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Energy-Water Desalination Hub

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Energy-Water Desalination Hub is the final report for project EPC-20-001 conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

The National Alliance for Water Innovation (NAWI) is an Energy Innovation Hub created in 2020 and funded by the U.S. Department of Energy to conduct early-stage research on desalination and associated water-treatment technologies to secure affordable and energy-efficient water supplies for the United States from non-traditional water sources. NAWI's five-year research program was guided by a national road mapping process designed to engage stakeholders from the water-treatment and water-use ecosystem and by several requests for preproposals to solicit research ideas through a competitive, peer-reviewed process.

Major reductions in cost and energy use, and improvements in water supply resilience, can be achieved by enabling distributed water desalination and reuse. To achieve these reductions, research is needed to establish water systems that are autonomous, precise, resilient, process-intensified, modular, and electrically (collectively referred to as A-PRIME) powered. This A-PRIME strategy will transform the energy sector's produced water from a waste product to a valuable resource; significantly lower the freshwater use intensity in United States power plants; expand water reuse and resource recovery from municipal and industrial wastewater; and accelerate the deployment of distributed, resilient, smart grid–enabled water supplies for United States industries and communities.

NAWI's research program was structured around three research topic areas. The Materials and Manufacturing topic area focused on the discovery of better-performing desalination materials and components and enhanced desalination manufacturing processes. The Process Innovation and Intensification topic area focused on the development of novel water treatment and desalination processes, intensified process concepts, and automation methods and systems. The Data, Modeling, and Analysis topic area focused on the development and enhancement of high-fidelity computer models for water-treatment process and system optimization, a suite of data management and techno-economic analytical tools, and novel methods to enable quantitative analysis of the impact of water treatment.

Keywords: Distributed water desalination, water reuse and resource recovery, novel water treatment, lower cost for water treatment

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Executive Summary

The National Alliance for Water Innovation (NAWI), headquartered at Lawrence Berkeley National Laboratory, was competitively selected by the U.S. Department of Energy to build a 5-year, $110 million program in early-stage applied research to lower the cost, energy, and carbon footprint of desalination and water reuse.

NAWI recognized that the greatest potential to lower the cost and carbon intensity of marginal water supply to the nation's communities and industries lay in lowering the cost of small-scale desalination and water reuse systems. These systems allow non-traditional water sources to be adaptively deployed and reused close to the source, and they minimize the substantial energy and cost associated with transporting water over long distances. Small scale systems are particularly advantageous when conveyance infrastructure does not yet exist, when centralized systems are far above or below their design capacity, and where secondary uses for fit-for-purpose water are plentiful (for example, within buildings or industrial facilities).

NAWI identified six "A-PRIME" challenge areas (and later added a seventh) that are essential to dramatically dropping the cost, energy, and carbon intensity of small-scale desalination and reuse systems. These challenge areas also yield substantial benefits for large-scale systems:

- Autonomous operation
- Precision separations
- Resilient system designs
- Intensified brine management
- Modular membrane technology
- Electrification
- Circular water economies systems analysis

NAWI combined the strongest academic researchers in the field of desalination and water reuse with a world-class set of national laboratories and industry partners to create a compelling vision to enable "pipe-parity" water treatment through an integrated program of early-stage applied research and development. "Pipe-parity" is defined as the levelized cost of the current marginal water supply. Most communities have a portfolio of water sources that have different levelized costs. "Pipe-parity" would mean lowering the cost of treatment for a non-traditional water source down to that of most expensive conventional water supply currently in use.

Since beginning operations on February 12, 2020, NAWI quickly grew to be a major force in advancing the frontier of water treatment and shaping a national strategy for a circular water economy. Unlike earlier innovation hubs, NAWI created an open membership whereby new Research Consortium members would join the Hub when their research projects were competitively selected. NAWI also introduced a second innovation: a no-cost Alliance program that enables the widest possible range of stakeholders in water treatment and water resources to engage in NAWI activities. The vision was to create an innovation ecosystem where water treatment technologists, sponsors and supporters of technology development, and water

stakeholders could connect. This strategy not only enabled NAWI to become the largest community of any U.S. Department of Energy (U.S. DOE) hub or institute, with 109 Research Consortium member organizations and more than 500 Alliance Organizations and individuals but also led Alliance members to numerous sponsored research projects outside of those funded by NAWI itself.

In addition to supporting overall management and operations of the Hub, California Energy Commission funding supported five specific research products within the NAWI program.

Water DAMS: The NAWI Water Data and Analysis Management System provides U.S. DOE and the public access to foundational data associated with each of NAWI's 60-plus research projects. The Water Data and Analysis Management System is built on open energy information and leverages substantial investments made in data and knowledge management by other U.S. DOE programs (for example, Water Power Technologies Office, Solar Energy Technologies Office, Geothermal Technologies Office) to enable secure collaboration for U.S. DOE and project partners, proper attribution of metadata, data curation, standardization of data formats, and the automatic dissemination of public information to a network of data sharing partners that includes Data.gov and the U.S. DOE's Office of Scientific and Technical Information.

Water Research and Development Roadmapping: In year one of the NAWI program, a team of researchers and water professionals engaged in a detailed process of evaluating water uses, state-of-the-art technologies, emerging technologies, and existing uses of desalination and advanced water technologies within five major water user categories in the United States. The resulting Water User Sector Roadmaps were complemented by a baseline analysis of a suite of representative treatment systems conducted by NAWI researchers working in collaboration with the Hub's industrial partners. More than 400 experts and practitioners contributed to the NAWI roadmapping and baselining initiatives. The Master Roadmap, which synthesizes the findings from these different efforts as well as feedback from members of NAWI's Research Advisory Council, serves as the basis for identifying NAWI's research areas of interest.

PROTEUS: PROTEUS (later renamed Water Treatment Technoeconomic Assessment Platform [WaterTAP]) is an open source Python-based Water Techno-economic Assessment Modeling Platform. It is publicly accessible on GitHub and allows users to quantitatively evaluate cost, energy, and effectiveness of novel water treatment systems. WaterTAP allows users to input influent characteristics and desired effluent water qualities, select desired unit processes or a default treatment train, and run and optimize variants (https://github.com/watertap-org).

Computational Testbed for Predictive Fouling Control: Physicochemical models of the chemical stability of common precipitates are restricted to dilute solutions, making it difficult to predict when and to what extent scale formation will negatively affect reverse osmosis performance. This project developed computational tools capable of predicting reverse osmosis membrane scaling as a function of brine composition and module design to identify and optimize new operating schema for existing reverse osmosis modules (for example, closed circuit reverse osmosis).

Machine-Learning Platform for Catalyst Design: Electrocatalysts offer a promising low-cost and energy-efficient alternative to biological and sorption processes for selective removal of trace metal ions such as selenium. This project developed a novel computational and experimental platform for discovery and design of high-efficiency electrochemical interfaces with oxyanion reduction functionality: the ability to chemically reduce oxyanions such as selenium, thus removing it from water.

NAWI supported a total of 66 research projects and leveraged more than $33 million in cash and in-kind cost share from state agencies, universities, and industry partners. Despite starting within the first month of the COVID pandemic, NAWI successfully built the largest community of water treatment researchers ever assembled and carried out vigorous interactive activities including annual meetings and a highly regarded webinar series.

Project Purpose and Approach

The overarching project deliverable is a set of innovations in desalination and water treatment that substantially lower the cost of producing clean water from "non-traditional" water supplies whose salinity and composition are not economically treatable with current technologies. The NAWI program was organized into three research topic areas with 5–25 projects in each. Projects were selected based on a rigorous technical merit review, and progress toward NAWI's overarching goal was tracked using state-of-the-art techno-economic analysis methods and data sets. When these projects are completed, it is anticipated that results will be detailed in hundreds of peer-reviewed research publications and numerous patents and innovations adopted by industry.

Key Results

NAWI achieved success and impact in its five years of operation. As a team, NAWI:

- Developed and published five sector roadmaps and a Master Technology Roadmap that have collectively been downloaded more than 14,000 times. This definitive analysis has influenced many other academic and industrial water treatment research programs and was cited by Rio Tinto, an international mining company, as key to guiding its applied research program in water treatment.
- Developed WaterTAP, an open-source modeling tool built on the U.S. DOE's process systems engineering platform Institute for Design of Advanced Energy Systems that enables researchers, developers, and system designers to collaborate on prioritizing new technology developments and quantifying the system benefits of treatment train innovations.
- Developed WaterDAMS to provide access to foundational water treatment technology data that enables researchers and decision-makers to identify and quantify opportunities for technology innovations to reduce the cost and energy intensity of desalination. It is the submission point for all data generated by research conducted by the NAWI Alliance and is designed to be used by the broader water research community.

- Issued five competitive funding opportunities, eliciting nearly 600 concept papers resulting in the selection of 54 research projects to date https://www.nawihub.org/research/projects/.
- Successfully convened six Alliance-wide meetings and three Research Consortium meetings and workshops, with a combined registration of more than 1,000.

Knowledge Transfer and Next Steps

From the start of the program (February 6, 2020) NAWI vigorously communicated its progress and results through several channels of knowledge transfer including:

- More than 130 peer-reviewed technical publications (see Appendix A for the publication list for the six projects supported by the California Energy Commission).
- Creation of the NAWI Alliance — a no-cost membership organization that gives participants access to all of NAWI's digital content, webinars, and invitations to NAWI's biannual Alliance meeting.
- Interviews with numerous news organizations including the *New York Times*; KQED, *The Economist*; *The Sacramento Bee*; *Popular Science*; *Wired*; My Climate Journey (podcast), and The Chip Franklin Show.

CHAPTER 1: Introduction

The U.S. Department of Energy (U.S. DOE) recognized the critical interdependency of water, energy, and climate when it released funding opportunity announcement (DE-FOA-0001905) on December 13, 2018, requesting proposals to establish a new Energy Innovation Hub (Hub) focused on desalination and water reuse. The U.S. DOE saw a unique opportunity to make a once-in-a-generation science and technology investment to address climate-driven water supply instability and water resource inequity.

The National Alliance for Water Innovation (NAWI), headquartered at Lawrence Berkeley National Laboratory (LBNL), was competitively selected to build the Hub for several reasons:

- NAWI recognized that the greatest potential to lower the cost and carbon intensity of marginal water supply to the nation's communities and industries lay in lowering the cost of small-scale desalination and water reuse systems. These systems allow non-traditional water sources to be adaptively deployed and reused close to the source, and they minimize the substantial energy and cost associated with transporting water over long distances. Small-scale systems are particularly advantageous when conveyance infrastructure does not yet exist, when centralized systems are far above or below their design capacity, and where secondary uses for fit-for-purpose water are plentiful (for example, within buildings or industrial facilities).
- NAWI identified six "A-PRIME" challenge areas (and later added a seventh) that are essential to dramatically dropping the cost, energy, and carbon intensity of small-scale desalination and reuse systems. These challenge areas also yield substantial benefits for large-scale systems:
    - Autonomous operation
    - Precision separations
    - Resilient system designs
    - Intensified brine management
    - Modular membrane technology
    - Electrification
    - + Circular water economies systems analysis

NAWI combined the strongest academic researchers in the field of desalination and water reuse with a world-class set of national laboratories and industry partners to create a compelling vision to enable "pipe-parity" water treatment through an integrated program of early-stage applied research and development. "Pipe-parity" is defined as the levelized cost of the current marginal water supply. Most communities have a portfolio of water sources that have different levelized costs. "Pipe-parity" would mean lowering the cost of treatment for a non-traditional water source down to that of most expensive conventional water supply currently in use.

Since beginning operations on February 12, 2020, NAWI quickly grew to be a major force in advancing the frontier of water treatment and shaping a national strategy for a circular water economy. Unlike earlier innovation hubs, NAWI created an open membership whereby new Research Consortium members would join the Hub when their research projects were competitively selected. NAWI also introduced a second innovation: a no-cost Alliance program that enables the widest possible range of stakeholders in water treatment and water resources to engage in NAWI activities. The vision was to create an innovation ecosystem where water treatment technologists, sponsors and supporters of technology development, and water stakeholders could connect. This strategy has not only enabled NAWI to become the largest community of any U.S. DOE hub or institute, with 122 Research Consortium member organizations and more than 500 Alliance organizations and individuals, but also led Alliance members to numerous sponsored research projects outside of those funded by NAWI itself.

CHAPTER 2:
Project Approach

The NAWI program was built around the fundamental principles of openness, transparency, and merit. The goal was not only to accelerate progress toward cost-competitive distributed desalination and water reuse, but also to create a larger innovation ecosystem in which researchers could directly interact with industry and water resource managers so that more practical and impactful research projects could be developed. One indicator of the success in creating this ecosystem is that numerous NAWI researchers reported that:

- They initiated new sponsored research through a contact they made within the NAWI community.
- The NAWI-funded research project often brings together research partners that have not worked together previously.

This strategy enabled NAWI to build the largest community of applied water researchers in the United States (see Appendix B for complete list of Alliance members).

In each of the tasks in the California Energy Commission (CEC) funded portion of the program, NAWI adopted novel and catalytic approaches to accelerating innovation and stimulating progress in water treatment.

Development, Deployment, and Refinement of the Water Technology Data and Analysis Management System (Water DAMS)

Research Objectives: The objective of creating the NAWI Water DAMS was to provide the U.S. DOE and the public access to foundational data associated with each of NAWI's 60-plus research projects.

Project Partners and Advisors: National Renewable Energy Laboratory (NREL); Electric Power Research Institute (EPRI); Colorado School of Mines; Stanford University; and LBNL

Overall Methods, Approach, and Key Objectives: Water DAMS is built on open energy information (OpenEI) and leverages substantial investments made in data and knowledge management by other U.S. DOE programs (for example, Water Power Technologies Office, Solar Energy Technologies Office, Geothermal Technologies Office) to enable secure collaboration for U.S. DOE and project partners, proper attribution of metadata, data curation, standardization of data formats, and the automatic dissemination of public information to a network of data sharing partners that includes Data.gov and the U.S. DOE's Office of Scientific and Technical Information.

Key Milestones:

- Version 1.0 of the Water DAMS Collaboration Space – completed 9/1/2020
- Version 1.0 of the Water DAMS Data Repository – completed 12/31/2020

- Water DAMS Documentation, Maintenance, and Support Manual – V1.0 – completed 12/31/2020

Roadmap to Research and Development Cycle: Technology Baselines, NAWI Performance Tracking, and Technology Roadmapping

Research Objectives: The goal of this task was to develop and release a national Desalination Roadmap that tabulates current energy and cost baselines for the treatment of different non-traditional water sources and identifies the key technical barriers to lowering the cost and energy of desalination and water reuse. The roadmap process also tracked the technical progress the NAWI research program made toward achieving its technical goals.

Project Partners and Advisors: New Mexico State University, Colorado State University, Colorado University at Boulder, University of Cincinnati, University of Southern California, Washington University of St. Louis, Texas A&M University, University of Texas at Austin; Colorado School of Mines; University of California, Berkeley; University of California, Irvine; Yale University, BlueTech Research, Oak Ridge National Laboratory; NREL; EPRI; Stanford University; and LBNL.

Overall Methods, Approach, and Key Objectives: Launched five End-use Roadmapping teams to gather baseline information on treatment methods and cost and energy for specific treatment processes. Teams met regularly to coordinate data collection and analysis. NAWI developed and conducted a national written survey of water users to obtain baseline information (administered by the Nexight Group). NAWI conducted expert interviews to identify key barriers to lowering the cost and energy of desalination for specific end uses. Notes from interviews were posted on Water DAMS. NAWI published five End-use Roadmaps and a Master Roadmap at the end of Year 1 to identify specific research Areas of Interest for subsequent requests for proposals.

Key Milestones:

- Desalination Roadmap (Final) – published 5/4/2021
- Critical Project Review Report – submitted 9/1/2022

PROTEUS: Integrated Computational Capability for Optimizing Advanced Water Treatment Systems

Research Objectives: The goal of this task was to develop ProteusLib (renamed Water Treatment Technoeconomic Assessment Platform [WaterTAP]), a new library of water-specific property, process unit, and network models built on the Institute for Design of Advanced Energy Systems (IDAES) framework.

Project Partners and Advisors: Oak Ridge National Laboratory; NREL; EPRI; Stanford Linear Accelerator Center; LBNL; and OLISoft Inc.

Overall Methods, Approach, and Key Objectives: Institute for Design of Advanced Energy Systems (IDAES) consists of computational tools that enable the use of advanced solvers and computer architectures for: (1) process simulation and optimization, (2) process synthesis and conceptual design, (3) integration of multi-scale models, and (4) dynamic

modeling and control. It includes an extensible, hierarchical model library that covers physicochemical properties and process units typically associated with chemical and energy production. In this task, NAWI leveraged the capabilities of IDAES and applied them to water treatment by developing property packages that represent the physical and thermodynamic properties for bulk and trace brine components in water sources of interest, process unit models of existing and novel water treatment technologies, and network models of water management systems. Within its first year of work, ProteusLib developers created models representing a full water treatment train including pre-treatment, reverse osmosis (RO) desalination, and post-treatment. Besides demonstrating the advanced optimization capabilities for the conventional seawater RO desalination, the flexibility of the platform was demonstrated through technoeconomic assessments of early-stage treatment technologies including high pressure RO and low salt rejection RO.

Key Milestones:

- Property and Unit Models — initial release March 15, 2021 — current updates released quarterly
- Training Documentation — initial release June 30, 2021 — current updates released quarterly
- Tutorials — these have been ongoing since March 2021

Computational Test Bed for Predictive Fouling Control

Research Objectives: The goal of this task was to develop and apply predictive models linking meso-scale reactive transport phenomena that occur on and within RO membranes to system-level desalination performance and to validate those models against experimental membrane crossflow experiments.

Project Partners and Advisors: University of Texas at Austin; Colorado School of Mines; and LBNL.

Overall Methods, Approach, and Key Objectives: The research team developed computational tools capable of predicting RO membrane scaling as a function of brine composition and module design to identify and optimize new operating schema for existing RO modules (for example, closed circuit RO). They then developed novel cross-flow experiments to validate model predictions.

Key Milestones:

- Draft manuscript tentatively titled ”Predictive Modeling of RO Fouling,” submitted April 1, 2023

Machine Learning Platform for Catalyst Design

Research Objectives: The goal of this task was to build new research capabilities in the water treatment area, using state-of-the-art U.S. DOE user facilities at LBNL (National Energy Research Computing Center, Molecular Foundry) for materials discovery with a specific focus on nitrate treatment. The current state of the art for nitrate removal from water streams is biological treatment; however, biological processes are expensive, operationally challenging,

and require significant amounts of land. Developing a novel catalyst to selectively and precisely remove these constituents may offer a more cost-effective treatment alternative to the state-of-the-art. However, a major challenge with developing new catalysts is identifying a material composition that not only can react with and remove the constituent of concern, but do so quickly, and in a cost-effective manner. While researchers have traditionally taken the "brute-force-method" approach by using heuristics to identify viable electrode materials, there are a seemingly endless number of material combinations possible making this approach time consuming and highly inefficient.

Project Partners and Advisors: Carnegie Mellon University; EPRI; and LBNL.

Overall Methods, Approach, and Key Objectives: The research team developed a high-throughput platform for identifying new water desalination materials that integrates machine learning, high fidelity simulation, and combinatorial experimental screening. The group then screened 50,000-plus possible multi-component alloys for their theoretical effectiveness in reducing nitrate, boron, and selenium.

Key Milestones:

- Draft manuscript tentatively titled "Machine Learning Methods for Catalyst Design in Water Treatment"

CHAPTER 3:
Results

Management and Operations

Website and Public-facing Outreach Activities

NAWI established a website that allowed Hub participants and the general public to obtain updates on the progress of the research program and access to data sets and software products (www.nawihub.org). Key features included:

- A publicly accessible section providing details of Hub research activities, calendars, and resources for prospective Alliance members
- A password-protected section providing access to data sets, software, and research products for Alliance members
- Monthly technical webinars (roughly 12 per year), which present updates on research progress and communicate research priorities to the Hub community.
- Annual meetings in 2020, 2021, 2022, 2023, and 2024 in which researchers and stakeholders interacted, shared results, and developed new research partnerships
- Interviews of NAWI leadership in numerous news and podcast sites about its work advancing the field of desalination. Highlights of these events included:
    - The Chip Franklin Show, August 20, 2021 — Interview with NAWI Executive Director Peter Fiske
    - *The Economist*, April 2, 2022 — The Promise and Pitfalls of Desalination
    - *Popular Science*, April 3, 2022 — Mini Desalination Plants Could Refresh the Parched West
    - *Physics Today*, September 19, 2022 — Bringing Arsenic-safe Drinking Water to Rural California
    - *New York Times*, June 6, 2023 — Beyond the Yuck Factor: Cities Turn to 'Extreme' Water Recycling
    - *Wired*, July 7, 2023 — Everyone Was Wrong About Reverse Osmosis — Until Now
    - *Nature*, November 21, 2023 — City-based Scientists Get Creative to Tackle Rural Research Needs
    - My Climate Journey Podcast, April 2, 2024 — Diving into Desalination with Peter Fiske

Research Solicitation Activities

In early 2022, NAWI issued a request for information on innovative, small-scale desalination and water-reuse technologies and systems. This effort was followed by a request for proposals to build and operate small-scale systems to treat unconventional water sources and achieve pipe parity (meaning similar- or higher-quality water than conventional water treatment methods produce).

In 2022, NAWI issued an internal proposal request process that involved the nomination of research subject areas from the NAWI Technical Team, followed by the solicitation of concept papers, followed by development of a set of invited full proposals.

In 2022, NAWI issued a Request-For-Information followed by a Notice of Intent and then an open Funding Opportunity Announcement for pilot-scale demonstrations of advanced desalination and water reuse systems. NAWI used a U.S. DOE-approved process involving external technical merit reviews and an internal Source Selection Committee to select 11 projects to proceed into negotiation.

Also in 2022, NAWI issued an internal proposal request process to select research projects focused on several specific areas of technology development not sufficiently represented in previous funding calls.

In 2023, NAWI announced an additional pair of processes to elicit research scope aligned with current active research projects. The Project Enhancement Grant process invited researchers to submit additional research proposals for tasks that would link two or more existing NAWI research projects. These were rigorously reviewed, and a subset was approved to begin activity in late 2023.

Finally, in 2023, NAWI announced a novel funding opportunity called the Rapid Reaction Fund to receive small (less than $50,000), short-duration (less than six months) research project proposals on a rolling basis that could rapidly advance a specific subject of water treatment or desalination. This program received 12 submissions since its inception and competitively selected six projects.

Water DAMS (NAWI 3.02)

Water DAMS (Water Data Analysis and Management System) is a flexible, secure, and adaptable data management system to facilitate automated data collection, standardization, secure internal data sharing, and public information dissemination. Water DAMS provides the U.S. DOE, CEC, and the public access to foundational data that enable researchers and decision-makers to identify and quantify opportunities for technology innovation to reduce the cost and energy intensity of non-traditional source water desalination and quantify the security, resiliency, and circular economy benefits of tapping non-traditional water sources.

Water DAMS is the submission point for all data generated by research conducted by NAWI and is used by the broader water research community.

With publicly accessible contributions from a variety of academic and industrial partners, Water DAMS seeks to enable data discoverability, improve accessibility, and accelerate collaboration

that contributes to pipe parity and innovation in water treatment technologies. Water DAMS, which is hosted externally on OpenEI and maintained by the NREL, provides:

1. Universal access to U.S. DOE-funded research projects and foundational data via a flexible, adaptable data management system
2. Insights so researchers and decision-makers may identify and quantify opportunities for technology innovation to reduce the cost and energy intensity of non-traditional source water desalination
3. Intuitive upload and submission processes, as well as standardized submissions and metadata, curated by a team of experts
4. Water DAMS also links directly with WaterTAP and the Water Technoeconomic Analysis Pipe Parity Platform (Water-TAP3), which are both available on GitHub, which is currently under development. This interconnection provides the most recent data to inform comprehensive calculations of technology performance and pipe-parity metrics.

Water DAMS support documentation and instructional videos are available on the Water DAMS website.[1]

Roadmap to Research and Development Cycle (NAWI 3.04)

The goal of this task was to develop and release a national Desalination Roadmap that tabulates current energy and cost baselines for the treatment of different non-traditional water sources and identifies the key technical barriers to lowering the cost and energy of desalination and water reuse.

To recycle wastewater while reducing energy use and water treatment costs, NAWI published five technology roadmaps (and one master roadmap) tailored to five sectors: power, resource extraction (which includes mining for minerals and oil), industrial, municipal, and agricultural, collectively identified as PRIMA and described in the following bulleted list. Many desalination technologies are still relatively expensive. But NAWI's roadmaps can guide technology developers and adopters to overcome technological and economic barriers as well as social and cultural hurdles.

- Power: NAWI researchers explored the economic and technical feasibility of extracting salt from seawater for use in power plants, for example, as well as reusing water that cools machinery in power plant facilities to keep them running safely.
- Resource Extraction: NAWI researchers assessed how novel water treatment technologies and strategies can help mining operations reclaim water used to clean quarried material. They also studied how the oil and gas industries could transition to new water treatment technologies to reclaim and reuse the wastewater generated from cooling the rigs used to extract oil from the ground.
- Industrial: Including food and beverage companies, data centers, and industrial campuses, industry makes up the fourth largest category of water use in the United

[1] https://www.nawihub.org/knowledge/water-dams/

States. In this study, researchers at NAWI explored the potential for industrial wastewater to serve as an alternative water resource for these same companies, irrigation of farms or city parks, or drinking water.

- Municipal: Two NAWI studies examined the cost and energy needed for alternative municipal water treatment methods and the challenges and opportunities of desalinating brackish water from groundwater, for use in irrigation or as drinking water.
- Agricultural: A significant amount of freshwater is used to grow fruits and vegetables and raise livestock in the United States. In fact, irrigation for farms may account for 42 percent of total freshwater use in the United States, according to the 2021 NAWI study, which examined the institutional and economic barriers preventing states from reusing agricultural drainage.

NAWI's master roadmap synthesized the highest-priority research needs for state-of-the-art, emerging, and existing desalination and advanced water technologies. In 2021 and 2022, NAWI added to its growing list of guides and tools, publishing eight foundational, sector-specific, baseline studies that provide a comprehensive assessment of challenges and opportunities associated with different source waters, which could help accelerate the creation of a circular water economy. Several of these studies relied on a new analytical tool developed by NAWI researchers. Called the Water Technoeconomic Assessment Platform, this tool evaluates water treatment costs, energy needs, environmental impacts, and resiliency trade-offs in a consistent manner across sectors.

To date, the five end-use roadmaps and the master roadmap have been downloaded more than 20,000 times.

PROTEUS (NAWI 4.02)

The PROTEUS project, later renamed WaterTAP, underwent significant modification during the project performance period. ProteusLib development began in 2020, with an initial library of water-specific property, process unit, and network models built on the IDAES framework. IDAES consists of computational tools that enable the use of advanced solvers and computer architectures for (1) process simulation and optimization, (2) process synthesis and conceptual design, (3) integration of multi-scale models, and (4) dynamic modeling and control. It includes an extensible, hierarchical model library that covers physicochemical properties and process units typically associated with chemical and energy production. NAWI leveraged the capabilities of IDAES and applied them to water treatment by developing property packages that represent the physical and thermodynamic properties for bulk and trace brine components in water sources of interest, process unit models of existing and novel water treatment technologies, and network models of water management systems.

PROTEUS also had an Excel-based techno-economic analysis tool that would take "0-D models" of water treatment unit processes (models that calculate a single operational parameter and do not resolve spatial or temporal variation in that parameter within the system) and enable users to calculate high-level treatment cost and energy usage for different water treatment trains.

Both PROTEUS and PROTEUSLib were merged in 2021 to create WaterTAP. WaterTAP is an open-source Python-based software package that supports the technoeconomic assessment of full water treatment trains. By merging PROTEUS and PROTEUSLib to form WaterTAP, NAWI sought to provide the broader water research community with an integrated modeling and simulation capability to consistently evaluate cost, energy, and environmental tradeoffs across water treatment options and identify high impact opportunities for innovation including novel materials, processes, and networks. WaterTAP uses open-source models and data indexed in the Water DAMS platform, NAWI's primary data repository.

To date, WaterTAP expanded to comprise more than 60 unit process models in its library and has been used by more than 20 research project teams within NAWI. WaterTAP training sessions in 2023 and 2024 exposed additional users to the tool, and several water treatment and design projects outside of NAWi successfully used the tool to optimize system design or perform detailed cost analysis.

Computational Test Bed for Predictive Fouling Control (NAWI 5.04)

This project aimed to develop a comprehensive methodology and test bed for evaluating fouling and scaling of RO membranes by developing computational models simulating feed flows and inorganic scaling in spiral-wound RO elements. The models sought to understand the formation and growth of scale and unsteady flow effects in the membrane module feed channel. An important element of this project was the development of experimental capabilities to quantify the fouling characteristics of commercial membranes and feed spacers for variable feedwater compositions. This testing capability produced data sets to validate model predictions of reduced membrane performance due to scale formation.

While the overall goals of building the physical testbed and developing high-fidelity models was accomplished, it became clear that detailed phenomena not captured in the fluid flow models dominated the process of scaling, and without an accurate geochemical model integrated with the fluid flow model, limited insights could be gained. Therefore, after achieving the immediate technical milestones described, the project was closed.

This project produced the following publication:

Jacob Johnston, Sarah M. Dischinger, Mostafa Nassr, Ji Yeon Lee, Pedram Bigdelou, Benny D. Freeman, Kristofer L. Gleason, Denis Martinand, Daniel J. Miller, Sergi Molins, Nicolas Spycher, William T. Stringfellow, Nils Tilton. 2023. "A Reduced-Order Model of Concentration Polarization in Reverse Osmosis Systems with Feed Spacers." *Journal of Membrane Science*. https://doi.org/10.1016/j.memsci.2023.121508

Machine Learning Platform for Catalyst Design (NAWI 6.02)

The team's goal was to identify, synthesize, and test new alloys that could electro-catalytically reduce nitrate in water to nitrogen gas or ammonia and that 1) were stable in water; 2) showed potentially high turnover frequency for NO3-; 3) had a large number of potentially active sites, and; 4) cost less than $500/kilogram (kg) (compared to $30,000/kg for platinum-

based alloys). Prior work mapped out the major reaction pathways for catalytic reduction of nitrate and provided the team with a head start on methods to predict how different alloys would perform as electro-reductive catalysts. NAWI further evaluated and refined the theoretical framework for identifying promising alloys and used NREL's EAGLE supercomputer to screen nearly 60,000 candidate alloys, many of which had never been synthesized.

NAWI initially found that nickel-based alloys seemed to have promising potential, but, after refining the team's theoretical methods, NAWI changed course and eventually found that a number of copper-based alloys appeared to fit the bill. Copper alloys had been known to have potential as an electrocatalyst for nitrate reduction, but the study identified a number of new alloys that looked particularly good. NAWI made some progress in synthesizing candidate alloys but didn't get as far as it had hoped, mainly due to COVID constraints on how and when researchers could access synthesis equipment and laboratory space. Some candidate compounds were not easily synthesized, and others showed the potential for deleterious reactivity. The research team is currently in the process of writing up some of the experimental results for journal submission and can provide more information to interested researchers.

This project produced the following publication:

Richard Tran, Duo Wang, Ryan Kingsbury, Aini Palizhati, Kristen Aslaug Persson, Anubhav Jain, Zachary W Ulissi. 2022. "Screening of bimetallic electrocatalysts for water purification with machine learning." JCP Emerging Investigators Special Collection. https://doi.org/10.1063/5.0092948

CHAPTER 4: Conclusion

NAWI achieved success and impact in its five years of operation. As a team, NAWI:

- Developed and published five sector roadmaps and a Master Technology Roadmap that were collectively downloaded more than 12,000 times. This definitive analysis influenced many other academic and industrial water treatment research programs (specifically, Rio Tinto).
- Developed WaterTAP, an open-source modeling tool built on the U.S. DOE's process systems engineering platform IDAES that enables researchers, developers, and system designers to collaborate on prioritizing new technology developments and quantifying the system benefits of treatment train innovations.
- Developed Water DAMS to provide access to foundational water treatment technology data that enables researchers and decision-makers to identify and quantify opportunities for technology innovations to reduce the cost and energy intensity of desalination. It is the submission point for all data generated by research conducted by the NAWI Alliance and is designed to be used by the broader water research community.
- Issued five competitive funding opportunities, eliciting nearly 600 concept papers and resulting in the selection of 54 research projects to date.
- Successfully convened six Alliance-wide meetings and three research consortium meetings and workshops, with a combined registration of more than 1,000.

NAWI's competitively awarded research projects have also begun to yield substantial innovations that reduce the cost and energy intensity of operational treatment systems. In the Budget Period 1 Funding Opportunity Announcement, NAWI funded six projects (commencing in the second and third quarters of 2021) focused on reducing the cost and carbon intensity of brine concentration through process characterization, optimization, and intensification.

While many of the funded projects in Budget Period 2 and Budget Period 3 are still active, several research teams have already reported a range of high-impact results aligned with NAWI's A-PRIME+C Challenge Areas that defined its competitive solicitations including:

A: Development and fielding of novel fault-resilient control and automation algorithms in a state-of-the-art non-RO Direct Potable Reuse Mobile Treatment Trailer in Aurora, Colorado.

P: The first successful use of theoretical materials discovery to identify low-cost electrocatalyst materials for selenium and nitrate reduction.

R: A major breakthrough in the team's understanding of water transport through reverse osmosis membranes.

I: Significant progress toward a low-compaction membrane for high pressure reverse osmosis that would significantly reduce the cost and energy consumption of brine concentration relative to state-of-the-art technologies.

M: A novel manufacturing platform for rapidly scaling the production of novel polymeric desalination membranes at square meter scales.

E: A universal and fully electrified pretreatment technology combining electrocoagulation (the process of removing suspended particles in water using electrically generated metal ions), electrooxidation (the process of using electrical current to generate oxygen radicals), and electroprecipitation (the process of using electrical current to drive suspended and dissolved constituents into particulate forms for physical separation) with submerged ultrafiltration membranes.

C: A generalizable, multi-scale framework for optimizing dynamic planning strategies of long-term infrastructure deployment and short-term drought response in urban settings.

Among the many learnings obtained so far in the NAWI program are several that relate to California's energy future. First, small-scale desalination and localized water reuse has a much lower carbon footprint than the same volume of water treated with large-scale centralized systems. Even though unit water treatment costs may be higher with small-scale systems, the avoided cost and greenhouse gases associated with building and maintaining a distribution system are substantial. Second, desalination should not be thought of as an isolated treatment process or water source: desalination is an integral tool in realizing California's needs for greater water reuse.

Scaling of NAWI innovations will largely require that the water sector applies these innovations in a wider range of water treatment environments and scales. NAWI's strategies to accelerate their further technical development and market adoption include: 1) building a large-scale Alliance program with more than 400 private-sector entities as members, 2) requiring that every research project have an industry partner, and 3) having each research project advised by a "Project Support Group" made up of industry advocates. These strategies allowed NAWI researchers to get direct and early advice for how to pivot their research ideas to the most valuable and implementable solutions that would have maximum market uptake.

One indicator of the national success of the NAWI program comes from the U.S. DOE itself. In March 2024, the U.S. DOE announced the renewal of the NAWI program for a second five-year term and an additional $75 million in federal funding.[2] NAWI will continue to invest in cutting edge technologies to lower the cost and energy of desalination and water reuse, moving to higher technology readiness level research. Most of NAWI's research will be in the form of fully operational pilots of novel water treatment unit processes and full treatment trains operating in realistic water production environments. The next five-year term ("NAWI 2.0) began in January 2025 and will run through December 2029.

[2] https://www.energy.gov/eere/articles/department-energy-announces-75-million-national-alliance-water-innovation-advance

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
A-PRIME	autonomous, precise, resilient, process-intensified, modular, and electrically
CEC	California Energy Commission
EPRI	Electric Power Research Institute
IDAES	Institute for Design of Advanced Energy Systems
kg	kilogram
LBNL	Lawrence Berkeley National Laboratory
NAWI	National Alliance for Water Innovation
NREL	National Renewable Energy Laboratory
PRIMA	power, resource extraction, industrial, municipal, agricultural
RO	reverse osmosis
U.S. DOE	U.S. Department of Energy
Water DAMS	Water Data and Analysis Management Systems
WaterTAP	Water Technoeconomic Analysis Pipe-Parity Program

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Hejase, Charifa A., et al. 2021. "Opportunities for Treatment and Reuse of Agricultural Drainage in the United States." *ACS ES&T Engineering*. https://pubs.acs.org/doi/abs/10.1021/acsestengg.1c00277

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CALIFORNIA ENERGY COMMISSION

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APPENDIX A: Publications and Communications

June 2024 | CEC-500-2025-xxx

APPENDIX A:
Publications and Communications

Project #	Title	Date Published	Type
3.02	The team gave a data management and submissions best practices training on February 8, 2021, to about 20 participants, most of whom were cartographers. There were a number of good questions asked during the training, and the overall feedback was positive.	2/1/2021	Webinar
3.02	The latest NAWI Water DAMS submission training video is available on YouTube here: https://youtu.be/wOMlnqbd8yI		Webinar
3.02	Weers, Jon. ""3.02 – Development, Deployment, and Refinement of the Water Technology Data and Analysis Management System (Water DAMS)." NAWI Peer Review 2023. May 9, 2023	5/9/2023	Presentation
3.02	Interactive Data Sharing and Collaboration: Water DAMS unconference session." NAWI Alliance Spring Meeting 2023. May 25, 2023	5/25/2023	Presentation
3.04	Sim, A.Y. and Mauter M.S.; Cost and Energy Intensity of U.S. Potable Water Reuse Systems, Environmental Science: Water Research & Technology, 2021, DOI: 10.1039/D1EW00017A https://pubs.rsc.org/en/content/articlehtml/2021/ew/d1ew00017a	2/1/2021	Journal Publication
3.04	PRIMA Roadmaps were released: Power Sector: https://www.nrel.gov/docs/fy21osti/79894.pdf	5/1/2021	Technical Report
3.04	PRIMA Roadmaps were released: Resource Extraction Sector: https://www.nrel.gov/docs/fy21osti/79895.pdf	5/1/2021	Technical Report
3.04	PRIMA Roadmaps were released: Industrial Sector: https://www.nrel.gov/docs/fy21osti/79886.pdf	5/1/2021	Technical Report
3.04	PRIMA Roadmaps were released: Municipal Sector: https://www.nrel.gov/docs/fy21osti/79889.pdf	5/1/2021	Technical Report
3.04	PRIMA Roadmaps were released: Agriculture Sector: https://www.nrel.gov/docs/fy21osti/79881.pdf	5/1/2021	Technical Report
3.04	The Agriculture, Seawater, and Unconventional/ Conventional Produced Water Baseline papers were submitted to ACS ES&T Engineering in July		Journal Publication

Project #	Title	Date Published	Type
3.04	The Mining Baseline paper was submitted to ACS ES&T Engineering in June		Journal Publication
3.04	Meese, Aidan Francis, et al. "Opportunities and Challenges for Industrial Water Treatment and Reuse." ACS ES&T Engineering. 2021. https://pubs.acs.org/doi/abs/10.1021/acsestengg.1c00244	10/20/2021	Journal Publication
3.04	Hejase, Charifa A, et al. "Opportunities for Treatment and Reuse of Agricultural Drainage in the United States." ACS ES&T Engineering. 2021. https://pubs.acs.org/doi/abs/10.1021/acsestengg.1c00277	11/17/2021	Journal Publication
3.04	Giammar, Daniel E., et al. "Cost and Energy Metrics for Municipal Water Reuse." ACS ES&T Engineering. 2021. https://pubs.acs.org/doi/10.1021/acsestengg.1c00351	12/6/2021	Journal Publication
3.04	Quon, Hunter, et al. "Pipe Parity Analysis of Seawater Desalination in the United States: Exploring Costs, Energy, and Reliability via Case Studies and Scenarios of Emerging Technology." ACS ES&T Engineering. 2021. https://pubs.acs.org/doi/10.1021/acsestengg.1c00270	12/8/2021	Journal Publication
3.04	Sophia L. Plata, Connie L. Devenport, Ariel Miara, Kurban A. Sitterley, Anna Evans, Michael Talmadge, Kurt M. Van Allsburg, Parthiv Kurup, Jordan Cox, Samuel Kerber, Andrew Howell, Richard Breckenridge, Cheyenna Manygoats, Jennifer R. Stokes-Draut, Jordan Macknick, and Amy E. Childress Zero Liquid Discharge and Water Reuse in Recirculating Cooling Towers at Power Facilities: Review and Case Study Analysis https://pubs.acs.org/doi/full/10.1021/acsestengg.1c00377	1/31/2022	Journal Publication
3.04	Xuesong Xu, J. Erik Ness, Ariel Miara, Kurban A. Sitterley, Michael Talmadge, Barbara O'Neill, Katie Coughlin, Sertac Akar, E. M. N. Thiloka Edirisooriya, Parthiv Kurup, Nalini Rao, Jordan Macknick, Jennifer R. Stokes-Draut, and Pei Xu* Analysis of Brackish Water Desalination for Municipal Uses: Case Studies on Challenges and Opportunities	2/24/2022	Journal Publication

Project #	Title	Date Published	Type
	https://pubs.acs.org/doi/full/10.1021/acsestengg.1c00326		
3.04	Cooper, Carolyn M., et al. "Oil and Gas Produced Water Reuse: Opportunities, Treatment Needs, and Challenges." ACS ES&T Engineering. 2021. https://pubs.acs.org/doi/10.1021/acsestengg.1c00248	12/13/2021	Journal Publication
4.02	Bartholomew, T.V.; Lee, A.; Miller, D.C.; ProteusLib: A Comprehensive Process Model Library for Optimizing the Design and Operation of Water Desalination Systems; AGU Fall Meeting; December 11,2020	12/11/2020	Conference
4.02	"ProteusLib: A new process modeling library for water treatment" by M&S team members Dr. David C. Miller, Dr. Timothy Bartholomew , Dr. Markus Drouven, and Dr. Deb Agarwal on February 22, 2021. https://vimeo.com/516470638	2/1/2021	Webinar
4.02	"ProteusLib: A new process modeling library for water treatment" by M&S team members Dr. David C. Miller, Dr. Timothy Bartholomew , Dr. Markus Drouven, and Dr. Deb Agarwal on February 22, 2021. https://vimeo.com/516470638	2/22/2021	Conference
4.02	Dudchenko, A.V.; Bartholomew, T.V.; Mauter, M.S.; Cost optimization of multistage gap membrane distillation. Accepted by the Journal of Membrane Science on February 25, 2021 https://www.sciencedirect.com/science/article/pii/S0376738821001782	6/1/2021	Journal Publication
4.02	Dudchenko, A.V.; Bartholomew, T.V.; Mauter, M.S.*, High Impact Innovations for High Salinity Membrane Desalination, Proceedings of the National Academies of Science, 2021, 10.1073/pnas.2022196118	9/1/2021	Journal Publication
4.02	Atia, A.; Young, E.; Knueven, B.; Allen, J.; Bartholomew, T. Cost optimization of low salt rejection reverse osmosis. Desalination. 2023, 551, 116407. https://doi.org/10.1016/j.desal.2023.116407	4/1/2023	Journal Publication
5.04	D. J. Miller. "Membrane Fouling: Laboratory Experiments to Predictive Models." Water: Grand Challenges for Molecular Science and Engineering. Telluride Science Research Center. July 14, 2021	7/14/2021	Conference

Project #	Title	Date Published	Type
5.04	J. Johnston, P. Bigdelou, S. M. Dischinger, M. Nassr, J. Y. Lee, N. Tilton, D. J. Miller, W. T. Stringfellow, N. Spycher, S. Molins Rafa, K. L. Gleason, B. D. Freeman. "Computational fluid dynamics simulations of unsteady vortex shedding and concentration polarization in reverse osmosis systems		Publication
5.04	P. Bigdelou, J. Johnston, S. M. Dischinger, M. Nassr, J. Y. Lee, N. Tilton, D. J. Miller, W. T. Stringfellow, N. Spycher, S. Molins Rafa, K. L. Gleason, B. D. Freeman. "Reduced-order models of concentration polarization in reverse osmosis systems with feed spacers."		Publication
5.04	S. M. Dischinger, M. Nassr, J. Y. Lee, K. L. Gleason, P. Bigdelou, J. Johnston, W. T. Stringfellow, B. D. Freeman, N. Spycher, S. Molins Rafa, N. Tilton, D. J. Miller. "Standard methods for characterization of mineral scale formation in crossflow reverse osmosis."		Publication
5.04	J. Y. Lee, W. S. Stringfellow, S. M. Dischinger, M. Nassr, K. L. Gleason, P. Bigdelou, J. Johnston, W. T. Stringfellow, B. D. Freeman, N. Spycher, S. Molins Rafa, N. Tilton, D. J. Miller. "Analytical method for determination of scaled area of reverse osmosis membranes.		Publication
5.04	S. Molins Rafa, N. Spycher, S. M. Dischinger, M. Nassr, J. Y. Lee, J. Johnston, P. Bigdelou, N. Tilton, K. L. Gleason, W. T. S. Stringfellow, B. D. Freeman, D. J. Miller. Predictive Models of Crossflow Reverse Osmosis Filtration from Geochemistry Models."		Publication
6.02	Jain, Anubhav: "Machine Learning Platform for Catalyst Design". NAWI webinar (virtual), Aug 13 2020	8/1/2020	Webinar
6.02	Kingsbury, Ryan: "An experimentalists guide to atomistic materials modeling". NAWI webinar (virtual), Oct 7 2020	10/1/2020	Webinar
6.02	Podar M, May AL, Bai W, Peyton K, Klingeman DM, Linson DAF, Mathieu J, Augusto D, Beneyto I, Stadler L, Pinhas Y, Löffler FE, Alvarez P, Kumar M. Microbial diversity of two full-scale membrane seawater desalination treatment trains provides insights into membrane biofilm formation. Journal of Membrane Science Letters JMS Letters 1(1)100001 https://www.sciencedirect.com/science/article/pii/S2772421221000015	12/1/2021	Journal Publication

Project #	Title	Date Published	Type
6.02	Lei Tao a 1, Jinlong He a 1, Tom Arbaugh b, Jeffrey R. McCutcheon c d, Ying Li e, Machine learning prediction on the fractional free volume of polymer membranes https://www.sciencedirect.com/science/article/pii/S0376738822008766?via%3Dihub	8/17/2022	Journal Publication
6.02	Richard Tran, Duo Wang, Ryan Kingsbury, Aini Palizhati, Kristin Aslaug Persson, Anubhav Jain, and Zachary W. Ulissi, "Screening of bimetallic electrocatalysts for water purification with machine learning" https://aip.scitation.org/doi/10.1063/5.0092948	8/17/2022	Journal Publication

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ENERGY RESEARCH AND DEVELOPMENT DIVISION

APPENDIX B: NAWI Alliance Membership as of December 23, 2024

June 2024 | CEC-500-2025-XXX

APPENDIX B:
NAWI Alliance Membership as of December 23, 2024

Organization (Org)	Date Signed
2S Water Inc.	10/25/2021
A2K Consultants, LLC	5/18/2022
AAW Infrastructure Partners	3/15/2024
ABT Inc.	3/1/2024
Acciona Agua Corporation	12/8/2021
ACQUA Solutions	11/8/2024
Active Membranes, LLC	3/20/2023
ADL Ventures	6/15/2020
Adrian Brozell	11/20/2021
Agua DB Ltd.	10/12/2021
AIChE, American Institute of Chemical Engineers	6/17/2020
AIL Research, Inc	10/9/2020
Alliance for Pulp & Paper Technology Innovation	2/22/2021
Ally Power Inc.	10/11/2022
Alpheus Water Fund	10/27/2020
Amantsy, Inc.	8/6/2020
Ambiunt Environmental and Regulatory LLC	9/10/2020
American Water Chemicals (AWC)	11/12/2023
American Waterworks Association	7/23/2020
Ames National Laboratotry	10/7/2020
ANSYS, Inc.	4/22/2024
Applied Specialties, Inc.	6/29/2020
Aqua Membranes Inc.	6/8/2021
Aqua Pulsar	1/19/2022
Aqua Research, LLC	3/26/2022
Aquagga Inc.	8/11/2020
Aquatech	10/26/2021
Arcadis	6/2/2021
Argonne National Laboratory	7/31/2020
Aris Water Solutions	12/8/2022

Organization (Org)	Date Signed
Arizona State University	6/15/2020
Ascend Engineering	4/24/2023
Atmospheric Water Generator, LLC d/b/a Quench Innovations	10/21/2020
Auburn University	9/15/2020
Aurora Water	7/27/2023
Avivid Water Technology, LLC	10/9/2020
Awtt, LLC	6/29/2020
Baleen Process Solutions	3/30/2021
Baryon Inc.	9/7/2022
Baylor University	2/2/2021
BeDimensional	7/9/2021
Bells Craig	7/29/2022
Beyond The Dome	10/10/2022
BioFiltro	3/20/2023
Bioionix, Inc.	3/30/2021
Biwater, Inc.	12/6/2022
Black & Veatch	5/11/2021
BlueDesal, Inc.	9/6/2022
BlueTech Research	10/30/2020
Bottom Up Enterprises	7/4/2020
BranchWater Solutions	4/8/2021
Brenntag	4/8/2022
Brewer Science, Inc.	7/29/2020
Brian Ray	11/14/2023
Brightwater Tools	8/15/2024
BRISEA Group, Inc.	12/26/2021
Brookhaven National Laboratory	11/9/2021
Brown and Caldwell	12/23/2021
Cactus Materials, Inc.	3/2/2021
California Department of Conservation	6/29/2020
California State Polytechnic University, Pomona	6/20/2022
California State University, Northridge	3/20/2023
California State University, San Bernardino	1/14/2022
Caltech	7/24/2020
CAP Holding	9/29/2021
Carnegie Mellon University	10/13/2020

Organization (Org)	Date Signed
Carollo Engineers	7/26/2021
Cascade Technologies, Inc.	8/7/2021
Casey Claborn	9/7/2022
CDM Federal Programs Corporation	4/1/2022
Cellen H2	12/20/2022
Central Valley Salinity Coalition	9/10/2020
CERAFILTEC US, LLC	1/23/2024
Cetos Water	11/8/2024
CGP, Inc.	10/20/2021
Chasm Advanced Materials	2/22/2021
Chemfinity Technologies, Inc.	7/31/2024
Chemsearch FE	11/14/2023
ChemTreat	1/31/2024
CHESS + Evans LLC	6/22/2021
Chevron Technology Ventures	2/10/2022
Chino Basin Desalter Authority	4/24/2023
ChloBis Water, Inc.	5/27/2021
ChlorTainer	4/30/2024
Chuck Hannon	9/8/2022
Cimarex Energy Co.	8/5/2020
City of Antioch	11/30/2021
City of Boulder	1/10/2024
City of Clearwater Public Utilities	5/8/2023
City of Goodyear	12/15/2020
City of Santa Barbara	4/21/2023
Clarkson University	4/6/2021
Clayste Energy Systems, Inc	12/1/2024
Clean Engineering Technologies Inc.	10/26/2020
Clean Water Ventures, Inc.	7/27/2021
CleanBlu Innovations, Inc.	10/24/2023
Clemson University	6/30/2020
Cliff Tsay	6/26/2020
Collaborative Energy	9/11/2022
Colorado School of Mines	12/14/2021
Colorado State University	7/6/2020
Columbia University	2/5/2022

Organization (Org)	Date Signed
Con Edison	3/16/2023
Concurrent Technologies Corporation	6/30/2020
Confluence, Water Technology Innovation Cluster	2/22/2021
ConocoPhilips	12/4/2020
CryoDesalination, LLC	11/16/2021
Crystal Clearwater Resources, LLC	8/7/2020
CSIRO: Commonwealth Scientific and Industrial Research Organisation	5/31/2021
Damilola Daramola (Individual)	1/19/2022
Daniel Leontieff (Individual)	2/17/2022
Darling H2O Consulting	6/16/2020
David Collins	5/31/2022
Day Zero Water	9/11/2022
DayLyte Batteries	5/17/2022
De Nora Holdings US Inc.	2/22/2021
Deep Blue	8/19/2024
Desolenator	12/7/2022
Diablo Water District	8/18/2021
Dietrich Consulting Group, LLC	12/8/2020
DiFilippo Consulting	9/10/2020
Driking Water Trust	10/24/2023
Drip.AI pte ltd	9/12/2024
DuPont Water Solutions	6/29/2020
Dynamita SARL	5/23/2022
Eastman Chemical Co.	8/3/2021
Ecomerit Technologies	2/18/2021
Eden Park Illumination, Inc.	6/9/2023
El Paso Water Company	6/21/2022
ElectroCell Systems	6/22/2022
Element Six Technologies US Corporation	1/24/2024
Elemental Excelerator	2/23/2021
Endress+Hauser	2/28/2023
Energi, Inc.	6/14/2023
Energy Recovery, Inc.	4/25/2024
EnergyX	2/1/2022
Enspired Solutions	12/12/2022
Environmental Defense Fund	2/10/2021

Organization (Org)	Date Signed
Environwave Solutions	4/24/2023
Epiphany Environmental, LLC	8/10/2020
EPR Consulting Services, LLC	7/29/2022
EPRI - Electric Power Research Institute	8/16/2021
Evaporation King	3/15/2024
Evoqua Water Technologies	4/30/2021
EVUS, Inc.	9/26/2021
ExxonMobil Upstream Research Company	9/11/2020
Finsterle GeoConsulting	5/26/2021
Florida Gulf Coast University	6/15/2020
Florida State University	1/7/2022
Floris Consulting	4/9/2022
Flow-Tech Systems	12/8/2020
Fluid Technology Solutions, Inc.	10/17/2022
Foss Toilets	1/24/2024
Franklin W. Olin College of Engineering, Inc.	3/27/2023
FREDsense Technologies	8/3/2022
Freeport McMoRan - El Paso Refinery	5/31/2022
FSubsea AS	5/3/2023
Garver	3/3/2021
Gary Hines (individual)	10/26/2020
GeneBiologics	7/28/2022
Genus-Bioenergy	9/28/2020
Geofabrica, Inc.	1/14/2022
George Mason University	10/26/2020
George Washington University	10/1/2020
Georgia Tech Research Corporation	7/6/2020
Geosyntec Consultants Inc.	9/7/2020
Giner Inc.	5/2/2022
Glacier Tecnologies International Inc.	11/9/2021
Glanris	3/23/2023
Global Energy Mentors	1/26/2022
Global Oasis, LLC	6/26/2023
Global Research and Development Inc.	8/5/2020
Global Water Innovations, Inc.	7/13/2020
Global Water Technologies	7/31/2024

Organization (Org)	Date Signed
Glycosurf, Inc.	4/7/2022
Golder Associates Inc.	4/5/2021
Gradiant Corporation	6/15/2020
Great Lakes Water Authority	2/14/2022
Greeley & Hansen	2/19/2021
Green Zero Energy Solutions	7/9/2021
GreenBlu	9/16/2020
GreenTech California	6/29/2020
GreenTech California (GTC), Inc. {Delaware Public Benefit Corporation}	10/26/2020
Greg Bohannon	7/13/2021
GVD Corporation	9/9/2022
Hach	10/21/2023
Hallmark Group	4/26/2023
Harmony Desal	1/19/2022
Hawaii Natural Energy Institute	11/23/2021
Hazen and Sawyer, D.P.C.	4/21/2023
Hess Corporation	4/7/2021
Hetrom Technologies, Inc	7/11/2022
HMD Systems	10/11/2022
Hydroflow USA, LLC	7/29/2022
Hypore Environmental Solutions LLC	10/14/2022
Idaho National Laboratory	6/29/2020
IDE Technologies	9/10/2020
Imagine H20	6/12/2020
InCtrl Solutions	5/17/2022
Indra Water	1/24/2024
Inframark	7/29/2022
Innov8ai Inc.	7/28/2022
Innovative Treatment Products, Inc. (Innovatreat)	8/15/2024
IntelliFlux Controls, Inc.	3/30/2021
International Code Council	8/14/2024
International Desalination Consulting Associates LLC	6/15/2020
Intuitech, Inc.	3/4/2022
Iowa State University	6/30/2020
Isle, Inc.	11/14/2023
IX Power Clean Water, Inc.	10/24/2023

Organization (Org)	Date Signed
J M Smith International, LLC	9/25/2020
Jacobs Engineering Group, Inc.	12/5/2022
Jamie Niu	4/19/2024
Jerri Pohl	2/24/2023
JMCS Services	12/5/2022
Kairospace Technologies	4/7/2022
Karl E. Longley	3/2/2023
Karl Seckel	3/1/2021
Katz Water Technologies	9/15/2020
Kazadi Enterprises	11/17/2021
KB Science	2/23/2021
Kennett Technologies	5/12/2022
Kent Dawson (Individual)	3/4/2022
Kiewit	1/17/2024
KII, Inc	12/7/2020
Kim Adamson	11/15/2023
KIT Professionals, Inc.	9/29/2021
Knowlege Ops, Inc.	8/5/2020
Knoxville Utilities Board	1/14/2022
Las Virgenes Municipal Water District	12/24/2021
LASAN and Environment	10/30/2023
Lauren Greenlee	5/1/2024
Lawrence Berkeley National Laboratory	5/21/2020
Lawrence Livermore National Laboratory	6/15/2020
Lehigh University	9/10/2020
Lewis Bay Research Center, Inc.	4/26/2023
Lincus, Incorporated	9/15/2020
Little Green Bamboo	4/4/2023
Local Bounti	4/13/2022
Los Alamos National Laboratory	6/17/2022
Louisiana State University	7/27/2023
M. Davis & Sons Inc.	12/23/2021
Magna Imperio Systems	6/22/2020
Magrathea Metals	10/11/2022
Marina Coast Water District & Groundwater Sustainability Agency	7/3/2024
Massachusetts Institute of Technology (MIT)	10/7/2021

Organization (Org)	Date Signed
Matt Clement	5/12/2022
Max-IR Labs	12/27/2021
MBL Energy	7/28/2021
MEDRC	5/25/2022
MegaVessels, Inc	11/8/2023
Membrion, Inc.	7/22/2020
Meridian Institute	3/7/2022
Mesa Advisors	8/3/2023
Metropolitan State University of Denver	11/11/2024
Metropolitan Water District of Southern Ca	7/23/2020
Mezzetti & Associates	6/23/2021
Michigan State University	9/29/2020
Michigan Technological University, Department of Chemical Engerring	8/21/2023
Mickley & Associates, LLC	2/22/2021
Mickols Consulting, LLC	9/30/2020
Micronic Technologies	8/17/2020
MICROrganic Technologies, Inc.	4/7/2022
Minerals Technologies	7/27/2021
Modelon, Inc.	8/19/2021
Municipal Water District of Orange County	7/13/2021
NALA Systems	5/26/2021
Natasha Wright	1/19/2021
National Energy Technology Laboratory (NETL)	11/12/2020
National Renewable Energy Laboratory (NREL)	9/8/2020
National Water Research Institute	6/30/2020
Natural Ocean Well Co.	8/5/2020
NavNeet Roa	3/19/2024
New Jersey Institute of Technology	6/30/2020
New Logic Research	11/11/2023
New Mexico State University	7/23/2020
New York State Center for Clean Water Technology	12/11/2020
Newterra Corporation Inc.	6/15/2023
Nexight	10/16/2020
Next Rung Technology	9/15/2020
NFAqua Consolidated Inc.	9/6/2022
Niagra Bottling	8/8/2022

Organization (Org)	Date Signed
Niterra Co., Ltd.	9/9/2024
NLB Water LLC	10/19/2020
Nooter Eriksen Water Solutions	10/5/2022
Noria Energy	11/20/2023
Noria Water Technologies, Inc.	6/29/2020
North East Biosolids & Residuals Association	5/16/2024
NOVA	6/15/2020
NOVA Geotechnical & Inspection Services	7/23/2020
NUMiX Materials, Inc	6/15/2020
Oak Ridge National Laboratory	7/14/2020
Ocean Pacific Technologies	6/20/2020
OceanSpace LLC	11/8/2024
Oceanus Power & Water, LLC	12/11/2020
OceanWell	8/14/2024
Ohio State University	9/28/2020
Ohio University	1/7/2022
OHM Advisors	11/30/2022
Oisann Engineering, Waterfountain	7/2/2021
OLI Systems, Inc.	7/14/2020
Olokun Minerals	6/11/2024
Onvector LLC	9/12/2020
Orange County Water District	7/16/2020
Oregon State University	8/19/2024
Pacific Northwest National Laboratory	9/3/2020
Pacific Research Group	6/15/2020
Pacifica Water Solutions	6/15/2020
Partanna	6/17/2023
Partnership International, Inc.	12/8/2021
Paul Deuter	12/28/2021
Pax Scientific, Inc.	9/9/2022
Peckham P.G., LLC	11/21/2020
Pennsylvania State University	11/10/2022
Pepsi Co.	10/21/2020
Permionics Separations, Solutions, Inc.	10/16/2021
Perpetual Water	3/26/2021
Personal Water Systems	8/21/2023

Organization (Org)	Date Signed
Pheneovate Graphene	6/12/2020
Phillips 66	7/16/2020
Physical Sciences Inc	6/3/2024
Pia Ramos (Individual)	12/4/2022
Pioneer Natural Resources	1/4/2023
Pivotal Fluid Solutions	3/15/2024
Plug Power	6/3/2024
Posy Global	3/14/2022
Powell Water Systems, Inc.	10/27/2023
PRD Tech, Inc.	2/17/2021
Princeton University	7/24/2020
Priti Brahma	9/6/2022
ProcessWerx LLC	5/31/2024
Produced Water Recycle, LLC	2/12/2024
Punhasa Senanayake (Individual)	3/20/2023
Purafide	4/25/2022
Purdue University	9/11/2020
Pure Blue Tech, Inc.	10/23/2021
Pureous Products, LLC	9/15/2020
Puriphied	8/14/2024
Quinbrook Infrastructure Partners	4/26/2022
Quinbrook Infrastructure Partners	4/26/2022
Reactwell	10/15/2021
Refinery Water Engineering & Associates	9/2/2020
Rema Slutions	4/25/2023
Resolute Marine Energy, Inc.	8/5/2020
Resolved Analytics	9/25/2020
Resource Monitor	1/23/2024
ReThinkH2O	7/8/2020
Rich Earth Institute, Inc.	9/11/2020
Rio Tinto Services Inc.	3/15/2022
RJ Lee Group	11/2/2020
Roadrunner Venture Studios	8/19/2024
Robert Bosch LLC	12/7/2020
Rockwell Automation	12/4/2020
RODI Systems Corp.	6/30/2020

Organization (Org)	Date Signed
Roya Mansour (Individual)	2/11/2022
RyKor LLC	8/5/2020
Sally Gutierrez Water Consulting	4/18/2024
Salt River Project	2/12/2024
Saltworks Technologies Inc.	12/18/2020
San Diego State University	9/2/2020
Sandia National Laboratories	1/13/2021
Sanjana Chintalacheruvu (Individual)	3/22/2023
Santa Ana Watershed Project Authority	12/23/2021
Saurwin Inc.	7/28/2022
Schneider Electric	8/18/2021
Select Energy	5/25/2022
Sentry: Water Monitoring & Control	3/9/2022
Sephton Water Technology, Inc.	4/15/2021
Sierra Nevada Brewing Co	8/27/2024
SIVI LLC	9/10/2020
SK Innovation	4/30/2021
SLAC National Accelerator Laboratory	5/6/2021
Solar Multiple LLC	6/3/2024
SolMem LLC	1/12/2021
South Dakota School of Mines and Technology	1/19/2022
Southern Company Services, Inc.	7/23/2020
Southwest Research Institute	10/20/2020
Sparkflow LLC	11/16/2024
Spectra Watermakers/Katadyn Group	6/23/2021
Spiral Water Technologies, Inc	2/3/2024
Square One Coating Systems, LLC	12/23/2021
Stanford University	10/26/2020
Sterlitech Corp	5/12/2022
Stewart Environmental	3/30/2021
Stony Brook University	6/22/2020
SUDOC, LLX	10/1/2020
Sunchem	3/25/2023
Sunny Clean Water LLC	6/29/2020
Sunvapor, Inc	9/14/2020
Surge H2O	10/27/2023

Organization (Org)	Date Signed
Susheera Pochiraju (Individual)	3/20/2023
Sustainable Design & Consulting, LLC	5/28/2022
Sustainable H20 Technologies	10/18/2022
Sustainable Synthesis Limited, PBC	4/29/2021
Swenson Technology, Inc.	5/2/2023
Sylvan Source	8/18/2020
Tallgrass Water	10/26/2020
Talon Metals	2/24/2023
Tennessee Technological University Water Center	7/8/2020
Tennessee Valley Authority (TVA)	11/28/2021
Terra Seco Solutionws	3/1/2023
Tetra Tech, Inc.	2/3/2022
Texas A&M Engineering Experiment Station (TEES)	2/18/2021
Texas A&M University-Kingsville	10/2/2020
Texas A&M University-San Antonio	4/4/2022
Texas Tech University	9/15/2020
The 3D Printing Store	6/26/2020
The Board of Regents of the University of Wisconsin System	3/8/2023
The Dow Chemical Company	2/10/2022
The Estee Lauder Companies	8/19/2024
The Grand Water Research Institute	8/22/2021
The Salt Miner LLC	2/23/2021
The University of Alabama	10/15/2021
The University of Texas at Austin	8/7/2021
The Water Council	9/8/2020
The Water Research Foundation (WRF)	12/14/2020
The Water Tower	12/10/2020
Thermojunction Technologies	7/13/2021
Thomas Wolfe	8/26/2020
tntAnalysis	12/29/2021
Tomorrow Water	6/17/2020
Toray Membrane USA, Inc.	6/29/2020
Total Event & Association Management, Inc.	10/16/2020
Tracy Still (Individual)	8/20/2024
Transcend	8/14/2020
Trevi Systems, Inc.	8/5/2020

Organization (Org)	Date Signed
Triangle Institute LLC	6/20/2023
Trident Desalination Inc.	3/30/2021
Trident Environmental	7/13/2021
Trimeric Corporation	6/4/2021
True North Venture Partners	9/10/2020
Trussell Technologies, Inc.	12/24/2021
TSFGroup.us	11/29/2022
Tufts University	8/25/2020
TWB Environmental Research and Consulting, Inc.	6/22/2020
Tyson Foods, Inc.	12/22/2020
University of Arizona	1/4/2021
University of Arkansas	10/8/2020
University of Arkansas at Little Rock	1/27/2023
University of California, Berkeley	9/28/2021
University of California, Davis	2/15/2022
University of California, Irvine	3/24/2022
University of California, Los Angeles	7/21/2020
University of California, Merced	10/26/2020
University of California, Riverside	6/30/2020
University of California, Santa Barbara	1/4/2022
University of Cincinnati	8/20/2020
University of Colorado	9/2/2020
University of Connecticut	6/4/2021
University of Delaware	8/5/2020
University of Georgia	10/17/2023
University of Hawaii at Manoa	5/3/2021
University of Houston	8/5/2020
University of Illinois at Chicago	4/21/2021
University of Illinois Urbana-Champaign	1/12/2022
University of Maryland, Baltimore County	11/18/2021
University of Michigan	7/21/2020
University of Missouri-Columbia	3/22/2021
University of New Hampshire	7/23/2020
University of New Mexico	8/25/2020
University of North Carolina at Chapel Hill	3/23/2021
University of North Carolina, Charlotte	10/22/2021

Organization (Org)	Date Signed
University of Oklahoma	9/28/2020
University of Pittsburgh	8/12/2020
University of Southern California	8/5/2020
University of Tennessee	7/29/2020
University of Texas at Dallas	7/28/2022
University of Texas at El Paso	10/20/2020
University of Texas Permian Basin	4/26/2022
University of Toledo	7/14/2020
University of Utah	2/11/2022
University of Virginia	3/27/2023
University of Wyoming	8/12/2020
Urban Land Institute	6/15/2020
Urban Rain Gardens	7/29/2022
US Bureau of Reclamation	2/18/2022
USG Corporation	5/26/2021
Ushio America Inc.	4/14/2024
Utah State University	6/30/2020
Valley Water	6/29/2020
Vanderbilt University	10/27/2020
Verico Technology	4/17/2024
Vern Novstrup	11/8/2024
Verno Water, Inc.	3/23/2021
Via Separations	4/18/2024
Virginia Polytechnic Institute and State University	10/2/2020
Virtual Curtain Limited	4/2/2024
Virtus Resource Association	10/17/2022
Voltea, Inc.	6/10/2022
Vortex Engineering	9/7/2022
Washington University in St. Louis	8/13/2021
Waste To Power And Water llc	1/30/2024
watec.nevada	10/4/2020
Water and Waste Management (WWM) International	10/24/2023
Water Bros Desalination, LLC	7/28/2022
Water Cycle LLC	8/21/2023
Water Innovation Accelerator	5/4/2021
Water Replenishment District of Southern California	5/16/2024

Organization (Org)	Date Signed
Water Research Consulting LLC	5/18/2023
Water Reuse Technology, Inc.	3/28/2022
Water Unity Networks	5/7/2024
WATERFX Innovations	6/16/2020
WaterStart	9/8/2022
WaterTectonics	9/14/2020
WaterUS LLC	11/8/2024
Wayne State University	7/14/2021
West Basin Municipal Water District	11/17/2022
West Point	7/22/2022
West Virginia University Research Corp for West Virginia University	9/10/2020
West Yost	3/4/2022
Westlands Water District	8/3/2023
Wild Horse Innovation, Inc.	3/30/2021
William Marsh Rice University	6/15/2020
Wisewater Global, LLC.	2/22/2021
Wist Inc.	10/18/2020
Xiaoyu Tang	6/16/2023
XiO	7/13/2020
XPrize	3/21/2024
Xylem	5/7/2021
Yale University	5/27/2021
Yalin Li	5/12/2022
Yokogawa Corporation of America	5/5/2022
zNano WaterTech	12/10/2020
ZwitterCo, Inc.	2/22/2022