NAWI

National Alliance for Water Innovation

POWER SECTOR

TECHNOLOGY ROADMAP

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CONTENTS

1. EXECUTIVE SUMMARY 2

1.1. Introduction to NAWI and the NAWI Roadmap 2
1.2. Water User Sector Overview 4
1.3. Water Treatment and Management Challenges 4
1.4. Research Priorities 6
1.5. Next Steps 10
1.6. Appendices 11

2. INTRODUCTION 12

2.1. Growing Challenges with Water 12
2.2. Establishing an Energy-Water Desalination Hub 13
2.3. Pipe Parity and Baseline Definitions 14
2.4. Nontraditional Waters of Interest 16
2.5. A-PRIME 19
2.6. Desalination Hub Topic Areas 21

3. POWER WATER USER SECTOR OVERVIEW 22

3.1. Background on the Power Sector and Water Utilization 23
3.2. Primary Uses of Water for Thermoelectric Power Generation 25
3.3. Current State and Power Industry Trends 27
3.4. Changes to Energy Sector Profile 28
3.5. Pipe Parity 30
3.6. Water Treatment and Management Strategies 31
3.7. Traditional and Nontraditional Sources of Water for Power Generation 36
3.8. Compounding Issues Affecting the Power Sector 42

4. TECHNICAL CHALLENGES 46

4.1. Technical Challenges 47
4.2. Non-Technical Challenges 50

5. RESEARCH PRIORITIES 52

5.1. **Autonomous**
Sensors and Adaptive Process Controls for Efficient, Resilient, and Secure Systems 54

5.2. **Precise**
Targeted Removal of Trace Solutes for Enhanced Water Recovery, Resource Valorization, and Regulatory Compliance 58

5.3. **Resilient**
Reliable Treatment and Distribution Systems that Adapt to Variable Water Quality and Are Robust to Corrosive Conditions 61

5.4. **Intensified**
Systems and Process Optimization to Maximize Brine Reuse, Improve Brine Concentration and Crystallization, and Manage Residuals 67

5.5. **Modular**
Materials, Manufacturing, and Operational Innovations to Expand the Range of Cost-competitive Treatment Components and Eliminate Intensive Pre/post-Treatment 71

5.6. **Electrified**
Electrifying Water Treatment Processes and Facilitating Clean Grid Integration 74

6. NEXT STEPS 80

Appendix A: Acronyms 82
Appendix B: NAWI A-PRIME Expanded Descriptions 85
Appendix C: DOE Water Hub Development Background 89
Appendix D: Roadmap Teams 90
Appendix E: Development of the NAWI Power Sector Technology Roadmap 92
Appendix F: Contributors 95
Appendix G: References 101

TABLE OF FIGURES

Figure 1 ... 17
Schematic of traditional and nontraditional sources of water, as defined by NAWI

Figure 2 ... 19
PRIMA and the industries covered in each area

Figure 3 ... 25
Simplified water flow path in an example thermoelectric power plant

Figure 4 ... 26
Key water-saving opportunities at a power facility

Figure 5 ... 27
Distribution and relative electricity production of U.S. power plants

Figure 6 ... 28
Net electricity generation by power source

Figure 7 ... 29
U.S. Power Sector evolution over time for the mid-case scenario

Figure 8 ... 31
NAWI Roadmapping Pipe Parity Scope

Figure 9 ... 32
Relationship of evaporation, blowdown, and makeup water in a cooling tower with cycles of concentration

Figure 10 ... 34
Brine concentrator at APS Redhawk Station

Figure 11 ... 36
Breakdown of percentage of facilities using 10 types of alternative water sources

Figure 12 ... 39
Municipal wastewater generation as a percentage of the potential water demand associated with new electricity generation forecast for 2025

Figure 13 ... 40
Palo Verde Nuclear Station, Arizona Public Service

Figure 14 ... 41
Water sources used for thermoelectric power production, 1950–2015

TABLE OF TABLES

Table 1 4
Synopsis of Technical and Non-technical Industry Challenges to Utilizing Nontraditional Water Sources for the Power Sector

Table 2 24
Power Plants' Freshwater Withdrawal and Consumption by Cooling System Type and Fuel Generation Category in the Conterminous United States

Table 3 34
Flow and Chemistry Characteristics of Plant Sources of Wastewater

POWER SECTOR
TECHNOLOGY ROADMAP

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.***

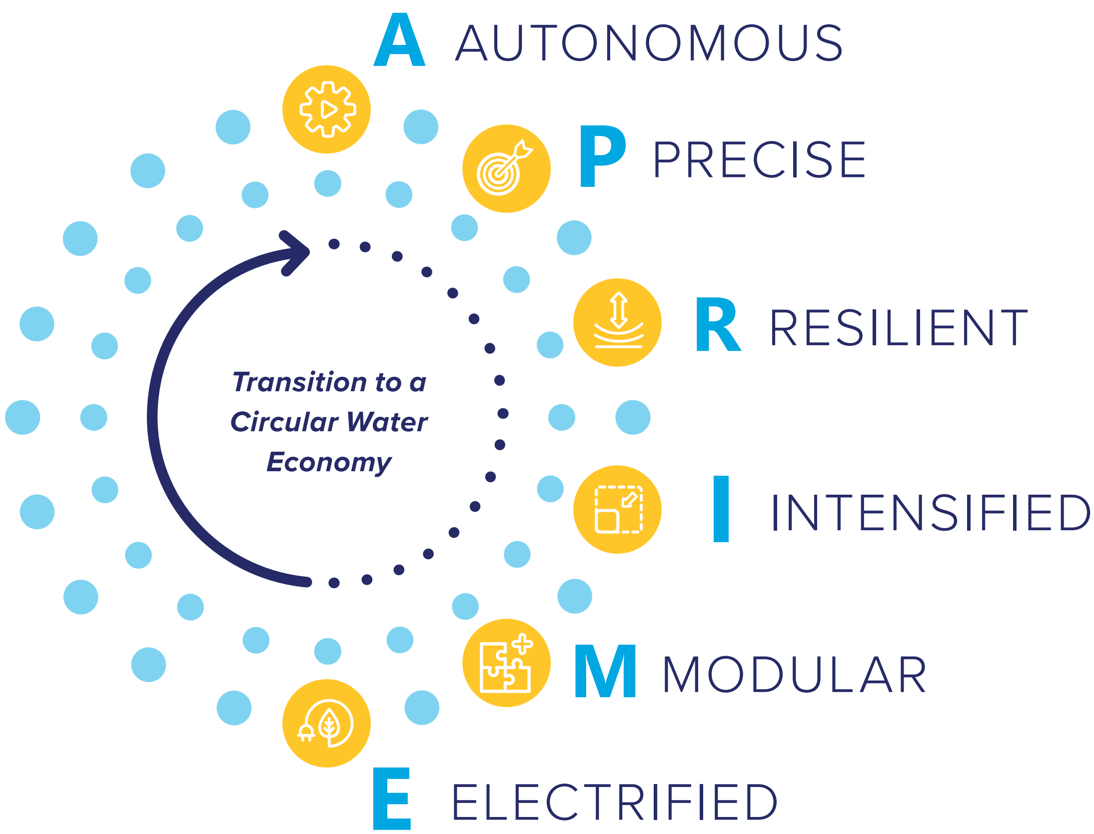
The nontraditional source waters of interest include brackish water; seawater; produced and extracted water; and power, mining, industrial, municipal, and agricultural waste waters. When these desalination and treatment technologies are fully developed and utilized, they will be able to contribute to the water needs of 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 **Power Sector** roadmap aims to advance desalination and treatment of nontraditional source waters for beneficial use in public water supplies 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 Power 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

Thermoelectric power generation (e.g., natural gas, coal, petroleum, nuclear) in the United States accounts for 41 percent of the country's water withdrawals, or 500 billion liters per day (130 billion gallons per day [Bgal/day]). Most of these water needs stem from cooling systems to transfer heat between streams. Many older thermoelectric power plants use once-through cooling where water passes through the main condensers in a single pass to remove waste heat.[1] There are also evaporative cooling schemes that are consumptive but require far fewer water withdrawals than once-through cooling systems. Due to existing regulations in many areas (e.g., California), facilities with once-through cooling schemes are now being eliminated.[2,3] Renewable energy sources use significantly less water. The primary source of water for power plants is fresh surface water, though some plants take advantage of local opportunities, like municipal drinking water, municipal wastewater, groundwater, seawater, and recycling water onsite.

Power plants taking advantage of nontraditional source waters are motivated by water stress and accessible, cost-competitive local alternatives, but the majority of power facilities are purposefully located near surface water sources, both fresh and saline. However, as competition for large volumes of water increases, nontraditional source waters can play a larger role in reducing regional water stress.

1.3 Water Treatment and Management Challenges

Table 1 identifies broad industry challenges that need to be addressed to enable the Power 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 levels (TRLs) Level 2–4 technologies that are crosscutting across the PRIMA areas and that address some technical limitations discussed below, and welcomes complementary efforts by other research organizations.

Table 1. Synopsis of Technical and Non-Technical Industry Challenges to Utilizing Nontraditional Water Sources for the Power Sector

TECHNICAL

Treatment Design

- Removing elevated levels of organics, inorganics, biological organisms, and selective ions from nontraditional source waters requires rigorous treatment.
- Industry needs improved data analytics tools, robust sensors, and connected operations to design and manage efficient, cost-effective water treatment trains.

TECHNICAL

Constituent Removal

- More stringent discharge regulations increase the complexities of water treatment processes and the pressure on monitoring technologies to verify removal.
- More diverse and targeted treatment is required to maintain compliance with environmental discharge regulations and to facilitate increases in cycles of concentration.

System Enhancement

- Most research has focused on creating new pathways for reverse osmosis (RO) instead of improving the durability of existing, non-membrane treatment.
- As a primary method for water treatment, RO membranes are still costly, are susceptible to fouling and damage, and lack the ability to treat certain constituents and challenging feed streams.
- Many facilities are unfamiliar with designing treatment trains for nontraditional water sources, specifically those with challenging constituents.
- As operations grow to include variable renewable energy sources, flexible operations can conflict with the existing steady state designs of water treatment. Unsteady operation is more important for renewable power and for peaking plants (typically gas) than for baseload power.

Waste and Nutrient Management

- Existing methods for removing nutrients from blowdown water are expensive to install in existing power plants.
- Zero-liquid discharge (ZLD) systems are cost prohibitive and require a top-to-bottom approach to implement correctly.

NON-TECHNICAL

- **Cost**: The costs of retrofitting a power plant to accommodate nontraditional source waters can be prohibitive for electricity providers.
- **Liability and Risk**: Power plants must consider risks associated with system shutdowns, transient operation, and power sector changes that could impede operations and impact customers.
- **Environmental**: In addition to leaks and pollution, power facilities must consider decreased quality of surface and ground waters and decreased supply caused by climate change when evaluating nontraditional water source availability.
- **Workforce and Training**: Power facilities must continue to train and build expertise in their staff, as advanced water treatment trains are complex to operate and maintain.
- **Regulations**: Power plants are facing more stringent regulations that limit a facility's access to traditional and nontraditional water sources as well as their ability to discharge facility waste streams.

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 Power 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. At the end of this summary of topics, a short discussion on the benefits of new technoeconomic analysis (TEA) and LCA (life cycle analysis) research is also provided.

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

- **Develop sensors and sensor groups for bulk assessments of diverse water quality parameters that can indicate organic, inorganic, and biological fouling propensity, surface corrosion, and water quality violations.** The transition from traditional water to nontraditional water use means that power plants must contend with higher loads of organics, inorganic ions, and inconsistency of the water quality in the nontraditional supply. More advanced sensors could rapidly identify the constituents in the inflow water and allow facilities to strategically adjust treatment strategies. Affordable, disposable sensors and ex situ sensors that do not need inline installation, maintenance, and calibration would reduce the operating expenses (OPEX) of treatment facilities.

- **Develop algorithms to integrate sensor data with dynamic system operation and control.** There is a significant gap in connecting water quality monitoring results with the instantaneous and dynamic operation of water treatment processes; new software could bridge this gap for rapid treatment process control. The creation of digital twins of the water treatment process would enable process optimization for cost reduction through simulations. Transitioning from human-operated systems to artificial intelligence-controlled treatment plants can also translate into savings in personnel time and energy through more efficient operation.

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 novel adsorbents and absorbents that integrate physiochemical and biological processes with regenerative capabilities for efficient and enhanced removal of contaminants.** Certain solutes are more challenging to the power industry (e.g., silica, chloride, fluoride, barium, and nitrate) because of their impacts on fouling, scaling, and corrosion. They reduce the power plant water efficiency and limit the ability to achieve higher cycles of water use for cooling. To overcome these challenges, researchers must investigate new materials with improved physiochemical properties and engineering processes to selectively remove these constituents, improve material lifespan, and reduce fouling and scaling.

- **Create effective methods for purification and extraction of valuable compounds in power plant discharge water.** Some constituents in power plant water—such as rare earth elements, lithium, and barium—have the potential to be transformed into valuable products through precision separation technologies that can effectively recover and purify valuable solutes.

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

- **Design of materials and treatment components that can maintain integrity throughout periods of operation in unsteady regimes.** Water treatment systems supporting power plant operations must be responsive to power changes, variable operation, and shutdowns. Areas of research that could improve resiliency and reliability of the power industry's water treatment systems include materials and treatment components to address unsteady conditions that exist during unexpected power changes and system adjustments.

- **Design processes that can be preserved or maintained during pauses in operation.** Unscheduled shutdowns at a power facility—as a result of unanticipated environmental factors or equipment/operational failures—can increase corrosion rates and encourage biofilm growth, both of which can reduce start-up efficiency. Research pathways such as processes that can withstand scheduled and unscheduled pauses, membrane preservation, and biological water treatment microbial preservation are key to weathering fluctuating operations.

- **Design pre-treatment and desalination processes that can tolerate water quality variability and provide reliable treatment.** Both pre-treatment and desalination processes must be resilient to water quality changes. The performance of the RO process is affected by the efficacy of pre-treatment processes designed to limit fouling of the RO membrane. Membrane materials, alternative oxidation, and disinfection processes that offer better resistance to fouling and the development of membranes that exhibit a greater ability to withstand more physically or chemically intense cleaning methods will improve system longevity.

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

- **Study and apply chemical kinetics for complex solutions.** In the past decade, the Environmental Protection Agency (EPA) issued its most stringent effluent discharge regulations for the Steam Electric Power Generating Sector, motivating the power industry to begin implementing ZLD technology. A key first step in achieving ZLD is to comprehensively characterize brine streams, which can vary greatly.
- **Modify existing processes and develop integrated or hybrid processes to improve ZLD systems.** The main challenges in designing and operating ZLD systems are their high energy and operational costs, especially with increasingly complex brine streams. In order to reduce these costs, research is needed to modify existing processes and develop new integrated/hybrid processes (e.g., thermo- or electro-catalytic processes, combined filtration and catalysis).
- **Integrate with sensor/control systems and whole-plant operations.** ZLD operations are labor intensive, and they impact how an entire plant operates. In order to implement them, a facility must modify every element of its production process. Resilient sensor/control systems that can ensure reliable operations with less human intervention are required. Future research must address the challenges of treating brine streams while also optimizing the rest of the operation.

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. Specific research areas include:

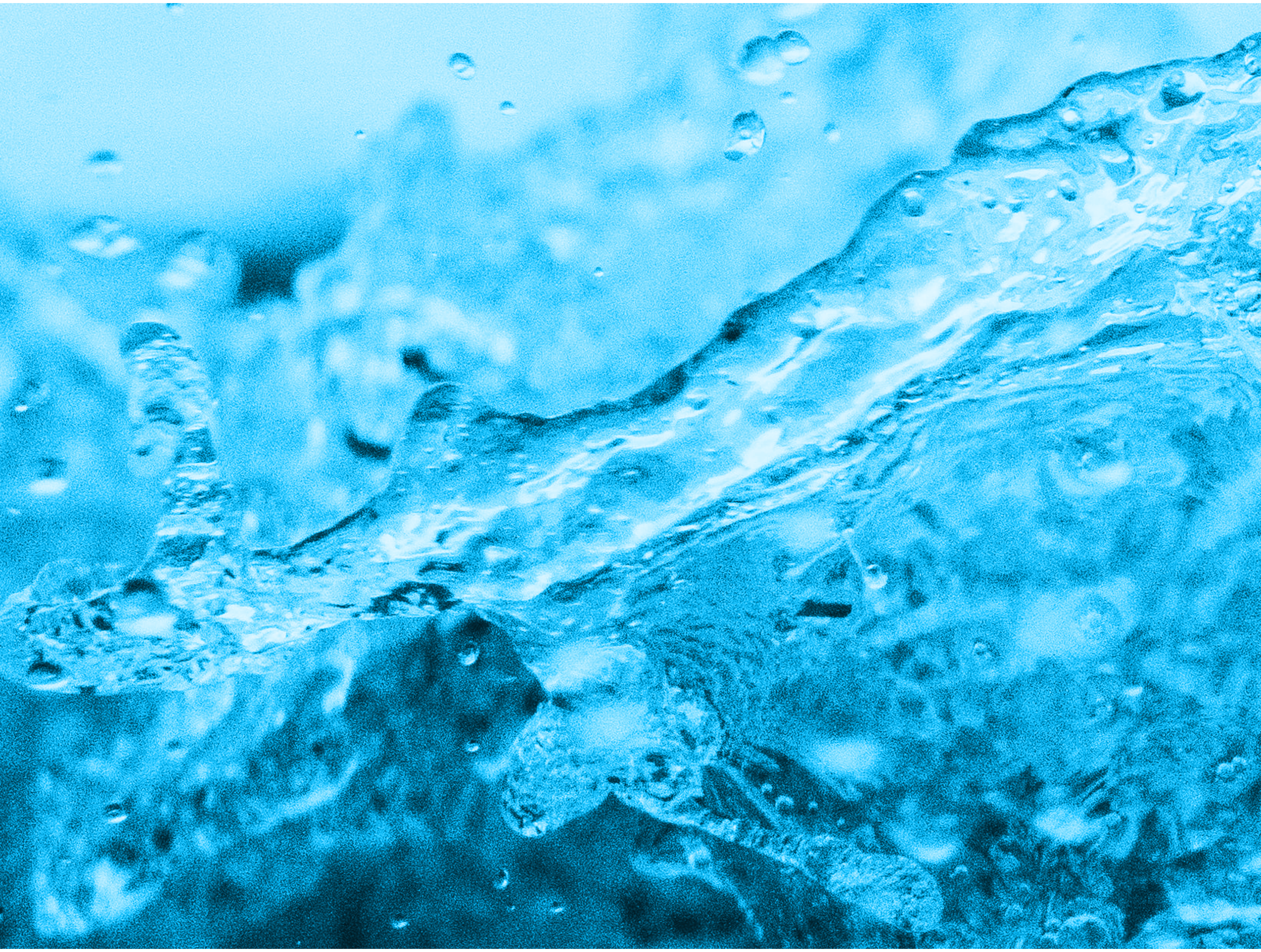
- **Develop flexible and reliable water treatment systems built on modular components to address unsteady operation, reliability, and reactor-in-series needs at power plants.** Implementing modular systems would increase the flexibility of power plants to coincide treatment with price fluctuations throughout the day. Replacing singular treatment trains with multiple processes in parallel could also increase operation flexibility and reliability. If valuable compounds or hard-to treat compounds are identified in power plant effluents, modular systems can also be used for extraction and removal.
- **Advance dual-function membrane manufacturing approaches that enable their cost-effective production at scale.** For treatment processes at power plants that involve membranes, there are opportunities to develop dual-function membranes that combat fouling and biofouling provided that these membranes can be manufactured in a cost-effective manner at scale.

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 electrified processes and the scientific basis for these processes that can provide chemical-free removal of specific constituents.** The water streams in power facilities contain several constituents (e.g., selenium, arsenic, mercury, magnesium, calcium) that require chemically intensive methods to remove and generate large amounts of solid residuals. New types of electrified treatment processes may improve process performance, lead to the development of larger-scale systems, and replace chemically intensive treatment processes.
- **Lower the chemical intensity of water management at power plants through electrified approaches to disinfection and scale inhibition.** High doses of chemicals are used to reduce scaling, limit biological growth, and manage effluent water before it is disposed of. There are methods that can significantly reduce the amount of chemicals required in a treatment train, such as replacing chemical disinfectants with ultraviolet (UV) light or ozone. These technologies are advertised to the power industry, but uptake is slow because their underlying chemical and physical properties are not well understood.
- **Create new methods for producing water of sufficient quality for hydrogen production and enable hydrogen production directly from lower-quality water supplies.** In the transition to a hydrogen economy, water of sufficient quality and quantity will be required for hydrogen production through both electrolysis and steam methane reforming. As current processes stand, trace constituents in treated water can precipitate or deactivate the catalysts.

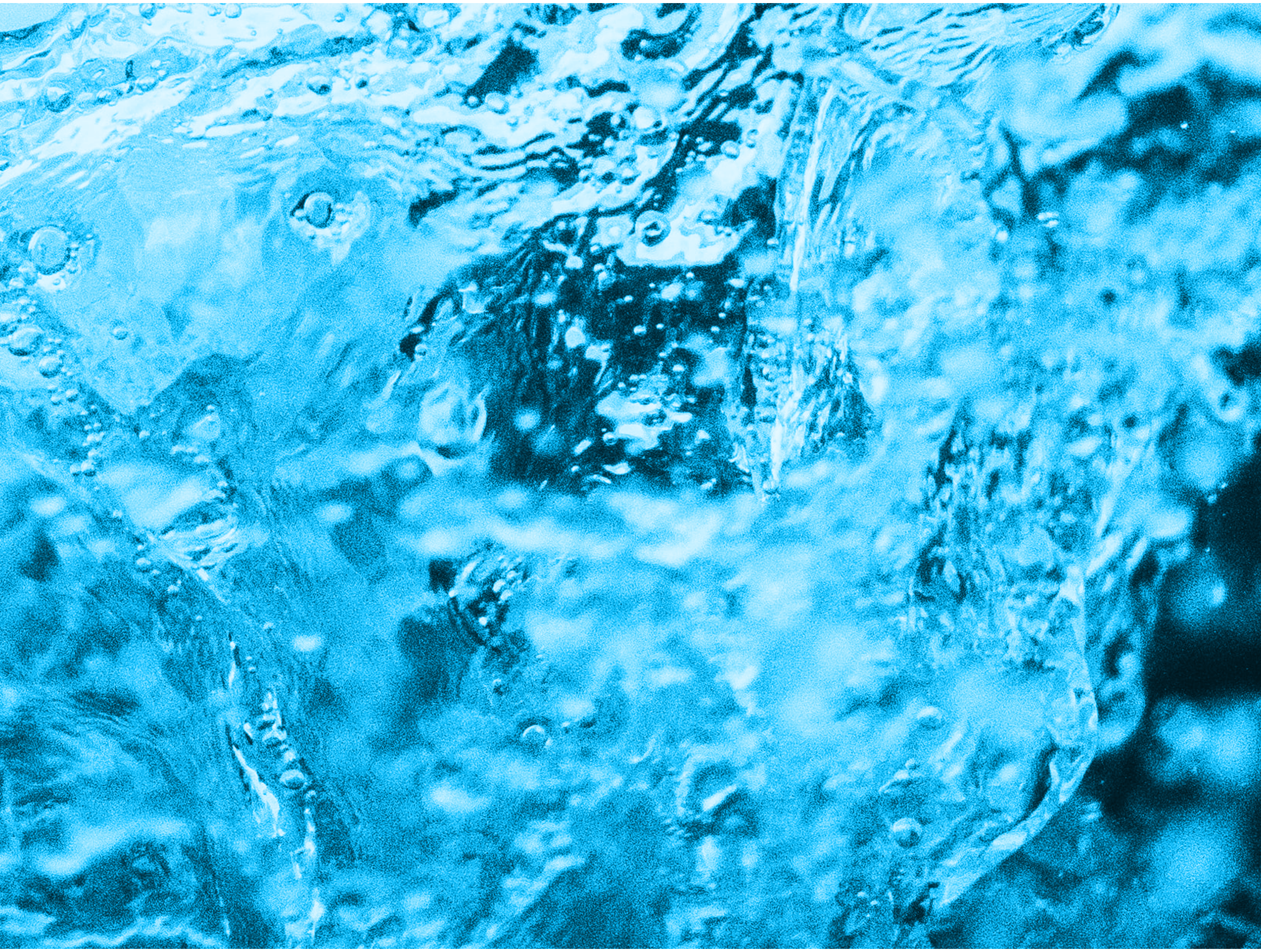
1.5. Next Steps

NAWI's comprehensive and dynamic roadmap for desalination and water treatment technologies for the Power 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.[4] Water managers in 40 states expect water shortages in some portion of their state in the next several years.[5] As water insecurity grows in severity across the United States and populations increase in regions with limited conventional sources, using 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.[6] 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[7]) to address water security issues in the United States. NAWI was funded to address this critical component of 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 Power 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, resource extraction, 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 as 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 hydrological 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 typical total dissolved solids (TDS) between 30,000 and 35,000 milligrams per liter (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 or 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

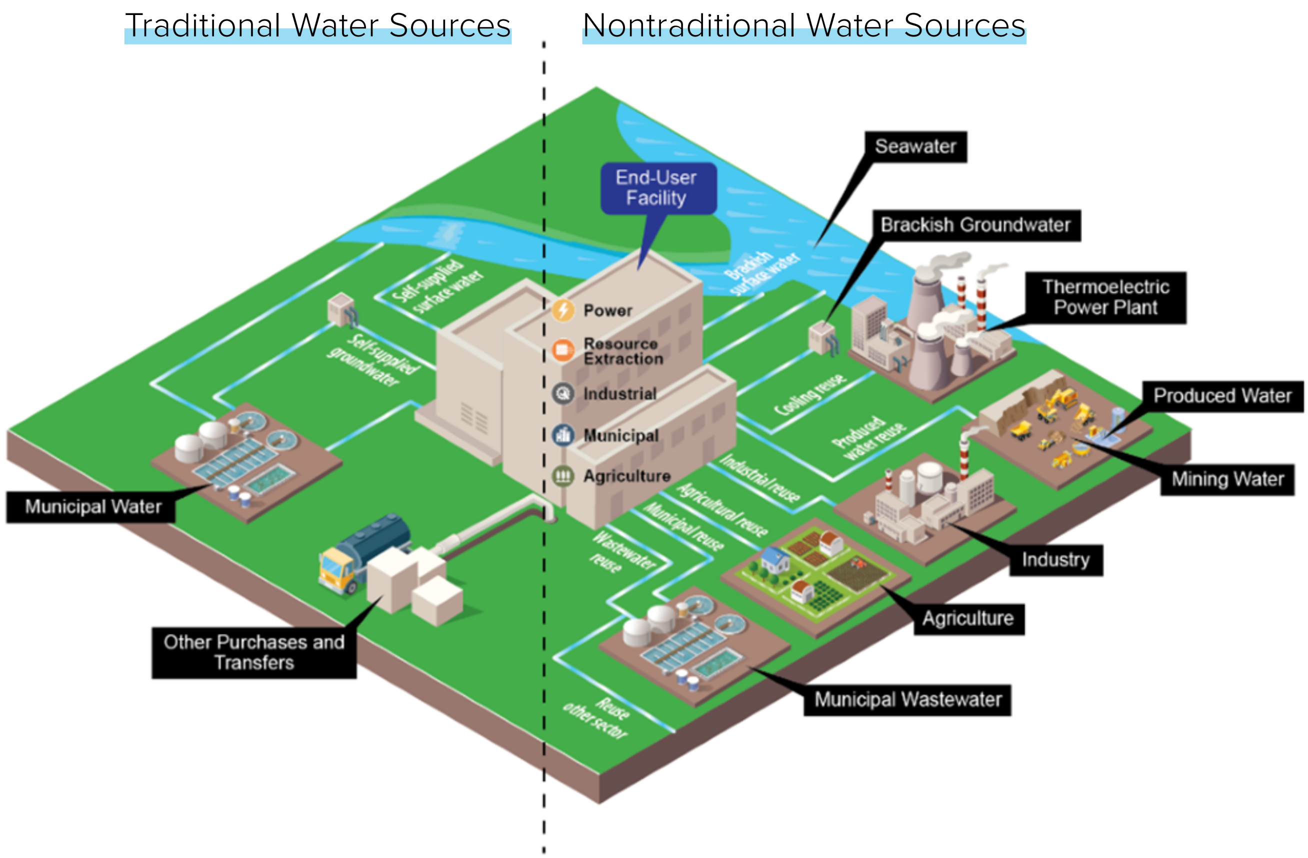


Figure 1. Schematic of traditional and nontraditional sources of waters, as defined by NAWI

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 water 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 (A-PRIME) technologies that support distributed and centralized treatment at a cost comparable to other inland and industrial sources.[8] 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.

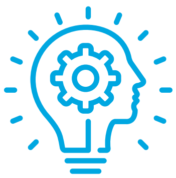
I The **Intensified** area focuses on innovative technologies and process intensification for brine concentration and crystallization and the management and valorization of residuals.

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.

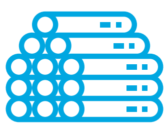
2.6. Desalination Hub Topic Areas

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:



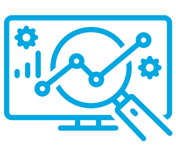
Process Innovation and Intensification R&D

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 are 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 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. POWER WATER USER SECTOR OVERVIEW

This overview of the Power 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.

An abundant supply of high-quality water is critical to the operations and economics of power production. Proximity to a water source, fuel, transmission access, and load demand are primary requirements for siting power plants. However, water has become an increasingly challenging siting issue as population and economic growth have increased competition for water resources. Power plants must compete with the demands of municipalities, agriculture, and industry for surface and groundwater supplies. Water costs are rising, and long-term trends suggest increasing environmental restrictions on the use and discharge of water by all users.[9]

3.1. Background on the Power Sector and Water Utilization

There is much published research defining the link between electricity generation and water on national and regional scales; these efforts have identified water as a limiting resource for power in some parts of the United States.[10,11] Water is used within power plants primarily as a working fluid in steam turbines and as a cooling fluid in condensers. The Power Sector's primary use of water is for cooling in thermoelectric generation.[12] The two primary types of cooling systems are recirculating cooling systems and surface-water cooling systems. Surface-water cooling systems include once-through cooling and recirculating cooling ponds.

Some facilities have chosen water conservation methods like dry cooling systems that use air instead of water to remove heat. Dry and hybrid cooling accounts for three percent of all U.S. thermoelectric generating capacity, and many of these facilities were built after 2000, with a projected increase as new plants are designed with dry cooling capabilities. The transition to renewable energy generation also reflects a net positive improvement toward the energy-water nexus. Water recycle loops are another strategy power plants are using to reduce their water withdrawals, with more than 61 percent of the thermoelectric energy capacity in the U.S. using some form of recirculating cooling.

Different types of cooling systems require different quantities of water for an equivalent amount of power production, both in terms of water withdrawals and water consumption.[13] The term "withdrawals" refers to the volume of water that is removed from a water source for power generation. In a report of water use by the U.S. Geological Survey (USGS) across all sectors, 41 percent of freshwater withdrawals are associated with the Power Sector, with 34 percent of all freshwater withdrawals primarily due to once-through cooling. The term "consumption" refers to water that is not returned to the immediate water source; it represents water that is typically lost to evaporation. Compared to water withdrawals, much less freshwater consumption (three to five percent) is associated with the Power Sector.[14]

All water use involves some amount of consumption, but for the Power Sector there is a significant distinction between consumption in once-through cooling systems and consumption in recirculating cooling systems. In once-through cooling systems, consumption within the power plant is nearly zero, although consumption does occur in the receiving water body because of raised temperatures (commonly referred to as "forced evaporation"). Forced evaporation represents a small fraction of withdrawal (approximately 400 to 1,100 liters per MWh, or less than 1 percent of withdrawal values).[15] In recirculating cooling systems, consumption often represents a significant fraction of withdrawal.

Since 1980, almost all new thermoelectric plants have been designed with wet recirculating towers; however, many once-through cooling plants remain in use, and as noted, their contribution to Power Sector water withdrawal is significant. Renewable sources of power generation (e.g., wind, solar photovoltaic (PV), and hydroelectric) do not use cooling water or only account for a relatively small fraction of the electricity supply (e.g., geothermal and concentrating solar power).[16] However, water may still be used for non-cooling purposes (e.g., for cleaning solar panels) or lost (e.g., via evaporation in surface water reservoirs).

Water withdrawal and consumption data by technology and cooling system type are summarized in Table 2. The estimated freshwater withdrawal totals approximately 530,000 million liters of water per day (MLD) (or 139,800 million gallons per day [MGD]). Of this, once-through cooling constitutes the vast majority at 96 percent. Recirculating cooling is responsible for withdrawals less than five percent. The total estimated consumption of water by thermoelectric plants (all plants in Table 2 except nuclear) is 14,876 MLD (3,930 MGD). Of this, all forms of recirculating cooling are associated with a consumption of 70 percent.

Table 2. Power Plants' Freshwater Withdrawal and Consumption by Cooling System Type and Fuel Generation Category in the Conterminous United States[17]

Fuel Type	Cooling Type	Number of Plants	Capacity (MW)	Withdrawals (MLD)	Consumption (MLD)
Biomass	R	95	8,018	348	163
	OF	5	439	1,681	4
Coal	R	278	202,752	10,380	6,405
	OF	188	136,809	278,477	2,082
	OC	20	21,987	46,000	526
Gas	R	823	361,221	6,348	2,850
	OF	39	27,832	34,606	273
	OC	14	12,773	17,265	307
Nuclear	R	14	23,591	1,749	969
	OF	14	21,102	50,255	352
	OC	17	33,491	77,272	803
Oil	R	84	12,408	837	49
	OF	6	5,238	4,024	83
			Once-through subtotal	509,516	4,429
			Recirculating subtotal	19,646	10,448
			Grand Total	529,200	14,877

R= all forms of recirculating cooling; OF= once-through cooling systems on rivers; and OC= once-through systems with cooling ponds

3.2. Primary Uses of Water for Thermoelectric Power Generation

Water requirements for thermoelectric power generation are influenced by a number of factors, but most significantly by the type of plant, fuel, and power plant cooling system. Secondary influences are the local climate, source of water, environmental regulations to which the plant is subject, and type of water management system employed.[18] Figure 3 is a simple illustration of some of the primary process flows and their respective paths.

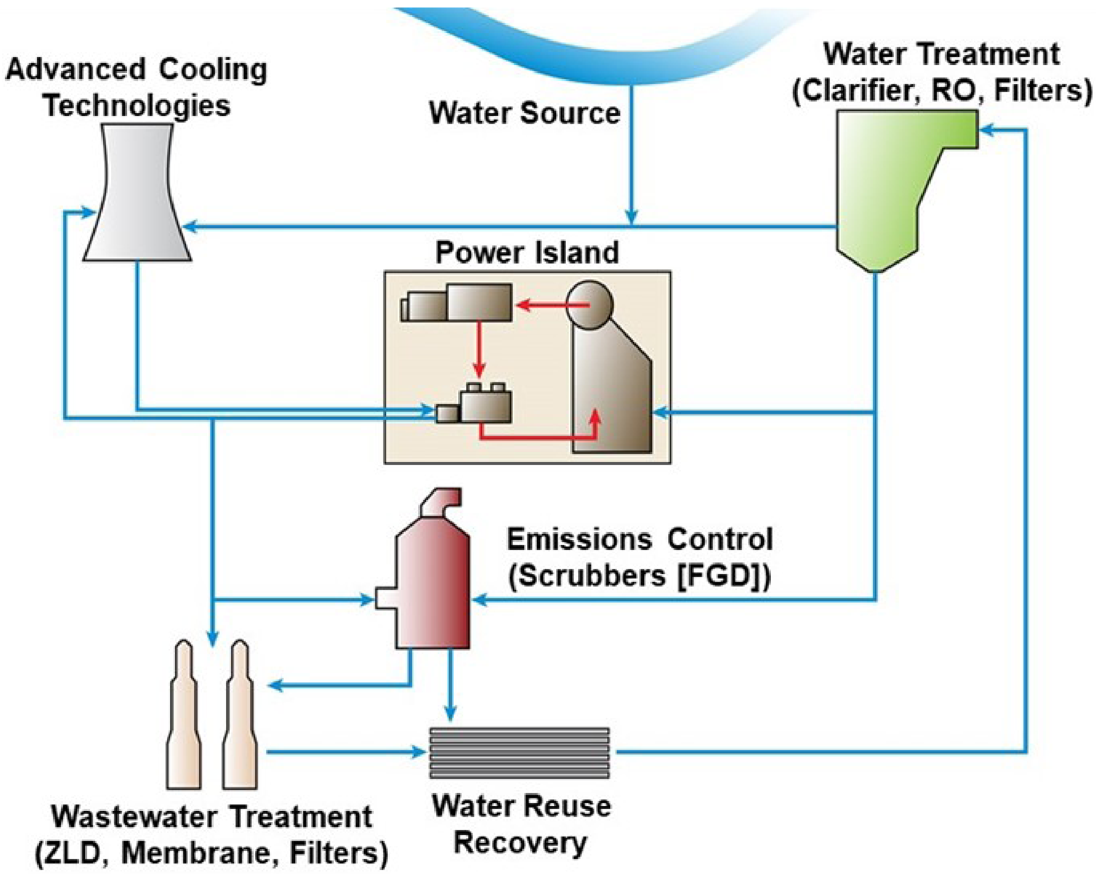


Figure 3. Simplified water flow path in an example thermoelectric power plant

FGD= Flue gas desulfurization. ZLD= Zero-liquid discharge

Figure courtesy of EPRI

In recirculating systems, water is withdrawn from an external source and circulated over multiple cycles within a cooling system to achieve heat transfer through evaporation; a significant fraction of the withdrawn water is evaporated. For a given quantity of power generated, recirculating systems require much smaller volumes of water to be withdrawn than once-through systems. In once-through systems, water is withdrawn, heat transfer occurs by conduction to the withdrawn water, and the water is released back to the environment at a warmer temperature. Once-through systems return essentially the same amount of water to the environment as they withdraw, except for the water lost to forced evaporation in the receiving water body.

Water is also used in many other systems at power plants in smaller quantities. At coal-fired power plants, water is used for dust suppression, ash handling, and FGD scrubbing. FGD is a process in which water is used for reagent slurries to manage environmental requirements. Almost all thermoelectric power plants employ additional cooling systems. Examples include: chilling systems for natural gas air intakes to optimize fuel combustion and maximize system efficiency, auxiliary cooling systems for key components such as lube oil or bearings, and emergency cooling systems. Service water is also essential for fire protection and water and wastewater treatment reagent feed systems that may have pre-treatment and post-treatment applications.

In the Power Sector, reclaiming and reusing water is a common practice, especially in locations where water availability, water cost, and discharge regulations are key issues. Power facilities commonly rely on opportunities to save water, reuse water, and minimize wastewater discharge. Figure 4 shows some of the water-saving opportunities at a power facility.

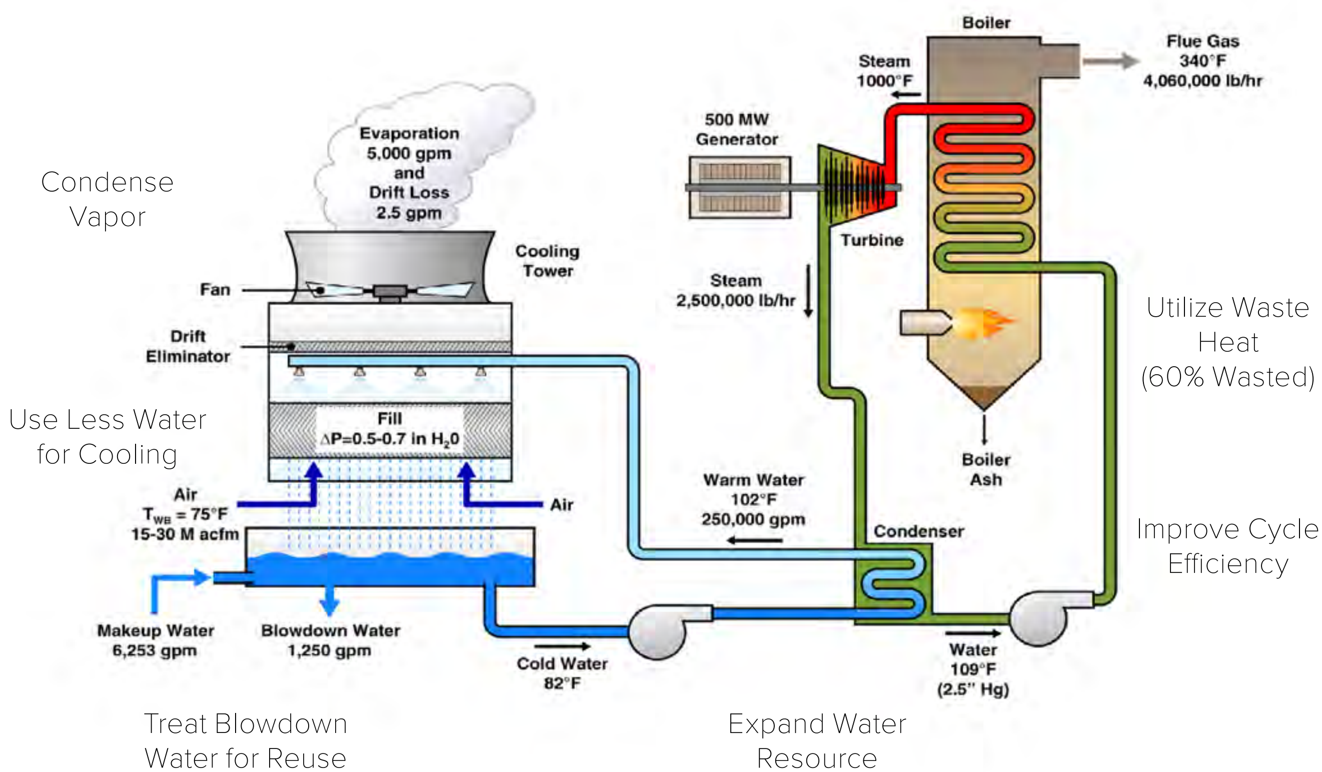


Figure 4. Key water-saving opportunities at a power facility

Figure courtesy of EPRI

3.3. Current State and Power Industry Trends

As noted, thermoelectric power plants require large amounts of water, and for this reason, water availability has played a key role in locating power plants. Power plant distribution in the United States (Figure 5) reflects this, with Eastern states accounting for 84 percent of total thermoelectric-power-water withdrawals due to the greater abundance of surface water sources. Specifically, Figure 5 is a visualization of the EPA's eGRID data system that includes all U.S. facilities and their electricity outputs. Coal production facilities are primarily clustered around the largest coal producing regions: Appalachian* (26 percent of all coal produced in the United States), Interior† (18 percent), and Western regions** (55 percent).[19] Natural gas (orange) is an important fuel source with 70 percent produced in Texas, Pennsylvania, Louisiana, Oklahoma, and Ohio.[20]

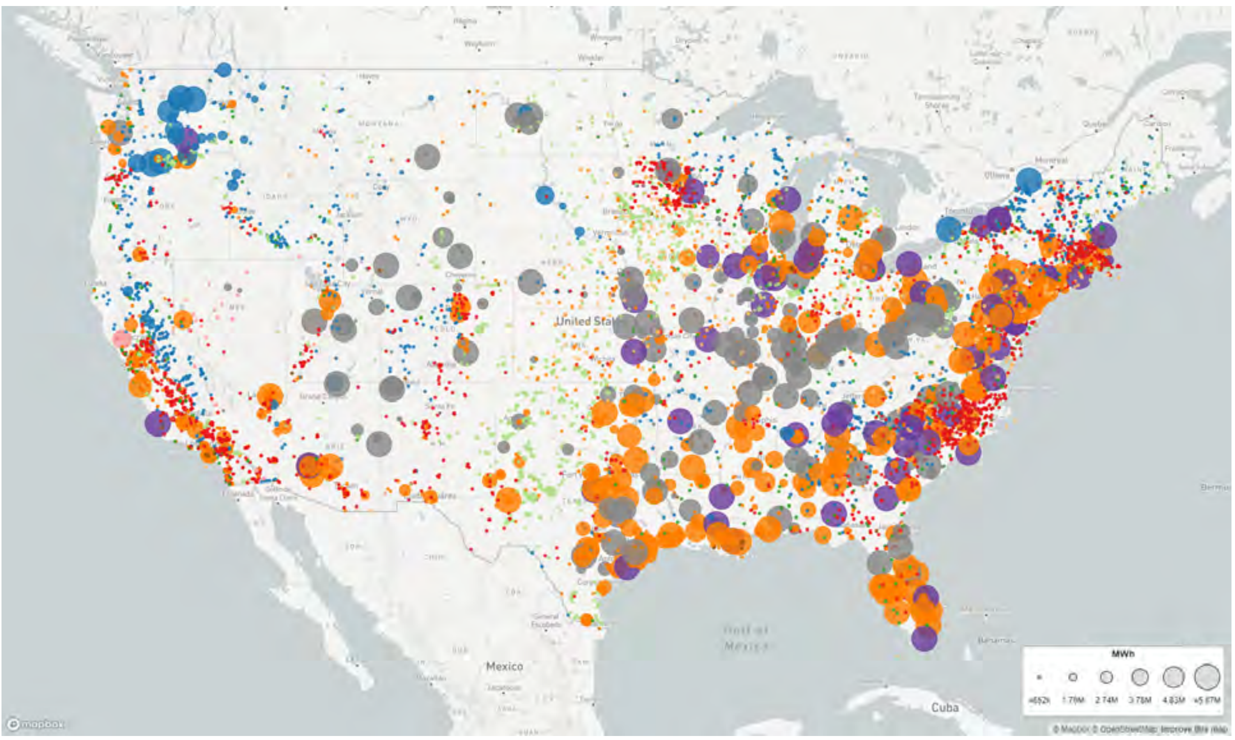


Figure 5. Distribution and relative electricity production of U.S. power plants

Coal = Gray; Natural gas = orange; Nuclear= Purple; Oil= Yellow; Hydroelectric= Blue; Biomass= Dark green; Wind= Light green; Solar= Red; Geothermal= Pink

Graphic courtesy of Daniel V. Schroeder, Weber State University

Nuclear energy is more geographically limited—in 2020, only 58 nuclear power plants were operational in 29 U.S. states, and only 12 nuclear power plants were located west of Louisiana. Long lead times for permitting, constructing, and managing nuclear plants, as well public opposition and high capital costs, have historically limited the growth of nuclear power.[21,22]

* Appalachian region includes Alabama, Eastern Kentucky, Maryland, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia.

† Interior region includes Arkansas, Illinois, Indiana, Kansas, Louisiana, Mississippi, Missouri, Oklahoma, Texas, and Western Kentucky.

** Western region includes Alaska, Arizona, Colorado, Montana, New Mexico, North Dakota, Utah, Washington, and Wyoming.

Renewable energy installations tend to be more dependent on public policy decisions and portfolio standards made regarding greenhouse gas emissions, as well as local, geographic, or meteorological conditions, than their fossil fuel or nuclear counterparts. Wind turbines may be preferentially located in places with high average windspeeds. But wind energy is also terrain-dependent, and wind turbines may be located on flat lands without wind barriers; this results in high concentrations of wind energy facilities in the central portion of the country (Iowa, Kansas, Oklahoma, and South Dakota). Hydroelectric power is slightly less widespread, with some high-capacity locations (e.g., the Grand Coulee Dam in Washington with a capacity of 6,809 MW) but only few states (e.g., Washington, Oregon, Vermont, and Idaho) having significant concentrations of hydropower infrastructure.[23]

3.4. Changes to Energy Sector Profile

Over the last 20 years, the U.S. Power Sector has experienced regulatory and political pressure to become more efficient and emit fewer greenhouse gases. Electricity generated in the United States has grown 8.3 percent in the last 20 years to 4,117 billion kWh in 2019. In the same time period, coal-based electricity shrunk by 54 percent.[24] Since 2000, natural gas-based electricity grew from 16 percent of the U.S. energy profile to 37 percent in 2018, and renewable energy doubled, from 9.4 to 19 percent.[25]

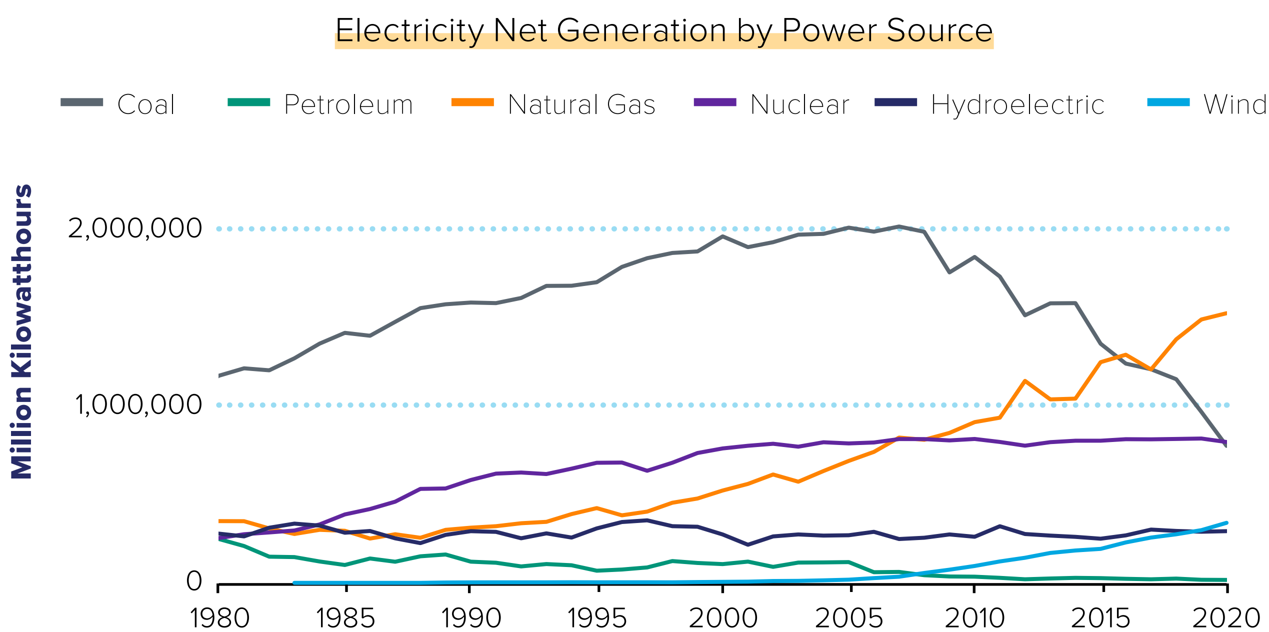


Figure 6. Net electricity generation by power source

Source: U.S. Energy Information Administration Annual Energy Review, 2019, Table 7.2b Electricity Net Generation by Fuel Source

Coal facilities across the country have, are closing down or transitioning to other fuels sources, have already done so, or may do so in the future, with very few new coal plants replacing them. While coal is a cheaper primary fuel source than natural gas ($2.06/MMBTU vs. $3.55/per metric million British Thermal Unit [MMBTU]), combined-cycle natural gas power plants have a higher thermal efficiency that can offset the cost of the fuel. Additionally, since 2005, natural gas generation has continued to increase due to sustained cost-competitive prices caused by fracking,[26,27] leading natural gas to surpass coal as the predominant electricity generation source in 2016.[28] Natural gas also has lower greenhouse gas emissions per MW and generates less air pollution than coal—in 2018 alone, the switch from coal to natural gas fuel for power reduced U.S. CO_2 emissions by 255 million tons.[29]

An illustration of the U.S. Power Sector generation portfolio and a mid-case (i.e., reference case used as a baseline scenario for comparison) future evolution over the next 30 years are seen in Figure 7, taken from The National Renewable Energy Laboratory (NREL) 2019 Standard Scenarios Report. This figure outlines the predicted shift in the energy profile over the next 30 years, which projects intensifying increases in natural gas and renewables and reduced usage of coal- and nuclear-based

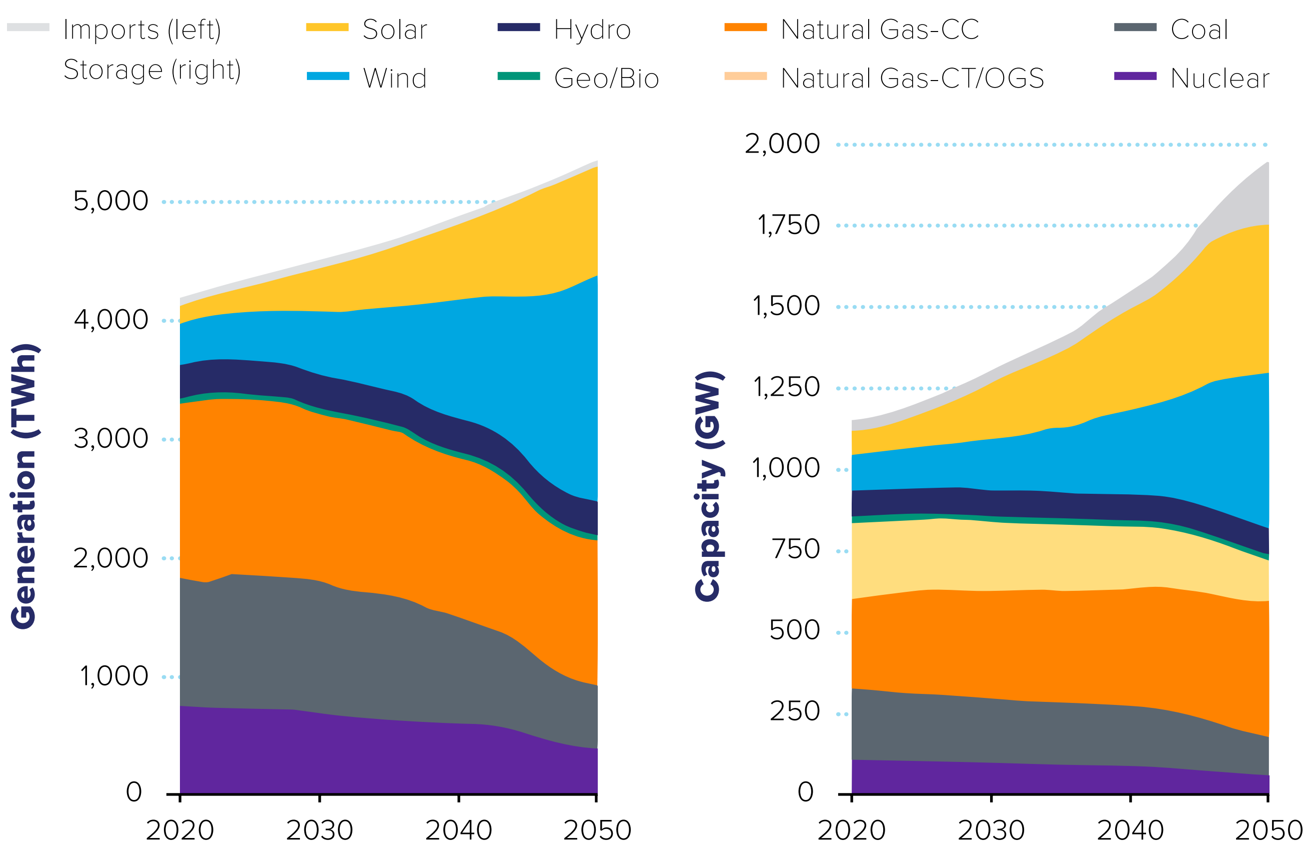


Figure 7. U.S. Power Sector evolution over time for the mid-case scenario

Source: NREL 2019 Standard Scenarios Report: A U.S. Electric Sector Outlook

Note: The light gray area represents imports from Canada in the left figure and storage capacity in the right figure. Storage generation is not shown because storage always has a negative net generation (due to losses). NG-CC is natural gas combined cycle, NG-CT is natural gas combustion turbine, OGS is oil-gas-steam, Geo/Bio is geothermal and biopower, TWh is terawatt-hours, and GW is gigawatts.

electricity generation. This transition in the national electricity generation portfolio for baseline scenarios predicts an 80 percent reduction in national water withdrawals and a 34 percent reduction in national water consumption for 2050 compared with 2010.[30]

Carbon intensity for the energy industry has also been in decline. Since 2007, energy-related Carbon dioxide (CO_2) emissions have declined 8 out of 12 years.[31] This trend is connected to the decline of CO_2 coal emissions after 2007, and since then, more than a billion metric tons of CO_2 have been saved. In this time period, carbon intensity for coal, natural gas, and petroleum generation has dropped from 0.851 metric tons (mt) of CO_2/per megawatt-hour (MWh) in 2005 to 0.646 mt of CO_2/MWh in 2019.[32] Part of this trend is a result of the movement towards low or zero-carbon electricity generation.

As the Power Sector evolves, transitioning from fossil fuels to carbon-free resources will impact the water-energy nexus. Existing natural gas power plants will be important in maintaining the reliability and resiliency of electric supply as increasing amounts of variable renewables are integrated onto the grid. Further, natural gas plants equipped with carbon capture utilization and storage (CCUS) technologies will provide an option for reliable and resilient electricity supply in a fully decarbonized electricity sector. Additionally, the blending of synthetic natural gas and/or hydrogen into the existing gas network will begin to decarbonize applications which currently use natural gas. Increasing the use of these low-carbon fuels in the network may be part of an effort to support applications which cannot be electrified easily. They may also serve as a long-duration storage asset for excess power produced by variable renewable resources.[33] Carbon policies, state regulations, and technology cost and performance improvements could all substantially affect future projections of the national electricity portfolio.[34]

Renewable energy growth has been driven by a steep increase in deployment of wind and solar energy in the United States. Wind and solar energy have grown, both starting from <1 percent in 2000, to 7 and 2 percent of the electricity market in 2019 respectively, which was partially incentivized by the 2005 Energy Policy Act. The solar generation market includes small-scale PV, utility-scale PV, and concentrating solar generation.

3.5. Pipe Parity

NAWI's mission 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 ten years. To effectively assess the opportunities, pipe-parity metrics, which consider information that is useful to decision makers regarding investments related to the utilization of different source water types, are used.

For power plant operators, pipe parity depends on securing long-term reliable access to water resources without increased operational costs or reductions in system efficiency. This includes minimizing parasitic energy loads that might be incurred due to the adoption of alternative cooling systems or treatment required for the use of alternative water resources, while ensuring that any increases in parasitic energy loads and system complexity are offset by increases in system reliability.

Figure 8 helps visualize how pipe parity can be considered. A technology achieves pipe parity for a particular metric (shown as cost in Figure 8) when its performance at the end of the study period (far right bar) is the same as that of the marginal water source (second from the left bar). A **preliminary set of metrics** identified by NAWI is detailed below:

- **Levelized cost of water (dollars per cubic meter [$/m^3])**
- **Energy intensity (kilo-Watt-hours per cubic meter [kWh/m^3]) for treating water**
- **Water intensity/efficiency (m^3/unit)**
- **System reliability and resilience (days to restart)**
- **Use of alternative energy sources & water resources**

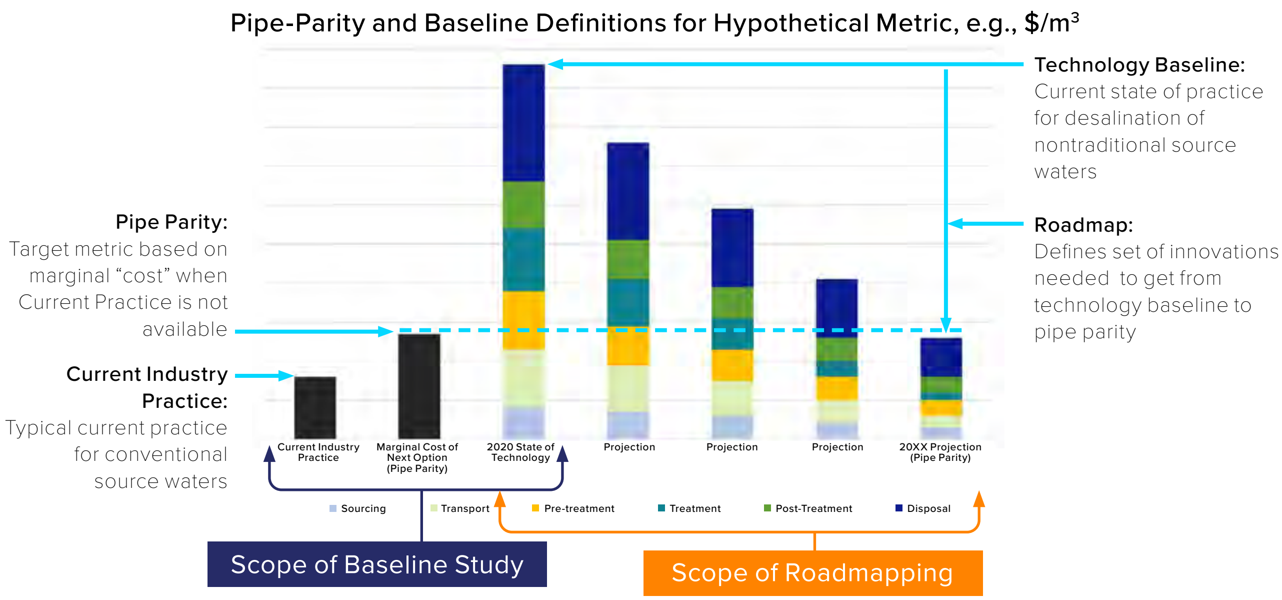


Figure 8. NAWI Roadmapping Pipe Parity Scope

For the Power Sector, reliable access to water without an increase in operational costs or decrease in system efficiency is crucial. Energy intensity is also important to maintain net-positive power generation. Alternative energy sources touch on hybrid power generation, which is considered to be a more stable electricity generation method. Therefore, these five metrics are critical for evaluating the use of nontraditional source waters. Other relevant metrics include carbon intensity, system redundancy, and system complexity (as it relates to operability of advanced systems with the workforce).

3.6. Water Treatment and Management Strategies

Water management and conservation approaches utilized in the Power Sector have generally been categorized as opportunities to reduce and reuse.

Reducing water withdrawals and consumption can be achieved through improved operations of existing equipment and processes. A common practice to reduce water withdrawals and limit wastewater discharge is to increase the cycles of concentration in the cooling towers. Increasing the cycles of concentration reduces the volume of blowdown water from the cooling tower, which in turn, reduces the volume of makeup water required.

The relationship between the flow of makeup and blowdown water as a function of the number of cycles of concentration is shown in Figure 9.[35] As cycles of concentration increase, the volume of makeup and blowdown required decreases up to seven or eight cycles. Beyond eight cycles, water withdrawals must be maintained to reduce the risk of scale formation or corrosion.[36] In arid regions where water resources are scarce, cycles of concentration are commonly maximized to limit water withdrawals, requiring measures to account for the risk of scale formation or corrosion in the cooling tower. Moreover, as cycles of concentration increase, blowdown water will have higher concentrations of dissolved solids, which can have downstream impacts on the facility.

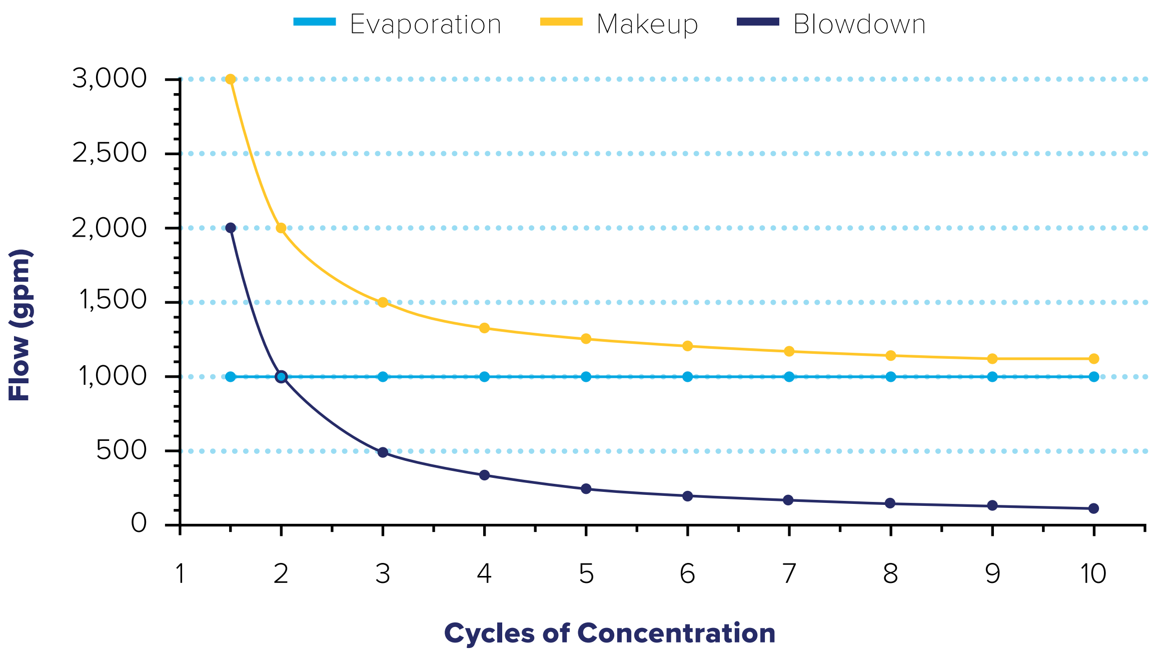


Figure 9. Relationship of evaporation, blowdown, and makeup water in a cooling tower with cycles of concentration

Adapted from EPRI's Water Treatment for Power Plant Cooling Towers: A supplement to the EPRI 2012 RFI for those unfamiliar with the power industry

Reuse can be done directly in a cascading manner (without additional treatment). For example, cooling tower blowdown might be used as makeup water for a scrubber reagent, ash conveyance, or road dust suppression. **Reuse can also be done in an ascending manner (with additional treatment).** In these scenarios, it is critical to assess the impact of increasing the number of concentration cycles on downstream uses to ensure that increasing the number of cycles of concentration does not excessively compromise downstream processes.

One process methodology for water reuse without additional treatment is the collection of wastewater streams in sumps. An example stream is regeneration wastewater from on-site demineralizer trains.

Most of the wastewater produced during the regeneration cycle of a demineralizer resin contains high concentrations of dissolved salt. Reuse for this stream is limited to processes that can tolerate high-ionic strength waters. However, there may be opportunities to obtain water with lower amounts of salt by only collecting at the beginning and end of the regeneration process. For example, a common primary step is to backwash the demineralizer vessels to expand the resin bed to allow for enhanced regeneration, often using high-purity water. In the final rinse step of the regeneration process, a low-TDS stream is discharged as the column is thoroughly rinsed for an extended amount of time to become suitable for demineralized water makeup to the boiler and steam condensate cycle. This low-TDS rinse water would be more than adequate quality for cooling tower makeup until the tighter specification of condensate makeup is achieved.

Treatment in this case is required so the water would be suitable for reuse. For some water systems, cooling tower blowdown may be too high in dissolved solids for use as makeup water for other power plant processes. However, treating the cooling tower blowdown with technology such as RO and/or thermal evaporation may produce water that could be reused in the boiler and steam turbine with just a simple demineralizer polishing step.

Aside from dry cooling that relies on convective heat transfer to reject heat from the working fluid,[37] ZLD technologies have the potential to maximize water utilization. ZLD operation is not just the coupling of five to six unit operations; it is a holistic philosophy that affects how the entire facility operates. Facilities do not choose to implement ZLD—they only do so if required by regulation. ZLD denotes that no water leaves the site and all water is used to the fullest capacity. Evaporators have been used at power plants since the 1920s to distill feedwater for high-pressure boilers. Evaporators for plants managing wastewater with ZLD systems appeared in the early 1970s.[38]

ZLD can be achieved by discharging waste streams to an evaporation pond or deep-well injection;[39] however, the water is lost either to the atmosphere or the subsurface. Alternatively, ZLD can be achieved through the use of advanced water treatment processes to increase reuse and limit liquid waste.

While ZLD systems are typically unique systems that are supplied by different manufacturers and depend on water volumes/flowrates, discharge requirements, and available land area, there are three general steps in most ZLD systems:

i. pretreatment and conditioning
ii. pre-concentration
iii. evaporation/crystallization[40,41,42]

In pretreatment and conditioning, suspended solids, metals, hardness, and silica are typically filtered and/or precipitated out. Pre-concentration typically involves high-pressure membrane processes (typically RO), brine concentrators, or electrodialysis to concentrate the stream even further, usually recovering 60–80 percent of the water.[43,44] Finally, in evaporation/crystallization, a solid is generated through an evaporative or thermal process and the evaporated water is often collected for reuse. The remaining waste is then sent through a crystallizer which continues to evaporate all liquid water and results in a solid waste product that can either be reused or disposed of at a later time.[45,46]

As of 2016, there were 72 power facilities in the United States. that employed ZLD systems with a total combined capacity of 119,000 m^3/day to treat process streams such as cooling tower blowdown and low-volume wastewater, with few installations treating FGD wastewaters.[47] Using ponds as an evaporative system is common in arid regions of the world for wastewater treatment, but challenges exist for power plants where natural evaporation options are limited.[48]

Engineered thermal systems for ZLD face high maintenance, operational, and capital costs for evaporation and crystallization or spray drying.[49,50] When these factors are coupled with the industry's minimal experience with challenging streams (e.g, FGD wastewater), power facilities are faced with the dilemma of investing substantial financial resources into ZLD technologies that may not consistently meet objectives because they are challenging to operate and suffer frequent breakdowns.[51]

Table 3 shows a generic summary of flow ranges and chemistry characteristics of wastewater from power plants.

Table 3. Flow and chemistry characteristics of plant sources of wastewater

SOURCE	FLOW RANGE (LPM)	TDS RANGE (MG/L)	TSS RANGE (MG/L)
Large Volume Sources			
FGD Purge Water	189–1,893	10,000–40,000	100–500
Cooling Tower Blowdown	1,893–5,678	3,000–30,000	< 100
Small Volume Sources (typically intermittent)			
Drum-Type Boiler Blowdown	57–189	< 100	< 100
Washdown Water	< 379	< 1,000	< 1,000
RO Reject	189–757	500–3,000	< 10
Condensate Pol Regen	< 379	< 20,000	< 10
Storm Drains	189–757	< 100	50–1,000

Figure 10. Brine concentrator at APS Redhawk Station

Source: EPRI 2017

Prior to resorting to high-recovery reverse osmosis (HRRO) and/or brine concentrators and crystallizers to meet ZLD regulations, the size of the evaporation pond (if an evaporation pond is available) is a key consideration. The ZLD system is typically sized based on flow volumes and concentrations that exceed evaporation pond capacity. Although evaporation ponds have capital costs (e.g., land area, liner materials), their reliance on solar energy, low operating costs, and simplicity of operation give them treatment primacy, particularly in arid and semi-arid climates where evaporation rates are high.[52] In the future, as ZLD systems costs decrease and reliability increases, dependence on evaporation ponds should be re-evaluated. For example, the cost of evaporation ponds (e.g., land and liners) should be weighed against ZLD cost and performance.

HRRO processes (e.g., closed-circuit RO) are relatively new technologies to improve water recovery while keeping energy consumption low;[53] HRRO processes may provide high enough recovery that brine concentrators and crystallizers are not necessary. Avoiding brine concentrators and crystallizers is desirable because these processes are known to be operationally complex and have low reliability due to frequent breakdowns.[54]

For all ZLD systems, the power required by the processes must be considered and will result in a

$$\mathrm{LCOW} = \frac{\left(\text{capital cost x}\,\frac{r(1+r)^{n}}{[(1+r)^{n}]-1}\right) + \text{annual O\&M costs} + \text{R\&R costs}}{\text{average annual yield in acre}-\text{feet}}$$

reduction of the total house power (i.e., the power rating of the facility). To select a commercial ZLD system, metrics such as levelized cost of water (LCOW) and energy intensity can be compared. LCOW is the sum of costs to treat the water divided by the total volume of water treated ($ per m3 of water treated) and is calculated using: where the capital costs are amortized over the system's life using a discount rate of r and useful life in years of n. O&M costs are annual operation and maintenance costs, and R&R costs are annual repair and replacement costs.

3.7. Traditional and Nontraditional Sources of Water for Power Generation

For some electric power facilities, water scarcity and/or water quality may hinder or preclude freshwater use. Water scarcity may be the result of local conditions, drought, or increased competition for water. Water quality concerns affecting freshwater use relate to poor source water quality or receiving water impacts and regulations. Nontraditional water supplies can be a viable option for many facilities and have been used in place of traditional freshwater sources by the Power Sector for decades, either as a primary source or as a backup source employed in times of need.[55] Certain nontraditional water sources have proven to be a viable option for electric power facilities seeking to decrease their dependence on freshwater sources. For example, in 1977, the California Department of Water Resources recommended that municipal wastewater, brackish water, or agricultural runoff be used for power generation in place of freshwater when it is available.[56] Existing electric power facilities that incorporate nontraditional source waters provide insight for facilities considering an alternative supply.

Potential alternative water supplies are varied and include municipal wastewater effluent, industrial effluent, water from oil and gas production, mine pool water, agricultural runoff, stormwater, or brackish groundwater. In some regions, interbasin transfers of water may be an alternative to a local freshwater supply.

Information from the U.S. Energy Information Administration formed a primary basis for cataloging alternative water supply use by electric power facilities, although information was also obtained from other resources. Figure 11 shows a breakdown of facilities using ten types of alternative water sources.

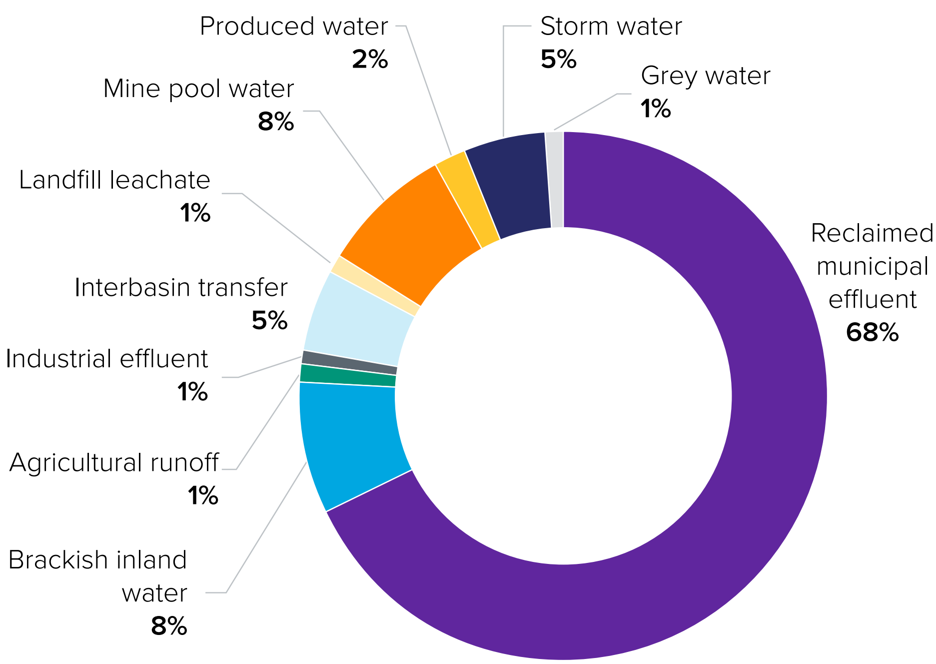


Figure 11. Breakdown of percentage of facilities using 10 types of alternative water sources

Source: EPRI 2017

Treated municipal wastewater is the most common nontraditional supply in current use and appears to be the most promising due to quantity and quality reliability. Inland brackish water, stormwater, mine pool water, agricultural runoff, and interbasin transfer are also being successfully used. Stormwater and agricultural runoff have challenges related to variable quantity and quality but may be viable alternatives when there is a water quality-related driver (e.g., regulatory, financial, or reputational incentives to reuse degraded water rather than discharge to vulnerable receiving waters). Mine pool water, brackish water, and industrial effluent have variable water quality and require treatment; however, careful planning, well-defined agreements, and a backup source can support successful use of these sources. Interbasin transfers and produced water appear to be the least promising supplies for the future because they may not provide consistently reliable quantities of water of reasonable quality and/or cost over the long term.

Despite its attraction, the use of nontraditional water in the Power Sector is uncommon because it requires strong drivers, such as a lack of a traditional freshwater supply and/or water quality-related constraints. In some cases, nontraditional water sources have not been developed because high costs for conveyance and treatment prohibit replacing a traditional freshwater source implementation with an alternate water supply.[57] However, in some cases, nontraditional water provides regulatory and quality-related benefits to the water supplier which further incentivizes the project. More timely approval of new plant construction can occur when water less desirable for other public uses is accepted for power generation cooling. Common factors for successful use of nontraditional water supplies included good planning, establishment of well-defined conditions and quality metrics with the water supplier, as well as the availability of backup supplies.[58] Additional treatment is typically needed regardless of the water source.

The quality of the nontraditional water supply is also an important consideration. To use these potential alternatives to freshwater in cooling towers, for example, certain criteria should be met related to mineral constituents that might affect cooling tower operations through scaling, corrosion, and fouling as well as any constituents that may be regulated for public health via aerosol emissions from the tower. Specific constituents of potential concern include sodium, calcium, magnesium, alkalinity, chlorine, silicon dioxide, pH, boron, nitrate, barium, strontium, and Total Organic Carbon (TOC).[59]

Incorporating reclaimed water into an existing power plant is a complex endeavor and requires:

- physical infrastructure to transport water from the treatment plant to the electric utility
- designing and retrofitting equipment that can accept, treat (if necessary), and integrate wastewater into the power plant
- defining and monitoring water quality requirements and constituent limitations
- developing contingency plans for handling wastewater quality and quantity variations and unanticipated future operational problems

Finally, due to the size of the assets and the critical requirement to maintain electricity service, power plant managers and operators are highly sensitive to real or perceived risks. Successful projects require that wastewater treatment plant and electric utility operators, two groups that seldomly work together, make a concerted effort to minimize risk by collaborating from the earliest planning stages of any project.

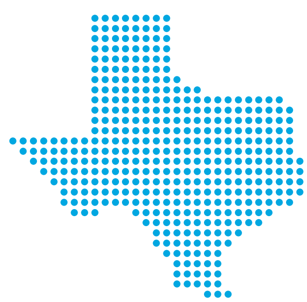
In 2012, EPA issued an update to Guidelines for Water Reuse.[60] The document was intended to facilitate further development of water reuse by serving as an authoritative reference on water reuse practices. In addition to describing regional variations in water reuse, advances in wastewater treatment technologies relevant to reuse, best practices for involving communities in planning projects, international water reuse practices, and factors that will allow expansion of safe and sustainable water reuse, the document includes a section focused on reuse of municipal effluent for cooling towers and boiler makeup water.

Successful projects incorporating municipal wastewater reuse into electric utilities have launched in areas that experience regular freshwater shortages or have regulations that favor such approaches, such as Florida, Arizona, California, and Texas. However, these projects typically take a long time to develop, and in some regions, are not even under consideration. Projects must offer a reliable supply of reclaimed water of consistent quality at a reasonable price, overcome public and political perceptions about the use of "wastewater," and be technically and logistically feasible. These requirements pose significant challenges to wastewater treatment plants and electric utilities that make it difficult for them to launch new projects on their own.

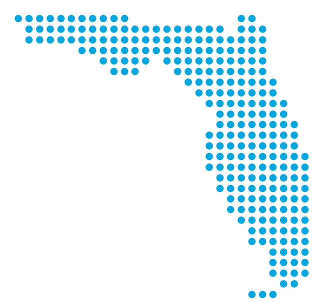
Sixty percent of the cataloged facilities using reclaimed municipal effluent are located located in:

California

Texas



Florida[61]



Geographic proximity to alternative water sources is considered in the design of new plants. It is estimated that 81 percent of power plants proposed for construction could potentially use a municipal effluent supply within a 10-mile radius of the plants. Regulatory requirements for water quality levels can also drive facilities to use municipal water and wastewater, which have predictable output water quality and quantities. Facilities can perform additional onsite treatment to fit their needs. The Electric Power Research Institute (EPRI) noted a high potential for municipal effluent use for thermoelectric cooling in highly populated states such as California, Florida, Illinois, Michigan, and Ohio.[62] The study also mapped the cooling water needed to support projected new generation as a percent of the existing supply of municipal wastewater (Figure 12).

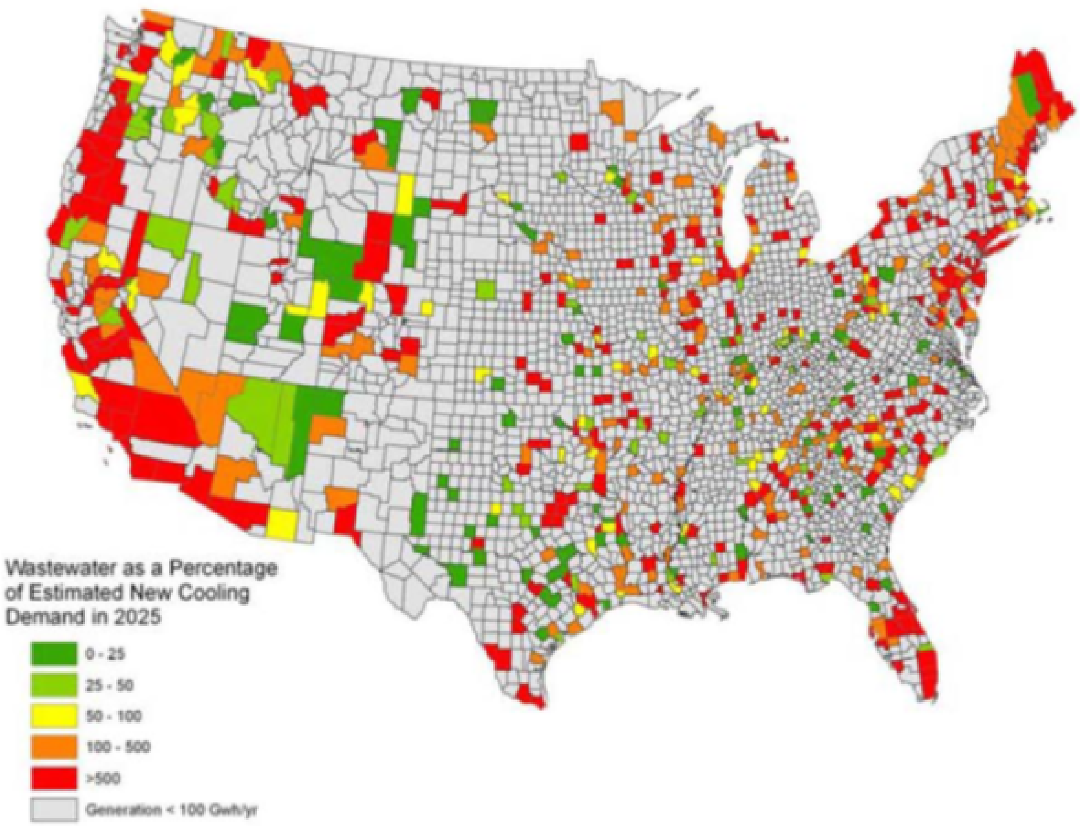


Figure 12. Municipal wastewater generation as a percentage of the potential water demand associated with new electricity generation forecast for 2025

Source: EPRI 2013

Perhaps the most well-known power plant using municipal wastewater effluent is the 4000 MW Palo Verde Nuclear Generating Station (Figure 13). Palo Verde is the largest nuclear generation plant in the United States and the only nuclear power facility that uses 100 percent reclaimed water for cooling, due in large part to its desert location in Arizona. Unlike other nuclear plants, Palo Verde operates as a ZLD system, which means that no water is discharged to rivers, streams, or oceans. The source of this water is the 91st Avenue Wastewater Treatment Plant in the Phoenix metropolitan area. This facility provides the Palo Verde Water Reclamation Facility (WRF), which is located onsite at the generating station, up to 340 MLD (90 MGD) of tertiary treated secondary effluent from the cities of Phoenix, Scottsdale, Tempe, Mesa, Glendale, and Tolleson. The 91st Avenue Wastewater Treatment Plant has a capacity of reclaiming 774 MLD (204.5 MGD) and sends roughly 37,004,400 m^3 yearly to the nearby Buckeye Irrigation District, and another 28,500 acre-foot (AF) to the Tres Rios Wetland facility in addition to the 65,000 AF to Palo Verde. Since the commissioning of the generating units at Palo Verde in the 1980s, Palo Verde has demonstrated successful utilization of municipal wastewater as a valuable resource that now even has competition for the water among end users.[63]

Figure 13. Palo Verde Nuclear Station, Arizona Public Service

Image courtesy of Bob Lotts, Arizona Public Service

In Texas, the San Antonio Water System (SAWS) has provided municipal water reuse for power generation cooling since the 1960s.[64] By 2000, SAWS was operating one of the largest reclaimed water systems in the United States, an expansion partly driven by federal court decisions restricting aquifer use to maintain several endangered species. These factors have enabled the use of reclaimed water in several projects. For example, CPS Energy uses 55.5 million m^3/year) of reclaimed water from SAWS for its cooling lakes.

In Colorado, the Denver recycling plant treats up to 113 million liters of effluent a day coming from the neighboring Metro Wastewater Reclamation District Plant, then pumps the water to several users, the largest of which is an adjacent Xcel Energy power plant, Cherokee Generating Station. The success of this project depends on collaborating on steps to provide adequate water quality (suitable chlorination, biological treatment to convert ammonia to nitrate, reduction of phosphate by precipitation with iron), evaluating and monitoring the impact of fuel source changes on water quantity requirements, addressing groundwater permitting issues, and understanding industrial pretreatment standards.[65]

Figure 14 illustrates the spread of surface and groundwater use over the last 65 years, which has historically been a key factor when choosing power plant locations. Increased water scarcity has motivated facilities to pivot to treating water onsite before use. In 2015, 28 percent of water withdrawals were saline surface water sources, a stark contrast to 20–30 years ago, when desalination technology was first growing in widespread use. Of all saline water withdrawals in the United States in

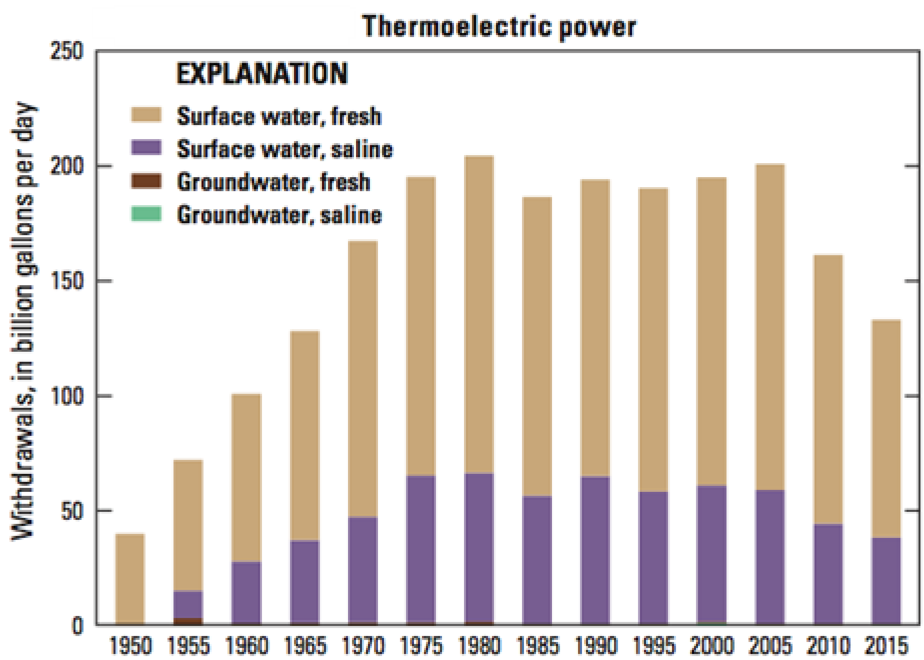


Figure 14. Water sources used for thermoelectric power production, 1950–2015

Source: USGS 2015 Water Use Report

2015, 97 percent were used for thermoelectric generation (37.8 Bgal/day).

California, Florida, and New York have the largest use of saline water for existing power plant cooling (25, 22, and 7 percent of total saline water for thermoelectric generation, respectively).[66] Saline water use is decreasing in California due to a policy, first adopted in 2010 but amended as recently as 2020, that restricts once-through cooling with coastal and estuarine waters at power plants. As of 2019, 10 of 19 seawater-cooled power plants in the state had been retired or retrofitted for air cooling.[67] All power plants must comply with the order by 2030.

On-site water reuse is inherent in power plant processes in the concentration cycling that occurs for many processes (e.g., boiler and cooling water treatment).[68] As cycles of concentrations increase or as boiler-water condensate is reused, freshwater consumption and wastewater discharge decrease.[69] Water reuse also occurs in a cascading manner, where lower-quality water from upstream processes can be used (with or without treatment) in downstream processes. Reuse can also occur in an ascending manner, where lower-quality water from downstream processes is treated and reused in upstream processes. Implementation of ZLD is expected to increase opportunities for water reuse in an ascending manner.

3.8. Compounding Issues Affecting the Power Sector

There are a variety of regulatory and compounding water challenges facing the Power Sector.

Long-term Water Reliability

Water availability, which may be limited by physical scarcity or inadequate water rights, is a major issue for facilities throughout the U.S. Although an existing facility may have secured their legal right to water through riparian or prior appropriation rights,[70] there is still a concern of not meeting demand based on the physical availability of water.[71] This is more of a concern for facilities in arid and semi-arid regions that struggle with issues of water scarcity;[72,73,74] however, it can still impact other regions that are subject to changes in water rights as water demands from other sectors increase.[75] However, facilities may be subject to water reductions or reallocations by regulators based on the needs of the region, leading to challenges with securing a long-term water supply.[76,77] For example, the Colorado River Compact, which allocates specific quantities of the Colorado River for agricultural irrigation, municipal uses, industrial uses, recreational uses, fish and wildlife, and power production, is based on average flows from 1905–1922.[78] These flows, however, are above current averages and are expected to continue to decrease as the effects of climate change worsen, leaving stakeholders at risk of not meeting demand. Moreover, the Colorado River Compact does not directly address shortage sharing, which has made it difficult for stakeholders to agree upon a long-term solution.[79]

Long-term Water Reliability (cont.)

Reliable future supplies must also account for water quality sufficient to be safely be used for cooling with minimal corrosion and scale potential as well as supplying makeup water to the high-purity demineralizer treatment system and many other auxiliary water systems. Even degraded sources of water may not be sufficient in supply for long-term reliability, as competing demands for freshwater could expand into the supply and demand for alternative nontraditional water sources.

Regulations on Watershed Protection

Watershed protection is an important strategy for protecting freshwater sources such as rivers, lakes, and other ecosystems. Regulations under the U.S. Clean Water Act provide guidance for the restoration of impaired waters and for protecting all watershed systems. Power plants that discharge into a receiving stream must comply with strict total maximum daily loads (TMDLs), the maximum amount of a pollutant that a body of water can receive while still meeting water quality standards. The Clean Water Act authorizes EPA to assist local agencies in the establishment of TMDLs that the power utility must meet and the compliance reporting requirements in local discharge permits.

Watershed protection has four major features:

1. Targeting priority problems
2. Involving stakeholders
3. Developing integrated solutions that make use of the expertise and authority of multiple agencies
4. Measuring success through monitoring and other data gathering

Watershed protection accommodates the management and protection of ecosystems and human health at three levels: the state, the basin, and the watersheds within each basin. Some issues are best addressed at the watershed level, such as controlling nutrient loading to small lakes or restoring headwaters' riparian habitat quality. Other issues may be best addressed at the basin level, such as phosphate detergent bans, wetlands mitigation banking, or nutrient trading. Still other activities and solutions are best implemented at the state level, including policies on toxics control or the operation of permit programs. Typically, each basin is studied, and a watershed plan developed, on a five-year cycle.[80]

Aquatic Species Protection Regulation

The Power Sector pays special attention to targeted regulations for aquatic species protection. The goal is to have affordable, reliable, safe use of water and energy, but to do this in an environmentally responsible manner. There are numerous fish protection rulings and other regulations that address this issue addressing safe fish passage in hydroelectric facilities, thermal discharge, and cooling water intake structures. Power plants that withdraw at least 25 percent of their water from an adjacent water body exclusively for cooling purposes and have a design intake flow of greater than 7.6 MLD (2 MGD) are subject to these regulations.

Withdrawing cooling water can affect numerous aquatic organisms, including phytoplankton, zooplankton, fish, crustaceans, shellfish, and many other forms of aquatic life. Cooling water intake structures cause adverse environmental impacts by pulling large numbers of fish and shellfish or their eggs into a power plant cooling system. Organisms may be killed or injured by heat, physical stress, or chemicals used to clean the cooling system (i.e., entrainment). Organisms may be killed or injured when they are trapped against screens at the front of an intake structure. This is known as impingement. EPA estimates that the nation's industry withdraws about 1,135 billion liters of cooling water each day from waters of the United States. Section 316(b) of the Clean Water Act, through the National Pollution Discharge Elimination System (NPDES) program, establishes requirements and standards for the location, design, construction, and capacity of cooling water intake structures to avoid entrainment and impingement.[81]

Effluent Guidelines Regulation

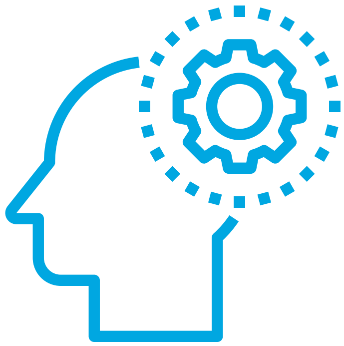
EPA promulgated the Steam Electric Power Generating Effluent Guidelines and Standards (40 CFR Part 423) in 1974, and amended it as recently as 2020. The regulations cover wastewater discharges from power plants operating as utilities and are incorporated into NPDES permits. Steam electric plants are defined as those which use nuclear or fossil fuels to heat water in boilers and generate steam. The steam is used to drive turbines connected to electric generators. The plants generate wastewater in the form of chemical pollutants and thermal pollution (heated water) from their water treatment, power cycle, ash handling, and air pollution control systems, as well as from coal piles, yard and floor drainage, and other miscellaneous wastes. EPA, on August 31, 2020, finalized a rule revising the regulations for the Steam Electric Power Generating category (40 CFR Part 423). The rule revises requirements for two specific waste streams produced by steam electric power plants: FGD wastewater and bottom ash transport water.

In 2015, EPA issued a final rule that set the first federal limits on the levels of toxic metals in wastewater that can be discharged from power plants. That rule was subject to legal challenge and the agency received two petitions for administrative reconsideration, including one from the U.S. Small Business Administration's Office of Advocacy. In response, EPA agreed to reconsider the Effluent Guidelines for two waste streams. This 2020 rule contains the final revised regulations for those two waste streams.[82] For the coal-fired power plants, the Effluent Limitation Guidelines (ELGs) have been the focus of much research this past decade. This is, however, only two of several pieces of the water management and environmentally responsible effluent puzzle power plants face. Bottom ash and flyash classification and handling compound the challenge of reliable and affordable FGD wastewater treatment systems. Tight mercury, arsenic, and selenium limits are difficult to maintain in a cycling operating status in today's environment of power generation.

4. TECHNICAL CHALLENGES
And Associated Knowledge Gaps

There are challenges standing in the way of enabling energy-efficient desalination technologies in the United States at the cost, environmental impact, and efficiency targets outlined by NAWI.

Feasibly integrating nontraditional source waters across the Power Sector requires addressing various technical and non-technical challenges and design gaps.



These challenges have been identified through a structured roadmapping process with subject matter experts. They are too large and far-reaching for any one organization to devote all the resources needed to develop suitable solutions. As a research organization, ***NAWI intends to invest in the most promising TRL 2–4 technologies to address the most pressing technical limitations.***

4.1. Technical Challenges

4.1.1. Constituent Detection

Organics, inorganics, biological organisms, and selective ions are all concerns when using nontraditional source waters. Water quality is factored into cooling system design, and more constituent-heavy water streams will impact treatment systems at a faster rate. These substances increase fouling and scaling, reducing the number of water cycles, and larger amounts of brine concentrate will increase environmental disposal costs. Retrofitting existing water treatment could be more challenging than installing a new system when accommodating adjusted levels of contaminants.

Data analytics tools using robust sensors and connected operations will heavily influence a treatment train's efficiency. It is crucial for power plants to closely track constituent levels and bulk water quality parameters to ensure treatment effectiveness. The challenge is that data and analytical tools are not available to measure and monitor all compounds or to account for dynamic operations. Current sensors can only capture certain parameters, like temperature, salinity, pH, turbidity, and dissolved oxygen, and calibrating and maintaining sensors is a large operational burden. Harsh environmental conditions can also damage sensors and reduce their lifetimes. These sensors also operate individually, and this data is largely not connected to real-time autonomous operations control. Sensor data requires secondary processing in order to inform decisions, and rapidly changing parameters must be adjusted manually.

4.1.2. Constituent Removal

Water treatment processes and monitoring technologies are crucial to meet tightening discharge regulations. New environmental regulations imposed by EPA—known as ELGs— have lowered the environmental discharge limit for selective constituents in power plant discharge water. The challenges in meeting the low discharge permit levels mandated by ELGs for arsenic, selenium, mercury, and nitrate will be amplified when dealing with nontraditional source waters that may have increased constituent levels.

The power industry will need to implement diverse and targeted treatment to reach low levels of contamination and increase cycles of concentration. Contaminants that are at elevated levels in nontraditional source waters can irreversibly damage equipment and processes. Fouling and hardness caused by organics, inorganics, and biological organisms reduces power plant water production efficiency. Certain solutes (e.g., silica, chloride, fluoride, nitrate) can concentrate quickly in recycle loops and can reduce the number of cycles of concentration possible before disposal. Effective technologies to alleviate biofouling and inorganic scaling are still not well developed, and strict discharge limits for specific constituents will require additional cost and time to treat water for environmental disposal.

4.1.3. System Design and Enhancement

In addition to exploring new pathways for selective treatment, **researchers and industry must push the barriers to cultivate and improve existing treatment pathways.** Treatment pathways outside of RO have limited applications, may not be well advertised, or are only competitive in niche conditions. In addition, overall system resiliency is a significant concern amongst industry members because damaged treatment systems result in increased maintenance, lost production time, and lost revenue. Treatment technologies must be durable in the face of unsteady conditions, especially with water sources that have varying constituent levels. Preserving treatment pathways from damage will also require new methods.

As a primary method for water treatment, RO membranes can also be improved to match the needs of industry. Many feedwaters, especially nontraditional source waters, have high constituent levels, clogging membranes and reducing their overall removal efficiency. RO membranes are costly and have limited flexibility with varying feedwater quality. Fouling and scaling agents also have the potential to irreversibly damage membranes. Membrane cleaning and disinfection procedures can also easily damage equipment, as cleaning methods to remove buildup are extensive and require operator assistance.

Many facilities are unfamiliar with nontraditional water source parameters to best design treatment trains and incorporate them into the Power Sector. More steps are required when evaluating a nontraditional source water for power operations—availability, locations, relative amounts, extraction sites, and a sufficient water chemistry analysis. There are no standard approaches or easily accessible modeling tools to evaluate these sources or predict their treatment capabilities, so more manual analysis and validations are required. If power plants decide to pull water from multiple sources, this increases the complexity because different water sources will require different levels of treatment.

As operations grow to include variable water and energy sources, flexible operations can conflict with the existing steady-state designs of water treatment. Some operations are paired with load following and low-load operations to match changing demands for power supply. Water treatment, however, is still currently a steady-state operation, consuming energy to treat water as needed. These processes will require improved storage capacity to capture both energy and clean water for operations, as well as estimation tools for storage capacity and projections based on variable operation.

4.1.4. Waste and Nutrient Management

When evaluating cost-reduction opportunities for treatment trains, there are limited methods for blowdown nutrient recovery to offset installation and retrofitting costs. Effective treatment technologies must also consider blowdown operations and nutrient recovery. Technologies that effectively capture nutrients and pure salts in bulk are not widely available. There are limited economic analysis tools and feasibility studies that review pathways for capturing waste heat from both water- and air-cooled systems.

ZLD systems are cost-prohibitive with high maintenance costs, and they require a top-to-bottom approach to implement correctly. Regulatory amendments have called for zero discharge of pollutants from fly ash, bottom ash, and FGD wastewater. Power plants moving towards ZLD systems must deal with increasingly concentrated brine streams, elevated operation costs, and less sustainable methods for concentration (e.g., fast brine evaporator pond lining deterioration).

4.2. Non-Technical Challenges

The list below identifies non-technical challenges associated with enabling nontraditional water sources to be utilized for the Power Sector. These concepts are included here for thoroughness in identifying other kinds of gaps that could limit the use of nontraditional waters, but, with the exception of cost, are out of the scope of the NAWI focus.

4.2.1. Cost

The costs of retrofitting a power plant to accommodate nontraditional source waters can be prohibitive for electricity providers. Treatment systems must compete against other plant initiatives for capital and real estate, and other projects may have higher returns on investment (e.g., solar power or energy storage over reservoir ponds). Cost elements factor into the final price of a nontraditional treatment process, especially when power plants do not have recycle loops in place. Because power suppliers consider water availability when building new plants, they struggle to demonstrate a monetary benefit to switching to a new water source, particularly a source that requires extensive water treatment.

Cost considerations include:

- Capital costs to install new treatment technology
- Operational costs to treat water
- Equipment modifications to accommodate recycle loops
- Transportation fees to move nontraditional source waters
- Water storage options (for limited sourcing)
- Any other associated purchasing costs of new water sources

4.2.2. Liability and Risks

There are risks that power plants must consider when installing new equipment that could impede their operations or impact their customers. The number of complexities when retrofitting existing equipment may deter power plants from investing in new water treatment systems for fear of disrupting operation. Installation complications can also hinder plant operability, decrease system reliability, reduce power output, and increase the risk of water contamination in the environment. Designing treatment systems for multiple water streams amplifies the risk, as water chemistry must be compatible with equipment to prevent short-term damage. With each new water source, new disposal options must be considered, adjusting siting, design and operation parameters.

4.2.3. Environmental

In addition to leaks and pollution, power facilities must consider the impacts of environmental degradation and climate change when evaluating nontraditional water source availability. As mentioned above, nontraditional source waters with higher contaminant levels will require rigorous treatment if power plants discharge their water to the environment. Any environmental damage could result in fines, regulatory restrictions, and public backlash. Environmental degradation could also impact intake water, reducing its quality and creating a positive feedback loop that forces power facilities to use lower-quality water. Algal blooms and industrial wastewater with variable quality are only a few examples of this. Droughts and reduced rainfall, intensified by climate change, could also reduce intake water quality and availability, all of which jeopardizes power operations.

4.2.4. Workforce and Training

Having a well-trained workforce will determine the longevity of a water treatment system in the power industry. Complex treatment processes require operator knowledge, but initial and ongoing training increases the costs to integrate and maintain complex technologies for nontraditional source waters. Such training may be required, as some plants do not initially have the staff or knowledge base to deal with water treatment, and there is a high learning curve. Finding and training a competent workforce in water treatment for power applications is crucial, and continuous training will prevent loss of knowledge. Without a trained staff, power plants may be operating complex equipment incorrectly, which can lead to decreased lifetimes, lowered system efficiency, equipment damage, and safety violations.

4.2.5. Regulations

Power plants are facing increasing regulations, as well as changing water control, access, and ownership. As mentioned in Section 4.1, tightening restrictions on environmental disposal play a role in selecting treatment technologies and methods. As power plants investigate new nontraditional water sources, the question of water ownership—the push toward shared water rights and respecting neighbors/environment—will influence their decision making. Water ownership varies by state, and water rights and agreements are not as established in the East. This could also become a problem if supply is stressed (via drought), which could compromise nontraditional source waters and supply agreements.

5. RESEARCH PRIORITIES

Areas of Interest for Power 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 source waters for the Power 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 constituents 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 Power Sector.***

Each identified priority follows with a short discussion on the current research challenges (a technology or problem that has not been sufficiently answered by existing studies) and continues with specific TRL 2–4 research needs. Advances in these technologies aim to reduce the cost of treating nontraditional source waters to the same range as traditional water sources, thereby achieving pipe parity.

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 sensors and sensor groups for bulk assessments of diverse water quality parameters that can indicate organic, inorganic, biological fouling propensity, surface corrosion, and water quality violations.**

Challenges

The transition from traditional surface water and groundwater to municipal wastewater, industrial discharge, brackish water, and on-site reuse water for power plant cooling is challenged by the high loads of organics, inorganic ions, and inconsistency of the water quality in the nontraditional water supply. For example, municipal wastewater contains high concentrations of organic carbon, nitrogen, and microorganisms. If not properly removed, the organic matter and microorganisms can attach to the surface of the water distribution pipeline, storage tanks, and membrane surfaces to form biofilm. Biofouling, the growth of biofilm on surfaces, has become an important challenge to power plants, which increases the frequency of cleaning needs and lowers the efficiency of water use for cooling towers. Brackish water and industrial discharges that contain high concentrations of solutes, such as calcium, magnesium, silica, and barium, form scales on pipe surfaces, while anions, such as sulfate, are corrosive to the equipment and pipe surfaces. Rapidly identifying the constituents in the inflow water allows adjustment of treatment strategies for effective removal of challenging water quality constituents. However, current water quality sensors are limited to the measurement of an individual parameter or a few parameters.

The operation, calibration, and maintenance of the water quality sensors are a significant burden to the power plant operation. These sensors are also sensitive to environmental conditions and can only operate within a limited range. Disposable sensors that are cheap to make and ex situ sensors that do not need inline installation would both reduce the demands for maintenance and calibration. Research at TRLs 2–4 on sensor technologies can advance current water quality monitoring, which can translate to reduction in biofouling, inorganic scaling, and corrosion of the facility and reduction in labor cost.

Impacts

Reliable, real-time sensing would create conditions that enable all power plants that use water cooling systems to adopt nontraditional water sources that are in reasonable proximity. Sensors that provide advanced warning of fouling propensities can result in remediation actions to prevent fouling-induced operational and economical losses. These new sensors can translate to reduction in cleaning and replacement of plant parts, prevention of environmental water quality violations, and reduction in fixed labor cost for plant maintenance and updates. This could dramatically reduce freshwater impacts and water management costs at over 1,500 power plants that withdraw more than 530 billion liters per day, more than 15 billion liters of which is consumed (see Tables 2 and 3).

A1.

RESEARCH NEEDS:

- **Develop** inline sensors to measure bio-available organic carbon and microbial biomass as indicators for biofouling propensity (TRL 2–4; 2–4 years).
- **Create** sensor groups for bulk assessments of diverse ions in water (e.g., sparsely dissolved salts or sulfate) that provide advance warning of inorganic scaling and pipe corrosion, are tolerant of harsh conditions, and require minimal human intervention during operation (TRL 2–4; 2–4 years).
- **Advance** methods of manufacturing of disposable sensors that are inexpensive and easy to replace (TRL 2–4; 3–5 years).
- **Evaluate** ex situ sensing methods (e.g., fluorescence, density, color) that can detect water quality changes remotely (TRL 2–4; 2–4 years).

A2. Develop artificial intelligence and algorithms to integrate sensor data with dynamic system operation and control.

Challenges

Currently, power plant operators spend a significant amount of time reviewing water quality data collected from existing monitors and laboratory results from grab sample tests. The water treatment operation is then adjusted after detecting the water quality changes. The adjustments are often significantly delayed due to the lag time in getting water quality data and for human decisions on treatment operation adjustment. Water quality issues are sometimes not detected until significant fouling, scaling, or corrosion has already occurred.

There is a significant gap in connecting water quality monitoring results with the instantaneous and dynamic operation of water treatment processes. New software and digital control systems are needed to take water quality data from sensors directly as inputs to adjust the water treatment operations for water quality assurance. Current methods of assessing "what if" scenarios that can provide means of achieving cost and energy savings often require lengthy pilot testing or modifications of full-scale operations. Creation of digital twins of the water treatment process would allow process optimization for cost reduction through simulations. Research at TRL 2–4 on digital control systems could avoid the operation delay in treatment adjustment and achieve autonomous water treatment operation. The transition from human-operated systems to artificial intelligence-controlled treatment plants can translate into savings in personnel time and energy through more efficient operation.

Impacts

Artificial intelligence developed using rich sensor data has the potential to promote the digital transformation of power plants and improve performance across the power industry. Because artificial intelligence can provide dynamic response to operational needs more sensitively and rapidly than human decisions, artificial intelligence implementation can reduce material and labor cost in power plants, especially those that are small and/or remote.

A2.

RESEARCH NEEDS:

- **Develop** artificial intelligence that enables learning systems that are trained with water quality data and engineering operation data to provide dynamic controls to adjust product water quality based on source changes (TRL 2–4; 1–2 years).
- **Create** digital twins of water treatment operation using empirical data of source water quality and engineering operation as input parameters and finished water quality as the outputs to estimate the cost and energy consumption (TRL 4; 1–2 years).
- **Develop** dynamic models that use both intake and effluent water quality parameters as inputs to determine the critical control points (CCPs) for engineering operation (TRL 2–4; 1–2 years).

5.2. Precise

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

P1. Develop novel adsorbents and absorbents that integrate physiochemical and biological processes with regenerative capabilities for efficient and enhanced removal of contaminants.

Challenges

Among the diverse classes and types of contaminants in nontraditional sources of water, selective subtypes of constituents are especially challenging to the power industry. Fouling caused by organic and inorganic compounds and microorganisms reduces the power plant water efficiency for cooling needs. Effective technologies to alleviate biofouling and inorganic scaling are still not well developed. Past studies of biofouling control have primarily focused on disinfection of microbial biomass and removal of organics by filtration.

These approaches are effective to a certain degree, but they cannot effectively prevent biofouling. Ecological-based approaches for biofouling reduction (e.g., encouraging growth of bacteria that scavenge trace nutrients and balancing nutrient composition to avoid inducing biofilm formation) have potential but are largely untested. In addition to the fouling concerns, high concentration of selective ions (e.g., silica, chloride, fluoride, barium, and nitrate in the water) limit the ability to achieve higher cycles of water use for cooling needs. In situations where power plant discharge is permitted, the strict discharge limit for specific ions such as selenium, mercury, and chlorine residual requires additional treatments before environmental disposal, which drives up the cost and energy of power plant operation. New nanocomposite materials, metal organic frameworks, biosorbent proteins, and other materials that have excellent binding adsorption affinity and selectivity to specific ions or molecules can currently be produced only in limited quantities and in batch (as opposed to continuous flow) operations.

Impacts

This research could have an impact on all power plants in the nation that rely on water cooling (see Tables 2 and 3). Effective technologies to alleviate biofouling and inorganic scaling can improve water production and reduce energy cost significantly, though the degree of improvement will depend on the specific plant conditions. New materials or technologies with selective separation capacity for challenging substances such as silica, chloride, fluoride, barium, and nitrate will allow the plant to achieve higher levels of concentration, reducing withdrawal requirements. New nanocomposite materials, metal organic frameworks, or biosorbent proteins that have excellent binding adsorption affinity and selectivity to selenium, mercury, and chlorine residual, for example, can also improve regulatory compliance and reduce the cost of environment disposal.

P1.

RESEARCH NEEDS:

- **Develop** new materials with improved physicochemical-based adsorption and in situ biological transformation/degradation capacity for selective removal of trace organic compounds and specific ions of concern (e.g., boron, selenium, chlorine, sulfates) (TRL 2–4; 3–5 years).
- **Pursue** advanced manufacturing processes that can lower the production cost of engineered materials that have high adsorption/degradation efficiency and high selectivity for target solutes (TRL 3–4; 2–5 years).
- **Enable** in situ regeneration of selective adsorption sites on engineered material surfaces for sustainable operation that can prolong the lifespan of the engineered materials (TRL 2–4; 3–4 years).
- **Advance** understanding of microbial physiology, ecology, and engineering structures that can advance the effort for biofouling reduction for the power industry in pre-treatment systems that rely on biological treatment processes (TRL 2–4; 3–5 years).
- **Incorporate** photocatalysis into water treatment processes used at power plants, including through the incorporation of photocatalytic materials into membrane processes (TRL 2–4; 3–4 years).

P2. Create effective methods for purification and extraction of valuable compounds in power plant discharge water.

Challenges

Some of the troublesome pollutants in power plant water have the potential to be transformed into valuable products through the development of precision separation technologies for effective purification and extraction of selective compounds. Power plant effluent may contain rare earth elements (REE) and lithium, which have both economic and strategic value. Barium, a well-known element that plagues power plant operation with significant scaling, was recently recognized as an important resource for barium sulfate production to meet the need of diverse industries. Mineral recovery could provide additional revenue streams for the power industry. Research at TRL 2–4 on precision separation for revenue generation offers new opportunities to reach pipe parity.

Impacts

Resource recovery from power plant discharges are highly dependent on site-specific conditions, including the fuel used, design geographic sitting, water source, and discharge location. Industry experts consulted during NAWI roadmapping estimate that there is potential for resource recovery and valorization in at least 50 percent of existing thermoelectric power plants.

P2. RESEARCH NEEDS:

- **Perform** detailed resource characterization to identify species and concentrations of REE and other valuable elements in power plant recirculating and discharge water (TRL 2–4; 1–2 years).
- **Develop** precision separation technologies for selective recovery and purification of target elements from complex solutions (TRL 2–4; 2–5 years).

5.3. Resilient

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

R1. Design materials and treatment components that can maintain integrity throughout periods of operation in unsteady regimes.

Challenges

Water treatment systems supporting power plant operations must be responsive to power changes, variable operation, and shutdowns. This somewhat unique characteristic of the Power Sector can be challenging for water treatment; thus, unsteady water treatment must be considered from operational and environmental perspectives. This includes intermittent or variable-flow treatment of water for cooling and operational purposes and treatment of on-site waste streams prior to being discharged or recycled. When power facilities undergo transient operation, they are subject to system shocks and rapid start-ups.

Fluctuations in power plant operation are typically based on demand from the grid and power changes due to energy source availability—particularly for renewables, which are more intermittent sources. Areas that require further study to increase the resiliency and reliability of water treatment systems in the Power Sector involve materials and treatment components to address the unsteady conditions that exist during unexpected power changes and system adjustments. This is particularly true for stagnant conditions, as many system failures have a root cause of occurring when the system is down, whether in standby or lay-up. For example, the thin-film composite RO membranes in spiral-wound modules can lose integrity if they become delaminated, if the glue lines release, or if the O-rings fail under operational extremes.

Impacts

Water treatment systems supporting power plant operations must be responsive to power supply and demand changes resulting in variable operation. The need for flexibility at all thermoelectric power plants will increase as the proportion of renewable generation on the grid increases (see Figure 7).

R1.

RESEARCH NEEDS:

- **Characterize** performance and mechanical integrity of membrane materials when subject to variable operation and system shocks (TRL 4; 2–4 years).
- **Evaluate and optimize** membrane module components (e.g., glue lines and O-rings) to resist failure under periodic exposure to operational extremes (TRL 4; 2–4 years).
- **Integrate** this research pathway with Autonomous Operation research pathways to develop algorithms that can predict and mitigate system shocks (TRL 2; 3–5 years).

R2. Design processes that can be preserved or maintained during pauses in operation.

Challenges

In addition to experiencing system shocks and rapid start-ups, power facilities require pauses in operation and shutdowns. Scheduled shutdowns are typically timed to coincide with planned maintenance needs or refueling cycles, while unscheduled shutdowns typically result from unanticipated environmental factors or equipment/operational failures.[83,84] While many operations consider water storage options as buffers to prevent interruptions, stagnant conditions can increase corrosion rates and encourage biofilm growth, both of which can reduce start-up efficiency. Transport of corrosion byproducts and plugged filters can result.

Areas that require further study to increase the resiliency and reliability of water treatment systems in the Power Sector involve processes that can withstand scheduled and unscheduled pauses or shutdowns due to maintenance or emergencies. For example, membrane preservation is a key consideration. Also, biological water treatment systems (e.g., for selenium and arsenic removal as well as FGD wastewater treatment) become more cost- and time-intensive if whole microbial populations need to be replaced during transitions. TRL 2–4 research that enables microorganisms to remain in a low metabolic state during unsteady conditions would be beneficial.

Impacts

As the electricity grid decarbonizes, all thermoelectric power plants may be subjected to more flexible operations to balance supply and demand and maintain grid stability. The water treatment systems at the power plants must be able to recover quickly and without great expense when these changes in operations occur.

R2.

RESEARCH NEEDS:

- **Evaluate** corrosion and biofilm growth in process streams upon start-up (after period of shutdown) (TRL 4; 2–4 years).
- **Characterize** membrane deterioration and aging during shutdown/standby periods when membranes are preserved in biocide (or a combination of biocides) (TRL 4; 2–4 years).
- **Develop** an approach to enable microorganisms to remain in a low metabolic state during pauses in operation and shutdowns. For example, robust microorganisms that can slow down or pseudo-hibernate during temperature or outage fluctuations would provide flexibility in changing source waters (TRL 2; 3–5 years).

R3. Design pretreatment and desalination processes that can tolerate water quality variability and provide reliable treatment.

Challenges

Fluctuations and shutdowns (both scheduled and unscheduled) not only result in unsteady operations at power plants but also variability in water quality (including temperature). Variable water quality can also occur with seasonal changes, differences in how personnel operate a facility, and changes in water source to achieve pipe parity (load following, production cycles, energy storage). For example, if a cooling system transitions from lake water to well water, the higher chlorides in the well water can lead to corrosion. Both pre-treatment and desalination processes must be resilient to water quality changes. Also, cooling loops must be periodically disinfected with chlorine, and the chlorine residual must be fully removed prior to blowdown. Because chlorine is not needed continuously (as it is at municipal water treatment facilities), chlorine is either made onsite (which has high capital costs that may not be justified if used only periodically) or purchased and stored onsite (cheaper but not ideal to store).

As on-site reuse become more prevalent due to water scarcity and increasingly strict discharge regulations, three main areas must be considered: pre-treatment, desalination, and post-treatment. Feedwater pre-treatment is critical for desalination to occur efficiently and cost-effectively. RO is highly subject to the efficacy of feed pre-treatment to maintain performance and limit fouling of the RO membrane. RO membrane materials have historically remained the same, with polyamide membranes accounting for the vast majority of the market. Membrane materials that offer better resistance to fouling and greater ability to withstand more physically or chemically intense cleaning methods are needed. Additionally, alternative oxidation and disinfection processes are also needed, particularly those that can meet pre-treatment and post-treatment/residual requirements for RO systems while limiting the formation of carcinogenic or toxic byproducts.

Impacts

This research is likely applicable to all power plants that would utilize alternative water resources. Adopting nontraditional water sources is likely to result in more variable water quality compared to freshwater sources, and the success of desalination processes will depend on developing flexible pretreatment. RO is highly subject to the efficacy of feed pre-treatment to maintain performance and limit fouling of the RO membrane. Membrane materials, alternative oxidation, and disinfection processes that offer better resistance to fouling and greater ability to withstand more physically or chemically intense cleaning methods will improve system longevity and lower costs.

R3.

RESEARCH NEEDS:

- **Quantify** energy and costs for existing pre-treatment and determine tolerance for new systems on a per-cubic-meter basis (TRL 4; 2–4 years).
- **Improve** adaptability of pre-treatment processes (e.g., evaluate responsiveness of variable-speed pumps and develop predictive tools to anticipate chemical dosing and backwash frequency changes) (TRL 4; 3–5 years).
- **Improve** understanding of variable treatment operation and evaluate integrated processes (e.g., combined ozone and ultrasound techniques for bio-foulant removal) (TRL 4, 3–5 years).
- **Advance** membrane technologies (e.g., ceramic membranes, chlorine-resistant membranes) to resist fouling, sustain cleaning, and have longer lifespans (TRL 3; 3–5 years).

5.4. Intensified

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

I1. Increase understanding and applications of reaction kinetics for complex solution chemistries.

Challenges

In September 2015, EPA issued its most stringent discharge regulation for the power industry since 1982.[85] A new rule amending 40 CFR Part 423 under the Clean Water Act set new effluent guidelines for the Steam Electric Power Generating category that called for zero discharge of pollutants from the fly ash and bottom ash waste streams.[86,87] In August 2020, the new rule was updated to include FGD wastewater and bottom ash transport water in order to limit levels of toxic metals in wastewater that could be discharged from power plants.[88,89] This has forced the power industry, and particularly coal and natural gas plants, to take leadership in ZLD implementation. ZLD is complicated by the complex solution chemistries that are unique to different process streams. A key first step in achieving ZLD is to comprehensively characterize brine streams. USGS, EPA, and EPRI have done some characterization, but in general, data for brine streams is not readily available.

Impacts

EPA's effluent discharge regulations will increase the use of ZLD technology at thermoelectric plants, and this research will be applicable to all power plants examining ZLD approaches. Characterizing brine streams, which can vary greatly between facilities and over time at a given facility, and understand how common constituents react, will allow for better planning for ZLD systems.

11.

RESEARCH NEEDS:

- **Systematically and comprehensively characterize** brine streams (TRL 3; 2–4 years); integrate this research pathway with Precision Separations research pathways to ensure removal of critical materials occurs at the appropriate time.
- **Fundamentally study** nucleation and crystal growth at high salinity and/or high temperatures to advance chemical models and predict precipitation of recoverable pure salts to inform design and treatment of brine streams (TRL 3; 2–4 years).
- **Model** complex solution chemistries to evaluate scaling for a range of operating conditions (e.g., temperature, pressure, and presence of organic, colloidal, and/or biological species) to predict and improve process performance (TRL 3; 3–5 years).
- **Advance** gradient, freeze/thaw, nucleation, and solute activity techniques for salt recovery (TRL 3; 2–4 years).

12. Modify existing processes to improve ZLD systems and develop integrated or hybrid processes to improve ZLD systems.

Challenges

ZLD systems are typically unique systems that are supplied by different manufacturers and depend on water volumes/flowrates, discharge requirements, and available land area. The main challenge in the design and operation of ZLD systems is the high energy/operational cost associated with treatment of an increasingly concentrated brine stream.[90,91] Also, the processes in ZLD systems (in particular, the crystallizers) are known to be challenging to operate and to suffer frequent breakdowns. Modifications to existing processes or new integrated/hybrid processes are needed. For example, implementation of thermo-catalytic processes could be useful in sectors that generate waste heat. Implementation of electrocatalytic processes could be useful otherwise. More generally, combined filtration and catalysis could be beneficial in carrying out separation and degradation in one process.

Impacts

Managing energy consumption and operational costs associated with ZLD is critical for power plants affected by EPA's new regulations. Intensified, integrated treatment processes can dramatically reduce costs for installing and operating ZLD systems in the Power Sector and likely in other sectors as well.

12. RESEARCH NEEDS:

- **Modify** thermal techniques using electrified approaches, such as by using ultrasonic and/or vibrating plates to increase the slurry speed of thermal evaporators to reduce deposition on heat exchanger surfaces (TRL 3; 3–5 years).
- **Develop** new high-pressure membranes (e.g., new selective and supporting layers of materials) and modules at lower costs to increase the viability and success of ZLD systems (TRL 4; 3–5 years).

13. Integrate with sensor/control systems and whole-plant operations.

Challenges

The brine concentrator and crystallizer are dependent on the steam from a facility's boiler system. Thus, ZLD systems may not operate continuously; they are also known to break down frequently. It is not uncommon that the failure of one process creates a domino effect. Also, changes in source waters to ones with greater organic and nitrate concentrations have posed challenges.

ZLD operation is not just the coupling of five- to six-unit operations, it is a holistic philosophy that affects how a whole plant operates. ZLD systems are known to be labor-intensive. Resilient sensor/control systems that can ensure reliable operation with less human intervention are required. Future research pathways and strategies must not only address the challenges of treating a concentrated brine stream, but also optimization of whole plant operations.

Impacts

The ZLD systems that exist today are particularly labor intensive and subject to high costs associated with cascading failures of the system. Similar to the benefits associated with Autonomous AOIs, sensors and control systems will reduce operational and maintenance costs, especially labor, at power plants and other facilities with ZLD systems. This will be particularly beneficial in small and/or remote facilities. Also, fault detection algorithms that can prevent cascading failures from shutting down the entire power plant will reduce cost, both due to avoided maintenance and to the increased reliability of the whole plant. These systems can also save on capital costs if the increased reliability reduces the redundancies that must be designed into the system.

13. RESEARCH NEEDS:

- **Systematically evaluate** the effect of changing source waters on brine concentrator processes, particularly with regard to organic and nitrate concentrations (TRL 4; 2–4 years).
- **Identify** key characteristics or chemical species (e.g., nitrate and organics) that adversely affect brine concentrator performance (TRL 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. Develop flexible and reliable water treatment systems built on modular components to address unsteady operation, reliability, and reactor-in-series needs at power plants.

Challenges

In general, water treatment systems at power facilities are already fairly modular; this includes cooling pond operation that is currently carried out in flexible and compartmentalized systems. However, a few opportunities have been identified. For example, implementation of modular systems would increase the flexibility of power plants, enabling ramping up and down of plants to account for price fluctuations.

This demand-response operation incentivizes water treatment operation that aligns with the duck curve electricity demand (i.e., high demand in the morning/evening and low demand in the middle of the day). Replacing singular treatment trains with multiple trains in parallel or replacing singular processes with processes in parallel would increase not only flexibility of operation, but also reliability. For example, ZLD systems that rely on several processes in series would benefit from modularity if the most unreliable process(es) could be duplicated and available for standby or for operation in parallel. If valuable compounds are identified in power plant effluents, modular systems can also be used for sequential extraction of critical materials and removal of hard-to-treat compounds prior to “bulk” ZLD through the use of reactors-in-series. Reactors can be individually adjusted or supplemented with chemical or electrical processes.

Impacts

Strategically implementing modular systems at power plants can increase reliability and avoid expensive unscheduled shutdowns or changes in operations. Modularity can also help the system manage variability in quantity and quality due to seasonal changes and differences in how personnel operate the facility. Benefits may be possible at all thermoelectric power plants, especially those with ZLD systems.

M1.

RESEARCH NEEDS:

- **Develop and optimize** modular systems that provide reliability and flexibility when treatment trains are partially turned on or off according to power plant needs; integrate this research pathway with Autonomous Operation research pathways to automate parallel process(es) in ZLD and other systems (TRL 3; 3–5 years).
- **Develop and optimize** modular reactors-in-series for sequential extraction of valuable or hard-to treat compounds; integrate this research pathway with Precision Separation for extraction of critical materials (TRL 3; 3–5 years).

M2. Advance dual-function membrane manufacturing approaches that enable their cost-effective production at scale.

Challenges

The application of membranes at power plants is negatively impacted by fouling and biofouling. For treatment processes at power plants that involve membranes, there are opportunities to develop dual-function membranes that combat fouling and biofouling. Dual-function membranes would need to be manufactured cost-effectively at scale.

Impacts

Fouling-resistant membranes would reduce maintenance costs and extend replacement periods at all power plants that include them in their treatment trains, as well as in membrane-based systems in other sectors.

M2.

RESEARCH NEEDS:

- **Prepare and evaluate** dual-function membranes that can produce free radicals that inhibit formation of biofilms and destroy constituents that contribute to fouling (TRL 2–3; 2–5 years).
- **Develop** manufacturing approaches that enable the cost-effective production of dual-function membranes (TRL 2–3; 2–5 years).

5.6. Electrified

Electrifying Water Treatment Processes and Facilitating Clean Grid Integration

E1.

Develop electrified processes and the scientific basis for these processes that can provide chemical-free removal of specific constituents.

Challenges

Thermoelectric power plants devote considerable labor and resources to managing the quality of water streams by chemical addition. The water streams range from large volumes of cooling water to smaller volume streams that are enriched in problematic contaminants (e.g., selenium, arsenic, mercury). Power plants often employ full-time process chemists in addition to the engineers who manage and operate treatment systems, and plants have needs for purchasing, storing, and delivering chemicals for water quality management. Lime softening for removal of hardness (i.e., magnesium ions and calcium ions) and dissolved silica is a chemically intensive process that also generates large volumes of solid residuals. The dominant process for removal of selenium at treatment plants is biological selenium reduction, but electrochemical treatment approaches may achieve faster removal and be more resilient to fluctuating water quality and flows.

The removal of both major and trace constituents in feedwater, recirculating cooling water, and discharge streams could be accomplished by electrified processes instead of chemical addition or biological processes. Some electrified technologies are limited in their application to weakly charged ions (e.g., electrodialysis), while the underlying mechanisms for others remain poorly understood. Research at TRLs 2–4 can advance the understanding of the underlying mechanisms responsible for electrified treatment process performance that can enable optimization of the processes and provide the foundation for designing larger scale systems.

Impacts

Electrified treatment can reduce costs and improve the safety of managing water quality, which can be more challenging when adopting nontraditional sources compared to freshwater sources. This would be relevant to all power plants utilizing chemicals during their operations.

E1.

RESEARCH NEEDS:

- **Develop** chemical-free approaches to cooling water pre-treatment that can remove hardness as well as weakly charged ions (e.g., dissolved silica and boron) (TRL 3–4; 3–5 years).
- **Tailor** electrocoagulation and other electrochemical processes to generate products that target the removal of specific constituents (e.g., arsenic, selenium, and mercury) through adsorption, incorporation, and surface-mediated oxidation-reduction reactions (TRL 2–4; 2–5 years).
- **Advance** the mechanistic understanding of processes at electrode-water interfaces for materials and aqueous compositions relevant to treatment of aqueous streams at power plants (TRL 2–3; 2–5 years).

E2.

Lower chemical intensity of water management at power plants through electrified approaches to disinfection and scale inhibition.

Challenges

Recirculating cooling water must be managed to prevent chemical scaling and limit biological growth. This is currently achieved by the addition of chemical disinfectants and antiscalants, and further chemical addition is often required to remove those chemicals (e.g., in dechlorination) before the blowdown of cooling water can be discharged to the environment. The recirculating nature of cooling water is amenable to electrified processes of disinfection and scale inhibition. The need for residual disinfectants in cooling towers may not make it possible to entirely eliminate the use of chemical disinfectants, but amounts could be dramatically reduced. UV disinfection and ozone are established electrified methods of disinfection with the potential for greater application in recirculating systems at power plants. A challenge to their application is the short lifetimes of residual disinfectant from these processes.

Chemical-free scale inhibition could potentially be achieved using electric currents, ultrasonic application, and radio frequency generators. While approaches that use these emerging technologies are being marketed to power plants, the underlying chemical and physical principles of their operation remain poorly understood.

Impacts

Reducing chemical consumption will be a particular source of cost savings at the almost 1,300 thermoelectric power plants with recirculating cooling processes across the United States. Together, these plants represent over 600 gigawatts (GW) of power generation capacity (see Table 3).

E2.

RESEARCH NEEDS:

- **Develop** methods to provide residual disinfectant from UV irradiation and ozone over the timescales of cooling water recirculation (TRL 3–4; 2–5 years).
- **Evaluate** the efficacy and mechanisms of enhancement of chemical disinfection by the application of electric fields. (TRL 2–4; 2–5 years).
- For cooling water systems that do rely on chlorine-based disinfectants, **develop** chemical-free approaches to dechlorination (TRL 4; 2–4 years).
- **Optimize** the integration of electrified and chemical treatment approaches for disinfection and scale inhibition (TRL 4; 2–4 years).
- **Advance** knowledge of the underlying physical and chemical principles of the operation of ultrasonic application and radio frequency generators used for scale inhibition (TRL 2–3; 2–5 years).

E3.

Create new methods for producing water of sufficient quality for hydrogen production and enable hydrogen production directly from lower-quality water supplies.

Challenges

A transition to a hydrogen economy will require water of sufficient quality and quantity for hydrogen production through both electrolysis and steam methane reforming. Using current processes, trace constituents that remain in treated feedwater can participate in side reactions in the electrochemical system, or they can deactivate the catalysts. Arid regions that are the most likely to benefit from electrolysis due to the abundance of wind and solar energy resources could have particular concerns around water availability and cost.

Impacts

As of 2018, there were over 10 million metric tons of hydrogen produced in the United States;[92] however, **currently, steam reforming of methane, not electrolysis, is the primary production process.** The economic potential of future hydrogen demand in the United States has been analyzed in the DOE H2@Scale initiative, with an estimated potential of "a two- to four-fold increase in potential hydrogen demand in five future scenarios."[93]

E3.

RESEARCH NEEDS:

- **Develop** technologies that can treat alternative sources of water to a sufficient quality for current methods of hydrogen production (TRL 4; 2–5 years).
- **Develop** new selective catalysts or membrane technologies to electrolyze saltwater directly without a prior desalination step (TRL 2-3; 2–5 years).

6. NEXT STEPS

This comprehensive and dynamic roadmap for low-TRL desalination and water treatment technologies for the Power 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 it 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 circular water economy for the Power 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

A-PRIME	Autonomous, Precise, Resilient, Intensified, Modular, and Electrified – NAWI R&D focus area
AOI	Areas of Interest
AMO	Advanced Manufacturing Office
Bgal/day	billion gallons per day
CCP	Critical control point
CCUS	Carbon capture utilization and storage
DOE	U.S. Department of Energy
DHS	U.S. Department of Homeland Security
ELG	Effluent Limitation Guidelines
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FGD	Flue gas desulfurization
GW	gigawatt
HRRO	high-recovery reverse osmosis
IoT	Internet of Things
kWh/m^3	kilo-Watt-hour per cubic meter
LCA	Life cycle analysis
LCOE	Levelized cost of electricity
m^3	Cubic meters
mg/L	Milligrams per liter
Mg	Magnesium
MGD	Million gallons per day
MLD	Million liters per day

MMBTU	metric million British Thermal Unit
MT	metric ton
MWh	megawatt=hour
NAWI	National Alliance for Water Innovation Hub
NETL	National Energy Technology Laboratory
NPDES	National Pollution Discharge Elimination System
NREL	National Renewable Energy Laboratory
O&M	Operations and maintenance
OCWD	Orange County Water District
OPEX	Operating expenses
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
PV	Photovoltaic
RAC	Research and Advisory Council
R&D	Research and development
REE	Rare earth elements
RFP	Request for projects
RO	Reverse osmosis
TDS	Total Dissolved Solids
TEA	Technoeconomic analysis
TECO	Tampa Electric Company
TMDL	Total maximum daily load
TOC	Total organic carbon

TRL	Technology readiness level
U.S.	United States
USGS	U.S. Geological Survey
UV	Ultraviolet
WRF	Water reclamation facility
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 parts per million (ppm) 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, modular, 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 schema, 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:[94]

- 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.[95] 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 experts (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 Power 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 condition. 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 the 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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