research will be required to get an understanding of the full-scale systems and operational complexity of this process.	3	Zhao et al., 2018 Wang et al., 2017a Wang X et al., 2017, Ni et al., 2015
Flexibility	System is capable of treating varying water quality.	Yes	Wang X et al., 2016, Zhao et al., 2018
Scalability	Scalability of this type of system is yet to be determined. Surface area exposure to the sun requires a large amount of surface area covered by the mesh material. For large-scale systems, the material cost to cover large land areas can be limiting.	No	Zhao et al., 2018 Wang et al., 2017 Wang X et al., 2016, Ni et al., 2015
Environmental constraints	Covering large areas with the mesh material is a constraint. Operation during storms and high winds can disrupt mesh or require additional systems to keep the mesh intact.	No	Zhao et al., 2018 Wang et al., 2017a Wang X et al., 2017, Ni et al., 2015
Process residual	Process residuals will remain in the water body. If saturation limits are reached, precipitates will result—which could require removal at some point.	Yes	
Land area availability	Requires a lot of land. Efficiency of solar energy vaporization is increased to 18 – 23 liters per m^2 per day in comparison to regular solar stills which has a rate of 10 liters per m^2 per day.	No	Zhao et al., 2018 Wang et al., 2017a Wang X et al.,2017,
Feed water quality limitations	There are no feedwater quality limitations, as long as constituents do not precipitate onto the mesh.	Yes	Zhao et al., 2018 Wang et al., 2017a Wang X et al., 2017 Ni et al., 2015

A6.1.3 Technology Capability

Table A-44 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

Table A-44. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	To date, some lab and pilot testing has been conducted. More research will be required to gain an understanding of the full-scale systems and operational complexity of this process.	3	Zhao et al., 2018 Wang et al., 2017a Wang X et al., 2016 Ni et al., 2015
Produces additional "usable" water	Vapor must be condensed into water, which requires additional energy.	1	Wang X et al., 2016 Ni et al., 2015

Table A-44. Technology Capabilities

Capability	Assessment	Score	References
If water is produced, anticipated water quality (salinity)	Vapor must be condensed for additional water production. If so, then the water produced will be pure.	3	Wang X et al., 2016
Overall process recovery (concentrate volume minimization)		0	
Residual waste disposal	Residuals will stay in the water bodies that are being evaporated. Cleaning the formed precipitates or flushing these ponds will be required.	1	
Limitations to large-scale utilization	Large land area requirements and surface cover with mesh material are a major limitation for wide-scale use of this technology. Evaporation rates and the scale of technology use need to be considered because sites with higher evaporation rates will be more efficient.	0	Wang X et al., 2017, Zhao et al., 2018 Wang et al., 2017a
Hardness removal	Pure water will be generated from vapor condensation.	3	Wang X et al., 2016 Zhao et al., 2018 Wang et al., 2017a
Heavy metals removal	Pure water will be generated from vapor condensation.	3	Wang X et al.,2016 Zhao et al., 2018 Wang et al., 2017a
Organic contaminant removal	Pure water will be generated from vapor condensation.	3	Wang X et al., 2016 Zhao et al., 2018 Wang et al., 2017a
Radionuclide removal	Pure water will be generated from vapor condensation.	3	Wang X et al., 2016 Zhao et al., 2018 Wang et al., 2017a
Low chemical demand	Treatment itself might not require many chemicals, but the mesh material will be required. Mesh processing can be chemical dependent.	1	
Energy demand	Capturing solar energy requires mesh material.	2	Zhao et al., 2018 Wang et al., 2017a Wang X et al., 2017 Ni et al., 2015
Labor requirements	Labor requirement should be low, but more testing is needed with larger system for full understanding	1	
Reliability	To be determined. Not much long-term testing has been done thus far.	0	Zhao et al., 2018 Wang et al., 2017a Wang X et al., 2017 Ni et al., 2015
Value added		0	

A6.1.4 Life-Cycle Costs

Large land areas are required for higher recoveries, which adds to capital and operation costs. Mesh material cost and support structure to cover large water surface areas will be costly. O&M costs are not understood. (Zhao et al., 2018; Wang et al., 2017a; and Wang X et al., 2017

A6.1.5 Research Needs

More research will be required to gain an understanding of the full-scale systems and operational complexity of this process:

- Longer term testing of systems
- Low-cost mesh material
- New mesh material for higher evaporation rates to lower land area requirement
- LCC s development based on extensive bench and pilot testing

A6.1.6 References

Delgado-Torres, A.M., and L. García-Rodríguez, 2007. Preliminary Assessment of Solar Organic Rankine Cycles for Driving a Desalination System. Desalination, 216(1-3): 252-275, https://www.sciencedirect.com/science/article/pii/S0011916407004419

Ghasemi H., G. Ni, A.M. Marconnet, J. Loomis, S. Yerci, N. Miljkovic, and G. Chen, 2014. Solar Steam Generation by Heat Localization. Nature Communications, 5: 4449, https://www.nature.com/articles/ncomms5449.

Neumann O., A.S. Urban, J. Day, S. Lal, P. Nordlander, and N.J. Halas, 2013. Solar Vapor Generation Enabled by Nanoparticles. ACS nano, 7(1): 42-49, https://pubs.acs.org/doi/abs/10.1021/nn304948h.

Ni, G., N. Miljkovic, H. Ghasemi, X. Huang, S.V. Boriskina, C-T. Lin, J. Wang, Y. Xu, M.M. Rahman, T. Zhang, and Chen, 2015. Volumetric Solar Heating of Nanofluids for Direct Vapor Generation. Nano Energy, 17: 90-301, ISSN 2211-2855, https://doi.org/10.1016/j.nanoen.2015.08.021.

Wang, G., Y. Fu, X. Ma, W. Pi, D. Liu, and X. Wang, 2017a. Reusable Reduced Graphene Oxide Based Double-Layer System Modified by Polyethylenimine for Solar Steam Generation. Carbon, 114: 117-124, ISSN 0008-6223, https://doi.org/10.1016/j.carbon.2016.11.071.

Wang, X., Y. He, G. Cheng, L. Shi, X. Liu, and J. Zhu, 2016. Direct Vapor Generation through Localized Solar Heating via Carbon-Nanotube Nanofluid. Energy Conversion and Management, 130: 176-183, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2016.10.049.

Wang, X., Y. He, X. Liu, G. Cheng, and J. Zhu, 2017b. Solar Steam Generation through Bio-Inspired Interface Heating of Broadband-Absorbing Plasmonic Membranes. Applied Energy, 195: 414-425, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2017.03.080/.

Zhao, F.;X. Zhou, Y. Shi, X. Qian, and M. Alexander et al., 2018. Highly Efficient Solar Vapour Generation Via Hierarchically Nanostructured Gels. Nature Nanotechnology, 1748-3387, April 2, 2018, https://doi.org/10.1038/s41565-018-0097-z.

Zielinski M.S., J.W. Choi, T. La Grange, M. Modestino, S.M. Hashemi, Y. Pu, S. Birkhold, J. Hubbell, and D. Psaltis, 2016. Hollow Mesoporous Plasmonic Nanoshells for Enhanced Solar Vapor Generation. Nano Letters, 16(4): 2159-2167, https://pubs.acs.org/doi/abs/10.1021/acs.nanolett.5b03901.

A6.2 Solvent Extraction

A6.2.1 Technology Description

Solvent extraction is a separation method for aqueous solutions. Solvent extraction, or partitioning, is a method to separate compounds based on their relative solubilities in two different immiscible liquids.

An ion-extracting solvent can be used in concentrate management to separate water from ions in an aqueous solution. This extracting solvent extracts either the ions or the water (figure A-26). Water free of ions or with a lower ionic content is recovered, and the solvent will contain the ions. Recycling of the solvent that contains the ions is required for a sustainable and cost-effective process; thus, extracted water or ions must be desorbed from the solvent. Thermally responsive polymers are typically used for the extraction, and slight changes in temperature can activate the release of ions or water from the polymer.

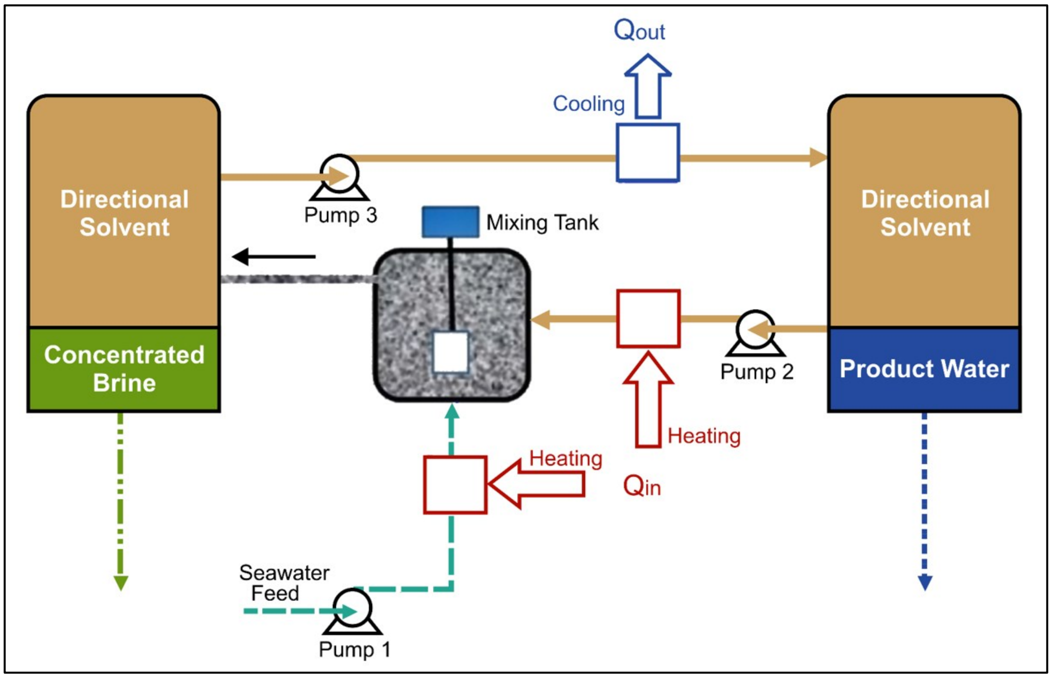

Figure A-26. Solvent extraction process (Alotaibi et al., 2017).

Extracting water into the extracting solvent is not cost effective (Sanap et al., 2015; Alotaibi et al., 2017) due to capital costs (25 times that of RO) and the energy requirement for solvent extraction operation (10 times that of RO). Therefore, this assessment sheet focuses on solvent systems that extract ions from aqueous solutions.

A6.2.2 Technology Constraints

Table A-45 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-45. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Technology is at an early stage.	5	Water Technology, 2014
Flexibility	Solvent extraction can handle a variety of feed water ionic constituents and concentrations.	Yes	Water Technology, 2014
Scalability	Scalability is a concern due to high cost of the solvents needed for extraction. Energy requirements for desorption are also limiting for larger-scale systems.	No	Smolyakov et al., 2018 Sanap et al., 2015
Environmental constraints	Organic solvents are typically required for extraction. Systems must ensure that this solvent is not present in the product water.	No	Smolyakov et al., 2018
Process residual	Currently, extracted residual is a mixed ionic compound.	Yes	Milosevic et al., 2013 Smolyakov et al., 2018
Land area availability	Land area requirement is not a constraint.	Yes	Milosevic et al., 2013 Smolyakov et al., 2018
Feed water quality limitations	High salinity feed water can limit ionic extraction, thus requiring additional treatment; however, there are no limitations on feed water quality.	No	Water Technology, 2014 Alotaibi et al., 2017

A6.2.3 Technology Capability

Table A-46 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A6.2.4 Life-Cycle Costs

The system's capital cost and the cost of solvents are high. Extracting ionic compounds is also a cost factor, along with desorption needed to recycle the solvent (Davison et al., 1958; Milosevic et al., 2013).

Table A-46. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	Technology is at an early stage.	5	Water Technology, 2014
Produces additional “usable” water	Produces desalinated water. Water will need additional processing to remove organics.	1	Smolyakov et al., 2018 Water Technology, 2014 Davison and Smith, 1968
If water is produced, anticipated water quality (salinity)	Produced water should be void of most ions.	2	Smolyakov et al., 2018 Water Technology, 2014 Davison et al., 1958
Overall process recovery (concentrate volume minimization)	Process will remove most of the ions from the concentrate, allowing for high overall process recovery.	2	Water Technology, 2014 Davison et al., 1958
Residual waste disposal	Residual will be highly concentrated and will contain organics that will require additional handling or separation for discharge.	1	Davison et al., 1958 Smolyakov et al., 2018
Limitations to large-scale utilization	Currently, costs are going to limit wide-scale adoption of this technology.	1	Sanap et al., 2015
Hardness removal	Process will remove the majority of multivalent ions.	3	Smolyakov et al., 2018
Heavy metals removal	Process will remove the majority of heavy metals.	3	Amer et al., 2017
Organic contaminant removal	Most solvents have an affinity for removing ionic species and, thus, are not very effective at organic removal.	1	
Radionuclide removal	Process should remove charged radionuclides.	2	Smolyakov et al., 2018 Amer et al., 2017
Low chemical demand	Requires additional solvent for extraction if not all of the solvent is removed.	1	Smolyakov et al., 2018 Water Technology, 2014 Davison et al., 1958
Energy demand	Requires energy to recycle solvents and to use heat to remove ions from the solvent.	1	Milosevic et al., 2013
Labor requirements	Monitoring of system for proper separation will be required.	1	
Reliability	System reliability needs to be proven through additional pilot and demonstration testing.	1	
Value added	Possibility of removing specific ions would be a great added value.	1	Smolyakov et al., 2018

A6.2.5 Research Needs

- Solvents with high affinity for ion extraction and lower temperatures swings to release extracted ions.
- Lower capital cost of systems.
- Lower operating cost of systems.
- Consider use of solvent extraction for dehydration of concentrated brine.

A6.2.6 References

Alotaibi, S., O.M. Ibrahim, S. Luo, and T. Luo, 2017. Modeling of a Continuous Water Desalination Process Using Directional Solvent Extraction. Desalination, 420: 114-124, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2017.07.004

Amer, B.A., M.H. Abdel-Aziz, E-S. El-Ashtoukhy, and N.K. Amin, 2017. Extraction of Heavy Metals from Aqueous Solutions in a Modified Rotating Disc Extractor. Journal of Water Reuse and Desalination, 7(2): 187-196, June 1, 2017, https://doi.org/10.2166/wrd.2016.178.

Davison, R. R., and W.H. Smith, 1968. Solvent Stability and Recovery in Solvent Extraction Desalination. Office of Saline Water Resources and Development Program Report No. 371, August 1968, Contract 14-01-0001-1180.

Davison, R., L.M. Jeffrey, U.G. Whitehouse, and D.W. Hood, 1958. Research on Liquid-Liquid Extraction for Saline Water Conversion. Available from the National Technical Information Service, Springfield, VA, 22161, as PB-161 396, Price Codes: A05 in Paper Copy, A01 in Microfiche.OSW Research and Development Progress Report No. 22, December 1958.

Milosevic, M., K.J.J. Staal, B. Schuur, and A.B. de Haan, 2013. Extractive Concentration of Aqueous Salt Solutions in Aqueous Two Phase Systems. Desalination, 324: 99-110, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2013.06.008.

Milosevic, M., K.J.J. Staal, G. Bargeman, B. Schuur, and André B. de Haan, 2014. Fractionation of Aqueous Sodium Salts by Liquid–Liquid Extraction in Aqueous Two Phase Systems. Separation and Purification Technology, 125: 208-215, ISSN 1383-5866, https://doi.org/10.1016/j.seppur.2014.01.058.

Sanap, D.B., K.D. Kadam, M. Narayan, and S. Kasthurirangan, 2015. Analysis of Saline Water Desalination by Directed Solvent Extraction Using Octanoic Acid. Desalination, 357: 150-162, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2014.11.020.

Smolyakov, G., S. Parrès-Maynadié, D. Bourgeois, B. Dautriche, and J. Pouessel, 2018. Efficient Liquid-Liquid Extraction of NaCl Governed by Simultaneous Cation and Anion Coordination. Desalination, 432: 40-45, ISSN 0011-9164, https://doi.org/10.1016/j.desal.2018.01.010.

Water Technology, 2014. Adionics Unveils New Desalination Technology. May 7, 2014, https://www.water-technology.net/news/news-adionics-unveils-new-desalination-technology-4262151.

A7 Additional Concrete Management Solutions

A7.1 Deep Well Injection

A7.1.1 Technology Description

Deep well injection (DWI) is a final disposal step where concentrate is injected into the subsurface in structurally isolated aquifers to prevent the contamination of other usable aquifers (figure A-27). Because this is a final disposal method, it can be used as the sole concentrate management method, or it can be used following other concentrate volume minimization technologies as the final residuals disposal method.

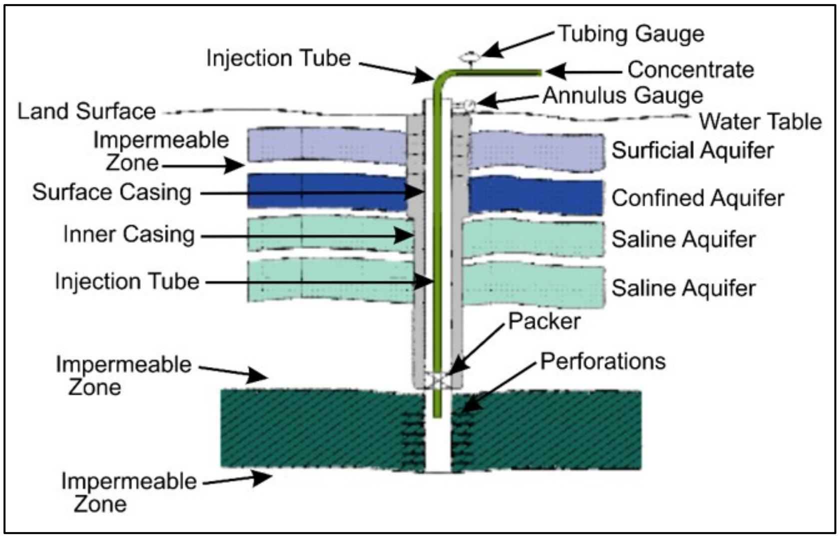

Figure A-27. Schematic diagram of injection well (Mackey and Seacord, 2008).

DWI of concentrate is regulated by EPA's Underground Injection Control Program. Concentrate injection wells are categorized as either Class I or Class V (Maliva and Manahan, 2016):

- Class I – Injection occurs below the deepest underground source of drinking water (USDW).
- Class V, Type A – Injection occurs in a USDW aquifer containing brackish water, concentrate injected into a Class V, type A must either meet primary drinking water standards, or the concentrate of constituents in the concentrate must be lower than those in the ambient ground water

- Class V, Type B – injection occurs into a non-USDW aquifer that has an underlying USDW.

- Class V, Type C – Injection occurs into a non-USDW aquifer in a location where there are no USDWs.

In Texas, HB 2654 allows for desalination concentrate injection into active Class II enhanced recovery wells or "dually permitted Class I-Class II wells through a Class II permit amendment process through the Railroad Commission (Texas Water Development Board, 2014).

A7.1.2 Technology Constraints

Table A-47 describes some of the usage constraints that may limit the applicability of the technology to certain applications. Constraint assessments are used to screen technologies from future consideration. Note that a Yes score for the technology indicates that the technology can be used for desalination processes with that constraint.

Table A-47. Technology Use Constraints

Constraint	Assessment	Score	References
Technology readiness level	Deep well injection is currently used for concentrate disposal. In the United States, approximately 13% of municipal desalination facilities use DWI.	9	Mickley, 2009
Flexibility	High salinity concentrates can be disposed of by DWI, although the water qualities of the brine and receiving aquifer must be evaluated to avoid precipitation and plugging of the injection well. Injection pressures will likely increase with increasing salinity, which may limit the applicability of this technology.	Yes	Mickley, 2009
Scalability	Scalability of injection wells is highly dependent on local geological conditions. The largest Class I injection well in the United States is 22 mgd (in Florida), although the largest Class I injection well in many states is less than 0.3 mgd. In areas with low subsurface permeability multiple injection wells could be constructed. Future expansion could require additional permitting if hydrogeological conditions allow for additional concentrate.	No	Mickley, 2009

Table A-47. Technology Use Constraints

Constraint	Assessment	Score	References
Environmental constraints	Feasibility (both technically and financially) of DWI is highly dependent on local geological conditions. Environmental permitting of DWI also varies by state. There are also seismic concerns associated with DWI practices.	No	
Process residual	None. Deep well injection is used as a final concentrate disposal step.	No	
Land area availability	Relatively low land area requirements for injection wells, although additional land or easements may be needed for a pipeline if the DWI site is not co-located with the desalination facility. Multiple wells may be required to accommodate the volume of concentrate.	Yes	
Feed water quality limitations	Well class permits have specific water quality requirements which vary by location. Water qualities of the concentrate and receiving aquifer must be evaluated to avoid precipitation and plugging of the injection well.	No	

A7.1.3 Technology Capability

Table A-48 describes the technology capabilities based on available literature, experience, and interpretation of available information on the criteria. Scores are used to compare technologies.

A7.1.4 Life-Cycle Costs

Capital and O&M costs can vary significantly based on well depth and diameter, local geologic conditions, and injection pressures. O&M costs are typically a relatively low portion of the overall cost (National Research Council, 2008).

A7.1.5 Research Needs

No research needs were identified, although a change in regulations could decrease the cost of DWI.

Table A-48. Technology Capabilities

Capability	Assessment	Score	References
Technology readiness level	DWI is currently used for concentrate disposal. In the United States, approximately 13% of municipal desalination facilities use DWI.	9	Mickley, 2009
Produces additional "usable" water	This is a disposal method. No usable water is recovered from the concentrate.	0	
If water is produced, anticipated water quality (salinity)	No water is produced.	0	
Overall process recovery (concentrate volume minimization)	No water is produced.	0	
Residual waste disposal	There are no residuals associated with DWI.	3	
Limitations to large-scale utilization	Large-scale use is constrained by local geological conditions.	2	
Hardness removal	Entire stream is disposed of in well.	3	
Heavy metals removal	Entire stream is disposed of in well.	3	
Organic contaminant removal	Entire stream is disposed of in well.	3	
Radionuclide removal	Entire stream is disposed of in well.	3	
Low chemical demand	Need for chemicals is dependent on concentrate quality and receiving aquifer quality. Anticorrosion additives, disinfectants, pH adjustment additives, and flocculation additives may be needed.	3	Mace et al., 2005 Mickley, 2006
Energy demand	Depends on injection depth and pressure.	1	Mackey and Seacord, 2008
Labor requirements	Primary operating costs are power (for pumping), chemicals, and labor. Pumping power is the most significant operating cost.	1	Mickley, 2006
Reliability	Proven to be effective and reliable for concentrate disposal.	3	Maliva and Manahan, 2016
Value added	None.	0	

A7.1.6 References

Texas Water Development Board, 2014. Manual for Permitting Process: Guidance Manual for Permitting Class I and Class II Wells for the Injection and Disposal of Desalination Concentrate, http://www.twdb.texas.gov/publications/reports/contracted_reports/doc/1004831106_injectionwells.pdf.

Mace, R.E., J-P. Nicot, A.H. Chowdhury, A.R. Dutton, and S. Kalaswad, 2005. Please Pass the Salt: Using Oil Fields for the Disposal of Concentrate from Desalination Plants. U.S. Department of the Interior, Bureau of Reclamation, Desalination and Water Purification Report 112, https://www.usbr.gov/research/dwpr/reportpdfs/report112.pdf.

Mackey, E.D., and T. Seacord, 2008. Regional Solutions for Concentrate Management. WateReuse Foundation, Alexandria, Virginia, https://www.waterboards.ca.gov/water_issues/programs/grants_loans/water_recycling/research/02_006d_01.pdf.

Maliva, R.G. and S. Manahan., 2016. Desalination Concentrate Disposal Injection Well Experiences in the USA And Caribbean. AWWA Conference Proceedings, February 1 - 5, 2016,San Antonio, Texas. http://docplayer.net/15037743-Conference-exposition.html

Mickley, M., 2006. Membrane Concentrate Disposal: Practices and Regulation (Second Edition). U.S. Department of the Interior, Bureau of Reclamation, Desalination and Water Purification Report 123. Denver, Colorado. https://www.usbr.gov/research/dwpr/reportpdfs/report123.pdf.

Mickley, M., 2009. Treatment of Concentrate. U.S. Department of the Interior, Bureau of Reclamation, Desalination and Water Purification Report 155. Denver, Colorado. https://www.usbr.gov/research/dwpr/reportpdfs/report155.pdf.

National Research Council, 2008. Desalination: A National Perspective. Washington, DC: The National Academies Press. https://doi.org/10.17226/12184.