National Alliance for Water Innovation

RESOURCE EXTRACTION SECTOR

TECHNOLOGY ROADMAP

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This report, originally published in May 2021, has been revised in November 2021 to:

- Add authors Carolyn Cooper, Cameron McKay, Kaleisha Miller, and James Rosenblum
- Correct grammatical errors
- Add new and deleted unused acronyms (Appendix A)
- Add and renumber end note citations in sequential order throughout document
- Revision to the following sections of Research Priorities: A2 Impacts (page 59), A3 Impacts (page 60)

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1. EXECUTIVE SUMMARY

1.1 Introduction to NAWI and the NAWI Roadmap

The National Alliance for Water Innovation (NAWI) is a research consortium formed to accelerate transformative research in desalination and treatment to lower the cost and energy required to produce clean water from nontraditional water sources and realize a circular water economy.

NAWI's goal is to ***enable the manufacturing of energy-efficient desalination technologies in the United States at a lower cost with the same (or higher) quality and reduced environmental impact for 90 percent of nontraditional water sources within the next 10 years.***

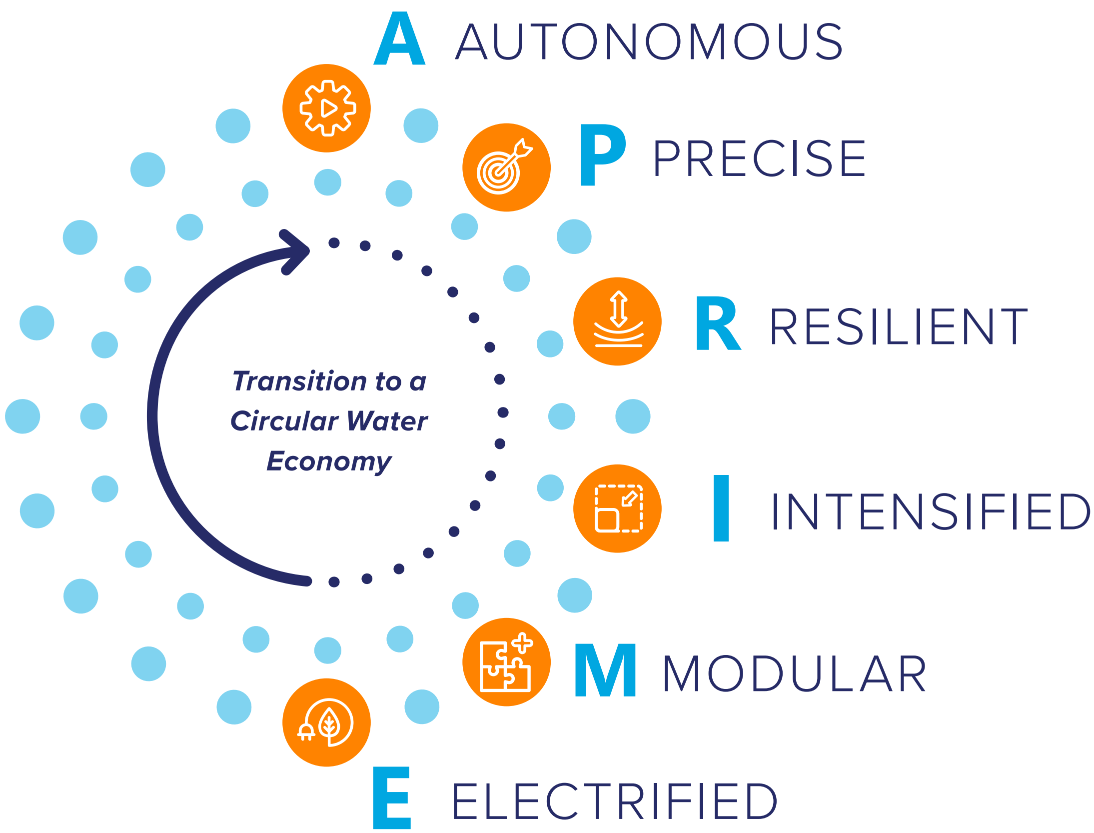
The nontraditional source waters of interest include brackish water; seawater; produced and extracted water; and power, mining, industrial, municipal, and agricultural waste waters. When these desalination and treatment technologies are fully developed and utilized, they will be able to contribute to the water needs for many existing end-use sectors. **NAWI has identified five end-use sectors that are critical to the U.S. economy for further exploration: Power, Resource Extraction, Industry, Municipal, and Agriculture (PRIMA).**

Power | **Resource Extraction** | **Industry** | **Municipal** | **Agriculture**

This roadmap aims to advance desalination and treatment of nontraditional source waters for beneficial use in the **Resource Extraction Sector** (i.e., oil and gas [O&G] and mining industries) by identifying research and development (R&D) opportunities that help overcome existing treatment challenges.

Under NAWI's vision, the transition from a linear to a **circular water economy** with nontraditional source waters will be achieved by advancing desalination and reuse technologies in six key areas: Autonomous, Precise, Resilient, Intensified, Modular, and Electrified, collectively known as the **A-PRIME** challenge areas.

Technological advances in these different areas will enable nontraditional source waters to achieve pipe-parity with traditional supplies.



Pipe-parity is defined as the combination of technological solutions and capabilities (e.g., resiliency enablers and strategies leading to long-term supply reliability) and non-technological solutions that make marginal water sources competitive with traditional water resources for end-use applications.

To effectively assess technology advances and capabilities, NAWI will use pipe-parity metrics relevant for the Resource Extraction End-Use Sector. These metrics can be quantitative or qualitative, depending on how an end-user would evaluate different potential water sources and whether they could be integrated into their supply mix.

1.2 Water User Sector Overview

Total "freshwater" withdrawals for the Resource Extraction Sector are about 15.5 million cubic meters (m^3) per day (4.1 billion gallons per day).[1] Traditional source waters for Resource Extraction include relatively proximal groundwater and surface water supplies. This sector can use both fresh and brackish water sources, depending on location, availability, and application. Internal reuse (i.e., recycled water) is also an important source of supply for resource extraction. Internal reuse of lightly treated O&G produced water as "clean brine" has increased significantly in upstream operations (i.e., exploration and production) due to advancements in hydraulic fracturing chemical technology. In the mining industry, water used in ore extraction and processing is reused back in the processing streams or to supply other water needs (e.g., dust suppression, washing). While some water-stressed locations have used nontraditional waters, technical, logistical, financial, and regulatory challenges must be addressed to achieve pipe-parity for these sources.

Key challenges within the Resource Extraction Roadmap include both the large volumes and complex chemical composition of waste streams generated from resource acquisition and processing activities. In 2017, the United States generated 3.88 billion m^3 (24.4 billion barrels or 1.025 trillion gallons) of produced water with salinities ranging from less than 2,000 to nearly 400,000 milligrams per liter (mg/L) total dissolved solids (TDS).[2] The total estimated water use by mining operations was approximately 8.6 billion m^3 (2.270 trillion gallons) in 2015.[3,4]* As mining operations often reuse or recycle process water to the greatest extent possible, significant water volumes containing a variety of problematic constituents (e.g., suspended solids, toxic metals, sulfates), must be managed, while water not reused or recycled is either lost through tailings entrainment or through evaporation. Currently reinjection (O&G) and evaporation ponds (mining) are the dominant management methods for these waste streams. However, the long-term sustainability of these approaches has been questioned. Treatment of these waste streams for beneficial reuse could address issues of sustainability and water scarcity for these and other industries. Moreover, resource recovery of valorized constituents could financially incentivize treatment of these complex waste streams.

1.3 Water Treatment and Management Challenges

Table 1 identifies broad industry challenges and key gaps that need to be addressed to enable the Resource Extraction Sector to efficiently use nontraditional source waters. These barriers have been identified through workshops and discussions with subject matter experts as part of a structured roadmapping process. The barriers are too large and far reaching for any one organization to solve on its own. NAWI intends to invest in promising technology readiness level (TRL) 2–4 concepts that are cross-cutting across the PRIMA areas and that address some technical limitations discussed below, and welcome complementary efforts by other research organizations.

* Based on average water use estimate of 2.39 m^3 per tonne of ore and the 3,590 million tonnes of ore processed in the United States in 2015. Derived from corporate sustainability and environmental management reports from 359 mining company reports from over 32 countries in 21 commodity groups.

Table 1. Synopsis of technical and non-technical challenges to utilizing nontraditional water sources for the Resource Extraction Sector.

TECHNICAL

Constituent and Detection Challenges

- The Resource Extraction Sector needs to compile data on concentrations of constituents of concern in nontraditional waters, establish analytical protocols for characterization, and develop sensors appropriate for complex nontraditional water sources.
- Accurate modeling of the geochemical behavior of constituents and their behavior in treatment systems, as well as analysis of complex matrices and treatment systems, are needed to use, reclaim, and reuse nontraditional waters efficiently and effectively.

Spacial/Temporal Challenges

- Resource extraction operations are often located in remote areas and experience difficulties in sourcing water, accessing resources, and developing infrastructure for water treatment, operations, and waste disposal.
- The locations of O&G wells, the magnitude of mining operations at a permanent mine, and the water quantity and quality at the operating locations all change over time, requiring scalable and flexible treatment systems.
- Beneficial reuse has limited options outside of resource extraction industries due to remote locations, water quality challenges and uncertainties, and a lack of regulatory guidance on what constitutes treated resource extraction wastewater.

Treatment Challenges

- The Resource Extraction Sector requires large volumes of water, often for short durations with limited flexibility in demand, leading to challenging planning and treatment requirements.
- The Resource Extraction Sector must treat and manage an array of water constituents, some at very high concentrations and others at trace concentrations, creating scenarios not typically seen in traditional water and wastewater treatment facilities.
- The Resource Extraction Sector requires durable process components constructed with materials suitable for treatment of Resource Extraction waste streams.

Disposal and Solids Management Challenges

- The Resource Extraction Sector is challenged by current residual management technologies that are energy intensive and/or produce large masses of residuals, some of which could be classified as hazardous waste.

NON-TECHNICAL

- **Cost:** Water is undervalued in the industry due to a variety of factors.
- **Standards Development:** Water/wastewater treatment, disposal regulations, and other requirements vary by location (federal, state, local, and tribal).

  Data collection and sharing are limited by lack of standards, liability concerns, intellectual property, and limited understanding of business and operational benefits.
- **Liability and Risk:** The Resource Extraction Sector faces business and operational risks related to the use of nontraditional water sources and the implementation of supporting technologies.
- **Environmental:** Increased reuse within the Resource Extraction Sector poses an environmental risk.
- **Workforce and Training:** Nontraditional water use introduces challenges related to the education and skills of the sector's workforce.
- **Regulations and Public Acceptance:** Technologies for nontraditional water use—including internal reuse and wastewater reuse outside of the Resource Extraction industry—can develop faster than related regulations or could spur additional, challenging regulations.

  Even if developments in nontraditional water use succeed technically and meet regulatory requirements, there will be additional challenges when trying to gain public acceptance.

1.4 Research Priorities

To overcome these industry challenges, strive towards meeting pipe-parity, and achieve NAWI's mission of expanding the use of nontraditional source waters for the Resource Extraction Sector, this roadmap lays out several research priorities that were identified through structured roadmapping processes with subject matter experts. These R&D Areas of Interest (AOIs) are grouped under the individual A-PRIME categories discussed earlier. Specific research gaps, technologies, or problems that have not been sufficiently answered by existing studies are also included with each development area.

The Autonomous area entails developing robust sensor networks coupled with sophisticated analytics and secure controls systems.
Specific prioritized research areas include:

- **Develop reliable, robust sensors to enable advanced autonomous control systems in distributed and remote work sites that are capable of withstanding the harsh environments and varying water quality present in O&G and mining applications.** These robust sensors should be durable, self-cleaning, and self-calibrating or low-cost and potentially disposable. They should be easy to install, operate, and maintain and should support real-time data collection and communications with control systems.
- **Develop automated data collection and processing programs and platforms to identify trends in process performance and anomalies; trends in feed, product, and brine chemistry; and early warning signals of changing influent water quality that allow adjustments to process performance.** Systems should monitor key operating conditions (e.g., temperature, pH, recovery rate) to inform process controls and operating systems and to enable predictions to avoid malfunctions and improve treatment effectiveness and efficiency.
- **Develop model-based control and data-driven models (digital twins) to enable optimization of process set-points and process dynamics, leading to energy reduction, fit-for-purpose quality, and optimal water productivity and recovery.** Models should reflect actual operating conditions in the process streams, include the most up-to-date understanding of system chemistry and interactions, and support accurate operational decision making. This will enable improved operations given water properties and operating conditions (including environmental, market, and grid conditions).

The Precise area focuses on a targeted treatment approach with precise removal or transformation of treatment-limiting constituents and trace contaminants. Specific research areas include:

- **Develop and expand selective separation** (e.g., membrane, sorption, ion exchange) and destruction (e.g., catalytic, electrochemical, and advanced oxidation) technologies for the selective separation/destruction of recalcitrant, soluble organic pollutants. These technologies should include improved analytics techniques and surrogates to manage complex constituents, enable precision separations, and improve energy efficiency and resilience of the processes.
- **Develop and expand selective separation technologies** (e.g., membrane, sorption, ion exchange) for altering the speciation or removing metal ions and nutrients that inhibit downstream processes or selected end uses or facilitate recovery of valuable minerals while treating complex produced waters, mining waters, and their concomitant brine streams. These technologies should enable separation of constituents from complex resource extraction wastewaters, enabling enhanced recovery of valuable minerals, preventing fouling and scaling, and enabling separation of previously recalcitrant constituents.
- **Develop high rate, pre-treatment technologies for bulk constituents** (e.g., insoluble organics, total suspended solids [TSS], naturally occurring radioactive materials [NORM]) to improve precision separations. These should include technologies that enable improved pre-treatment processes and selective separations of dominant ions, including spatially efficient oil-water separations, targeted removal of NORM with bulk constituents, and efficient separation of high-density sludge systems (HDS).

The Resilient area looks to enable adaptable treatment processes and strengthen water supply networks. Specific research areas include:

- **Develop autonomous water treatment systems that can quickly respond to and recover from changes in water quality, environmental conditions, and flow rates.** These systems should adjust pretreatment and treatment processes to provide efficient, fit-for-purpose treatment in response to current conditions.
- **Develop site-specific strategies for incorporating renewable energy and energy storage.** These technologies should include process protection in times of energy intermittency, and models for energy production, use, and storage that are applicable to remote or distributed treatment locations. These should also include development of water and wastewater treatment of high-salinity sources—the treatment of which might be cost-effective only because of intermittent or excess energy supply.
- **Develop integrated water distribution and collection pipeline bundles (similar to electrical grids) that enable users to simultaneously contribute various treated waters and withdraw various water types.** These technologies should include hydraulic and energy models for flows, pressures, temperatures, and materials for the pipeline system as well as chemical and biological models of the connected treatment plants. These should also include development of flexible, durable, and self-healing pipeline materials to improve water flow and minimize corrosion and other impediments to effective treatment.

The Intensified area thrust focuses on innovative technologies for brine concentration and crystallization and the management and valorization of residuals.
Specific research areas include:

- **Develop hybrid treatment trains (across scales) to further enhance water recovery from brines from desalination processes, high-salinity produced water, or mining wastewater.** These technologies should include robust desalination techniques for both hypersaline and lower-saline waters and technologies that would combine existing desalination processes with traditional or new brine concentrators.
- **Develop technologies for resource recovery from brines while minimizing hazardous waste generation.** These technologies should enable enhanced, modular, cost-effective recovery of specific minerals and ions from waste and concentrated brine streams. They should also incorporate the use of renewable energy and materials and should be supported by a techno-economic study of the potential for resource recovery.
- **Develop cost-effective methods for brine management and solidification.** These methods should include developing marketable products for local use of produced bulk solids and residuals, as well as technologies that enable solidification and stabilization of solids from minimal liquid discharge (MLD) and zero-liquid discharge (ZLD) systems.
- **Optimize the prediction and characterization of brine streams.** This should include developing methods to characterize and assess toxicity to ensure appropriate reuse, disposal, and solidification. This should be supported by geochemical modeling tools to predict and control fouling and scaling during treatment, transport, and ultimate disposal.

The Modular area looks to improve materials and manufacturing processes to expand the range of cost-competitive treatment components and eliminate intensive pre/post-treatment. Specific research areas include:

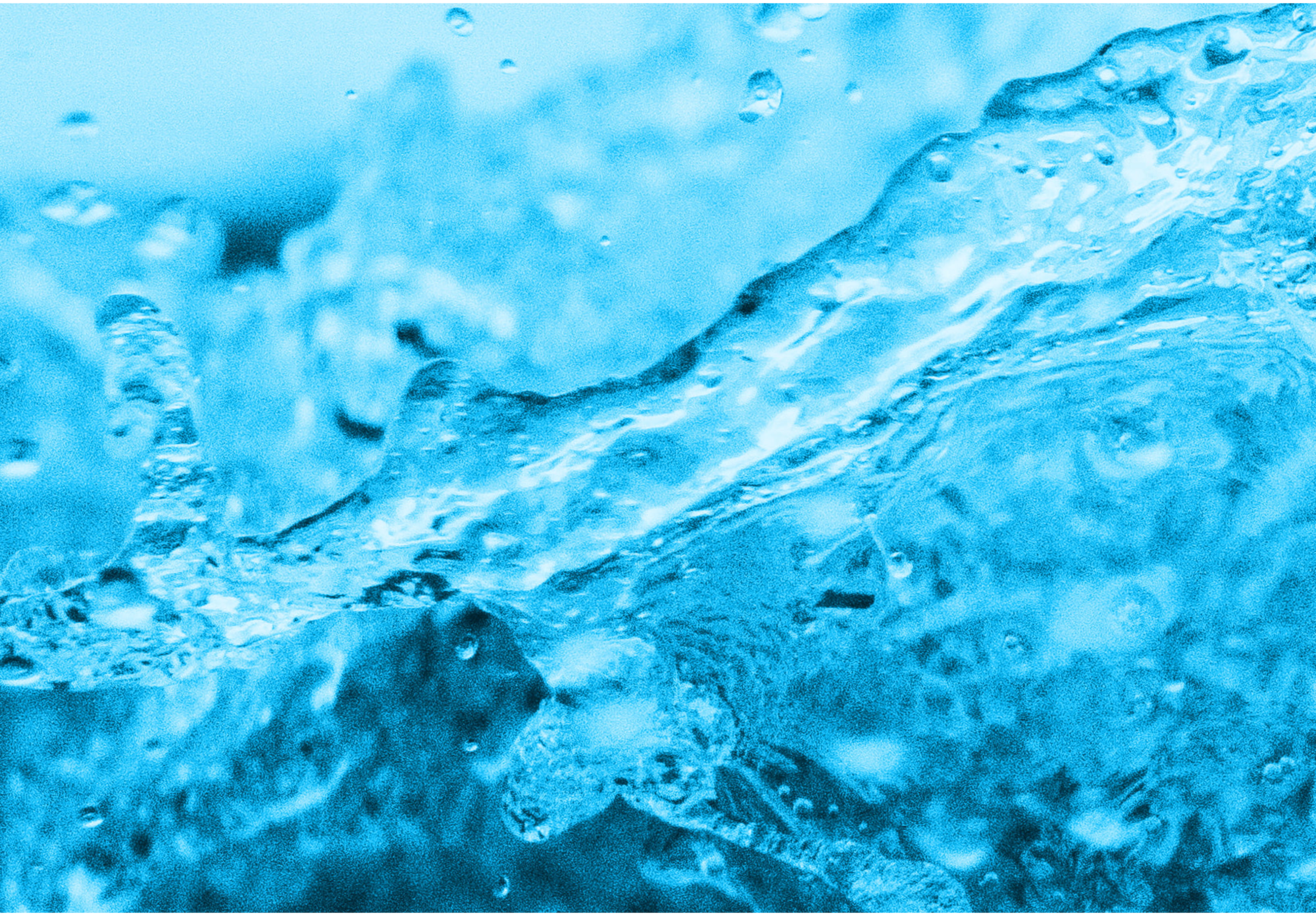
- **Increase flexibility, scalability, and portability of modular treatment systems and characterize operating limitations to enable cost-effective solutions and increase industry adoption.** These technologies should reduce the weight, size/footprint, and complexity of unit processes across the treatment train. Improvements should come from beneficial synergies between specialized unit processes, new filtration materials and systems for better scalability and improved system capacity. They should be supported by improved manufacturing methods to increase economies of scale and industry adoption.
- **Innovate on membrane module design for improved durability against various stress factors** (e.g., chemical, temperature, pressure) and application in high-salinity, high-pressure, and high-flow waste streams. These should include novel, hybrid processes as well as scalable membrane materials with improved chemistries and performance characteristics. These should be supported by a better understanding of the interfacial interactions between conventional and novel membranes and organic compounds to provide more cost-effective and resilient pre-treatment and longer operational lifetimes.
- **Improve regulatory and industry understanding of modular treatment systems and their benefits and limitations in context with the entire treatment system.** This should include a techno-economic assessment of modular systems to identify and assign the economic impacts of various environmental factors and current disposal practices. This should also include facilitating information sharing and discussion between researchers, resource extraction engineers, and regulators on the impacts on the costs and effectiveness of wastewater treatment.

The Electrified area aims to replace chemically intensive processes with electrified processes that are more amenable to variable or fluctuating operating conditions. Specific research areas include:

- **Develop and optimize electrified treatment processes** (i.e., electromagnetic field, electrocoagulation) to reduce chemical use and associated transportation logistics/costs. This should include identifying the potential benefits and limitations of electrocoagulation (EC) and its integration into treatment trains, assessing methods for optimizing electrolytic performance, evaluating electrodes and catalysts, and developing non-chemical approaches for fouling and scaling control. These developments should be supported by bench-scale testing over a range of relevant operating conditions.
- **Develop and evaluate performance, limitations, and implementation of electrical desalination processes.** These processes should include both low-to-moderate- and high-salinity electrical desalination technologies, cost-effective electrode materials and design, electric-based precision separations technologies, and integration of electrical desalination and crystallization methods.
- **Evaluate the use of water electrolysis and bipolar electrodialysis for generation of chemicals on site and in situ, including bleach, acids, and bases at resource extraction facilities.** This should include effective methods of chemical generation from resource extraction waters optimized for higher-salinity systems. These methods should ensure chemical purity control and should potentially include in situ disinfectant and chemical generation.
- **Investigate the use of alternative and renewable energy sources in electrified water treatment.** This should include exploring impacts of energy intermittency on process operation, effluent water quality, and equipment lifespan. This should also include analyzing opportunities and limitations for renewable energy supplies, nontraditional fossil fuels, and hydrogen from impaired water to support electrified treatment processes.

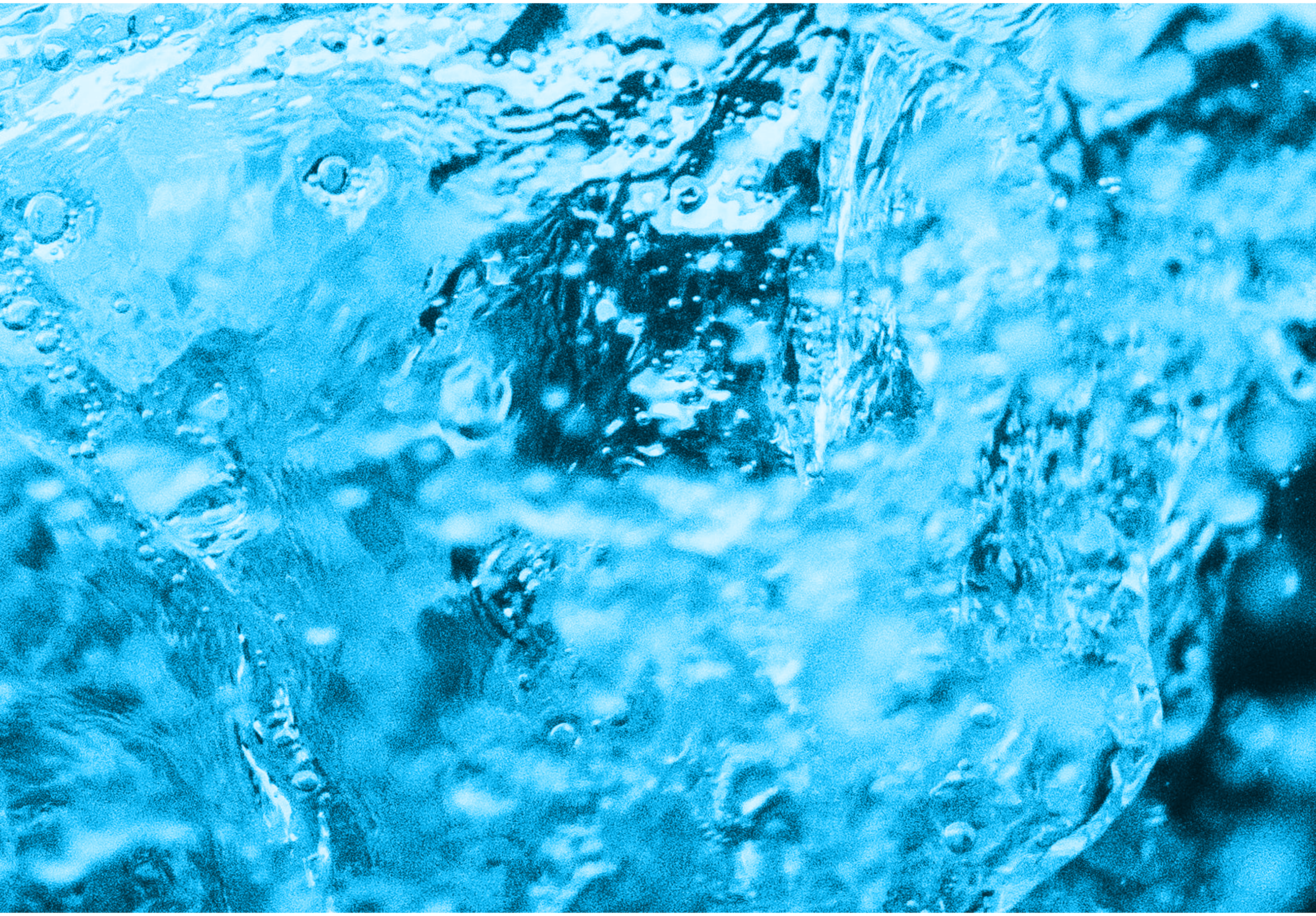
1.5. Next Steps

NAWI's comprehensive and dynamic roadmap for desalination and water treatment technologies for the Resource Extraction End-Use Sector is intended to guide future R&D investments throughout the duration of the research program. Because this roadmap forecasts into the future and is meant to guide NAWI throughout its existence, it should be considered a living document that is periodically re-evaluated and revised to ensure its continued relevancy. With ongoing input from industry stakeholders and support from academia, water utilities, water professionals, and other NAWI partners, the Alliance will update this roadmap to ensure it evolves to capture progress of high-priority objectives as well as the emergence of new technologies.



1.6. Appendices

The appendices include a list of relevant acronyms for this document (Appendix A); an expanded description of the NAWI A-PRIME hypothesis (Appendix B); Department of Energy (DOE) Water Hub Development Background (Appendix C); roadmap teaming structure (Appendix D); in-depth examination of the roadmap development process (Appendix E); technology roadmap contributors (Appendix F); and relevant references (Appendix G).



2. INTRODUCTION

2.1. Growing Challenges with Water

Clean water is critical to ensure good health, strong communities, vibrant ecosystems, and a functional economy for manufacturing, farming, tourism, recreation, energy production, and other sectors' needs.[5]

Water managers in 40 states expect water shortages in some portion of their state in the next several years.[6] As water insecurity grows in severity across the United States and populations increase in regions with limited conventional sources, water supplies traditionally ignored or avoided due to treatment challenges are being reconsidered.

Research to improve desalination technologies can make nontraditional sources of water (i.e., brackish water; seawater; produced and extracted water; and power sector, industrial, municipal, and agricultural wastewaters) a cost-effective alternative. These nontraditional sources can then be applied to a variety of beneficial end uses, such as drinking water, industrial process water, and irrigation, expanding the circular water economy by reusing water supplies and valorizing constituents we currently consider to be waste.[7] As an added benefit, these water supplies could contain valuable constituents that could be reclaimed to further **a circular economy.**

2.2. Establishing an Energy-Water Desalination Hub

In 2019, DOE established an Energy-Water Desalination Hub (part of a family of Energy Innovation Hubs[8]) to address water security issues in the United States. NAWI was funded to address this critical component of the DOE's broader Water Security Grand Challenge to help address the nation's water security needs. NAWI's goal is to ***enable the manufacturing of energy-efficient desalination technologies in the United States at a lower cost with the same (or higher) quality and reduced environmental impact for 90 percent of nontraditional water sources within the next 10 years.***

NAWI is led by Lawrence Berkeley National Laboratory in Berkeley, California and includes Oak Ridge National Laboratory, the National Renewable Energy Laboratory, the National Energy Technology Laboratory, 19 founding university partners, and 10 founding industry partners. This partnership is focused on conducting early-stage research (TRLs 2–4) on desalination and associated water-treatment technologies to secure affordable and energy-efficient water supplies for the United States from nontraditional water sources. NAWI's five-year research program will consist of collaborative early-stage applied research projects involving DOE laboratories, universities, federal agencies, and industry partners. DOE is expected to support NAWI with $110 million in funding over five years, with an additional $34 million in cost-share contributions from public and private stakeholders.

As a part of the NAWI research program, this strategic roadmap was developed for the Resource Extraction Sector to identify R&D opportunities that help address their particular challenges of treating nontraditional water sources. Recognizing the important sector-specific variations in water availability and water technology needs, NAWI has also published four other end-use water roadmaps, each with specific R&D and modeling opportunities (power, municipal, industry, and agriculture). Each roadmap has been published as a standalone document that can inform future NAWI investments as well as provide insight into priorities for other research funding partners.

2.3. Pipe-Parity and Baseline Definitions

A core part of NAWI's vision of a circular water economy is reducing the cost of treating nontraditional source waters to the same range as the portfolio of accessing new traditional water sources, essentially achieving pipe-parity. The costs considered are not just economic, but include consideration of energy consumption, system reliability, water recovery, and other qualitative factors that affect the selection of a new water source. To effectively assess R&D opportunities, pipe-parity metrics are utilized; they encompass a variety of information that is useful to decision makers regarding investments related to different source water types.

Pipe-parity is defined as technological and non-technological solutions and capabilities that make marginal water sources viable for end-use applications. Like the concept of grid parity (where an alternative energy source generates power at a levelized cost of electricity [LCOE] that is less than or equal to the price of power from the electricity grid), a nontraditional water source achieves pipe-parity when a decision maker chooses it as their best option for extending its water supply.

Specific pipe-parity metrics of relevance can include:

Cost

Cost metrics can include levelized costs of water treatment as well as individual cost components, such capital or operations and maintenance (O&M) costs.

Energy Performance

Energy performance metrics can include the total energy requirements of the water treatment process, the type of energy required (e.g., thermal vs. electricity), embedded energy in chemicals and materials, and the degree to which alternative energy resources are utilized.

Water Treatment Performance

Water treatment performance metrics can include the percent removal of various contaminants of concern and the percent recovery of water from the treatment train.

Human Health and Environment Externalities

Externality metrics can include air emissions, greenhouse gas emissions, waste streams, societal and health impacts, and land-use impacts.

Process Adaptability

Process adaptability metrics can include the ability to incorporate variable input water qualities, the ability to incorporate variable input water quantity flows, the ability to produce variable output water quality, and the ability to operate flexibly in response to variable energy inputs.

Reliability and Availability

System reliability and availability metrics can include factors related to the likelihood of a water treatment system not being able to treat water to a specified standard at a given moment, how quickly the system can restart operations after being shut down for a given reason, confidence in source water availability, the degree to which the process is vulnerable to supply chain disruptions, and the ability to withstand environmental, climate, or hydro-logical disruptions.

Compatibility

Compatibility metrics can include ease of operation and level of oversight needed, how well the technology integrates with existing infrastructure, how consistent the technology is with existing regulations and water rights regimes, and the level of social acceptance.

Sustainability

Sustainability metrics can include the degree to which freshwater inputs are required for industrial applications, the percentage of water utilized that is reused or recycled within a facility, and watershed-scale impacts.

To establish references on which pipe-parity metrics are most applicable in each sector, **baseline studies** for each of NAWI's eight nontraditional water sources have been conducted. These studies collect data about the use of each source water and evaluate several representative treatment trains for the targeted source water to better understand current technology selections and implementation methods. The baselines provide range estimates of the current state of water treatment pathways across pipe-parity metrics, which enable calculation of potential ranges of improvement.

Specific baseline information required includes:

a) information on the type, concentration, availability, and variability of impurities in the source water;
b) identification of key unit processes and representative treatment trains treating the source water and their associated cost, removal efficiency, energy use, robustness, etc.;
c) ranges of performance metrics for treatment of the source water for applicable end-uses; and
d) definitions of pipe-parity for the source water type and water use.

2.4. Nontraditional Waters of Interest

2.4.1. Sources of Nontraditional Waters

NAWI has identified eight nontraditional water supplies of interest for further study (Figure 1):

Seawater and Ocean Water	Water from the ocean or from bodies strongly influenced by ocean water, including bays and estuaries, with a typical TDS between 30,000 and 35,000 mg/L
Brackish Groundwater	Water pumped from brackish aquifers with particular focus on inland areas where brine disposal is limiting. Brackish water generally is defined as water with 1,000 to 10,000 mg/L TDS
Industrial Wastewater	Water from various industrial processes that can be treated for reused
Municipal Wastewater	Wastewater treated for reuse through municipal resource recovery treatment plants utilizing advanced treatment processes or decentralized treatment systems
Agricultural Wastewater	Wastewater from tile drainage, tailwater, and other water produced on irrigated croplands as well as wastewater generated during livestock management that can be treated for reuse or disposal to the environment
Mining Wastewater	Wastewater from mining operations that can be reused or prepared for disposal
Produced Water	Water used for or produced by oil and gas exploration activities (including fracking) that can be reused or prepared for disposal
Power and Cooling Wastewater	Water used for cooling or as a byproduct of treatment (e.g., flue gas desulfurization) that can be reused or prepared for disposal

Figure 1. Schematic of traditional and nontraditional sources of waters, as defined by NAWI

Graphic courtesy of John Frenzl, NREL

These water sources range widely in TDS (100 mg/L – 800,000 mg/L total) as well as the type and concentrations of contaminants (e.g., nutrients, hydrocarbons, organic compounds, metals). **These different supplies require varying degrees of treatment to reach reusable quality.**

2.4.2. End-Use Areas Using Treated Nontraditional Source Waters

When these water supplies are treated with novel technologies created through the NAWI desalination hub, these remediated wastewaters could be repurposed back to one or more of the following five end-use sectors.

Power — Water used in the electricity sector, especially for thermoelectric cooling

Resource Extraction — Water used to extract resources, including mining and oil and gas exploration and production

Industrial — Water used in industrial and manufacturing activities not included elsewhere, including but not limited to petrochemical refining, food and beverage processing, metallurgy, and commercial and institutional building cooling

Municipal — Water used by public water systems, which include entities that are both publicly and privately owned, to supply customers in their service area

Agriculture — Water used in the agricultural sector, especially for irrigation and food production

NAWI identified these broad "PRIMA" sectors because they are major users of water with opportunities for reuse. Figure 2 expands on the industries included in NAWI's PRIMA broad end-use sectors. These areas are not meant to be exhaustive, as nearly all industries and sectors rely on water in one way or another.

END-USE SECTOR	INDUSTRIES INCLUDED
Power	Thermoelectric Renewable energy
Resource Extraction*	Upstream oil and gas Hydraulic fracturing operations Mining
Industrial†	Refineries Petrochemicals Primary metals Food and beverage Pulp and paper Data centers and large campuses
Municipal	Public supply for use by residential, commercial, industrial, institutional, public service, and some agricultural customers within the utility service area
Agriculture	Irrigation Livestock Upstream food processing

Figure 2. PRIMA and the industries covered in each area

2.5 A-PRIME

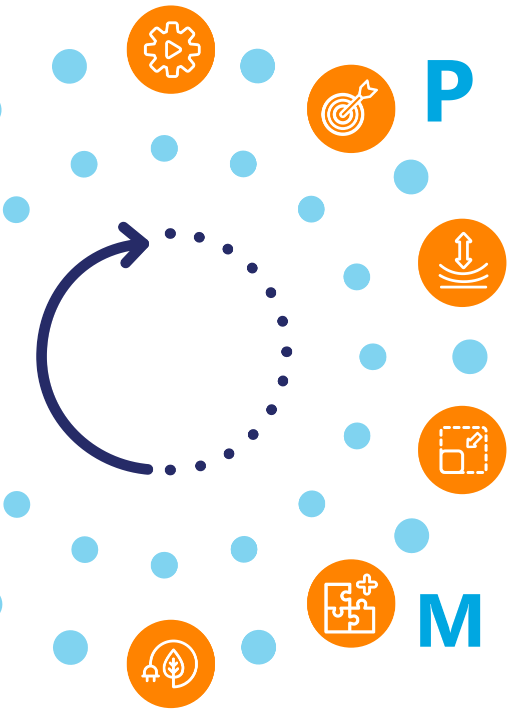
Securing water supplies for multiple end-uses requires technology revolutions that will transition the United States from a linear to a circular water economy.

These desalination and reuse advances will be realized by developing a suite of Autonomous, Precise, Resilient, Intensified, Modular, and Electrified technologies (A-PRIME) that support distributed and centralized treatment at a cost comparable to other inland and industrial sources.[2] Each aspect of this hypothesis has been vetted with water treatment professionals from each PRIMA industry sector as well as NAWI's Research Advisory Council (RAC) to ensure that it is a relevant means of advancing desalination and water treatment capabilities for nontraditional source waters. These areas may be modified as new priorities and opportunities are identified.

* An important distinction for oil and gas and mining operations: upstream drilling operations fall under the Resource Extraction and downstream refining operations fall under the Industrial Sector.

† This list of industries for the Industrial Sector is for baselining and initial roadmapping. This list will be reviewed in future roadmap iterations.

The NAWI A-PRIME hypothesis outlines the following six major challenge areas needing improvement for water treatment to reach pipe-parity for nontraditional waters. An A-PRIME synopsis is provided below; a more in-depth discussion on the A-PRIME challenge areas can be found in Appendix B.



A The **Autonomous** area entails developing robust sensor networks coupled with sophisticated analytics and secure controls systems.

P The **Precise** area focuses on a targeted treatment approach with precise removal or transformation of treatment-limiting constituents and trace contaminants.

R The **Resilient** area looks to enable adaptable treatment processes and strengthen water supply networks.

I The **Intensified** area focuses on innovative technologies and process intensification for brine concentration and crystallization and the management and valorization of residuals.

M The **Modular** area looks to improve materials and manufacturing processes and scalability to expand the range of cost-competitive treatment components and eliminate intensive pre/post-treatment.

E The **Electrified** area aims to replace chemically intensive processes with electrified processes that are more amenable to variable or fluctuating operating conditions.

2.6. Desalination Hub Topic Areas

There are key technology areas of R&D, modeling, and analysis that cut across the water sources and sectors in the NAWI Hub.

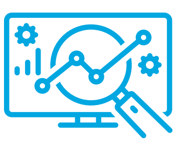
They can be categorized under four interdependent topic areas as summarized below:

Process Innovation and Intensification R&D

Novel technology processes and system design concepts are needed to improve energy efficiency and lower costs for water treatment. New technologies related to water pre-treatment systems (e.g., upstream from the desalination unit operation) and other novel approaches can address associated challenges such as water reuse, water efficiency, and high-value co-products.

Materials and Manufacturing R&D

Materials R&D has the potential to improve energy efficiency and lower costs through improved materials used in specific components and in water treatment systems. Desalination and related water treatment technologies can benefit from materials improvements for a range of products (e.g., membranes, pipes, tanks, and pumps) that dramatically increase their performance, efficiency, longevity, durability, and corrosion resistance.



Data, Modeling, and Analysis

In order to consistently define, track, and achieve pipe-parity in the highest impact areas, strategic, non-biased, and integrated data and analysis is needed. This data, in addition to studies and analysis tools, is necessary to guide the Hub's strategic R&D portfolio. A centralized data system will also fill the void in industry for shared information and provide decision-making tools related to water treatment implementation. Multi-scale models and simulation tools can inform R&D via performance forecasting, design optimization, and operation of desalination technologies and related water-treatment systems, leading into improved energy efficiency and lowered costs.

3. RESOURCE EXTRACTION WATER USER SECTOR OVERVIEW

This overview of the Resource Extraction Sector provides a high-level synopsis and rationale for this roadmap's focus—expanding the availability and reliability of water supplies with nontraditional water sources.

3.1. Background on the Resource Extraction Sector and Water Utilization

Water plays a significant role throughout the life cycle of both oil and gas wells and mines.[2,9,10,11] In 2015, the U.S. Geological Survey (USGS) water survey found that the O&G and mining sectors withdrew 15.5 million m^3 per day (4.1 billion gallons per day [BGD]), or 1 percent of total U.S. water withdrawals.*[1] Most of the water used was extracted from groundwater or surface water sources (72 percent). Even though this is a small amount of total U.S. water usage, this varies by state, with five states (TX, CA, UT, NV, and OK) making up 53 percent of mining water withdrawals. Furthermore, these withdrawals may impact local water supplies at a county level and in some semi-arid and arid regions.[1] Total water withdrawals in 2015 by state for the Resource Extraction Sector are shown in Figure 3. Yet, water withdrawals within the Resource Extraction Sector are increasing due to the expansion of unconventional O&G production. For example, hydraulic fracturing for unconventional natural gas and oil production consumes between 2,000 and 41,000 m^3 (0.46 and 11 million gallons) per well.[12] The large volumes of water used for extraction and processing, and the associated large volumes of wastewater produced, are spatially and temporarily variable, complex, and often require conveyance to and from remote sites.[4,13]

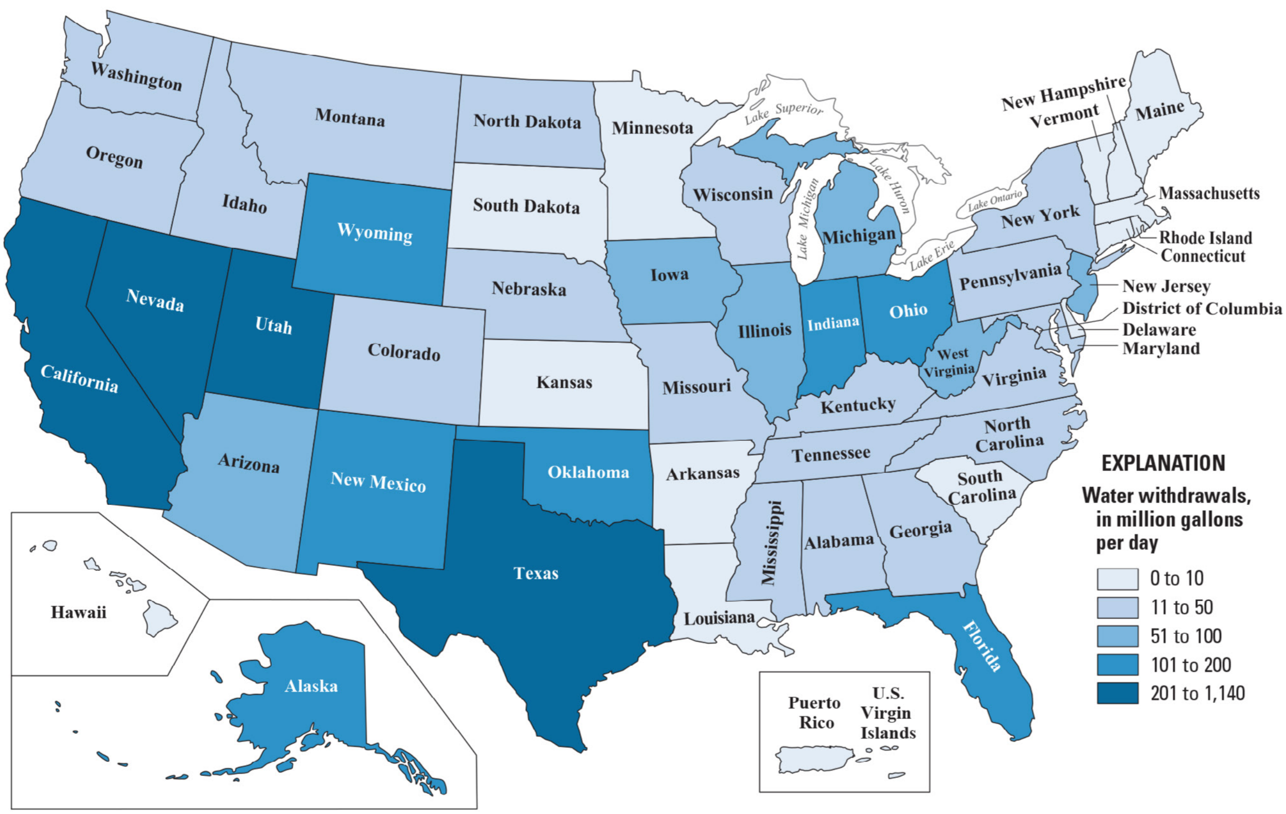


Figure 3. Resource extraction withdrawals by state in 2015. As previously noted, the USGS includes both mineral ore extraction as well as oil and natural gas production in mining water use.[1]
Source: USGS

* These values do not include dewatering operations from mining unless the water is beneficially reused.

Reclamation and reuse of the water within industry (especially O&G production) has increased in the last decade due to improvements in extraction chemicals and processes.[2,14,15] Yet, reuse of the waters generated, including extracted formation water, remains the most significant challenge for both O&G and mining given the high TDS and challenging constituents. Reuse is often facilitated by removal of precipitable TDS and heavy use of additives. When the next use of water (i.e., next development site) is too far away for reuse, disposal by reinjection and evaporation ponds are the dominant baseline technologies due to low costs and reduction of liability concerns. Due to the large volumes of water produced by these industries, especially in water-scarce regions, researchers and industry members have sought to find alternative water uses for other applications (e.g., agriculture, power, and aquifer recharge). However, high and often variable salinities (>100,000 mg/L TDS) and the presence of constituents of concern have prohibited widespread use to date.

Past research has explored desalination technologies for these waters. However, the development of sustainable reuse and disposal options for the brines and solids produced during desalination remains a concern.[16] The lack of cost-effective strategies for sustainable management or beneficial reuse of the produced salt may ultimately limit reuse of resource extraction wastewaters only to lower-salinity waters. For these cases, there is high potential to achieve pipe parity using A-PRIME to guide technology development.

3.2. Water Demand in Resource Extraction

3.2.1 Water Demand in the Oil and Gas Industry

The upstream conventional and unconventional O&G industry uses millions of cubic meters of water annually to extract hydrocarbon resources from subterranean geological formations. Within upstream O&G operations, water is used for many operations, but the primary use is for drilling and well completion (Figure 4).

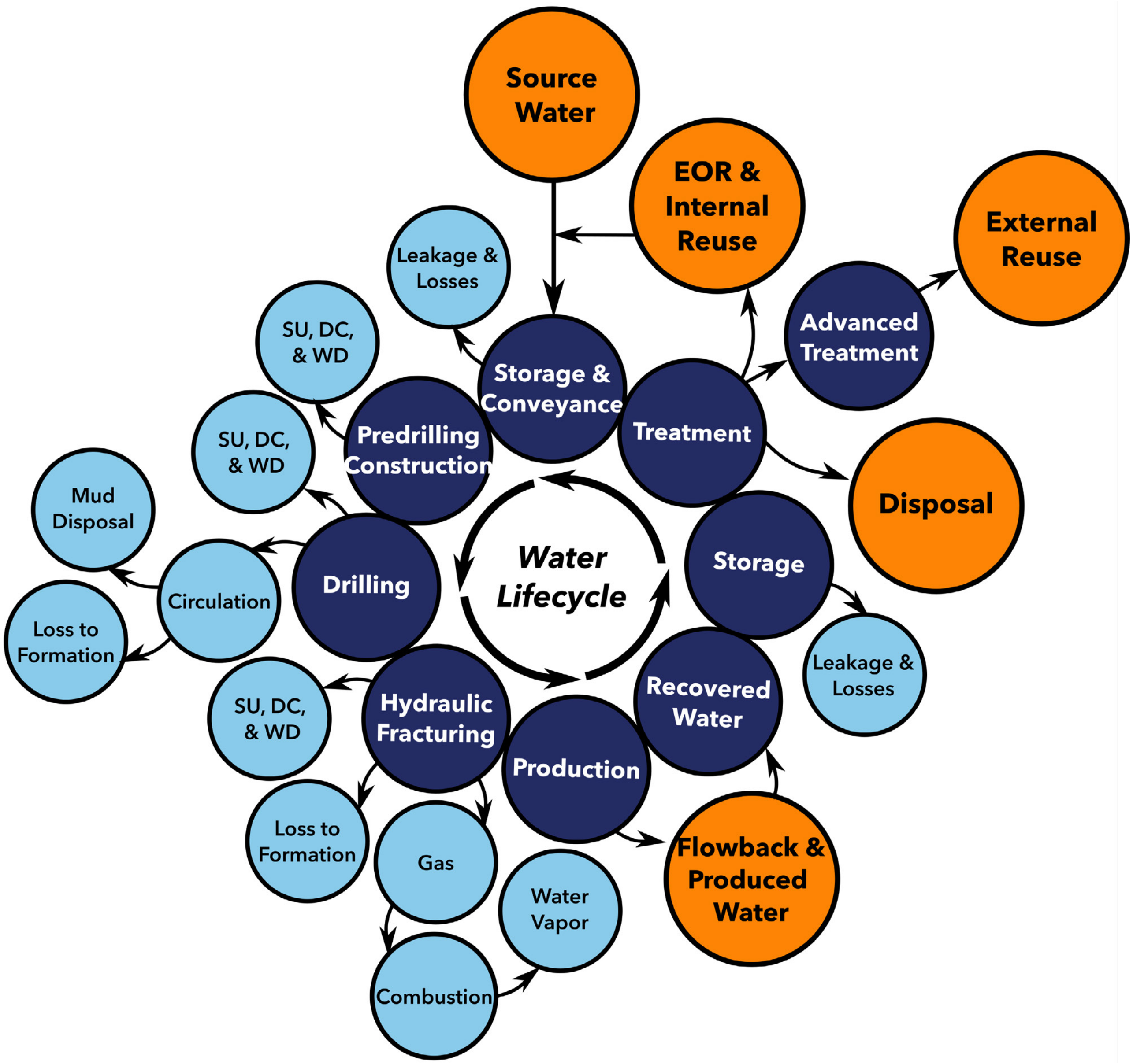


Figure 4. Upstream Operation Water Cycles. Abbreviations are as follows: dust control (DC), sanitary utility (SU), and wash decontamination (WD). Figure adapted from Flowback and Produced Waters: Opportunities and Challenges: Proceedings of a Workshop[17]

Conventional O&G wells are drilled into geologic formations that allow the oil or natural gas to readily flow to the wellbore.[18] In conventional O&G wells, water is used as a lubricant, to cool the drill components, and to remove oil mud while drilling. Conventional wells may also use water after well completion for enhanced oil recovery (EOR). EOR is a loose term that encompasses both secondary (e.g., waterflooding) and tertiary (e.g., gas injection, thermal recovery, and chemical injection) recovery techniques to increase oil production after the initial extraction phase. Water flooding and steam injection require water to increase oil recovery and prevent subsidence within the oil field. Water flooding involves pumping water into a well to increase the pressure within the formation and assist with extracting the remaining petroleum products. Steam injection involves injecting steam to raise the temperature which lowers the viscosity of the oil in the reservoir to allow for greater flow of the oil.

Traditionally, EOR has served an important role as a management strategy for conventional produced water. Yet, the fraction of produced water reused for EOR has decreased slightly (from 57.8 to 43.6 percent) since 2007, in part due to a natural decline of conventional waterflooding operations and the development of technologies (horizontal drilling and hydraulic fracturing) that enabled unconventional O&G production from shale formations.[2]

Compared to conventional O&G operations, unconventional O&G operations require a change in reservoir properties to increase the permeability of oil through the reservoir, often achieved through hydraulic fracturing or thermal stimulation. Unconventional O&G sources include shale gas, coal bed-methane (CBM), shale oil, tight-oil, and oil sands. In the United States, the most widespread unconventional O&G sources are tight-oil and shale gas extracted via hydraulic fracturing and CBM extraction. Water in unconventional O&G operations is predominantly used during hydraulic fracturing processes, although other components of drilling and completions (e.g., drill outs) and processes (e.g., CBM extraction) also require water. For hydraulic fracturing, source water is combined with proppants (e.g., sand) and multiple chemical additives (e.g., friction reducers, crosslinkers, biocides, corrosion reducers) to form a slurry. Thousands of cubic meters of hydraulic fracturing fluid is then pumped into the well at high pressures to create and keep open fractures within the shale formation to allow for the extraction of O&G. A significant portion of this water is returned to the surface as flowback water. During the production period of the well, produced water that resided within the formation also flows to the well bore. These waters contain TDS concentrations that can be as high as 150,000 mg/L and greater.

As shown in Figure 5, the water volumes necessary to develop unconventional hydraulic fracturing wells have increased over time due to a variety of factors. However, water requirements change over time and with geologic formation. One key reason for this increase in water is horizontal length that started at less than a mile and has grown to 3 miles or more, requiring substantially more water to complete a single well. For example, within the Permian Basin, the average water demand per hydraulic fracturing well increased from 4,900m^3 to 42,500m^3 between 2011 and 2016[19]. Less drastically, water demand per well within the Marcellus only increased by approximately 20 percent from 23,400m^3 to 27,950m^3 between 2011 and 2016.[19]

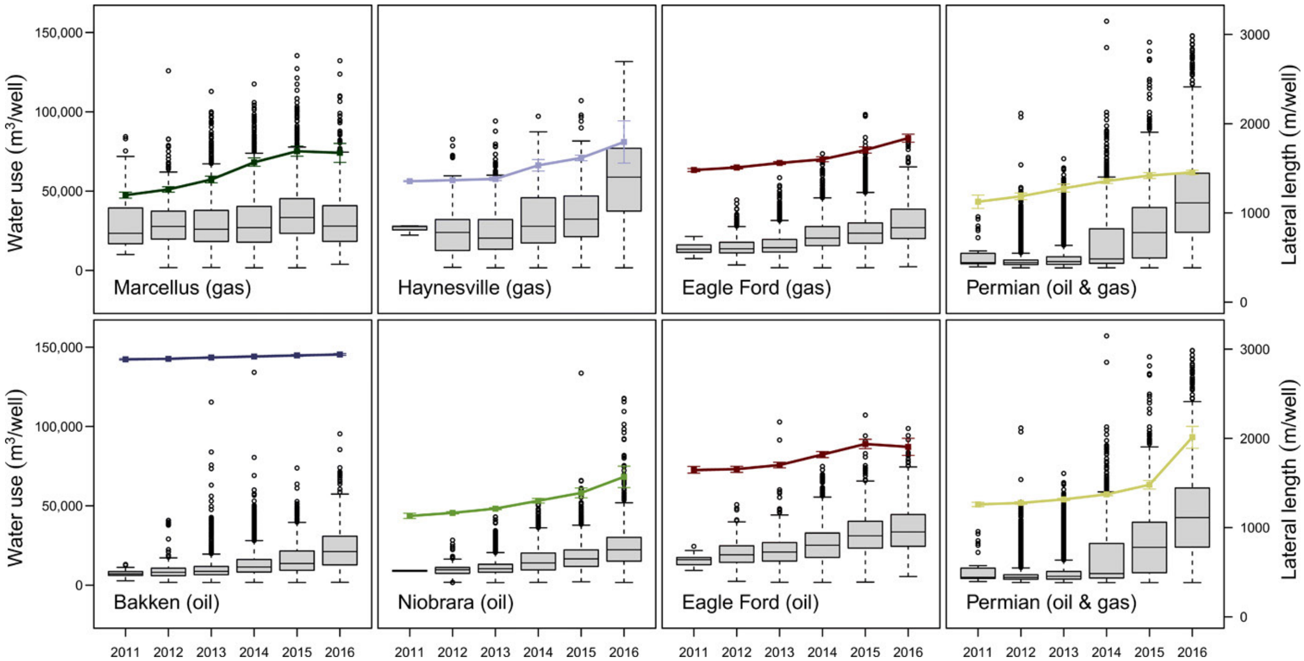


Figure 5. Hydraulic Fracturing Water Consumption Increases over Time (2011–2016). The top row shows water use per well for shale gas regions, while the bottom row shows water use per well for tight oil regions[19]

Projected water use for hydraulic fracturing and produced water generation over the life of major plays has been estimated in Figure 6 and highlights the growth of water demand for hydraulic fracturing over the life of the field.[20] Source water demand and wastewater generation associated with upstream O&G varies geographically due to the regionality of the hydrocarbon containing geological formations. For example, projected produced water volumes are anticipated to exceed hydraulic fracturing water demand by 2.1 and 3.7 times in the Bakken and Delaware plays, respectively, while the projected produced water volumes are anticipated to fall behind hydraulic fracturing water demand by a factor of 3 to 8.6 in the Eagle Ford play.[20]

The high-water demand of the O&G industry is an even greater concern for water stressed regions; hence, adoption of nontraditional water sources and reuse within upstream O&G has increased. Roughly 57 percent of the 109,665 wells hydraulically fractured between 2011 and 2016 were located in regions with high or extremely high water stress.[21] However, there is also a large presence of upstream O&G operations in traditionally water-rich regions such as the Marcellus shale formation in the Northeast. These regions have also faced challenges associated with produced water disposal and that challenge has led to extensive reuse within the industry. While the overall portion of water used for hydraulic fracturing is considered low (roughly one to two percent of overall state use), there are still risks to local and regional resources. This pressure on local resources can grow with increased oil-field development and potential refracturing in the future.[22]

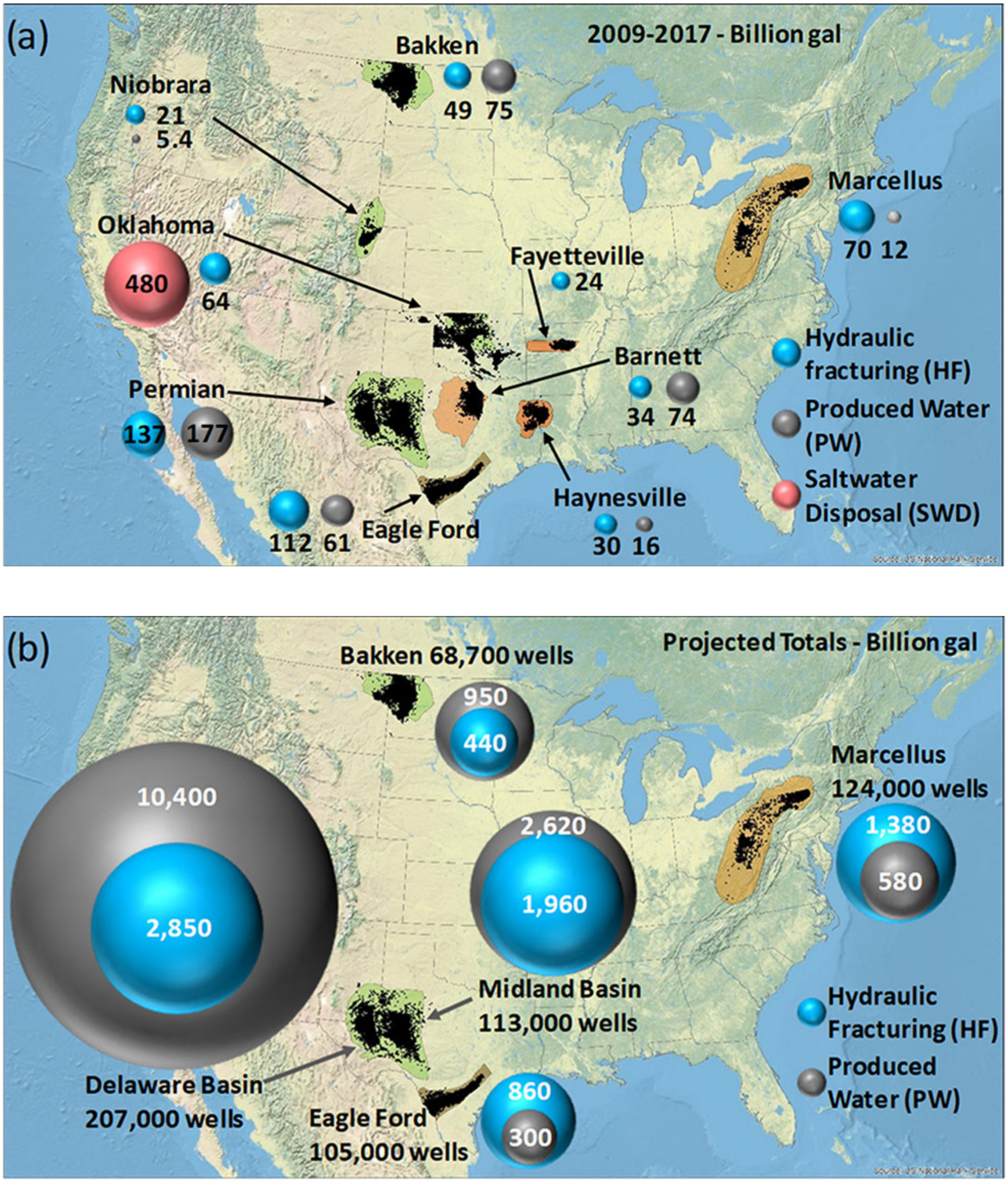


Figure 6. A) Historical (2009–2017) volumes of water used for hydraulic fracturing and produced water from unconventional wells in major tight oil (green) and shale gas (orange) plays. Eagle Ford includes both oil and gas. Saltwater disposal (SWD) is used in the place of produced water within Oklahoma since produced water volumes are not reported.

B) Projected (2018–End of Play Life) hydraulic fracturing and produced water volumes within the Bakken, Delaware, Eagle Ford, Marcellus, and Midland plays.[20]

3.2.2 Water Demand in the Mining Industry

Water serves a variety of functions in mining operations. Depending on the mine type, water is used as a leaching agent (both in situ and in heap-leaching) or to transport slurries of mined materials for ore extraction by chemical (froth flotation) or physical (centrifugal) separation processes.[23,24] Water is also used for dust suppression, potable consumption (i.e., drinking), cooling, sealing pump glands, reagent mixing, and other miscellaneous activities.[23,24] An example of the various water uses and flow rates for a typical copper mine is presented in Table 2. Declining ore grades and increased material demand are anticipated to increase a mine's water demand due to the higher processing volumes required to produce the same amount of concentrated material.[25,26]

Water demands are largely dictated by the mine type and associated processing methods. As shown in Table 3, the relative water intensity varies among key minerals and metals extraction. Regional water availability, a mine's water rights, and permits influence overall water usage.[4] Water scarcity and increased competition for available water resources drives mining operations to implement water efficiency measures and reuse available water when feasible.[27] Furthermore, stipulations of water rights, water tariffs, and discharge permits can impact consumption, efficiency, and reuse, all of which can impact cost. For example, in some particularly water-rich states, water tariffs are either low or non-existent while other states charge based on usage, which might encourage reuse and/or reduce consumption. Additionally, some water rights are only guaranteed if they are utilized, which can discourage mining companies from implementing more water-efficient processes that place their access to the water at risk.[27]

Table 2. Major water users in a typical copper mine.[23]

MAJOR WATER USERS	FLOW (m^3/d)
Flotation Process Water (30% solids by mass)	115,646
SAG Mill Cooling Water	4,100
Ball Mill Cooling Water	4,100
Compressor Cooling Water	4,100
Road-Dust Suppression	3,520
Froth Wash Water	2,880
Pump GSW	1,440
Reagent Dilution Water	720
Primary Crusher Dump Pocket-Dust Suppression	358
Coarse Ore Stockpile-Dust Suppression	121
Mine/Mill/Office Staff Domestic Water	58
Maintenance Shop	~0
Hose Stations – Clean Up	~0

3.3. Water Supplied to Resource Extraction

3.3.1 Traditional and Nontraditional Water Sources in O&G

Water for upstream O&G operations is mostly obtained from either surface or groundwater sources near a well site, and is frequently purchased from farmers, ranchers, or entities that own these water rights. In some locations (particularly in Western states), O&G operations are turning to municipalities for their treated wastewater as a source of completion water.[2829,30] The water quality of these source waters can vary drastically, from high-quality groundwater (e.g., low turbidity, organic carbon, nutrients, and TDS) to surface water heavily impacted by agriculture, creating a nutrient-rich (e.g., sulfate) and biologically laden water that can wreak havoc on well casings if not properly managed before injection. Particularly in Western states, this lower water quality must be considered in the planning and completion of any well or well pad.

Table 3. Water intensity of key minerals and metals.[31]

MINERAL/METAL TYPE	WATER USE
Copper	💧💧💧
Gold	💧💧💧
Coal	💧💧
Iron Ore	💧💧
Nickel	💧💧
Diamond	💧
Platinum	💧

High: 💧💧💧 Medium High: 💧💧 Medium Low: 💧

The O&G industry reuses a large fraction of the treated produced water whenever it is economically viable. Reuse is in large part driven by the high cost of water, especially in highly productive basins and in water-scarce regions. For example, base case market analysis predicted water costs for the Permian Basin shown in Figure 7 of 12.2 billion in 2018. Hauling, transfer, and disposal of water accounted for over 65 percent of spending in 2018. In contrast, sourcing, pre-treatment, and treatment only accounted for approximately 15 percent of spending in the same year.[32] Across major U.S., basins, produced water reuse ranged from 0-67 percent in 2017.[33]

Studies linking increased seismicity to increased volumes in saltwater disposal wells (SWD), regional water scarcity, and regulatory limitations on SWD have also incentivized internal and external reuse of produced water. Yet temporally and spatially mismatched supply and demand for produced water (Figure 8) often inhibits reuse without the presence of extensive water handling and transportation infrastructures.[28,33,34] At the beginning of an oil field development there is often not enough produced water to support hydraulic fracturing activities with reuse; this eventually shifts as the field is developed and produced water volumes overtake the need for hydraulic fracturing. Water resources and treatment need to consider the spatial and temporal differences.

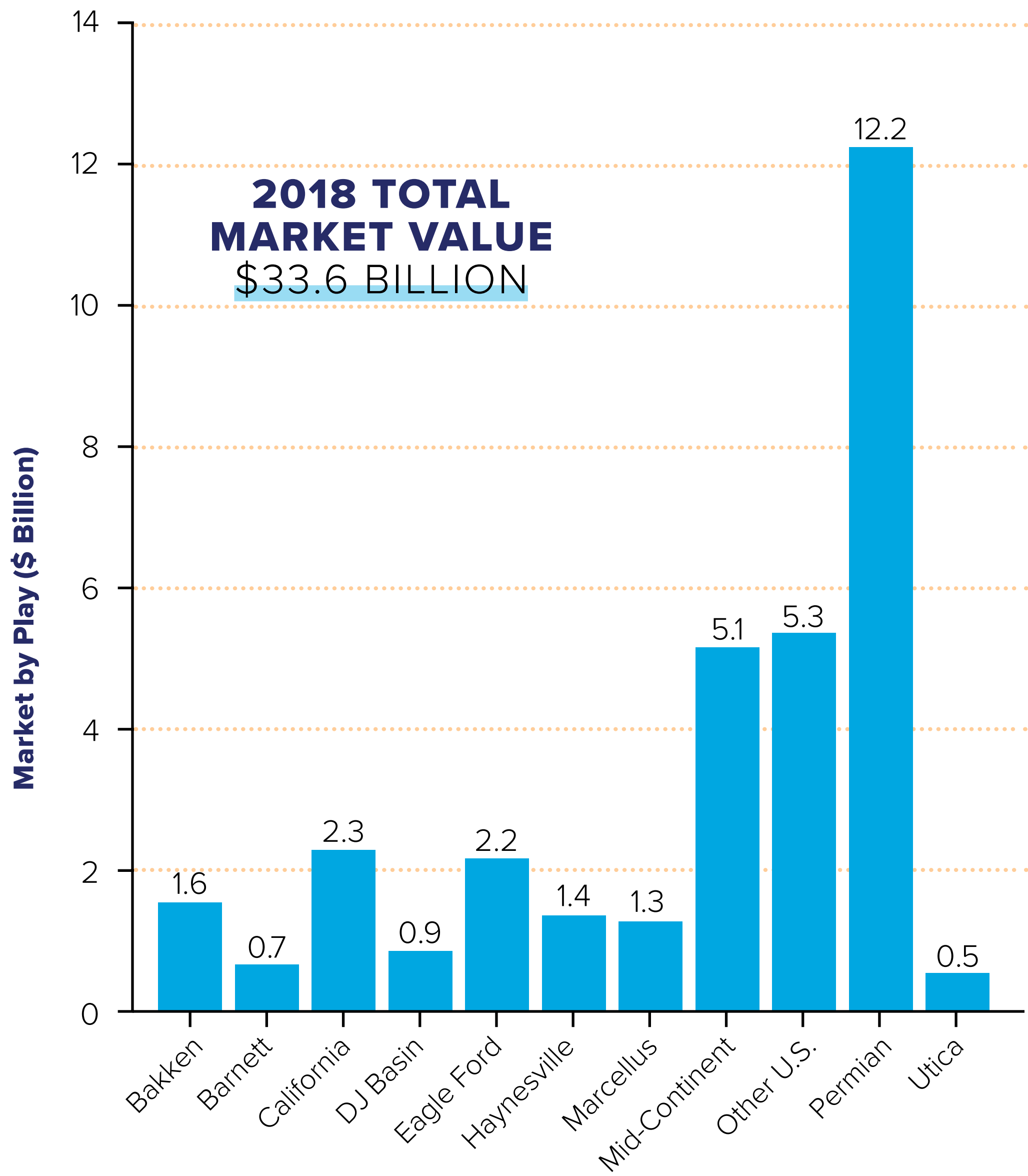


Figure 7. Water management market for upstream O&G operations in the United States in 2018

Adapted from IHS Markit[31]

To address this, some companies have developed centralized treatment facilities with extensive transportation systems combining produced water from multiple well-heads for treatment and redistribution.[9] However, due to the regionality of the quality and quantity of produced water internal reuse often cannot meet the upstream O&G water demands (Figure 8), and many facilities are left with a surplus of produced water that is currently not economically viable for reuse within O&G operations.

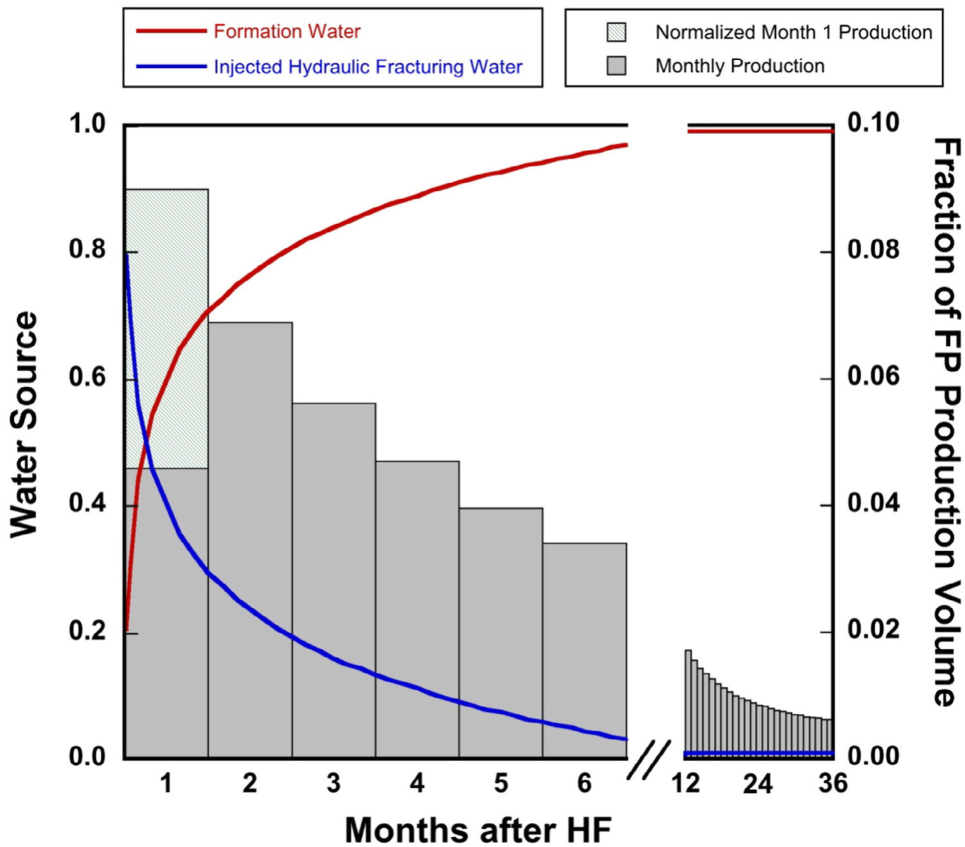


Figure 8. Temporal variation in the fraction of flowback and produced water (FP water) in comparison to the overall volume of FP water generated after hydraulic fracturing[35]

Wells supplying brackish groundwater from local aquifers have been used to service most of the O&G industry in Texas, but ground water depletion due to the O&G industry is a concern for semi-arid and arid regions.[36] The use of brackish groundwater for the O&G industry is limited by the availability of the brackish aquifers, the availability of fresh sources, the cost to transport water to the site, and the cost of minimal treatment needed to use the brackish water. On a limited scale, municipal wastewater has been used in O&G exploration in the Barnett Shale, relatively close to Dallas, Texas.[28] However, the remote location of most O&G upstream facilities limits the widespread adoption of this practice.

Advances in chemical additives and stabilizers to protect equipment from high salinity and other water quality aspects of seawater, as well as advances in desalination technology, also make seawater a viable option for upstream O&G operations. However, use of seawater would be limited to upstream O&G sites that are either within a reasonable distance from the coast or offshore because transportation costs contribute significantly to water source economics, limiting this application to a small subset of O&G operations.

3.3.2 Traditional and Nontraditional Water Sources in Mining

In mining, water availability dictates maximum production so mining companies consider the quantity and reliability of all available water supplies.[25,37] Mining companies often use traditional water sources, such as groundwater and surface diversions, as well as less traditional sources such as seawater, brackish groundwater, internal reuse of effluent, and water collected onsite through precipitation impoundment and dewatering activities.[1,23,24] Subsurface mines can (after active mining ceases) become flooded and develop significant mine pools. This water can be utilized for operations if managed properly.

Depending on the location, mining operations can also make use of other nontraditional water sources such as municipal and industrial effluents. Selection of alternative water supplies can have broad impacts on mining operations, including impacts on public perceptions, the environment, energy usage, and overall costs, as shown in the cause and effect diagram for the Chilean mining industry in Figure 9. As such, mines must carefully consider the holistic impact of any water source. Overall, data on water use for individual mines is not generally available to the public, due to lack of regulations and proprietary business practices.[1] Consequently, the USGS estimates water withdrawals for mining empirically based on mineral production data and water-use coefficients rather than documented usage statistics.[38]

Although mines already make use of nontraditional sources, water scarcity and supply risks (e.g., precipitation and climactic changes) can drive companies to pursue alternatives to freshwater supplies.[24] Perhaps one of the most significant alternative water sources for the mining industry is the internal reuse of mine effluent water, water created from dewatering activities, and accumulated precipitation and runoff stored on site, often captured passively in tailing storage facilities.[24] The industry has focused on accumulated rainwater because acquisition is inexpensive, locally available, takes advantage of current infrastructure, often contains valuable reagents and minerals, and reduces the amount of waste that is stored on site or discharged into the environment.

Despite these benefits, reuse of mine effluent water in processes (e.g., froth flotation) can impact the efficiency of mineral extraction and create disposal challenges by concentrating metals and reagents.[24,39] Transient water quality variations associated with mine effluent reuse requires operators to quickly tune the flotation basin water chemistry in response, introducing operational complexities and possible system performance deterioration.[24,40] The variability of water chemistry in mineral extraction processes is a barrier to reusing effluent water in froth flotation, which is one of the most water-intensive processes in mining. [40,41]

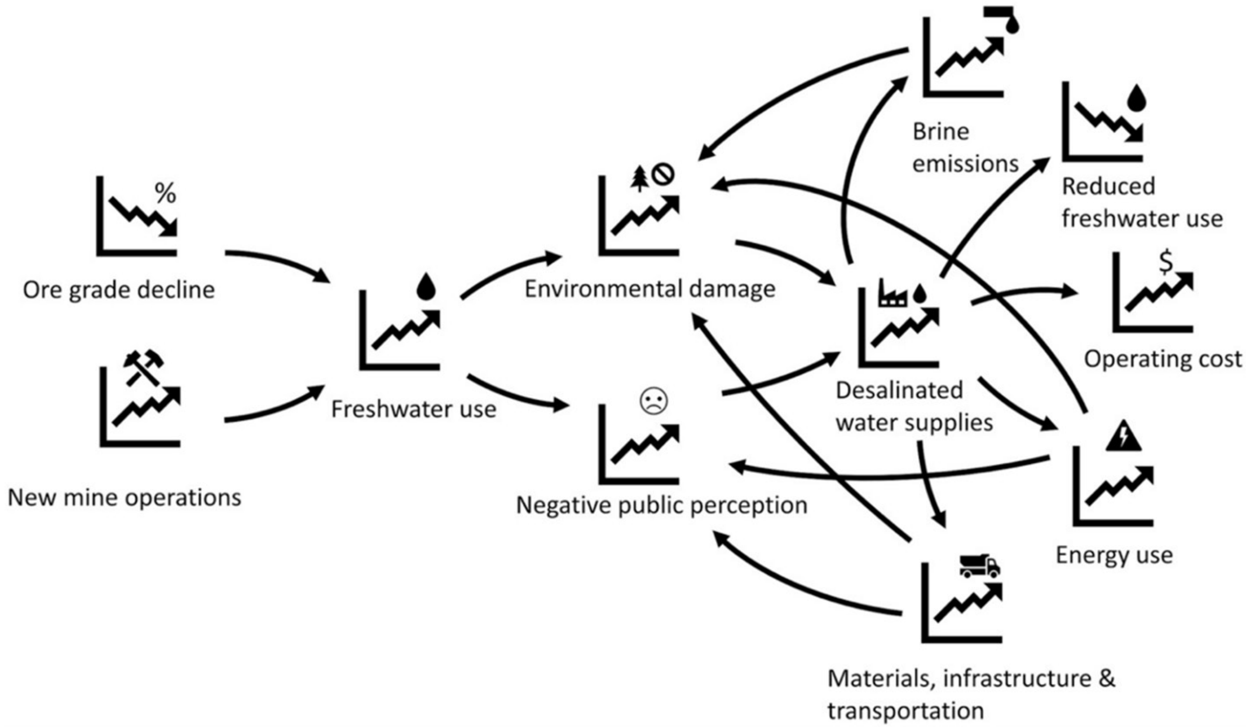


Figure 9. A cause-and-effect diagram of freshwater and seawater use in the Chilean mining industry[10]

Reused water can also be high in dissolved solids, reagents, and chemicals from previous processing cycles. While the presence of unconsumed reagents may reduce chemical dosing requirements, it can also decrease performance and increase the concentration of ions over several reuse cycles, negatively impacting flotation process efficiency.[11,42] Although effluent water quality can vary significantly depending on location and local geology, multivalent ions such as calcium, iron, aluminum, and sulfate are commonly present and are of particular concern in reuse due to their impact on the recovery and grade of mineral extraction.[40] An improved understanding of the impact of process water quality on the kinetics and efficiency of mineral extraction processes is required to reliably reuse mine effluent for froth flotation.[24]

3.4. Water Discharged from Resource Extraction

3.4.1 Produced Water in Oil and Gas

Overall, O&G producers often view produced water as a waste and generally choose the least expensive management option. Use of nontraditional water sources are only enabled through cost, co-location with a user, low salinity, or regulations that increase the cost of alternative management options. Nationally, >90 percent of produced water generated in the United States is reinjected into the subsurface for either EOR or in SWD in Class II* Underground Injection Control (UIC) wells. Nationally, there were approximately 180,000 Class II UIC wells in 2016, ~80 percent of which are utilized for EOR and ~20 percent of which are disposal wells.[43,44] Of the remaining produced water, ~5 percent is discharged as surface water, and ~1 percent is utilized for beneficial reuse in applications (e.g., crop irrigation, aquifer recharge).[2]

Produced water is not equally distributed, as evidenced by water-to-oil ratios that range from approximately 3:1 to 10:1.[13, 20, 45,46] Produced water quantity is influenced by factors including drilling method, completion type, and age of well.[13] Furthermore, regional variations (e.g., geographical conditions, regional regulatory limitations, co-location with other wells, mines, and industry) further complicate produced water management and may ultimately result in regional differences in reuse, recycle, and disposal. In particular, the U.S. Environmental Protection Agency (EPA) estimates that conveyance costs may comprise up to 25–75 percent of the total water management cost, which can vary widely by region.[47] **Thus, the economic viability of a management option may often be heavily influenced by proximity to end users.**

Produced water quality varies spatially, temporally, and depends on a variety of factors including geologic formation, state of the extracted hydrocarbon, lifetime of the reservoir, and the type of production occurring, conventional versus unconventional. The temporal and spatial variations in water quality complicate treatment, reuse, and disposal of produced water (Figures 8 and 10). Produced water includes a multitude of inorganics, organics, microorganisms, solids (e.g., microbial biomass, clays, precipitates, waxes, sand, formation solids, corrosion, and scale products), radioisotopes, and dissolved gases. Several references provide a list of contaminants identified in flowback and produced water[8,48,49,50,51,52,53,54] and Figure 10 highlights particular compounds of interest with respect to produced water reuse.

* Class II wells are those that inject fluids related to oil and gas production, including enhanced oil recovery, produced water and O&G production fluid disposal, and liquid hydrocarbon storage.

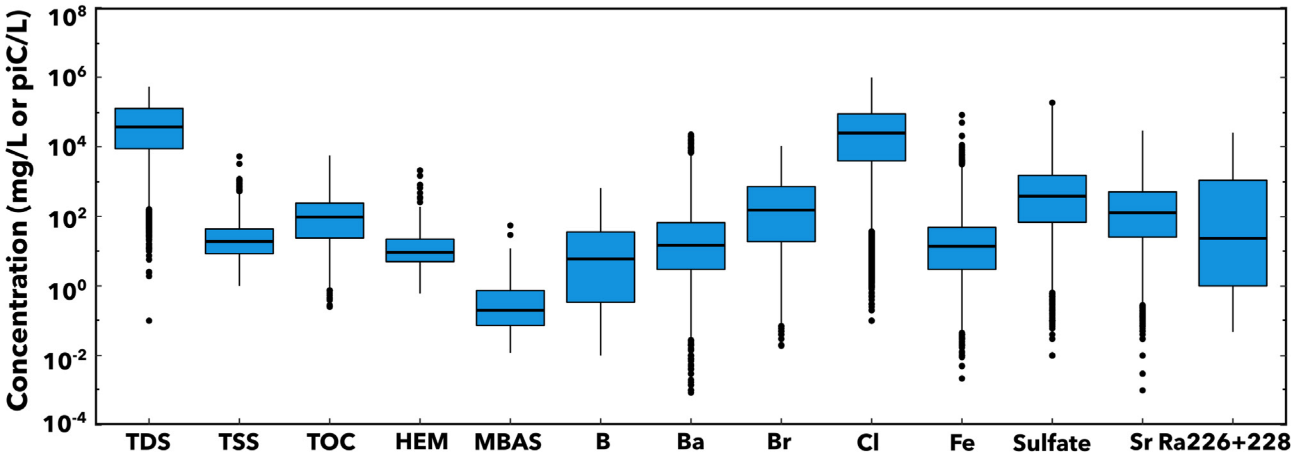


Figure 10. Concentrations of selected constituents in produced water from the USGS National Produced Waters Geochemical Database, V2.3.[55] Abbreviations are as follows: total dissolved solids (TDS), total suspended solids (TSS), total organic carbon (TOC), hexane-extractable material (HEM), and methylene blue active substances (MBAS).

Source: United States Geological Survey

Treatment approaches and cost for produced water are heavily influenced by physicochemical properties of the produced water stream. However, nearly all reuse and disposal require the separation of oil, grease, and suspended solids (Figure 11). Treatment of produced water for disposal via SWD traditionally uses conventional treatment methods (i.e., coagulation, flocculation, and sedimentation) and focuses on removal of dispersed oil and grease and TSS to minimize damage and plugging of both the surface and subsurface well equipment.[56]

Reuse within O&G is preferred when cost-effective. Advances in hydraulic fracturing chemicals have allowed for internal reuse of high-salinity produced water but come with an increase in chemical costs.[15] Often, reuse as "clean brine" requires minimal treatment of constituents like residual oil, TSS, bacteria, and iron. Clean brine is often generated via conventional treatment (i.e., coagulation, flocculation, and sedimentation) to remove solids and iron followed by disinfection.

Potential avenues for beneficial reuse of treated produced water could include options like dust suppression, irrigation, industrial process water, and surface discharge. However, beneficial reuse is often less cost-effective due to elevated treatment and transportation costs. Potential options are heavily influenced by produced water quality and regulatory constraints.[15] For example, low-salinity, high-quality produced water has been successfully treated to allow for long-term irrigation of almonds, citrus, and a variety of vegetable crops in California for over two decades.[57,58] However, widespread use of produced water for irrigation is limited, as utilization of lower-quality produced water for irrigation will require substantial treatment and cost to mitigate potential impacts to plant and soil health.[59,60,61] Other pilots for beneficial reuse (e.g., CBM in Wyoming, aquifer recharge in Texas) have been conducted, but none have been widely used throughout the region due to costs.[33]

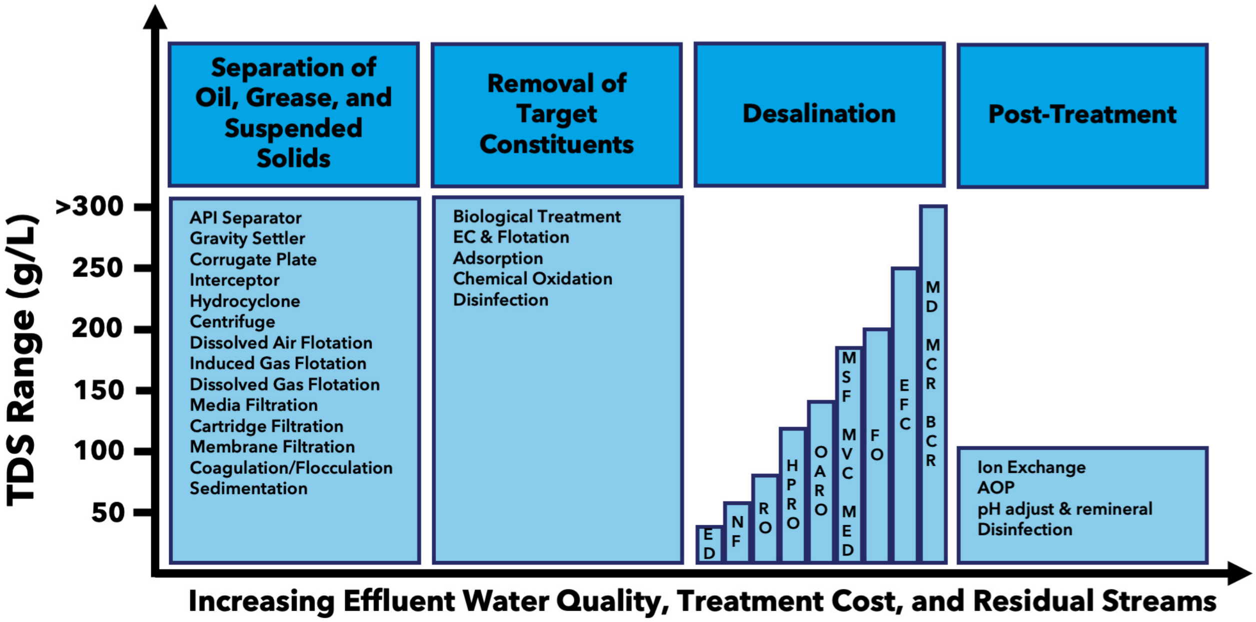


Figure 11. Common treatment approaches and technologies for treating produced water of varying TDS and desired end use. Abbreviations are as follows: total dissolved solids (TDS), electrodialysis/electrodialysis reversal (ED), nanofiltration (NF), reverse osmosis (RO), high-pressure reverse osmosis (HPRO), osmotically assisted reverse osmosis (OARO), multi-stage flash distillation (MSF), mechanical vapor compression (MVC), multiple effect distillation (MED), forward osmosis (FO), eutectic freeze crystallization (EFC), membrane distillation (MD), membrane crystallization (MCR), brine crystallizer (BCR), advanced oxidation processes (AOP), and electrocoagulation (EC). Figure adapted from Scanlon[46]

Ensuring safe and sustainable beneficial produced water reuse will also require improved analytical techniques and understanding of toxicity, fate, and transport of the constituents in produced water. The hypersaline nature of some produced waters often complicates and limits their characterization based on current analytical methods and assays.[62] Similarly, treatment of higher salinity, lower quality produced water will likely generate large residual streams whose management (and treatment co-product use and disposal) could be complicated by the quality, quantity, and potentially hazardous nature of concentrated brine streams.[63] Nevertheless, regulatory drivers that limit re-injection as an ultimate disposal option may incentivize produced water treatment for reuse.

3.4.2. Wastewater in Mining

Mining wastewater discharges are primarily limited to treated acid mine drainage (AMD) and disposal of select waste streams when reuse is not considered. Prior to discharge, both abandoned mine drainage (AbMD) and AMD must be treated according to the legal permit requirements, often to reduce the TDS concentration, neutralize pH, and remove problematic ions, particularly sulfate. AMD is typically treated either "actively" (e.g., chemical neutralization) or "passively" (e.g., aerobic wetlands, open limestone channels).[64] Discharge permit requirements vary based on jurisdiction, but separate mining discharge permits are generally required for each type of receiving water body in the United States.[27] Although wastewater discharges are often low due to the high rate of reuse, mines frequently experience a high rate of water loss through evaporation (partially those located in arid regions), water entrainment in tailings, and seepage. These water loss volumes are significant and constitute a barrier to a closed-loop water system for mining sites as external water sources are required to replace the losses.[23,25,26]

Closed and abandoned facilities accumulate mine pools and continue to accumulate until the mine void is filled or the water reaches equilibrium with the mine barrier and finds a way out via a seep or discharge point. Such waters are treated in perpetuity, with costs initially bore by mining bonds and then ultimately taxpayers. Lower-cost energy and chemical input treatment method improvements are necessary for these often remote areas with minimal connectivity to society via roads and electrical power.

3.5. Resource Recovery in Resource Extraction

3.5.1. Resource Recovery Considerations in Oil and Gas

Extraction of saleable constituents from produced water prior to disposal or reuse has the potential to offset some water treatment costs. Previous studies have demonstrated the potential to recover constituents including gypsum, sodium chloride, magnesium chloride, magnesium sulfate, bicarbonate, bromide, iodine, lithium salts, potassium salts, and metals such as copper.[65] With technological advances, it may also be feasible to extract rare earth elements from produced water. Similarly, enhanced water recovery methods from produced water could aid in reducing freshwater usage in the industry as issues of water scarcity complicate water sourcing. However, further research is necessary to both understand the markets and develop the technologies to enable economically viable extraction of constituents at scale.

While nearly all reuse and disposal of produced water requires oil-water separations, recovery of residual insoluble oils from produced water may allow for additional valorization of produced water during treatment. High-efficiency removal of insoluble oils and other foulants could also allow for greater use of advanced treatment processes to facilitate beneficial reuse. Produced water contains residual oil concentrations of 2–565 mg/L.[13] Conventional methods for oil-water separations include American Petroleum Institute (API) gravity separators, corrugated plate inceptors, hydrocyclones, and induced gas flotation.[13, 46,66]While approaches like membranes may allow for higher-efficiency separations, fouling often limits the practicality of traditional membranes in produced water applications. Ultimately, novel materials and approaches for oil-water separation may allow for high-efficiency oil-water separations with minimal fouling.

Lithium extraction from produced water has been suggested via approaches including adsorption, solvent extraction, electrolysis, and membranes.[65,67] At the industrial scale, lithium salts can be extracted from concentrated produced water brine using an advanced brine management treatment train and to generate additional distilled water and brine for reuse.[68] Iodine extraction from produced water has also been proposed utilizing methods such as ion exchange. Industrially, companies are separating iodine from Oklahoman produced water with elevated iodine concentrations.[9] However, the recovery of valuable ions is traditionally easier in concentrated brine streams.[67]

To enable resource recovery, it is necessary to both improve our understanding of which regions and basins generate produced water that is rich in saleable constituents and which constituents have economic potential. Similarly, while technological breakthroughs using novel materials, sorbents, or electric-based separation may allow for more cost-effective extraction of constituents from streams, extraction has traditionally been easier in concentrated brines. However, generation of concentrated brine streams that contain regulatorily hazardous levels of chemical compounds and elements may further complicate residuals management in produced water. Further analysis and research will be necessary to enable cost-effective resource recovery that minimizes and addresses generation of concentrated brine. For concentrated brines over 100,000 ppm TDS, the compromise between the economic and liability advantages of injection versus the potential for recovery of valorized products and generation of a reusable water stream is highly dependent on residual management options and costs.

3.5.2. Resource Recovery Considerations in Mining

The mining industry presents several opportunities for resource recovery in both the mine effluent water and AMD. Mineral extraction through leaching uses highly acidic or basic solutions to dissolve target metals. However, non-target minerals, including rare earth elements and platinum group metals, can also be extracted into solution through the leaching process at potentially valuable concentrations. Hybrid membrane processes coupled with electrodialysis have successfully recovered targeted metals from synthetic waters, but further testing using actual mine effluents is necessary to demonstrate cost-effectiveness and practical application, especially in the presence of impurities and interacting ions.[69] AMD and AbMD could be another potential source of metals including rare earths and uranium. However, studies documenting rare earth recovery methods are limited, and economical implementation of such techniques would be highly dependent on the efficiency and concentration of these elements.[67] Importantly, although uranium recovery from AMD has been demonstrated in laboratory conditions, there are limited studies documenting its economic recovery from environmentally relevant water samples at larger scales under field conditions.[70]

3.6. Residuals Management in Resource Extraction

3.6.1. Residuals Management in Oil and Gas

The development and operation of an O&G well generates several residuals. Residual streams from drill fluids and cuttings are generated during the drilling processes, drill out fluids are produced during completions, and the produced water is generated over the life of a well.[71] Produced water and its associated residuals (e.g., solids) as detailed above are by far the largest residuals by volume generated during O&G operations. Residuals may include waste generated from suspended solids management during coagulation/flocculation practices, filtering the water (e.g., bag filters), and solids generated during water softening.[72] The suspended solids are managed in a variety of ways, ranging from deep-well injection of sludges to landfilling of filter cakes generated via dewatering of these slurries.

Management of these potentially hazardous waste streams may result in additional economic and logistical challenges. For example, treatment of 5,000 barrels of produced water with 80 percent water recovery generates approximately 53 tons of filter cake.[33] The management of these dewatered or softened solids can concentrate hazardous substances to the point that they are classified as technology enhanced naturally occurring radioactive material (TENORM), requiring management in certified landfills able to handle these types of wastes. In the case of TENORM, which is of particular concern for O&G operations in the Marcellus and Utica shales, these wastes may have to be shipped long distances, substantially increasing the costs.

The residual management associated with environmental discharge of unconventional produced water is one of the most significant challenges. In arid regions like west Texas and New Mexico, irrespective of both regulatory and environmental concerns and limitations associated with the treatment and discharge of treated produced water, the management of the solids and particularly salt is probably the greatest barrier for arid regions like west Texas and New Mexico. Produced waters in those regions commonly have TDS levels exceeding 100 g/L or 10 percent solids that are mostly sodium chloride (NaCl). To put this in perspective, produced water from the Delaware Basin in 2017 was 160 billion liters, assuming TDS of 100 g/L and 100 percent water recovery would generate nearly 16 million tons of salt in a single year.[46] This illustrates the enormity of salt generated if select produced waters were treated to ZLD, demonstrating the challenges associated with high water recovery produced water treatments. This rudimentary example illustrates the need for alternatives, such as MLD that allows for the recovery of some of the water resource while preventing an overburden of salt and other solid residual management. This solution provides opportunities to consider a systems-level approach to produced water management where water recovery for reuse, resource recovery for valorization, and reinjection of highly concentrated produced water brines (that fall below mineral saturation) are balanced for local and regional sites.

3.6.2. Residuals Management in Mining

Residuals associated with mining include sludge generated from chemical neutralization and from secondary treatment designed to remove metals. The result is a toxic aqueous sludge that requires dewatering and is often stored on-site in tailings facilities, posing a continual environmental hazard.[73] Tailings storage facilities also contain residuals from the physical separation of entrained solids and effluent water. Tailings often contain high concentrations of metals, unused process reagents, and other minerals of economic interest.[24] Unfortunately, due to the chemical processes typical of water treatment, the resultant co-product yields metals in a form that is currently uneconomical to recover. Tailings storage facilities are subject to close scrutiny and increasing regulatory and social pushback due to past failures as well as ongoing environmental hazards such as the leaching and draining of contaminants such as toxic metals and radionuclides, compromising groundwater supplies.[74] As such, mining operations have environmental, social, and financial incentives to reduce onsite storage of mining wastes.[27] Areas that are landlocked but are in developing areas have looked to mine pools to utilize as sources of drinking water. However, many of these projects hit obstacles in terms of ownership, water rights, liability, and sustainability. Opportunities for applications and water reuse under such circumstances are available but need to be incentivized by reducing risks.

3.7. Societal Barriers

3.7.1. Societal Barriers for Upstream Oil and Gas

Social concern over the strain on freshwater resources required for oil production (e.g., fracking), deep well injection of produced water into Class II SWDs, and the potential reuse or disposal of either produced water or treatment residuals creates additional barriers for O&G operations and produced water reuse. Concerns associated with seismicity and the continued increase in produced water production may present future challenges for the industry that may drive innovation in produced water treatment and reuse.

A study by the USGS found that earthquake rates in proximity to wells with greater than 300,000 barrels per month of injection have increased in the Midwest since 2009 compared to background rates. Figure 12 and Figure 13 show the geographical distribution of associated earthquake events, along with the temporal trends on induced seismic events.[75]

The storage and transport of this water also raises concerns with respect to spills and contamination of surface and groundwater and potential exposure to hazardous air pollution. More importantly, concerns associated with the toxicity of produced water and its residuals, as well as the sheer volume of residuals that would be produced for even MLD, may limit reuse options and prohibitively increase the cost of treatment.[76,77] Moreover, long-term liability associated with reuse and disposal outside of the industry can deter the industry from investing in treatment for external reuse. While reuse within the industry has increased substantially over the past several years, produced water volumes in many locations will consistently exceed the demand for water for unconventional O&G operations.

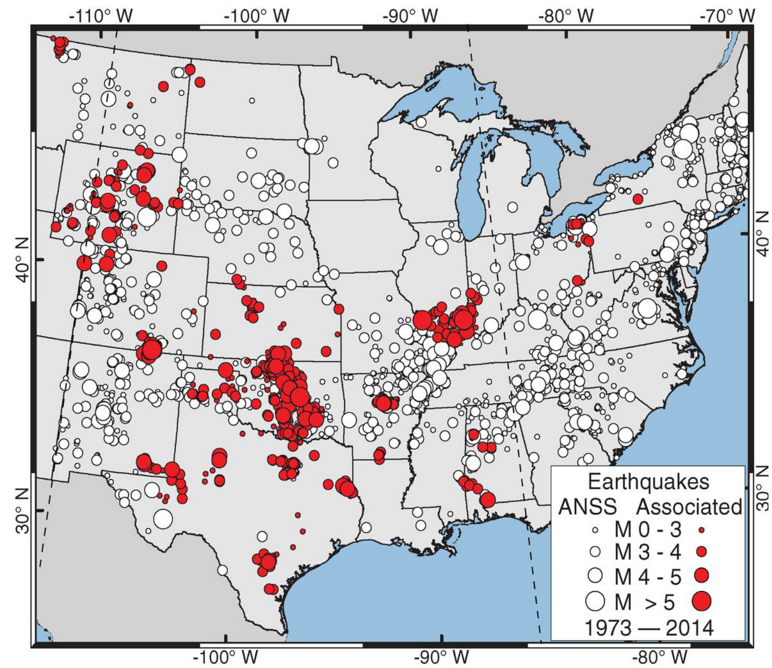


Figure 12. Spatiotemporal UIC Associated Earthquakes in CEUS 1973–2014[75]

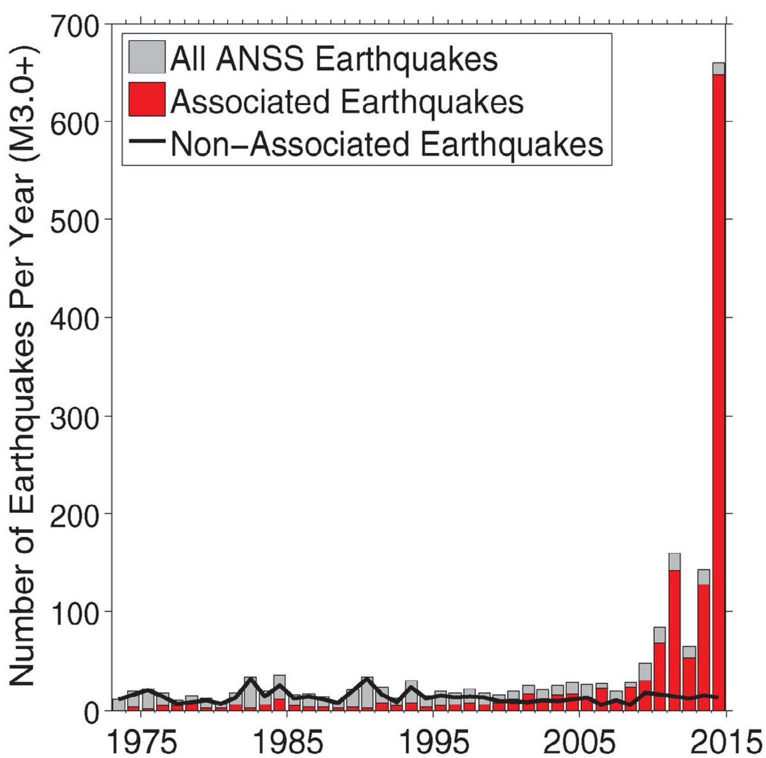


Figure 13. Associated and non-associated earthquakes per year in the U.S. midcontinent[75]

Thus, produced water reuse outside of the industry requires complete chemical characterization of the components within produced water as well as measurements of toxicity associated with human health, ecosystems, and soil and crop health.[78,79,80,81] The lack of information regarding composition and toxicity is partially due to the proprietary nature of the chemicals used within the industry and the lack of methodologies for assessing toxicity of complex waters. Efforts to address public access to the composition of produced water are being led by groups such as the New Mexico Produced Water Research Consortium who are advocating for the development of anonymous database approaches. There is a need to develop a regulatory framework that provides both opportunities for produced water reuse and ensures fit-for-purpose reuse quality. Similarly, there is a need for sustainable disposal and reuse options for solid residuals and liquid waste streams that support long-term protection of human health and ecosystems.

3.7.2. Societal Barriers for Mining

Societal barriers relevant to mining operations, like O&G, stem from strain on freshwater resources, as well as the environmental risks associated with tailings storage facilities and other mining wastes and soil and water pollution due to AMD and AbMD. Mines often compete with water usage for agriculture and municipalities. Dewatering activities required to maintain the stability of mining structures can also contribute to deterioration of local groundwater supplies, increasing the risk of aquifer collapse. Occasionally, dewatering generates larger volumes of water than what can be readily reused or stored, necessitating its direct discharge without beneficial use and angering the public in water-scarce areas. Environmental catastrophes associated with accidental release of mining wastes and ongoing discharges from closed “legacy” mines have increased scrutiny from both community stakeholders and regulators. AMD is challenging to prevent, costly to treat, and highly detrimental to the environment.[64] Beneficial reuse of mining effluents outside of mining operations is often difficult to accomplish logistically due to their remote location. Furthermore, public acceptance and regulations do not always encourage external reuse of mine effluent due to its potential toxicity and associated negative public perception.

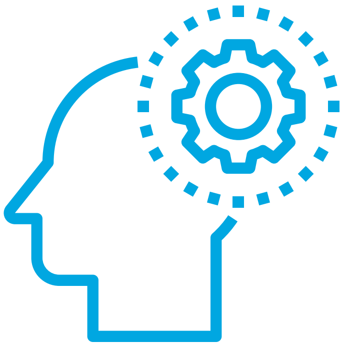
3.8. Pipe-Parity

The resource extraction industries are highly dependent on water for material extraction and processing and generate large volumes of challenging wastewaters that require treatment for reuse; therefore, the price of resources is highly dependent on water use efficiency. Pipe-parity in the Resource Extraction Sector is driven by the complexity and conveyance of the water. In many locations, the resource extraction industry lacks local water resources and depends on local communities for water needed for operation. Depending on market forces, the cost of water for these industries could substantially fluctuate. In addition, these industries might need flexible water treatment systems to bring the water quality from different sources to target quality needed for their operation. Two main problems associated with the industry’s wastewaters include (1) they are toxic to plants, aquatic life, and the many ecosystems because of the high concentrations of one or more constituents, and (2) their quality exhibits large spatiotemporal changes. Hence, off-the-shelf treatment technologies typically fail, necessitating advanced knowledge of aquatic chemistry and process engineering to design and successfully implement customized treatment technologies for water purification. In many instances, an extensive infrastructure for inexpensive wastewater disposal (e.g., disposal wells), approved by regulatory agencies, already exists; however, while these solutions are relatively inexpensive, water resources are lost, and environmental risk is high.

Therefore, the levelized cost of water for the extraction industry highly depends on availability and value of local water, the cost of disposal options (e.g., deep well injection or surface storage in holding ponds), and cost of water treatment, all of which will determine pipe-parity. Pipe-parity metrics vary regionally across the United States due to geographical variations in water/wastewater quality (and hence treatment costs), and beneficial reuse outside the resource extraction industry (e.g., agriculture or stream flow restoration) requires the development of a regulatory framework and long-term toxicological investigation, which might negatively impact pipe-parity. Yet, in places where valorization of valuable materials is possible (e.g., metals, rare earth elements, minerals, nutrients), pipe-parity can potentially be achieved via resource recovery and commercialization.

4. TECHNICAL CHALLENGES and Associated Knowledge Gaps

One of the biggest challenges for the Resource Extraction Sector is the cost for development, verification, acceptance, and implementation of new treatment and disposal technologies.



Regional and local variations in environmental and regulatory conditions, source water proximity, wastewater quality and quantity, and waste management opportunities (e.g., deep well injection) may cause the viability and utility of technologies to be both location- and application-dependent—capable of fit-for-purpose operation. Much like the installation of an O&G refinery that requires as-needed engineering and customization, water and wastewater treatment technologies and systems have unique requirements for each resource extraction application, site, region, and disposal or reuse option. Each site has changing needs and variables that create technical challenges not generally seen in other water and wastewater applications.

4.1. Technical Challenges

4.1.1. Constituent Detection

The Resource Extraction Sector needs to compile data on concentrations of constituents of concern in nontraditional waters, establish analytical protocols for characterization, and develop sensors appropriate for complex nontraditional water sources. Water quality can have a significant impact on industrial operations, causing corrosion and scaling in equipment, interfering in process chemistry, or creating additional challenges for disposal and reuse. The lack of proper methods and sensors for resource extraction wastewaters is primarily due to the large variety of constituents present with some at saturation levels while others are at method detection limits, which can be masked by those near saturation. The salinity is what typically exists at saturation, creating a critical challenge that needs to be incorporated in water chemistry and geochemical models and for analytical method development. Creating standard methods to assess resource extraction wastewaters, along with real-time monitoring and detection of general water quality indicators, could enable nontraditional reuse and improve operational decision making. With improved monitoring, decision makers can better design and customize treatment trains to fit their waste streams and they can better predict and prepare for fluctuations in water quality.

Accurate modeling of the geochemical behavior of constituents and their behavior in treatment systems, as well as analysis of complex matrices and treatment systems are needed to efficiently and effectively use, reclaim, and reuse nontraditional waters. Existing models could be improved through advanced characterization and data collection. Improved models of the resource extraction environment (e.g., wells, reservoirs, surrounding hydrology and ecology, temporal changes) could predict the interactions between source water constituents, treatment technologies, and process equipment and materials. Improved accuracy in these models could also enable better real-time decision making and adjustments in operations and achieve consistent water quality at minimal operating costs for fit-for-purpose water treatment.

4.1.2. Spacial/Temporal Challenges

Resource extraction operations are often located in remote areas and experience difficulties in sourcing water, accessing resources, and developing infrastructure for water treatment, operations, and waste disposal. Many resource extraction industrial sites lack access to traditional water sources, grid-based electricity, infrastructure, and even workforce. These sites may also experience additional challenges including high elevations, months of sub-zero temperatures, or even a simple lack of resources such as water (e.g., Texas) or disposal options (e.g., Pennsylvania). However, these challenges also present an opportunity to leverage nontraditional water supplies. Remote resource extraction sites need viable sourcing, transportation, and treatment technologies to enable nontraditional water use. These technologies should be amenable to remote or autonomous operation, have low-maintenance requirements, and integrate with energy sources available at the operation sites (e.g., non-grid-based power: renewables, geothermal, or waste gas).

- The locations of O&G wells, the magnitude of mining operations at a permanent mine, and the water quantity and quality at the operating locations all change over time, requiring scalable and flexible treatment systems.

The location of active O&G operations changes frequently and while mining operations do not change location frequently drilling activity at mines often shifts suddenly. Although mining and O&G operate differently with respect to footprint and frequency of relocation, they both experience changes in water quality and volume over time. A major challenge for the resource extraction industry is the long-term management of wells and mines, including managing tailing ponds, handling leachate, and other long-term issues (like AMD, AbMD, and produced water handling). Water demand for O&G may be high during drilling and completions, yet once a well is completed it requires almost no water, unless it is refractured. However, wells can generate a large volume of wastewater over time that operators must manage, with distributed sites all potentially producing significant amounts of water. Mining water volume requirements similarly vary over the life of the mining facility due to variations in ore grade. Additionally, mining operations must continuously manage tailing ponds and the presence or potential for AMD and AbMD resulting from mine-water interactions (e.g., precipitation accumulation or groundwater intrusion), both during active mine operation and after mine closure.

The industry needs water distribution, collection, and treatment systems that are mobile, flexible, and/or scalable to handle changing treatment and volume requirements. The sector needs effective and sustainable storage, treatment and waste disposal technologies that consider the long-term variability of resource extraction operations across the entire water/wastewater lifecycle.

Beneficial reuse has limited options outside of resource extraction industries due to remote locations, water quality challenges and uncertainties and a lack of regulatory guidance on what constitutes treated resource extraction wastewater. The primary resource extraction wastewater management techniques, especially for O&G, are internal reuse and deep well injection. However, due to factors such as high wastewater volumes, remote locations, high salinity, and the presence of other constituents of concern (including toxic metals or NORM), the industry faces significant challenges for expanding external beneficial reuse of wastewater. As the industry shifts away from deep well injection disposal, it needs to identify alternative water treatment technologies, residuals management methods, and disposal opportunities to enable more efficient reuse and disposal (e.g., more efficient separations, decreasing wastewater volume, better treatment to enable more disposal to surface waters).

4.1.3. Treatment Challenges

The Resource Extraction Sector requires large volumes of water, often for short durations with limited flexibility in demand, leading to challenging planning and treatment requirements. Water supply needs for resource extraction operations can reach 16,000 m^3 of water a day (4.23 million gallons per day [MGD]) for O&G and thousands to tens of thousands of cubic meters of water per day for mining; yet when operations are halted these demands can go to zero. Planning and storage of these on-demand volumes of water can be challenging, particularly for transient O&G operations. The resource extraction industry needs highly flexible, reliable systems that can accommodate large volumes one day and near zero the next, all while treating these highly variable nontraditional water sources.

The Resource Extraction Sector must treat and manage an array of water constituents, some at very high concentrations and others at trace concentrations, creating scenarios not typically seen in traditional water and wastewater treatment facilities. The resource extraction industry generates complex waste streams and brines that are often concentrated to or near saturation. The composition of these streams varies due to factors including the local geological formations, reservoirs, mining or drilling targets (ores or petroleum products), process chemicals, and hydraulic fracturing fluid chemicals. Furthermore, these streams may include challenging constituents like toxic metals, NORM, hydrocarbons, and other difficult organic and inorganic constituents ranging from silica to biocides. The industry needs to develop analytical methods and/or sensors to detect these constituents and remove them through robust treatment technologies.

The Resource Extraction Sector requires durable process components constructed with materials suitable for treatment of resource extraction waste streams. Due to the harsh operating conditions, the variety and concentrations of constituents, the array of chemical interactions, and temperature and pH variability, the resource extraction industry creates a challenging environment for various treatment processes (e.g., membranes and biological systems) and process components (e.g., reactors and sensors). The industry needs robust treatment processes and materials specifically developed for the Resource Extraction Sector to improve performance and long-term operation and maintenance of these systems.

4.1.4 Disposal and Solids Management Challenges

The Resource Extraction Sector is challenged by current residual management technologies that are energy-intensive and/or produce large masses of residuals, including hazardous waste. The industry needs to develop cost-effective and energy-efficient treatment technologies to create options for hazardous waste, brines, and solids. Most resource extraction streams are saline, and many are hypersaline (>200,000 mg/L TDS levels), making it a challenge to identify and implement cost-effective treatment options, particularly given the vast quantities of salt generated in ZLD scenarios. One rarely used approach for the O&G industry, comparable to ZLD and MLD, is to extract water from the brines up to their saturation point and then inject the saturated solution into a disposal well. This could be a viable approach to reduce the volumes managed in the mining industry, because disposal into tailings ponds is the most common practice, which is a long-term financial and environmental risk. However, these wells are not universally available, and as existing injection wells are used, and volumes of mine/well wastewater continue to increase, these options may be less viable as the costs and difficulty of disposal increases. Valorization of resources present in resource extraction waste streams can help reduce costs for sustainable residual management, but market strategies and improved separation technologies are needed to identify and efficiently extract value-added products, respectively.

4.2. Non-Technical Challenges

The sections below identify non-technical challenges associated with use of nontraditional water sources in the Resource Extraction Sector. These concepts are included here for thoroughness in identifying other kinds of gaps that could limit the use of nontraditional waters but are generally outside of the scope for NAWI.

4.2.1. Cost

Water is undervalued in the industry due to a variety of factors. Water should be valued holistically—not just by direct monetary costs—and that value needs to be communicated to industry personnel, regulatory or legislative entities, and the public. The value needs to consider the full lifecycle costs associated with sourcing, treatment, storage, disposal, and long-term impact management. The costs of incorporating nontraditional water sources and new treatment technologies and systems into existing plants and operations, or even into greenfield sites where they might affect proven operations, are often seen as prohibitive when the current water costs are undervalued.

4.2.2. Standards Development

Water/wastewater treatment, disposal regulations, and other requirements vary by location (federal, state, local, and tribal). These variances complicate the implementation and economic feasibility of water and wastewater management technologies, strategies, and systems. Varying treatment and handling standards may also influence transportation costs, energy costs, and regulatory compliance costs. Thus, the Resource Extraction Sector often requires fit-for-purpose water treatment and management systems, which limits technology development, manufacturing efficiency, and economies of scale. Standards are needed that can be implemented universally, dependent on only local physical conditions (geology, geography, hydrology, seismicity), the water systems (water quality as well as industry, population, and environmental considerations), constituents of concern, and industry processes involved.

Data collection and sharing are limited by a lack of standards, liability concerns, intellectual property, and limited understanding of business and operational benefits. Some companies and sectors have access to tremendous amounts of wastewater data, but the tools to use and analyze that data are often limited and used to prove regulatory compliance. Sharing data across the entire Resource Extraction Sector is challenging due to concerns regarding revealing proprietary business data, spurring increased regulation, or increasing legal liability. The benefits of data sharing could include supporting improved process modeling and operational decisions, reducing environmental impacts, and informing product and technology developers for better designs. The development of data collection, anonymization, sharing agreements, and standards is needed.

4.2.3. Liability and Risks

The Resource Extraction Sector faces business and operational risks related to the use of nontraditional water sources and the implementation of supporting technologies. As with other industries, the risks to resource extraction industries include coordinating with other industries on nontraditional water supplies, integrating nontraditional waters and new technologies into current operations, and increasing supply stress from climate change and droughts. However, in addition to these more generic risks, the Resource Extraction Sector also faces risks associated with linking market demand and economics of the resources extracted and operation. The potential for stranding capacity or resources as industry production changes with location and time represent both a short- and long-term risk. The industry also faces liabilities related to greater regulation of contaminants of emerging concern and resource extraction industry wastewater reuse in other sectors (i.e., impacts on water consumers like people, agriculture, and animals).

4.2.4. Environmental

Increasing reuse of Resource Extraction Sector wastewaters creates some environmental risk. Storage and transport of resource extraction waste streams may increase the risks for spills, leaks, and leachate migration into the local environment. While these environmental concerns are already present within the industry, additional research could help to identify and mitigate risk to air, soil, and water. Furthermore, external reuse of treated resource extraction waste streams may pose additional environmental and human risks. To enable external reuse, researchers must develop standardized toxicity testing to assess the potential impacts within the complex and variable matrices of resource extraction waste streams. Standardized analytical methods for characterizing and assessing the toxicity of these waste streams could then be utilized to develop reliable, robust treatment technologies to enable fit-for-purpose reuse.

4.2.5. Workforce and Training

Nontraditional water use and application of new technologies introduce challenges related to the education and skills of the sector's workforce. Staff at all levels may benefit from additional training related to their organization's water demand, potential production impacts, and business opportunities. Businesses are often unaware of their own water dependencies and the potential impacts of supply changes or treatment technology changes. Water considerations like these need to be integrated into every level of decision making. Familiarizing technicians, engineers, and decision-makers with capabilities and limitations as well as knowledge of installation, operation, and maintenance of new technologies is critical to achieve proper implementation and acceptance by the community. The Resource Extraction Sector faces the added challenge of having knowledgeable and trained workers at multiple, distant production locations—where labor costs and shortages of personnel trained in other process-related areas are often already a challenging issue.

4.2.6. Regulations and Public Acceptance

Technologies for nontraditional water use—including internal reuse and wastewater reuse outside of the Resource Extraction Sector—can develop faster than related regulations or could spur additional, challenging regulations. The lack of sufficient data and proper characterization of water quality imposes a significant challenge in developing a regulatory framework for reuse of water within the resource extraction industry. The range of contaminants and potential for treatment by-product formation further exacerbates the challenge. Moreover, regulations vary by state and are subject to modification. Thus, if regulations move in different directions, the development of these resources, especially for external reuse, could create investment risks and result in additional treatment and monitoring costs.

Even if developments in nontraditional water use succeed technically and meet regulatory requirements, there will be additional challenges from public acceptance. Public acceptance of resource extraction water reuse requires a more complete understanding of the toxicity of the treated water and the potential environmental and human impacts of various management options. The development of standard toxicity analyses (e.g., soil toxicity, plant uptake and toxicity, ecosystem toxicity, and/or human toxicity) could enable public acceptance of a broader range of fit-for-purpose end uses.

5. RESEARCH PRIORITIES

Areas of Interest for Resource Extraction End-Use Roadmap

To overcome the challenges presented in Section 4, this roadmap identifies the following set of research priorities needed to expand the use of nontraditional sources waters for the Resource Extraction Sector.

All the priorities are grouped under the A-PRIME categories: Autonomous, Precise, Resilient, Intensified, Modular, and Electrified. Advanced desalination and reuse will require a new generation of low-cost, modular processes that are inexpensive to customize, manufacture, operate autonomously, and maintain. This shift to small, connected, "appliance-like" water treatment systems that are mass-manufactured cannot be achieved by simply scaling down existing treatment plant designs or introducing marginal improvements to current treatment processes. Instead, a suite of next-generation desalination technologies that autonomously adapt to variable water chemistry; precisely and efficiently remove trace contaminants of concern; are robust to process upsets; desalinate water and concentrate brines in as few, modular units as possible; are readily manufactured; and do not require a constant resupply of consumable chemical reagents are needed. ***Investing R&D resources in the following priorities will lead to a revolution in desalination and treatment processes for the Resource Extraction Sector.***

Each identified area of interest follows with a short discussion of the current research challenges (a technology or problem that has not been sufficiently answered by existing studies) and continues with specific research needs. Advances in these technologies and capabilities aim to reduce the cost of treating nontraditional source waters to the same range as marginal water sources, thereby achieving pipe-parity. Where possible, quantitative estimates of potential impacts are given.

A The **Autonomous** area entails developing robust sensor networks coupled with sophisticated analytics and secure controls systems.

P The **Precise** area focuses on a targeted treatment approach with precise removal or transformation of treatment-limiting constituents and trace contaminants.

R The **Resilient** area looks to enable adaptable treatment processes and strengthen water supply networks.

I The **Intensified** area focuses on innovative technologies and process intensification for brine concentration and crystallization and the management and valorization of residuals.

M The **Modular** area looks to improve materials and manufacturing processes and scalability to expand the range of cost-competitive treatment components and eliminate intensive pre/post-treatment.

E The **Electrified** area aims to replace chemically intensive processes with electrified processes that are more amenable to variable or fluctuating operating conditions.

5.1 Autonomous

Sensors and Adaptive Process Controls for Efficient, Resilient, and Secure Systems

A1.

Develop reliable, robust sensors to enable advanced autonomous control systems in distributed and remote work sites and capable of withstanding the harsh environments and varying water quality present in O&G and mining applications.

Challenges

Current sensor technologies are not sufficiently resilient to the complex and harsh conditions (e.g., high TDS, TSS, organic content, temperature, and low pH) associated with produced water and mining wastewater streams.[13,82,83,84] Sensors often require regular maintenance, cleaning, and calibration, limiting their efficacy for remote sites and autonomous operations.

Impacts, continued

For the mining industry, this is relevant for mines aiming to maximize internal water reuse and recycling. Due to stringent water quality requirements in some mining processes (most notably froth flotation), sensors are needed to meet these high water quality requirements where mining process stream water quality can be adjusted based on influent recycled water quality. Froth flotation is a common processing technique in a majority of mines, most commonly for sulfide ores (e.g., silver, copper, lead, zinc, nickel, cobalt) along with other non-sulfide ores: soluble salt minerals such as potash, borax, trona; semi-soluble salt minerals such as phosphates, fluorite, calcite, barite; insoluble oxides and silicate minerals such as iron oxides, rutile, mica, quartz, feldspar; and other minerals such as talc, graphite, and coal.

Impacts, continued

For produced water from oil and gas operations, this is relevant for cases in which there is a need to concentrate or blend waters for disposal, reuse, or recycling. Improvements in produced water sensors have the potential to influence the treatment, disposal, and/or reuse of the approximately 3.88 billion m^3 (24.4 billion barrels) of produced water generated in the United States.[2] Different types of information and data are needed based on local conditions. Water quality and volumes might be important in different contexts. Autonomous sensors could be useful in terms of initially evaluating the water quality of influent streams in order to minimize overtreatment of produced water streams in centralized treatment facilities.

A1.

RESEARCH NEEDS:

- **Investigate** methods to collect data for a variety of water quality parameters crucial to the characterization of complex, high-salinity, and acidic produced water and mining waste streams prior to treatment and reuse, including total petroleum hydrocarbon (TPH), chemical oxygen demand (COD), specific ions, barium, 3D-fluorescence, multi-wave UVA, biological characteristics, toxicity, oil and grease, etc. Methods should be suitable for on-site analysis of water quality through online sensors (TRL 2–4).
- **Develop** durable, self-cleaning, and self-calibrating sensors that are easy to maintain. Alternately, low-cost, potentially disposable sensors with low drift should also be developed to facilitate accurate data collection and inform monitoring, operation, and maintenance of treatment processes in unstaffed or lightly staffed facilities, common in certain potentially hazardous produced water and mining facilities (TRL 2–4).

A2.

Develop automated data collection and processing programs and platforms to identify (a) trends in process performance and anomalies; (b) trends in feed, product, and brine chemistry; and (c) early warning signals of changing influent water quality that allow adjustments to process performance.

Challenges

Many water quality parameters crucial to the treatment and reuse of resource extraction wastewaters cannot currently be measured by online sensors and analyzers, requiring sample collection and processing in analytical labs, resulting in the inability to efficiently control and optimize water treatment systems in real-time. In order to achieve remote, autonomous, and fit-for-purpose wastewater treatment, and enable widespread reuse, it is necessary to develop new methods and expand on existing technologies for rapid on-line measurement. Reliable collection and analysis of water quality data would enable advanced autonomous controls, improve process monitoring, and allow for the development of expansive datasets for the generation of more reliable process models.

Collection, analysis, and immediate use of data gathered through process monitoring will improve the resilience and performance of treatment systems for the range and variability of produced and mining wastewaters. As methods of online water quality measurement and monitoring improve, it is necessary to investigate methods of garnering the maximum benefit from these datasets beyond autonomous, reliable operation of a specific wastewater treatment system. Of particular importance, these data sets could ultimately be extended to the development of various enhanced predictive methods and tools.

Impacts

For the mining industry, this is relevant for mines aiming to maximize internal water reuse and recycling. Improvements in automated data collection methods have the potential enable responsive and adaptive modifications to water treatment and or process control based on changes in influent recycled water quality.[41] This improved automated data collection platform could increase reliability of internal water reuse and recycling and thus improve industry adoption.

For produced water from oil and gas operations, this is relevant for cases in which there is a need to concentrate or blend waters for disposal, reuse, or recycling. Improvements in automated data collection methods for produced water have the potential to influence the treatment, disposal, and/or reuse of the approximately 3.88 billion m^3 (24.4 billion barrels) of produced water generated in the United States.[2] Different types of information and data are needed based on local conditions. Water quality and volumes might be important in different contexts. Automated data collection methods could be useful in terms of initially evaluating the water quality of influent streams in order to minimize overtreatment of produced water streams in centralized treatment facilities.

A2.

RESEARCH NEEDS:

- **Investigate** integration of data from supervisory control and data acquisition (SCADA) systems , lab data, and additional metadata with stream analyzers to predict/forecast water chemistry under variable process operating conditions (e.g., temperature, pH, recovery rates, etc.). (TRL 3–4; 2–3 years).
- **Develop** methods for early detection of potential process and system malfunction and failure. Further, investigate and develop methods of fault isolation/attribution to enable self-correction. (TRL 2–4; 3–5 years).
- **Develop** datasets to advance theories of supersaturation, evaporation, crystallization, etc. to increase sophistication of current trend identification and analysis specific to resource extraction water quality (TRL 2–4; 3–5 years).

A3. Develop model-based control and data-driven models (digital twins) to enable optimization of process set-points and process dynamics, leading to energy reduction, fit-for-purpose quality, and optimal water productivity and recovery.

Challenges

Autonomous and remote operation of fit-for-purpose wastewater treatment systems will require the development of advanced process models to ensure reliable and effective treatment. Further, the development of data-driven models and model-based process controls may allow for the targeted optimization of broader sustainability goals such as maximization of resource recovery and minimization of energy use. Although many resource extraction facilities are already gathering process and water quality data, the technical platforms used to analyze and leverage them to optimize treatment system operation and accurately forecast process failures needs improvement.

Impacts

For the mining industry, this is relevant for mines aiming to maximize internal water reuse and recycling. System information obtained through robust sensors and processed with data collection platforms can be leveraged through digital twins to optimize beneficiation processes, which have stringent water quality requirements, while maximizing internal water reuse and recycling. Preemptive water quality impact characterization on beneficiation efficiency has the potential to inform real-time modifications to water treatment and provide insight into long-term modifications based on past data collection.[41]

For produced water from oil and gas operations, this is relevant for cases in which there is a need to concentrate or blend waters for disposal, reuse, or recycling. Improvements in digital twin systems have the potential to influence the treatment, disposal, and/or reuse of the approximately 3.88 billion m^3 (24.4 billion barrels) of produced water generated in the United States.[2] Different types of information and data are needed based on local conditions. Water quality andvolumes might be important in different contexts. Digital twin systems could be useful in terms of initially evaluating the water quality of influent streams in order to minimize overtreatment of produced water streams in centralized treatment facilities.

A3.

RESEARCH NEEDS:

- **Develop** models to tailor and forecast operations and treatment for the variable feed water chemistries common to resource extraction facilities, process variations, and environmental conditions with feedback and adjustments to accommodate current and future conditions (TRL 3 and above; 3–5 years).
- **Develop** and optimize decision-support tools to enable optimal integration of a portfolio of energy sources, including traditional/fossil, renewable, and storage as grid energy availability is often limited at remote resource extraction facilities (TRL 3 and above; 2–4 years).
- **Develop** tools for optimization of water storage and conveyance infrastructure, addressed by water availability and demand, process capacity, energy availability and cost, and potential receiving environments and entities/markets (TRL 3 and above; 2–3 years).

5.2. Precise

Targeted Removal of Trace Solutes for Enhanced Water Recovery, Resource Valorization, and Regulatory Compliance

P1. **Develop and expand selective separation (e.g., membrane, sorption, ion exchange) and destruction (e.g., catalytic, electrochemical, and advanced oxidation) technologies for the selective separation/ destruction of recalcitrant, soluble organic pollutants.**

Challenges

Treatment and beneficial reuse of resource extraction waters is complicated by the wide spatial and temporal variation in both quantity and quality. While discussions of the treatment and reuse of produced water often focus on salinity, soluble organics (both bulk and recalcitrant) may also limit the efficacy of downstream processes. While technologies are needed to address bulk organic removal in high-salinity waters, precision separation of recalcitrant organics is also needed for these complex waters. The development of technologies to address recalcitrant, soluble organics is limited by both minimal characterization of produced water organics and their associated toxicity.[85,86,87] While standardized methods for characterization and toxicity will aid in this process, technologies and materials addressing these constituents must be resilient to variations in water composition and adaptable to dispersed, remote operation. Development of these technologies will aid in the ultimate goal of increasing reuse and recycling of resource extraction waters.

Impacts

This AOI has greater relevance for O&G produced water. Selective removal of organics is necessary for both the efficiency of downstream treatment processes as well as to reduce toxicity concerns for external reuse of produced water. Precise separation of organics would be particularly relevant to regions with high water-to-oil or water-to-gas ratios such as the Permian and Powder River Basins.[2,46]

P1.

RESEARCH NEEDS:

- **Develop** novel, high-performance materials that can be applied at scale (e.g., catalysts, adsorbents, membranes) for precision separations of recalcitrant organics, including production chemicals, aromatic hydrocarbons, anilines, and phenols, with detrimental impacts to treat resource extraction waters for specific end uses. Further, investigate methods of improving regeneration, resiliency, and selectivity of these materials while reducing fouling potential (TRL 2–4; 3–5 years).

- **Investigate** usage and energy efficiency of oxidation and reduction processes for destruction of recalcitrant organics in complex waters and the toxicity/biodegradability of end products. Improve the energy efficiency and performance of these processes in complex waters, including addressing the increased energy consumption and the generation of potentially toxic byproducts across the treatment trains. Identify methods to improve the regeneration and stability of catalysts used in organic separation/destruction to support advanced oxidation and reduction processes (TRL 3–4; 1–3 years).

- **Investigate** performance and resiliency of modular biological treatment technologies (e.g., membrane bioreactors [MBR], integrated fixed-film activated sludge) in the context of resource extraction waters (e.g., high TDS) as well as their potential for integration into hybrid treatment trains (e.g., electrocoagulation-MBR, reverse osmosis-MBR, advanced oxidation process-MBR) for simultaneous removal of bulk organics and enhanced removal of recalcitrant organics (TRL 2–4; 3–5 years).

- **Develop** standardized analytical techniques to characterize, assess toxicity (both synergistic and antagonistic effects) and develop surrogates for classes of organics to better target the development of precision separation within complex waters (TRL 3–4; 2–4 years).

P2. Develop and expand selective separation technologies (e.g., membrane, sorption, ion exchange) for altering the speciation or removing of metal ions and nutrients that inhibit downstream processes or selected end uses or facilitate recovery of valuable minerals while treating complex produced waters, mining waters, and their concomitant brine streams.

Challenges

Produced and mining wastewater contain a plethora of diverse inorganic constituents that are valuable, can hinder subsequent treatment and reuse, or simply create an environmental hazard.[4,13] Management and reuse of these wastewater streams will require the development of fit-for-purpose technologies that can selectively transport, transform, capture, and/or remove inorganic constituents[88] (e.g., lithium[65], rare earth elements[89], bromide[90], iodine[91], boron[92], arsenic[93,94], cyanide[95], copper[96], sulfates[97], selenium[98], silica[99], radionuclides[100]). Development of technologies that successfully address these contaminants will require a fundamental understanding of water chemistry (e.g., speciation), spectroscopic analysis, and geochemical modeling to guide the design of novel adsorbents, membranes, and other treatment materials to rapidly and effectively remove challenging solutes while limiting unwanted interfacial processes (e.g., fouling).[101,102] Further, consideration of these parameters in process-level design of hybrid processes will be crucial due to the wide variability in water quality and quantity.

In some resource extraction settings, such as the Silver Peak lithium mine in Clayton Valley, NV, precision separation technologies would facilitate the extraction and concentration of the target commodity (lithium), while reducing water losses due to evaporation. The Silver Peak lithium mine currently produces concentrated lithium brine through a series of evaporation ponds, which represented a significant capital investment during initial mine development. If precision separation technologies could be successfully implemented at the Silver Peak lithium mine to concentrate lithium in lieu of evaporative ponds, the water currently lost to evaporation could be sold and put to beneficial use in nearby agricultural applications.

Impacts

For mining operations using evaporative technologies to concentrate target commodities (e.g., potash, magnesium, lithium, salt), **selective separation technologies can reduce/eliminate water loss associated with evaporative concentration methods and provide effluent for other end users** (or for reuse at the mine site). Per MRDS active mine/plant data, active mines/plants for commodities commonly extracted through brine operations are as follows: Lithium - 1; potash - 7; magnesium (compounds + metal) - 12; salt - 68.[103*] Improved separation technologies also have potential for mines with acid mine drainage, which can contain significant concentrations of valuable products (e.g., antimony, arsenic, sulfuric acid, rare earth elements).[64]

For O&G produced water, this is relevant to basins that have economically viable concentrations of saleable constituents (e.g., lithium, iodine). For example, up to approximately 200 metric tons of lithium reside within the Mississippi Lime formation, and 20 metric tons of lithium reside within the Marcellus formation.[65] This is also relevant to basins and regions (Marcellus) which have high concentrations of inorganic constituents of concern like NORM, boron, arsenic, etc.

P2.

RESEARCH NEEDS:

- **Develop** specialized and resilient resource recovery techniques and materials (e.g., novel electrified selective precipitation methods or sequences, IX resins, unique specialized sorbents, metal-organic-frameworks, novel nanofiltration membrane materials, electrochemical methods) that can separate desirable constituents from complex resource extraction wastewaters (TRL 2–3; 2–4 years).
- **Investigate** biological and/or chemical treatment systems that alter the speciation (oxidation state) for better separation and provide enhanced recovery of metals to reduce discharge in solid or liquid effluent/residual streams (TRL 2–4; 2–3years).
- **Improve** selective separation between ions of different valency to expand potential beneficial reuse options and to prevent fouling and scaling on surfaces (TRL 3–4; 2–4 years)
- **Develop** and evaluate integrated, modular treatment trains (e.g., ED/RO, ED/NF, NF/RO, ozone [O_3]/EC) for enhanced removal of recalcitrant constituents. For example, it is necessary to reduce boron concentrations in produced water to acceptable levels for specific reuse applications (e.g., agriculture). Modular treatment systems for boron removal can be evaluated within the agricultural reuse baseline case (TRL 3–4; 2–4 years).

* These numbers represent all extraction types for these minerals, including both brine operations and hard rock mining.

P3. Develop high rate, pre-treatment technologies for bulk constituents (e.g., insoluble organics, TSS, NORM) to improve precision separations.

Challenges

High-efficiency, spatially independent pre-treatment processes of resource extraction wastewaters are necessary to enable subsequent precision separation. Bulk constituents (e.g., insoluble organics, TSS, NORM) may foul downstream processes and create large residual streams. For example, each baseline case study examined for O&G included oil-water separations. High-rate, cost-effective, high-efficiency oil-water separations could enable enhanced resource recovery from produced water while better protecting the efficacy of downstream treatment processes and equipment. Further, the accumulation of hazardous materials or radioactivity in these streams may prohibit cost-effective disposal and increase environmental risks. Consequently, it is necessary to investigate resilient, high-efficiency processes that are effective over a wide range of operating conditions and resilient to variable water quality.

Impacts

For mining, this is applies to advanced downstream selective separation treatment trains to reduce the risk of fouling. This can be particularly relevant when recycling (treating and reusing) stored water (from acid mine drainage and mining processing) from tailings facilities.

For O&G produced water, almost all treatment of produced water requires oil-water separations and the removal of suspended solids. Developing and optimizing pre-treatment of bulk constituents would apply to nearly all uses of produced water, in particular basins with high water-to-oil/gas ratios (e.g., Permian, Powder River Basin).

P3.

RESEARCH NEEDS:

- **Identify** pre-treatment processes and selective separations of dominant ions present at high concentrations to reduce fouling (e.g., calcium ions, sulfate ions), enhance recovery of beneficial materials (e.g., lithium ions, rare earth elements), and increase efficacy of downstream processes (TRL 2–4; 2–4 years).
- **Develop** high-efficiency, spatially efficient oil-water separation pre-treatment processes that exploit surface wettability to enhance separation, lower minimum size of removed droplets, and mitigate fouling for reuse and resource recovery from produced waters (TRL 2–4; 2–4 years).
- **Develop** pre-treatment processes that target removal of NORM with bulk constituents (e.g., radium removal with barium separation) to prevent radioactivity accumulation in either bulk water or solid waste that would limit disposal and reuse options (TRL 2–4; 2–4 years).
- **Develop** integrated treatment systems that allow high-rate precipitation/separation of TDS components (e.g., divalent and silica) (TRL 2–4; 2–4 years).
- **Develop** and optimize HDS to enable more efficient separation for reuse of mining and produced waters from high TSS streams and to produce sludges that are more easily dewatered (TRL 3–4; 2–3 years).

5.3. Resilient

Reliable Treatment and Distribution Systems that Adapt to Variable Water Quality and Are Robust to Corrosive Conditions

R1. **Develop autonomous water treatment systems that can quickly respond to and recover from changes in water quality, environmental conditions, and flow rates.**

Challenges

Due to the wide spatial and temporal variation in both water quality and quantity, successful remote operation of produced and mining wastewaters will require the development of resilient processes and materials.[4,13] Conventional technologies and treatment methods for these complex wastewater streams often require involved or extensive regeneration of materials, regular operator intervention, or are slow to adapt to changing water quality and quantity conditions. While aspects of autonomous control (discussed in Section A) will be necessary to successfully employ remote, decentralized wastewater treatment, the processes and materials themselves must be sufficiently robust to influent water quality (e.g., organics, surfactants, pH, TDS) and quantity. Consequently, it is necessary to simultaneously pursue robust processes, models, materials, and the corresponding autonomous control systems to enable remote, enhanced treatment of produced and mining wastewaters.

Impacts

For mining, this applies broadly across the sector for mines using froth flotation mineral beneficiation methods (see discussion of froth flotation prevalence in Section A1).

For O&G produced water, this applies across the sector, especially in unconventional O&G production. Unconventional produced water is estimated to account for around 1.5 million m^3/day (approximately 410 MGD).[45] Nationally, around 90 percent of unconventional produced water is disposed of via SWD. If 50 percent of unconventional produced water could be recovered via improvements in autonomous treatment systems, that could enable reuse of approximately 700,000 m^3/day (184 MGD) of produced water.

R1.

RESEARCH NEEDS:

- **Develop** model-based autonomous control systems that adapt changes in pretreatment and treatment processes in response to changes in feed water quality, environmental conditions, and flows. See A3 for additional details (TRL 3–4; 3–5 years).
- **Develop** efficient, fit-for-purpose pretreatment and treatment systems to rapidly respond to changes in water quality targets (e.g., flexible biological systems, robust side stream desalination, etc.). See sections P and I for additional details (TRL 3–4; 2–4 years).

R2. Develop site-specific strategies for incorporating renewable energy and energy storage.

Challenges

Integration of renewable energy and energy storage into resource extraction operations may help in both increasing the sustainability of these operations while enabling electrified treatment at isolated sites with minimal grid access. However, to ensure reliable operations with renewable energy, it is necessary to investigate methods of energy storage and the potential impact of intermittent energy on process resiliency.

Impacts

For mining, this applies broadly across the sector, especially in remote locations with a high potential for photovoltaic energy applications. The number of active mines/plants for states anticipated to have a high potential for photovoltaic energy applications are: Nevada (147 active mines/plants), Arizona (171), California (395), Utah (131), New Mexico (74), and Wyoming (68) likely have potential for photovoltaic energy applications.[103] Note, per MRDS active mine listing, there are 6,785 active mines/plants.

For O&G produced water, this applies across the sector, especially in remote locations.

R2.

RESEARCH NEEDS:

- **Develop** smart control systems to facilitate process protection when operating with intermittent energy sources (e.g., renewable energy sources). See section A2 for additional details (TRL 4; 2–3 years).
- **Develop** models for energy production (including renewable energy), use, and storage for distributed resource extraction water/wastewater treatment. Investigate energy storage requirements to sustain continuous operation of distributed treatment systems (TRL 4; 2–3 years).
- **Evaluate** the utilization of gas turbines, microturbines, solar, and wind to produce electricity and heat for water treatment, desalination, and brine concentration. Develop models for these forms of energy production, use, and storage for distributed resource extraction water and wastewater treatment (TRL 4; 2–3 years).
- **Evaluate** use of energy storage and excess renewables (hydrogen generation) for treatment of extremely high-salinity resource extraction waters with membrane distillation and other technologies that are cost-effective only because of the excess energy supply. Identify avenues for hydrogen generation using resource extraction byproducts and renewable supplies on-site (TRL 3–4; 2–4 years).

R3.

Develop integrated water distribution and collection pipeline bundles (similar to electrical grids) that enable users to simultaneously contribute various treated waters and withdraw various water types.

Challenges

The dispersed, remote nature of oil and gas and mining operations complicates transportation, treatment, and reuse of the effluent waste.[46] In particular, for resource extraction operations that produce and consume variable quantities of water, improving transportation and redistribution of water may expand reuse.[20,46] Development of wastewater and treated wastewater distribution networks have enabled increased reuse of wastewater within certain regions. For example, Newfield Exploration Company has leveraged an extensive transportation network in the SCOOP and STACK plays to enable enhanced reuse.[33]

Technologies that model and aid in the goal of developing wastewater, freshwater, and treated wastewater distribution for these dispersed and remote sites may aid in the ultimate goal of increasing cost-effective reuse.

Impacts

For O&G produced water, water distribution would be applicable to basins where production occurs in relatively compact regions which experience varying degrees of water supply and demand (e.g., Permian, SCOOP/STACK). Integrated water distribution systems could also aid in various beneficial reuse scenarios achieving pipe-parity.

R3.

RESEARCH NEEDS:

- **Utilize** a systems level approach to develop hydraulic and energy models for flows, pressures, temperatures, and materials for the pipeline system. See Section A3 for additional details (TRL 3–4; 2–3 years).
- **Develop** chemical and biological models for the water treatment plants contributing to the pipeline. Consider using Water TAP3 (the Water Technoeconomic Assessment Pipe-Parity Platform) as a tool to simulate multiple treatment plants in the network (TRL 4; 2 years).
- **Develop** flexible, durable, and self-healing pipeline materials (layflat vs. rigid) that minimize corrosion, scaling, leakage/damage, energy losses, etc. Develop techniques and materials for in situ restoration of pipelines and other water treatment infrastructure (TRL 3–4; 3–5 years).

5.4. Intensified

Systems and Process Optimization to Maximize Brine Reuse, Improve Brine Concentration and Crystallization, and Manage Residuals

I1. Develop hybrid treatment trains (across scales) to further enhance water recovery from brines from desalination processes, high-salinity produced water, or mining wastewater.

Challenges

Desalination of resource extraction wastewater streams often generates residual, concentrated brine streams. Previous studies have indicated potential to recover metals and other constituents from resource extraction wastewater and brine streams.[65,69] Similarly, enhanced water recovery from concentrated brines could help reduce freshwater usage in resource extraction operations. For example, improvements in desalination technologies for brines could potentially allow for further concentration of produced water brines prior to SWD.

Development and optimization of desalination technologies that will be suitable for the remote, dispersed sites common in resource extraction must consider:

1. Robust pretreatment processes to minimize unwanted interfacial processes
2. Enhanced water and resource recovery from concentrated brines
3. Minimized generation of concentrated brine streams

Impacts

For O&G produced water, this is relevant for locations with water treatment needs. Hybrid treatment trains would be relevant for basins with high water-to-oil/gas ratios (e.g., Permian, Power River Basin), limited access to injection (e.g., Marcellus, Oklahoma AOI), or concerns about future regulations limiting injection.

For mining, this is relevant for mines reusing/recycling decant water from tailings pond (See Autonomous Operations Topic#1 for further discussion). This is also relevant for brine operations (mining the brine for target minerals/metals) traditionally using evaporation for concentration (See Section P2 for further discussion on brine operations).

I1.

RESEARCH NEEDS:

- **Develop** cost-effective, high-rate, robust pretreatment processes that enable sustainable and high water recovery from enhanced desalination of brines as described above (TRL 3–4; 2–4 years). See Section P3 for additional details.
- **Develop** robust desalination techniques for hypersaline waters (e.g., eutectic freeze crystallization, temperature swing solvent extraction, water temperature/pressure swing absorption, ultra-high-pressure reverse osmosis, osmotically assisted reverse osmosis) as well as lower-salinity waters (e.g., liquid-liquid extraction, ion exchange). Investigate materials (e.g., hydrogels) to advance the development of future desalination technologies (TRL 2–4; 3–5 years).
- **Integrate** existing desalination processes with traditional or new brine concentrators such as solvent crystallizers, osmotically assisted reverse osmosis, membrane distillation and other membrane evaporation/crystallization technologies, vapor compression distillation, capacitive deionization, enhanced evaporation (engineered/natural) systems, hydrodynamic cavitation, and others, and demonstrate the techno-economic benefits of the proposed brine concentrators and desalination technologies (TRL 2–4; 3–5 years).

12. Develop technologies for resource recovery from brines while minimizing hazardous waste generation.

Challenges

Current desalination techniques often have limited capability to handle resource extraction wastewaters and brines due to excessive fouling and scaling. While resource recovery of valuable ions (e.g., lithium) is traditionally easier in concentrated streams, generation of concentrated, potentially hazardous brine streams complicates management and disposal.[67] Thus, while it may be feasible to valorize constituents in resource extraction wastewaters, technically and economically viable resource recovery technologies must minimize and address generation of concentrated, hazardous waste streams. For example, treatment processes geared to enable internal recycling of process water at the Lost Creek uranium mine located in central Wyoming generate a highly concentrated waste stream containing radioactive compounds, which require further treatment prior to deep well disposal. As wastewater storage, treatment, and disposal collectively account for 35 percent of the facility's levelized cost of water, improvements in concentrated brine management and disposal could reduce the levelized cost of water for the Lost Creek uranium mine and enable further internal recycling of process water.[104]

Impacts

For mining, this could have relevance for mines recycling water from tailings ponds (See discussion on Autonomous Operations Topic#1 for types of facilities that employ tailings ponds). Tailings ponds are likely for copper and gold mines. Note there are 40 active gold mines/plants and 27 active copper mines in the United States (out of a total of 6,785 active mines/plants).[103] Tailings water can contain potentially economically viable concentrations of minerals/metals along with processing chemicals.[25] This is also applicable in instances of acid mine drainage (common in hard rock mining).[25] See further discussion of acid mine drainage in Section P2.

For O&G produced water, this is currently not being done because of low concentrations and the lack of economic viability. For this to be relevant, more information is needed about concentrations, transformation processes, and potential markets.

12.

RESEARCH NEEDS:

- **Develop** enhanced, modular, cost-effective technologies (e.g., ion exchange, reactive membranes, electrified and non-electrified precipitation sequences, adsorption/desorption) for recovery of specific minerals and ion (e.g., lithium, rare earth elements, bromine, and iodine) from waste and concentrated brine streams. Evaluate the usage of renewable energy and materials in these technologies (TRL 3–4; 3–5 years). See Section P2 for a list of these separation technologies and their associated challenges.
- **Conduct** a techno-economic study of the potential resource recovery available with existing and novel/future technologies. Consider using WaterTap3 to simulate resource recovery in this context (TRL 1; 1–3 years).

13.

Develop cost-effective methods for brine management and solidification.

Challenges

O&G and mining wastewater may contain elevated TDS concentrations ranging from less than 2,000 mg/L to nearly 400,000 mg/L.[2] While existing/commercial membrane processes (e.g., NF, RO) are able to cost-effectively desalinate streams up to 45,000 mg/L TDS, development and optimization of alternative desalination processes (e.g., eutectic freeze crystallization, thermal distillation, ultra-high pressure RO [UHPRO]) will be necessary to provide cost-effective, energy-efficient desalination of resource extraction wastewaters and brines.[13]

Most methods of treatment and desalination of produced and mining wastewaters generate residual streams. Management of these residual streams is complicated by the quality, quantity, and potentially hazardous nature of concentrated brine streams. While the development and optimization of ZLD methods like solidification may provide additional options for residual management, the economic and technical feasibility of these methods must address the volume of solids generated for disposal. Further, solidification methods must solidify and stabilize brines while minimizing the leaching of hazardous chemicals. Ultimately, development and investigation of a combination of cost-effective ZLD and MLD techniques will be necessary to expand reuse of resource extraction wastewaters and brines.

Impacts

For mining, more effective methods for brine management are potentially relevant for mines with hypersaline mine water in areas where evaporation rates are low and evaporation ponds are not a sufficient measure for brine management (e.g., all active domestic iron mines/plants [n=8] are located in Michigan and Minnesota, which have lower evaporation rates than Western states).[103] Iron is typically processed using froth flotation, resulting in wastewater storage in tailings ponds.[105] Cost-effective brine management methods could be useful in similar applications.

For O&G produced water, this is relevant for high salinity basins (e.g., Marcellus, Permian, and Bakken). For example, estimates indicate that desalination of produced water from the Delaware Basin in 2017 could generate approximately “3,000 Olympic swimming pools” of solids.[20]

13.

RESEARCH NEEDS:

- **Develop** technologies that provide marketable products to utilize produced bulk solids and residuals (TRL 2–4; 3–5 years).

  Develop methods and solutions for solids management in remote locations. Identify viable options for residual management, such as deep well injection, solidification, and evaporation ponds.

- **Develop** new leaching technologies to enhance mineral and metal recovery (TRL 2–3; 2–3 years).

  Investigate extraction of acids for industrial needs.

  Explore leachate liquids to power microbial fuel cells.

- **Develop** cost-effective technologies for solidification and stabilization of solids from MLD and ZLD systems, with local utilization of the products (TRL 3–4; 2–4 years).

  Explore the long-term environmental impacts and stability of the transformation and solidification products.

  Investigate integration of byproducts/wastes to enhance the solidification process in order to reduce the reliance on carbon-intensive solidification methods.

  Develop technologies for the separation of constituents (e.g., keep calcium and magnesium) that optimize brine composition to aid in current solidification techniques.

  Develop technologies that effectively reduce leaching of difficult-to-solidify trace elements such as Se(VI).

14. Optimize the prediction and characterization of brine streams.

Challenges

The innate complexities of high-salinity concentrated brines, coupled with the wide spatial and temporal differences in brine/waste stream quality, increases the difficulty of characterizing and predicting brine behavior within O&G and mining. Existing geochemical models are often challenged when characterizing high-salinity, complex brine streams. Similarly, existing toxicity and hazard assessment methodologies (e.g., toxicity characteristic and leaching procedure) may fail to fully describe toxicity effects (individualistic, antagonistic, and synergistic) of brine and waste streams. Improved geochemical models and toxicity assessments could enhance understanding of in situ brine behaviors, environmental and toxicity risk during disposals or spills, and potential treatment, MLD, and ZLD methods.

Impacts

This can impact both the mining and O&G sectors. For mining, this is relevant where recovery opportunities are being evaluated, especially for mines recycling water from tailings ponds (e.g., copper and gold mines). For the O&G sectors, as operations move from one location to another, evaluating brine streams can be used to predict future instances of acid mine drainage or future ecological damage.

14.

RESEARCH NEEDS:

- **Develop** integrated geochemical modeling tools for brine chemistry to predict and control fouling and scaling during treatment, transport, and ultimate disposal (e.g., salt caverns and deep well injection) (TRL 2–4; 3–5 years).

  Develop an understanding of metastable behavior in super-saturated brines (and how resource extraction brines differ from other brines) to assess appropriate additives for stabilization and assist in the development of technologies and procedures for intermittent precipitation of different minerals at the boundary of supersaturation.

- **Develop** standardized methods to characterize and assess toxicity (e.g., environmental and human) of brines to ensure the appropriate methods of reuse, disposal, and solidification are used (TRL 3–4; 2–4 years).

5.5. Modular

Materials, Manufacturing, and Operational Innovations to Expand the Range of Cost-Competitive Treatment Components and Eliminate Intensive Pre/Post-Treatment

M1. Increase flexibility, scalability, and portability of modular treatment systems and characterize operating limitations to enable cost-effective solutions and increase industry adoption.

Challenges

Resource extraction facilities often experience variations in both water quality and quantity.[13,35] Consequently, water treatment processes are often challenging to implement in a cost-effective manner due to the changing needs of the system using available technology and treatment systems.

Adaptive, fit-for-purpose, modular systems may facilitate the adoption of advanced water systems to produce high-quality effluent for recycle or reuse. However, the available treatment systems lack flexibility and are costly to implement. System portability is lacking and prevents the easy relocation to different resource extraction facilities. Further, modular designs (spiral, tubular, etc.) for manufacturing integrations are needed for effective, scalable solutions. New reverse osmosis membranes also require modular design/development for industry acceptance. In addition to the lack of flexibility and scalability of currently available technology, the operating limits of certain treatment systems for the treatment of resource extraction waters are not well-defined. Specifically, the cut-off of osmotically assisted reverse osmosis and thermal systems in terms of TDS is unclear.[106]

Impacts

For mining, increased flexibility, portability, and scalability are potentially applicable across the sector, especially in remote locations and for small mines with capital expenditure limitations for water treatment. Also, declining ore grades coupled with increasing demand, may force existing mines to process increasing volumes of ore, resulting in incremental increases in water treatment capacity requirements. Improvements in modular water treatment systems will enable water treatment to grow alongside growing mines. Declining ore grades is common in many types of mines as higher ore grades are typically targeted first.

For O&G produced water, this is applicable across the sector, especially in remote locations and basins that have high water-to-oil/gas ratios (e.g., Permian, CBM Basins).

M1.

RESEARCH NEEDS:

- **Develop** treatment processes that reduce the weight, size/footprint, and complexity of unit processes across the treatment train to develop modular, versatile, high-rate, flexible, and highly portable treatment systems that reduce transportation cost to remote locations and between facilities (e.g., reduce footprint of existing processes such as conventional oil/water separations, coagulation/flocculation and sedimentation by 50 percent) (TRL 4; 2–4 years).
- **Identify** improvements in modular system flexibility and scalability through the use of beneficial synergies between specialized unit processes. For example, develop advanced pretreatment processes to allow membrane desalination technology implementation in treating produced and mining wastewater (flexibility) while limiting the production of waste material during pretreatment (scalability) (TRL 3–4; 2–4 years).
- **Develop** membrane filtration materials with effective and scalable solutions, including modular designs (e.g., spiral, tubular) for manufacturing integrations to allow for changes in system capacity in response to changes in produced water flow rates and/or variability in mine wastewater volumes (TRL 3–4; 2–4 years).
- **Identify** the cut-off of osmotically assisted reverse osmosis and thermal systems in terms of TDS concentration across the range of produced water and mine facility wastewater streams (TRL 3–4; 2–3 years).
- **Develop** manufacturing methods and treatment system components that provide resilient, low-cost, and flexible modular systems, which benefit from economies of scale, increasing industry uptake of modular treatment systems at dispersed and decentralized facilities, such as remote O&G production sites (TRL 4; 3–5 years).

M2. Innovate membrane module design for improved durability against various stress factors (e.g., chemical, temperature, pressure) and application in high-salinity, high-pressure, and high-flow waste streams.

Challenges

Desalination of high-salinity produced and mining wastewaters using current polymeric membranes is limited by a variety of factors, including detrimental membrane scaling/fouling, membrane collapse at high trans-membrane pressures, and poor membrane stability when exposed to high temperatures, certain organic compounds (e.g., cleaning), or high pH.[107,108]

Polymeric membranes may degrade irreversibly even upon a single exposure to certain dissolved organic compounds, requiring cost-effective but foolproof pre-treatment. When current polymeric membranes are used to treat resource extraction waters, they are preceded by extensive pre-treatment technologies, often increasing treatment system complexity and waste production.[107] Use of HPRO to treat high-salinity waters currently requires extensive pretreatment, is expensive, and poses potential safety hazards. In addition, membrane performance at high pressures is not well understood and limits reliable implementation of HPRO.[109] Alternative membrane materials, such as ceramic membranes, provide a higher chemical and thermal stability, but improvements to the membrane flux and ion rejections are needed to enable widespread, cost-efficient implementation.[107,110]

Impacts

For mining, this is applicable across the sector, particularly in scenarios where decant water from tailings ponds must be treated before reuse in mineral extraction processes. Also, for selective separations of target minerals from brines, high-rate membranes may be necessary to enable mining industry uptake of technology.

For O&G produced water, this is applicable across the sector, especially in basins with high water-to-oil ratios.

M2.

RESEARCH NEEDS:

- **Develop** novel, hybrid processes such as membrane bioreactors or combined oxidation/membrane systems that can overcome thermodynamic barriers and operate efficiently and reliably in high-salinity waters (TRL 2–4; 3–5 years).
- **Develop** scalable membrane materials with properties that reduce fouling while treating complex produced and mining wastewater chemistries and that can withstand and operate efficiently at high-transmembrane pressures (TRL 2–3; 2–4 years).
- **Develop** a better understanding of the interfacial interactions among conventional/novel membranes and organic compounds present in produced and mining wastewater. Utilize the enhanced understanding of the interfacial interactions to develop structure-property-processing relationships to design advanced cost-effective and resilient pre-treatments that prevent irreversible degradation to polymeric membranes upon exposure to certain dissolved organic compounds (TRL 2; 2–4 years).

M3.

Improve regulatory and industry understanding of modular treatment systems and their benefits and limitations in context with the entire treatment system.

Challenges

Modular systems are often misconceived as highly portable and simple solutions to remove a specific constituent of concern. In application, modular systems require substantial engineering, infrastructure, operator training and knowledge, and have operational and chemical limits. There is often a disconnect between resource extraction water treatment facility engineers and regulators as to the applicability and simplicity of modular systems which leads to a lack of industry uptake of systems marketed as modular.

Impacts

This is applicable across both the mining and O&G sectors, particularly for design engineers and architects planning future improvements for their drilling sites. This will provide organizations with methods that are accessible in the remote locations where they operate. For O&G, having modular and transportable treatment systems will allow them to shift their operations more easily from one location to another.

M3.

RESEARCH NEEDS:

- **Develop** a techno-economic assessment comparing modular systems for wastewater treatment against the current disposal practices in industry (e.g., well injection, evaporation ponds). Identify and assign economic impacts to environmental factors associated with current disposal practices to improve regulatory and industry understanding of water treatment in context to the economic impact of currently available alternatives (TRL 3–4; 1–3 years).
- **Develop** dialogue and understanding between researchers, resource extraction engineers, and regulators to develop and implement practical technology and systems for industry.

5.6. Electrified

Electrifying Water Treatment Processes and Facilitating Clean Grid Integration

E1. **Develop and optimize electrified treatment processes (i.e., electromagnetic field, electrocoagulation) to reduce chemical use and associated transportation logistics/costs.**

Challenges

Although electrified treatment processes represent an opportunity to reduce chemical usage and the associated transportation of hazardous chemicals to often remote resource extraction facilities, they must be optimized to compel resource extraction facilities to fundamentally change their existing water treatment processes. Similar to most other physicochemical processes, electrolytic treatment processes concentrate but do not fully remove constituents (e.g., mineralize). The resulting waste stream is a highly concentrated hazardous waste stream which must be disposed of or further treated. Additionally, the use of electrified treatment processes may increase the occurrence of problematic constituents or produce unanticipated byproducts when used to treat highly complex resource extraction waters. Water treatment using electrolysis is prone to excessive scaling for resource extraction waters and is inefficient for high conductivity waters, thus its widespread usage in the resource extraction sector is hindered.[111]

Membrane capacitive deionization (CDI) is a promising electrified treatment process, but its applications in high-salinity waters are not well defined and is energy intensive compared to electrodialysis reversal desalination. Electrocoagulation has not been systematically evaluated or implemented in the context of resource extraction water treatment and previous industry experience with the technology has resulted in reluctance to adopt electrocoagulation despite any claimed benefits.[112]

Impacts

For mining, this is applicable across the sector. Targeted applications include treating acid mine drainage and process water prior for recycling before sending to storage in tailings ponds. For O&G produced water, this is applicable across the sector, especially in remote locations.

E1.

RESEARCH NEEDS:

- **Perform** bench-scale testing of electrified treatment processes (e.g., electrocoagulation, electromagnetic field, electrocatalytic) to evaluate efficacy using resource extraction wastewaters over a range of relevant operating conditions. Testing should optimize reactor design and characterize the treatment process impact on the comprehensive constituent profile of the waste stream—not just target constituents (TRL 2–4; 2–3 years).
- **Evaluate** the potential benefits and limitations of EC across the range of resource extraction water qualities considering the common constituents in resource extraction waters (e.g., chloride, sulfate, organics) and integration of EC systems into treatment trains (e.g., EC/ozonation, EC/ultraviolet). Specific parameters to be evaluated include dose control (faradic efficiency), in situ coagulant generation, fluid dynamics and mass transfer, corrosion kinetics, passivation, and sludge production in high-salinity systems. A thorough technoeconomic analysis is critically needed to compare EC to chemical coagulation (TRL 3–4; 2–4 years).
- **Assess** methods for optimizing electrolytic performance (e.g., chemical additives, and system geometry) and evaluate dimensionally stable and sacrificial electrodes and catalysts for optimal performance while reducing waste generation (TRL 3–4; 2–4 years).
- **Develop** non-chemical approaches for fouling and scaling control (e.g., electromagnetic field, ultrasonic) on membranes, heat exchanger surfaces, pipelines, and other water treatment devices through an improved understanding of the science, mechanisms, and factors affecting the efficiency of these technologies for resource extraction water qualities (TRL 3–4; 2–4 years).

E2. Develop and evaluate performance, limitations, and implementation of electrical desalination processes.

Challenges

Electrical desalination processes have been effectively implemented in low salinity desalination applications but are often cost-prohibitive for high-salinity waters.[113] Electrode materials lack stability in certain electrical desalination setups and corrode easily, leading to regular and costly replacements.[114,115] Operational limitations of electrical desalination technologies (ED, CDI, membrane capacitive deionization, flow electrode capacitive deionization, EFT) are not well characterized in the context of resource extraction waters.

Integration of electric desalination technologies with thermal desalination technologies is not well understood. Although eutectic freezing may be a viable brine concentrating process, the process has not been fully evaluated in resource extraction waters.[116]

Impacts

For mining, this research is relevant in situations where water is desalinated to meet specific recycling water qualities. For O&G produced water, this is applicable across the sector, especially for high salinity basins (e.g., Permian, Marcellus, and Bakken).

E2.

RESEARCH NEEDS:

- **Evaluate** performance and limitations of low to moderate salinity electrical desalination technologies (e.g., ED, CDI systems) in the produced and mining water context (TRL 3–4; 2–4 years).
- **Develop** cost-effective electrode materials and design (e.g., thickness, pore size distribution) as well as investigate module design (e.g., flow hydraulics, spacers) (TRL 3; 3–5 years).
- **Evaluate** electrical precision separations technologies (e.g., ED, CDI) for constituent recovery (e.g., lithium) in complex waters (TRL 3–4; 2–4 years).
- **Evaluate** performance and limitations of high-salinity electrical desalination technologies (e.g., eutectic freeze crystallization) for resource extraction waters (TRL 3–4; 2–4 years).
- **Evaluate** the integration of electrical desalination with heating or cooling crystallization and reaction crystallization to determine the best combinations (TRL 3–4; 2–3 years).

E3. Evaluate the use of water electrolysis/bipolar electrodialysis for generation of chemicals on site and in situ, including bleach, acids, and bases, at Resource Extraction facilities.

Challenges

Although chlor-alkali processes for chemical generation are fairly mature, these processes are usually performed in a centralized location under the control of skilled operators because of the hazardous nature of the chemicals involved and the relatively secondary importance given to water in these industries that primarily focus on their value-added product (not water). **Current implementation of these processes to generate treatment chemicals are not suitable for remote, autonomous operation.** Moreover, on-site production of chemicals is beneficial if the chemicals are produced in quantities and concentrations that enable use on site. **In situ chemical generation and byproduct formation is not well understood in the context of resource extraction waters.**[117]

Impacts

For mining, this is applicable across the sector. There is particular interest in mine operations using froth flotation circuits, where chemical inputs could potentially be derived from waste products. Froth flotation is a widely used process in metal mining as well as some applications in mineral mining (see discussion of froth flotation in Section A1). For O&G produced water, this is applicable across the sector, especially in remote locations.

E3. RESEARCH NEEDS:

- **Investigate** bipolar electrodialysis functionality and pre-treatment requirements for chemical generation when using resource extraction waters, including the brackish reverse osmosis waste stream or produced water. Evaluate and optimize tailoring of bipolar electrodialysis systems for higher-salinity systems to reduce scaling/fouling (TRL 3–4; 2–4 years).
- **Assess** methods of chemical purity control for on-site generation with varying source water quality as well as the potential for byproduct formation (TRL 3–4; 1–3years).
- **Investigate** methods of in situ disinfectant and chemical generation with varying source water quality as well as the potential for byproduct formation (TRL 3–4; 2–3 years).

E4. Investigate the use of alternative and renewable energy sources in electrified water treatment.

Challenges

Electrical treatment systems that reduce required chemical inputs are attractive technologies for remote facilities which often have alternative energy systems in place. However, current water treatment system technologies and process flows may not accommodate variable energy supplies associated with the use of renewable energies.[118,119] Additionally, electrified volume reduction technology energy consumption is directly related to TDS concentrations, posing energy supply challenges (at remote and mobile sites powered by renewable energy supplies).

Although onsite generation of hydrogen has the potential to provide excess renewable energy to treat high-salinity waters, there is an inherent safety concern associated with hydrogen generation at remote and often unmanned facilities.

Impacts

For O&G produced water, this is applicable across the sector. For mining, this is applicable across the sector, although mines in off-grid locations may have greater incentive to investigate and adopt renewables/alternatives. Industry as a whole is trending towards electrification to reduce reliance on fossil fuels (and associated market volatility) which can improve a mine's social standing and decrease emissions.

Major challenges include a variable power supply and limited technical expertise related to renewables in mining. See discussion in Section R2.

E4.

RESEARCH NEEDS:

- **Evaluate** the potential impacts of energy intermittency on process operation, effluent water quality, and equipment lifespan for remote facilities entirely reliant on alternative and renewable energy sources to power electrified treatment systems in lieu of traditional chemical-based treatment systems (TRL 4 and above; 1–3 years).

- **Identify** limitations of renewable energy supplies and nontraditional fossil fuel energy sources (e.g., flare, stranded natural gas) to provide required electrical supply for energy-intense electrified treatment processes. Identify process changes to lower the energy intensity of these electrified treatment processes. Direct potable reuse (DPR) is a potential option for lower-salinity produced water; however, advanced treatment processes have high energy demand. Opportunities to integrate renewable energy could substantially reduce operating costs. The potential savings can be evaluated within the DPR baseline case (TRL 4 and above; 1–2 years).

- **Evaluate** the use of impaired water for energy generation. Investigate technologies to support repurposing water for hydrogen fuel cells and/or biologically or sustainably produce hydrogen and identify any unique characteristics of resource extraction water that support hydrogen production (TRL 3–4; 2–3 years).

6. NEXT STEPS

This comprehensive and dynamic roadmap for low-TRL desalination and water treatment technologies for the Resource Extraction End-Use Sector is intended to guide future R&D investments throughout the duration of the research program. NAWI's Master Roadmap will compile high-value, crosscutting themes across all PRIMA end-use water roadmaps, including this one, and will be categorized under the A-PRIME areas. In 2021, NAWI will begin implementing the crosscutting research priorities outlined in the Master Roadmap via requests for projects (RFPs) and a project selection process designed to align member needs with the Alliance's research and development efforts. The funded projects will represent the most impactful development opportunities that will ultimately motivate subsequent industry investments required to further enable the use of nontraditional waters sources in a cost-effective manner.

Because the roadmap is a forward-looking document meant to guide NAWI throughout its existence, the Alliance will update its roadmap annually. Annual updates will also be critical to ensure that NAWI's roadmap evolves with the changing landscape of U.S. water treatment technologies, including the advancement in materials R&D, new processes, novel modeling and simulation tools, and expanded integrated data and analysis capabilities. Each aspect of the A-PRIME hypothesis as well as the identified research priorities will be regularly vetted with water treatment professionals from each PRIMA industry sector to ensure that it is a relevant pathway to advancing desalination and water treatment capabilities with nontraditional source waters. In successive roadmap iterations, the feedback will be used to assess the relevance of each research priority to the roadmap and evaluate progress toward achieving its goal of enabling a water circular economy for the Resource Extraction Sector following the A-PRIME technology development hypothesis while considering all relevant pipe-parity metrics. NAWI will adjust its priorities and expand its available resources to maximize the impacts of its efforts.

The technology advancements developed by the NAWI research program are geared to help domestic suppliers of water desalination systems to design and manufacture critical equipment, components, and small-modular and large-scale systems.

- **Innovations from the NAWI Energy-Water Desalination Hub will promote energy-efficient, cost-effective water purification, ensuring a secure supply of clean water for the nation and the world.**

Appendix A: Acronyms

3D	Three dimensional
A-PRIME	Autonomous, Precise, Resilient, Intensified, Modular, and Electrified – NAWI R&D focus area
AMD	Acid mine drainage
AbMD	Abandoned mine drainage
AOI	Areas of interest
AOP	Advanced oxidation processes
BCR	brine crystallizer
BGD	Billion gallons per day
CBM	coal bed-methane
CDI	capacitive deionization
DC	dust control
DOE	U.S. Department of Energy
DPR	Direct potable reuse
EC	electrocoagulation
ED/NF	Electrodialysis/Nanofiltration
ED/RO	Electrodialysis/Reverse osmosis
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
HDS	high-density sludge system
HEM	hexane-extractable material
HPRO	high-pressure reverse osmosis
IoT	Internet of things
LCOE	Levelized cost of electricity
LCOW	Levelized cost of water

LED	Light emitting diode
MBAS	methylene blue active substances
m^3	Cubic meters
MBR	Membrane bioreactor
MCR	membrane crystallization
mg/L	Milligrams per liter
MGD	Million gallons per day
MLD	minimal liquid discharge
MRDS	Mineral Resources Data System
MSF	multi-stage flash distillation
MVC	mechanical vapor compression
NAWI	National Alliance for Water Innovation Hub
NF/RO	Nanofiltration/Reverse osmosis
NETL	National Energy Technology Laboratory
NORM	naturally occurring radioactive materials
NREL	National Renewable Energy Laboratory
O_3/EC	Electrocoagulation-Ozone
O&G	Oil and Gas
O&M	operations and maintenance
OARO	osmotically assisted reverse osmosis
pH	Potential of hydrogen to specify the acid or base strengths
ppm	Parts per million
PRIMA	Power, Resource Extraction, Industry, Municipal, Agriculture End-Use sector focus for NAWI
RAC	Research and Advisory Council
REE	Rare earth elements
R&D	Research and development
RFP	Request for projects

RO	Reverse osmosis
SCADA	supervisory control and data acquisition
SDWA	Safe Drinking Water Act
SU	sanitary utility
SWD	Saltwater disposal
TDS	Total dissolved solids
TEA	Technoeconomic analysis
TNORM	technology enhanced naturally occurring radioactive material
TOC	total organic carbon
TRL	Technology readiness level
TSS	total suspended solids
UHPRO	ultra-high pressure RO
UIC	Underground Injection Control
USGS	U.S. Geological Survey
UV	Ultraviolet
Water-TAP3	Water Technoeconomic Assessment Pipe-Parity Platform
WD	wash decontamination
WWTP	Waste water treatment plants
ZLD	Zero-liquid discharge

Appendix B: NAWI A-PRIME Expanded Descriptions

Autonomous:

Current water treatment systems are designed to operate at nominally steady-state conditions, relying on human intervention to adapt to variations in water quality and correct failures in process performance. Simple, robust sensor networks coupled with sophisticated analytics and controls systems could enhance performance efficiency and process reliability. These more adaptable, smart systems could also minimize the need for on-site, manual interventions. Together, these innovations would significantly lower the cost of distributed, fit-for-purpose desalination systems.

Early-stage applied research can improve Internet of Things (IoT) infrastructure to meet the need for water treatment that is generalizable, secure, and resilient when managing sparse data and calibration errors. System identification and physics-based approaches can be used to develop reduced-order models and adaptive methods for closed-loop feedback control and optimization of interdependent water treatment processes. The developed controls approaches can be augmented with statistical and machine-learning-informed process monitoring techniques to diagnose system inefficiencies and faults. Data needs for process control and monitoring include temporal, nonlinear, stochastic, and uncertainty aspects of process parameters.

Precise:

Current water treatment systems often rely on inefficient bulk separation processes to remove solutes that occur at trace levels. A more targeted treatment approach for trace contaminant removal can reduce the cost and energy intensity of treatment processes, while offering major reductions in system complexity and waste disposal costs. Precise separation or transformation of constituents also enhances the likelihood of profitable recovery and valorization of waste streams, offsetting the overall costs of desalination systems.

Early-stage applied research can improve the selectivity of materials and the efficiency of removal technologies for hard-to-treat or valuable-to-extract compounds (e.g., boron, hexavalent chromium, lead, nitrate, perchlorate, selenium, uranium, lithium, iodide). Simulation platforms can exploit molecular recognition principles in the design of highly selective materials. There is a need to synthesize and characterize these materials in high-throughput experimentation platforms. There is also a need to use process modeling and optimization tools to ensure that the high selectivity and affinity for target species, fast uptake kinetics, and efficient regeneration are fully exploited in continuous and intensified process designs. Such materials may become more cost-effective if they can tap into recent additive, gradient, and roll-to-roll manufacturing advances that lower production costs.

Resilient:

Current municipal water infrastructure relies on aging centralized water treatment, storage, and distribution systems that are energy-intensive, corroding, leaking, and costly to replace. In addition, key U.S. industries face complex logistics constraints in storing water and residuals and transporting them between remote locations, often via truck. While distributed treatment can reduce conveyance issues, these systems must function under conditions in which water quality, temperature, or water residence times undergo large fluctuations. Resilient water supply networks, adaptable treatment processes, and robust materials are needed if we are to realize the benefits of distributed, fit-for-purpose desalination systems.

Early-stage applied research to advance resilient water treatment and distribution systems will span molecular-scale to systems-scale research. Robust optimization techniques for materials and process design are needed to ensure compatibility with a wide variety of solution chemistries and accelerated materials. Aging platforms coupled with state-of-the-art in operando characterization tools can be used to test materials that resist corrosion and fouling in distributed desalination and conveyance systems. Step changes in treatment system reliability and resiliency can be enabled by the design of optimal sensor networks and analytics approaches that inform adaptive control techniques and allow processes to robustly operate over a wide range of feedwater quality levels. At the distribution system level, computationally efficient multiscale modeling and multi-objective optimization platforms are needed for water network designs that maximize reuse and minimize cost.

Intensified:

Current thermally driven brine management technologies are energy intensive, complex, and poorly suited for the modest flows of small-scale desalination systems. At the same time, there is an ongoing revolution in unconventional oil and gas development; expanded exploitation of inland brackish water resources; new regulatory requirements for effluent discharge at power generation, mining, and manufacturing facilities; and planning for future carbon storage in saline reservoirs, which are creating new demands for more efficient brine and concentrate management. Innovative technologies for brine concentration and crystallization would eliminate the need for brine conveyance, reduce dependence on finite injection well capacity, enhance water recovery from nontraditional sources, and lower energy intensity and cost of desalination facilities.

Early-stage applied research can focus on developing process alternatives to traditional, thermally driven brine management technologies, and materials innovations to improve the efficiency of existing processes. To concentrate brines between 75,000 and 200,000 mg/L TDS, there is a need for materials and manufacturing platforms that extend the pressure tolerance of RO membrane modules, process configurations that combine multiple driving forces, and systems that couple brine treatment with metals recovery and chemical synthesis. For higher-salinity brines treated by thermal processes, topology optimization and precision manufacturing methods can be paired to improve heat transfer in thermal processes, enabling efficient system integration with waste heat sources. Models of nucleation and crystalline phase growth that open new avenues for controlling scaling and promoting crystallization in energy-saving, small-scale units are also needed.

Modular:

Current seawater desalination systems use energy-efficient, and mass-manufactured RO membrane systems. When these same types of modules are used to desalinate organic and mineral-rich waters with higher fouling and scaling potential, energy consumption and maintenance costs increase. Furthermore, commercially available membranes are unable to separate ions of the same valence or remove low-molecular-weight neutral compounds from water. Finally, membranes are manufactured via poorly understood, highly nonequilibrium processes that limit property control and customization for specific feedwater compositions. Innovations in both membrane materials and manufacturing processes could vastly expand the range of water chemistries over which modular membrane systems are cost-competitive and potentially eliminate the need for intensive pre-treatment and post-treatment (e.g., multi-stage RO for boron removal). Further modularizing pre-treatment and post-treatment processes would increase reliability and reduce the costs of operating moderate-scale, distributed desalination systems.

Early-stage research is needed to advance the next generation of membrane materials and processes. These advances include the development of techniques that enable control of membrane properties during manufacturing, in operando materials characterization techniques that facilitate understanding of membrane performance under varying solute conditions, and manufacturing innovations that enable the scalable deployment of novel membrane materials in cost-competitive modules. It will also require process optimization models that explore the full range of process configurations, operating schemas, and treatment train configurations for minimizing fouling and scaling while maximizing recovery. Advances in computational methods for materials design and selection, modeling platforms for accurately describing coupled mass transport and reactivity in porous media, materials processing approaches (e.g., additive, roll-to-roll, spray coating), and multiscale simulation tools for process optimization are needed to enable the necessary improvements in membrane flexibility and performance.

Electrified:

Current water treatment trains use large volumes of commodity chemicals that are high in embedded energy, expensive, and difficult to implement in distributed treatment systems. These processes are typically designed for steady-state operation, reducing their ability to ramp in response to fluctuations in water quality and the price of electricity. Replacing chemically intensive, steady-state processes with electrified and intermittently operated processes will reduce operating costs and provide a means of exploiting renewable energy resources and temporal variations in the cost of electricity. It will also promote small-scale, distributed water treatment by reducing the need for chemical supply and minimizing the complexity of water desalination operations.

Early-stage research to extend material and component longevity during intermittent process operation will reduce wear associated with rapid or frequent ramping. Process simulation models can be used to identify low-wear component designs and advanced manufacturing processes to realize them cost-effectively. To expand the number of electrified processes that might be ramped, there is a need to develop high-fidelity simulation models of electrochemical processes that include chemical, flow, faradaic, and non-faradaic effects in a variety of complex fluid compositions. These models can be applied in pre-treatment, treatment, and post-treatment processes to design materials and processes that improve performance consistency, eliminate chemical use, or generate chemicals (e.g., caustic, chlorine) in situ. There is a need for in situ methods for characterizing poorly understood process conditions, such as precipitation kinetics, flocculation dynamics, and ion distribution in boundary layers. Maximizing the potential of electrified treatment processes will also require the development of integrated energy-water economic models to quantify the synergies between these two systems as well as system improvements in stability, reliability, and flexibility.

Appendix C: DOE Water Hub Development Background

DOE's Water Security Grand Challenge is a White House-initiated, DOE-led framework to advance transformational technology and innovation to meet the needs for safe and affordable water and help secure the nation's water supplies. Using a coordinated suite of prizes, competitions, early-stage research and development funding opportunities, critical partnerships, and other programs, the Water Security Grand Challenge sets the following goals for the United States to reach by 2030:[120]

- Launch desalination technologies that deliver cost-competitive clean water
- Transform the energy sector's produced water from a waste to a resource
- Achieve near-zero water impact for new thermoelectric power plants and significantly lower freshwater use intensity within the existing fleet
- Double resource recovery from municipal wastewater
- Develop small, modular energy-water systems for urban, rural, tribal, national security, and disaster response settings

The Energy-Water Desalination Hub, or NAWI Hub, will support the goals of the Water Security Grand Challenge.[121] Specifically, the NAWI Hub will:

- Address water security needs for a broad range of stakeholders, including utilities, oil and gas production, manufacturing, agriculture, and states and municipalities;
- Focus on early-stage R&D for energy-efficient and low-cost desalination technologies, including manufacturing challenges, for treating nontraditional water sources for beneficial end-use applications and achieve the goal of pipe-parity;
- Establish a significant, consistent, and multidisciplinary effort (i.e., using a broad set of engineering and scientific disciplines) to identify water treatment challenges and opportunities;
- Enhance the economic, environmental, and energy security of the United States; and
- Lead to fundamental new knowledge to drive energy-efficient and low-cost technological innovations to the point that industry will further develop and enable U.S. manufacturing of these new technologies to be deployed into the global marketplace.

DOE is expected to support NAWI with $110 million in funding over five years, with an additional $34 million in cost-share contributions from public and private stakeholders.

Appendix D: Roadmap Teams

Cartography Team

Each PRIMA end-use sector was led by a small group of academic (3–4 people). This group is collectively known as the cartography team (total of 10 researchers) and identified challenges and research needs associated with the recovery and reuse of nontraditional waters. They are the primary authors for their end-use sector roadmap. The Master and Deputy Master cartographers synthesized high-value, crosscutting themes across multiple end-use water roadmaps for the Master roadmap.

Core NAWI Teams

Each PRIMA end-use cartography team was supported by a small group of subject matter experts (3–5 people) from industry, national labs, government, and academia; they contributed regularly to NAWI's water user roadmapping effort to help identify and establish future research priorities for NAWI, focusing particularly on the needs and opportunities of one assigned group of water users (municipal, agriculture, power, industrial, or resource extraction). Their activities included:

1. **Participating in roadmapping meetings:** Meeting twice a month to provide input, shape the direction of roadmapping activities, discuss recent developments, and review materials.
2. **Identifying key experts and practitioners to participate in roadmapping activities:** Recommending participants for interviews, workshops, and/or surveys as part of the roadmapping data collection process to obtain a wide array of industry insights.
3. **Providing insight on current and future needs for water treatment technologies:** Participating in meetings, (virtual and/or in-person) workshops, interviews, and/or surveys.
4. **Providing insights into quantitative data to support industry analysis, when possible:** Connecting NAWI researchers to sources of data that would facilitate baseline assessments.

Broader Teams

Each end-use cartography team was supported by a broader, more diverse group of subject matter experts (10–20 people); they contributed periodically to NAWI's water user roadmapping effort to help identify and establish future research priorities for NAWI, focusing particularly on the needs and opportunities of one assigned group of water users (municipal, agricultural irrigation, power, industrial, or resource extraction). Their activities included:

1. **Participating in roadmapping meetings:** Meeting monthly to provide input, shape direction of roadmapping activities, discuss recent developments, and review materials.
2. **Identifying other key experts and practitioners to participate in roadmapping activities:** Contributing to discussion of identifying participants for interviews, workshops, and/or surveys as part of the roadmapping data collection process.
3. **Providing insights on current and future needs for water treatment technologies:** Participating in meetings, (virtual and/or in-person) workshops, interviews, and/or surveys.
4. **Providing insights into quantitative data to support industry analysis, when possible:** Connecting NAWI researchers to sources of data that would facilitate baseline assessments.

Appendix E: Development of the NAWI Resource Extraction Sector Technology Roadmap

Data Collection Process

The NAWI End-Use Sector Roadmaps were developed using a multi-step process coordinated by the NAWI end-use cartography teams. The key component of this process was a two-day virtual Technology Roadmapping Workshop—held in August 2020 and facilitated by Nexight Group—that included participants from industry, academia, national laboratories, and associations. Surveys and interviews with water and industry professionals were conducted in the months leading up to the workshop. Outputs from the surveys and interviews—including a comprehensive list of challenges and potential research solutions—were used to provide direction to the workshop sessions.

The result of these workshops was a refined list of industry-specific challenges and associated research solutions for each area of A-PRIME. These solutions were coupled with ongoing inputs from surveys, subject matter expert interviews and discussions, and other relevant documents to create the recommended list of research priorities in the End-Use Roadmaps. At several points during the roadmapping process, workshop participants, NAWI technical teams, and the DOE Advanced Manufacturing Office (AMO) reviewed the preliminary findings, intermediate, and final roadmap drafts prepared by NAWI and Nexight to further refine the content.

Activities Prior to the Technology Roadmapping Workshop

Online Survey

The NAWI teams and Nexight Group distributed an online survey to: 1) share a general understanding of water use and critical needs by sector; 2) identify critical barriers for nontraditional water treatment and reuse; and 3) identify early-stage applied research needs and opportunities (TRL 2–4) that will improve access and performance of nontraditional water desalination and treatment processes.

Between June and August 2020, the survey was sent to a diverse group of industry stakeholders covering all five of the end-use sectors. In the survey, participants were asked to provide their assessment and notional solutions to address these challenges. Additional optional questions were asked to gather targeted input based on the participant's sector (i.e., academia, industry, or government). The optional questions touched on the following areas: 1) decision criteria for using nontraditional water sources, 2) future water technology trends, 3) treatment system operations/design, and 4) regulatory conditions. The challenges and notional solutions identified from the survey findings were discussed and scrutinized during the technical workshops. Other findings were supplied to NAWI to further inform technical strategy and operations.

Subject Matter Expert Interviews

From June to August 2020, Nexight Group conducted more than 95 one-hour technical interviews with subject matter experts covering each of the 5 end-use sectors. These individuals were recommended by NAWI team members. These interviews were designed to engage stakeholders to 1) establish a baseline understanding of water use and minimum water quality for industry or business needs, 2) identify critical barriers for nontraditional water treatment and reuse, and 3) identify early-stage applied research needs that will improve access to and performance of nontraditional water desalination and treatment processes (e.g., by lowering the cost, decreasing energy use, increasing reliability, minimizing environmental impacts, maximizing resource recovery, removing contaminants, etc.). The challenges and notional solutions identified from the interview findings were discussed and scrutinized during the technical workshops. Other findings were supplied to NAWI to further inform technical strategy and operations.

Core and Broader Team Brainstorming

The end-use sector broader teams were engaged in an online brainstorming activity. They identified critical barriers for nontraditional water treatment and reuse, and the research needs that will improve access to and performance of nontraditional water desalination and treatment processes. The challenges and notional solutions identified from these brainstorming sessions were discussed and scrutinized during the technical workshops. Other findings were supplied to NAWI to further inform technical strategy and operations.

Technology Roadmapping Workshop

Workshop Purpose

The NAWI roadmapping workshop was designed to identify potential research topics needed to address industry's water challenges and achieve the NAWI vision and pipe-parity goals. Each of the five NAWI end-use sectors had its own two-part, virtual roadmap workshop. Each workshop was built on the input collected from nearly 300 NAWI stakeholders via surveys, interviews, and working meetings conducted from June to October 2020.

Workshop Format

During the weeks of August 10 and 17, 2020, Nexight Group conducted 2 two-hour virtual sessions (using Zoom Video Communications) of up to 25 participants, with a homework assignment in between sessions. A minimum of 24 hours between the virtual sessions was provided to allow the completion of homework assignments. Prior to the workshop, participants reviewed a preliminary set of findings from previously collected input.

During the first of the two workshops, participants shared ideas through facilitated sessions. Structured brainstorming and critical analysis were used to refine the proposed list of NAWI research topics and identify additional research topics. After the first workshop for each end-use, participants' homework consisted of ranking all potential research topics by a) probability of technical success, b) potential impact on NAWI goals, and c) timeframe to completion. These rankings were reviewed during the second workshop, and the research priorities were refined further based on feedback. After the second workshop, the raw data from the session was analyzed by Nexight and the cartography teams to arrive at a preliminary list of TRL 2–4 research priorities for each end-use sector. These topics were further reviewed, amended, and augmented by industry and expert engagement before being finalized in the five roadmap documents.

Workshop Outputs

The workshops were designed to deliver specific outputs necessary for the NAWI roadmapping process, including:

- Categorized sets of potential research topics for addressing water user challenges
- Ratings of each research topic in terms of probability of technical success and potential for impact on pipe-parity metrics
- Notional research timelines (near, mid, and long terms)

Preparation of the NAWI Technology Roadmaps

Research priorities in this roadmap are categorized under the six NAWI Challenge Areas (A-PRIME), which have been identified as critical to achieving a circular water economy. Using the information collected during the workshop and synthesized by cartography team, these preliminary findings were reviewed in September and October 2020 by the Core and Broader teams, NAWI Technical Teams, and DOE AMO staff. Concurrently, the Nexight Group and cartography teams compiled an initial draft (NAWI Internal Use Only) of the five roadmaps, which was reviewed by NAWI Technical Teams, Core and Broader Teams, and key DOE AMO staff in November and December 2020. Based on feedback from these sources, additional roadmap versions were developed and iterated on. A final public draft of the five NAWI roadmaps was then published.

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