U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Advanced Manufacturing Office Clean Water Processing Technologies

Workshop Series Summary Report

November 5-6, 2015
San Francisco, CA

July 10-11, 2017
Dallas, TX

August 23-24, 2017
Cleveland, OH

March 2018

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Foreword

The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

This document was prepared for DOE/EERE's AMO as a collaborative effort between DOE AMO and Energetics Incorporated, Columbia, MD.

Nomenclature or List of Acronyms

3D	Three-dimensional
AMD	Abandoned mine drainage
AMO	Advanced Manufacturing Office (DOE)
ARPA-E	Advanced Research Projects Agency-Energy
BBtu	Billions British thermal unit
BFD	Block flow diagram
BTEX	Benzene, toluene, ethylbenzene and xylene
C	Degree Celsius
CapEx	Capital expenses
CBM	Coal bed methane
CDI	Capacitive deionization
CHP	Combined heat and power
CP	Concentration polarization
CSP	Concentrated solar power
CT	Current typical energy consumption
CWA	Clean Water Act
DAF	Dissolved air flotation
DC	Direct current
DOE	U.S. Department of Energy
ECOP	Exergy coefficient of performance
ED	Electrodialysis
EDI	Electrodeionization
EERE	Office of Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FGD	Flue gas desulfurization
FO	Forward osmosis
GIPP	Generation for Interconnection Pilot Program
GIS	Geographic Information System
GOR	Gained output ratio
GPM	Gallons per minute

HDH	Humidification-dehumidification
IP	Intellectual property
IRR	Internal rate of return
kg	Kilogram
kWh	Kilowatt-hour
LCA	Life cycle analysis
LCOE	Levelized cost of energy
LCOW	Levelized cost of water
m	Meter
m^3	Cubic meter
MCDI	Membrane capacitive deionization
MD	Membrane distillation
MED	Multiple effect distillation
MF	Microfiltration
MFS	Multistage flash distillation
mg/L	Milligrams/liter
MGD	Million gallons per day
MIT	Massachusetts Institute of Technology
MJ	Megajoule
MLD	Minimum liquid discharge
MYPP	Multiyear program plan
MVC	Mechanical vapor compression
MW	Megawatt
MWh	Megawatt-hour
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NF	Nanofiltration
NGO	Non-government organization
NIST	National Institute of Standards and Technology
NNMI	National Network for Manufacturing Innovation
NORM	Naturally occurring radioactive materials
NPDES	National Pollution Discharge Elimination System

NREL	National Renewable Energy Laboratory
O&G	Oil and gas
O&M	Operations and maintenance
OpEx	Operational expenses
ORNL	Oak Ridge National Laboratory
Quad	Quadrillion British thermal units (Quads)
PAA	Paracetic acid
PEC	Pulse electro-coagulation
pH	Potential of hydrogen (scale)
PI	Process intensification
PM	Practical minimum energy consumption
PNNL	Pacific Northwest National Laboratory
PPA	Power purchase agreement
ppm	Parts per million
PV	Photovoltaics
R&D	Research and development
R2R	Roll-to-roll
RD&D	Research, development and demonstration
RO	Reverse osmosis
ROI	Return on investment
SAR	Sodium adsorption ratio
SDI	Slit density index
SME	Subject matter expert
SOA	State of the art
SWRO	Seawater desalination reverse osmosis
TDS	Total dissolved solids
TEA	Trace element analysis
TM	Thermodynamic minimum energy consumption
TRL	Technology readiness level
TSS	Total suspended solids
TVC	Thermal vapor compression
UF	Ultrafiltration

UIC	Underground injection control
USGS	U.S. Geological Survey
ZLD	Zero liquid discharge

Executive Summary

The U.S. Department of Energy (DOE) Advanced Manufacturing Office (AMO) held a series of three clean water processing technologies workshops focusing on technical challenges and opportunities. The first workshop focused on energy optimized desalination technology development and was held in San Francisco on Nov. 5th and 6th, 2015 at the Hilton San Francisco Union Square. The next two occurred in summer 2017 starting with a workshop held in Dallas, Texas at the Hilton Dallas Lincoln Centre on July 10th and 11th, 2017 followed by the third workshop in Cleveland, Ohio at the Wyndham Cleveland at Playhouse Square on August 23rd and 24th, 2017. Below is a high level summary of scope and outcomes from each workshop.

Energy Optimized Desalination Technology Development Workshop, November 5-6, 2015 (San Francisco, CA)

The first workshop was intended to bring together experts in desalination to discuss research and development (R&D) needs of promising desalination approaches for fresh-water at lower energetic, economic, and environmental costs comparable to existing technologies. Participants considered various water markets – municipal, agricultural, industrial, and produced water – and discussed both the current state-of-the-market and associated challenges and opportunities. They also gave their informed views on what should be the R&D priorities (such as thermal, pressure-based, and concentrate management technologies) and explored system integration challenges to include environmental, health, and safety issues; intake/outfall management; and energy and water network integration.

Clean Water Processing Technology Research and Development Workshops, July 10-11 and August 23-24, 2017 (Dallas, TX and Cleveland, OH)

The second and third workshops brought together leading scientific and technical experts across a range of clean water technologies to discuss opportunities for major advancements in science and technology for processing of clean water by exploring early-stage R&D in a broader array of clean water processing technologies. The workshops were organized under the broad themes of water purification and water systems integration with desalination included as part of this wider examination of clean water technologies.

In particular, a water purification theme track considered membrane and non-membrane based technologies (including integration of solar-thermal power with desalination), as well as pre-and post-treatment processes. The water systems integration track included topics such as sensors and controls (smart systems); intake, transport, and handling of water to include effluent processing and disposal; and water purification plant design and operation and maintenance (O&M) issues. The Cleveland workshop also included a cross-cutting water processing track that examined process intensification (PI), integration of renewable energy with desalination, and materials and minerals co-production.

This report first contains a synthesized summary of the results of the three workshops (Section 1). The results are presented in the manner in which the workshops were organized. The report then presents a summary of the workshop results (Section 2). Owing to its more specific focus, the San Francisco workshop results are presented separately, while the Dallas and Cleveland workshop results are combined. All results are based upon detailed feedback provided by the breakout session participants, key comments captured by note-takers during the ensuing discussions, and the session summaries presented to the entire audience at the conclusion of each breakout session.

Key themes discussed in the workshops include:

- Foundational scientific discovery and knowledge that will lead to new ideas generation and technical insights for materials, processes, components and systems to enable advances in: separations; water reuse; water and energy efficiency; process/system flexibility and integration with readily available heat and energy sources; smart water systems; alternative process designs; distributed water processing; water substitutes; the appropriate handling of concentrate as not to affect local or regional ecosystems; and other next generation clean water technologies.

- The importance of collaboration among material experts, process experts, and testing experts to improve/develop enabling technologies described above to meet cost and energy intensity targets.

During the breakout sessions, a set of priority topics for R&D emerged from discussions on the challenges and R&D needs identified. These topics represent areas where a concerted effort in R&D could help to overcome major material and technology barriers. The topics are summarized in section 2 (organized by topic).

The results presented here are not intended to be comprehensive of all topics discussed but rather they are a summary of those capabilities and opportunities that are relevant to stakeholder needs, potential metrics, challenges / barriers to moving forward, and identified R&D needs.

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1. Description and Scope of the Workshop Series

This chapter provides a high-level overview of the current technical challenges and research and development (R&D) needs of next-generation clean water production systems with special emphasis on desalination processes. It also provides a framework for the development of key technical targets, some of which are explored in the Advanced Manufacturing Office (AMO) multi-year program plan (MYPP) technology section on Clean Water[1]. Furthermore, the chapter summarizes the benefits, scope, plenary discussions as well as organization and collaboration opportunities of the clean water workshop series.

1.1. Introduction

Water scarcity, variability, and uncertainty are becoming more prominent, potentially leading to vulnerabilities in the U.S. energy infrastructure, which depends on water for energy harvesting and electricity generation, as noted in the U.S. Department of Energy's (DOE's) 2014 Water-Energy Nexus report[2]. The intertwined nature of water and energy are notable; thermoelectric cooling in power plants requires withdrawal of large quantities of water, hydraulic fracturing requires injection of water, and the extraction of oil and gas is accompanied with significant extraction of water.

Water sources are diverse; they include surface, ground, brackish, sea and produced water (such as those from oil and gas extraction). In addition, there is waste water from industrial and municipal use. We depend, however, largely on freshwater, since the purification requirements are low and access easy, in relation to the other sources. Purifying water from a given source for a specified need requires energy and tends to become more challenging with increasing salinity and impurities as depicted graphically in Figure 1.1.1. The purified water has a broad range of applications including municipal (drinking, etc.), agricultural, hydraulic fracturing, and industrial uses or needs.

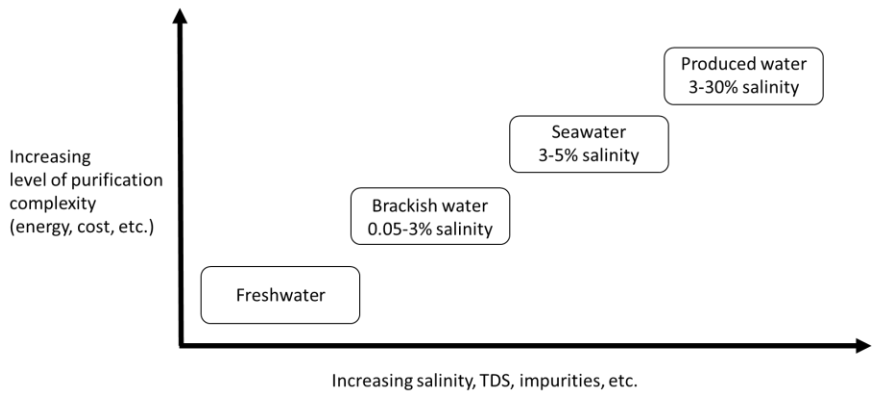


Figure 1.1.1 An illustration of the purification process energy, cost, etc. needs as function of salinity and impurity levels for four types of water sources.

Freshwater (surface, lake, and ground water) constitutes only about 3% of all the world's water. It is primarily withdrawn for municipal systems and agricultural needs but is additionally used for industrial, mining and thermoelectric cooling applications (> 40% of freshwater withdrawals in the U.S. are for power plants).

[1] https://energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017
[2] https://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities

Technologies for water treatment include coagulation and flocculation, sedimentation, filtration, and disinfection and removal of bio-contaminants.

Brackish water (0.05-3% salinity) may result from the mixing of seawater with fresh water, as in estuaries, or it may occur in brackish fossil aquifers. There are lakes and estuaries widespread throughout the U.S., for example in the arid southwest, Louisiana and Florida (lakes), and Delaware and Chesapeake Bays (estuaries). Treatment requires a degree of desalination in addition to the other steps.

Seawater (3-5% salinity) is a vast source of water that could potentially be an important supplement to water supplies in coastal areas. Civilian and military populations on islands could also increase their self-sufficiency if seawater could be efficiently utilized. Domestic processing of seawater currently relies on energy-intensive desalination. Today, seawater desalination approaches in the U.S. are dominated by reverse osmosis (RO).

Produced water (3-30% salinity) is the largest volume waste stream associated with hydrocarbon recovery. This water can be high in dissolved solids, metals, hydrocarbons and, sometimes, naturally occurring radioactive materials (NORM). Depending on the constituents, produced water can be mixed with freshwater to enable its reuse as fracturing fluid makeup water in subsequent wells. The current cost of re-injecting the contaminated water is approximately $5-6/m^3. Currently, in many cases, the costs of cleaning up the produced water stream exceed those of transport, disposal, and replacement from natural sources of freshwater. If cost-effective technologies are developed, treated produced water could potentially offset water needed for other uses (e.g., agricultural use or mineral extraction and processing). Desalination poses a challenge with regards to the hard-salts clogging pores, but offers opportunities as the concentrated salts favor new technology approaches such as forward osmosis (FO).

Sustainable water management requires the consideration of the 97% of water sources beyond freshwater. Vast amounts of untapped water resources could be utilized if key technical challenges are addressed, including processing and purifying of water in a low cost and energy-efficient manner. Wastewater, for example, which mainly sources out from industrial facilities is another category that could be added to the list of water sources listed in Figure 1. There are technologies to extract more energy from sludge, however, additional process improvements are required to make these processes more cost effective as there are some system integration barriers.

A common challenge to water purification is the wide variety of water sources and contaminants, both in type and quantity, making a single solution hard to achieve. This affects the energy intensity of the purification process. In general, energy intensity tends to increase with contaminant concentration. The opportunities in the energy savings space are, however, broader than one of minimizing energy use for steady-state water purification under constant conditions. Impurity levels and types and water temperatures may vary. If water can be purified in large amounts, then there are associated issues as to how to integrate with the electric grid; e.g., Can electricity storage be replaced with water storage? Can renewable power be integrated directly with purification systems?

Improvements in membrane performance are also essential to remove a wide array of impurities while enabling high throughput of recovered water. The development of cost-effective membrane separators with embedded and connected sensor technology (smart systems) to monitor when membrane systems need to be flushed or otherwise serviced is an opportunity. The entire system (intake, purification technology, power supply) needs to be integrated to enable optimal performance.

Technology advancements represent an opportunity for domestic suppliers of water purification systems to manufacture critical components and parts, including the design and manufacture of large-scale systems. Systems need to operate in a dependable way to ensure a consistent and safe water supply. Process materials such as pipes and pumps need to withstand harsh operating environments such as high pressures, corrosive salt concentrations, and bio-fouling. The costs of these components as well as the entire physical infrastructure need to be reduced, including for seawater desalination. Opportunities might include modular designs and process intensification (PI) approaches.

Investments in early-stage R&D opportunities that enable cost-effective and energy efficient clean water production are therefore needed. These investments will enhance U.S. manufacturing competitiveness and further the Administration's priority to ensure clean water supplies.

There has been an increasing interest in clean water R&D initiatives that focus on improving flexibility of clean water purification systems so they can accommodate a variety of water sources as well as utilize different sources of energy. These requirements present challenges as well as opportunities to advance the capabilities of current clean water production systems. For example, identifying the most energy intensive processes and/or sub processes provide opportunities to investigate potential energy savings, and can inform R&D investments in clean water production systems.

At the national scale, flows of energy and water are intrinsically interconnected, in large part due to the characteristics and properties of water that make it so useful for producing energy and the energy requirements to treat and distribute water for human use. This interconnectivity can be seen in the Sankey Diagram in Figure 1.1.2, which captures the magnitude of energy and water flows in the United States.

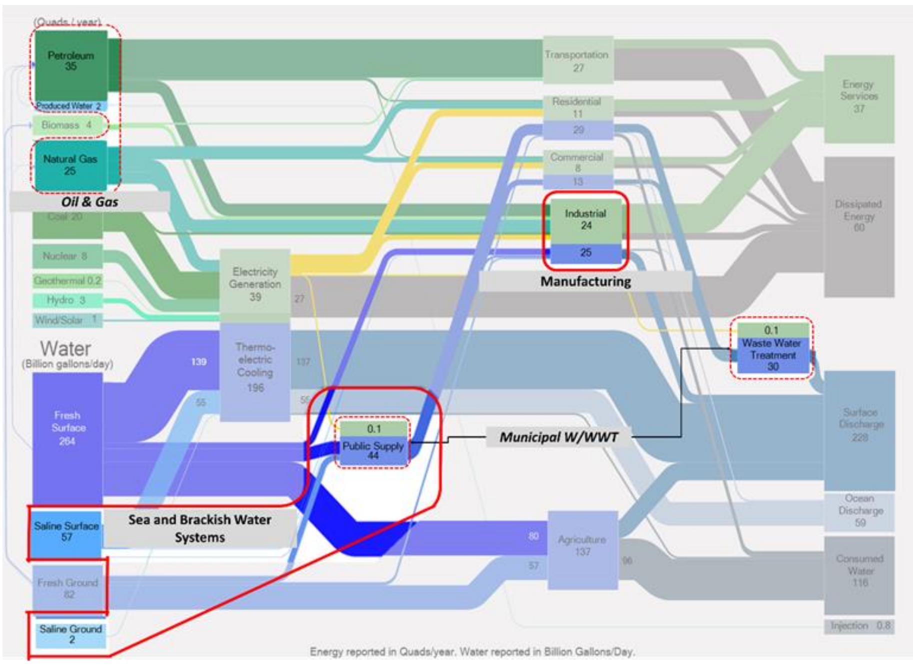


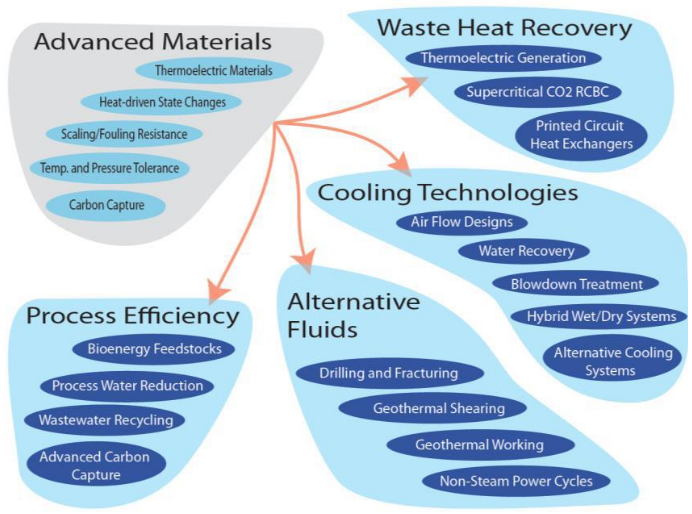
Figure 1.1.2 An energy and water flow diagram (Sankey Diagram) showing the interconnected relationship between the water and energy systems in the U.S., and highlighting sub-systems of key interest (e.g., desalination for potable water)[3]

Significant aspects of water and energy flows do not appear in Figure 1.1.2; e.g., flows change over time, and anticipated changes in flows are important to consider when prioritizing investments in technologies and other solutions.

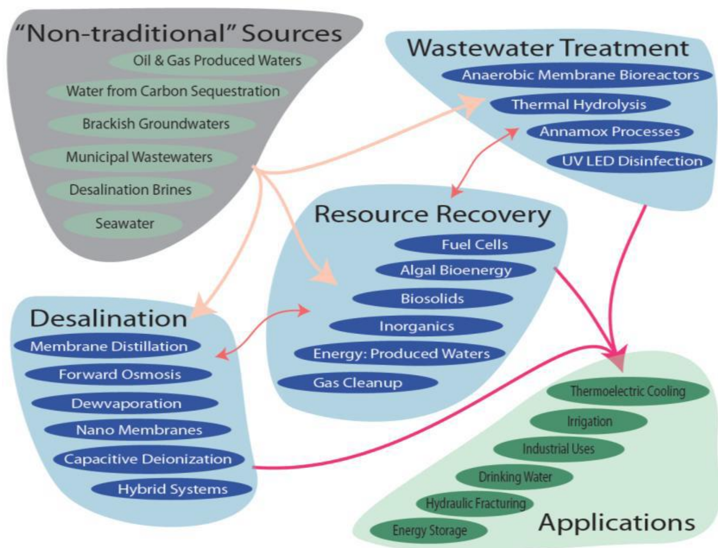
Potential focus areas can emerge when considering the interconnected relationship between water and energy. For example, water can be used for energy-production applications such as in thermoelectric cooling (for centralized electricity production) and hydropower technologies, as well as in energy demand applications

[3] https://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities

such as industrial process cooling and industrial waste heat recovery. Energy can also be used for or from water such as in the case of desalination or pressure retarded osmosis. Improvements in reverse osmosis, the dominant desalination process in the U.S., are nearing their practical limits. Attractive alternatives (e.g. thermal-based) exist, particularly those that utilize solar or waste heat, but they have not been commercialized at significant scale. These treatment techniques could enable beneficial use of produced waters from oil and gas and geothermal operations. Waste heat from the power plants could make certain alternatives, such as thermal-based approaches, advantageous when compared to RO. Figure 1.1.3 maps out a wide range of technology opportunities, and each must be assessed not only as an individual technology, but within the interconnected nexus between water and energy.



(a)



(b)

Figure 1.1.3 Representative (a) problem/opportunity spaces in water for energy and (b) problem/opportunity spaces in energy for and from water[4]

[4] https://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities

Building upon the energy flows in the Sankey Diagrams highlighted before, DOE's Energy Bandwidth Studies can serve as framework to benchmark the range (or bandwidth) of potential energy savings opportunities for a number of processes[5]. Bandwidth Studies examine energy consumption and potential energy savings opportunities for a given sector or technology; a bandwidth study of seawater desalination systems has recently been published (see Table 1.1.1). Industrial, government and academic literature are used to estimate the energy consumed in the various unit operations of a desalination system. The main unit operations that can be evaluated in this case include water intake, pre-treatment, desalination process, post-treatment, and concentrate management.

Three different energy consumption **bands** (or levels) can then be estimated for the various unit operations based on referenced energy intensities of current typical (CT), state of the art (SOA), and R&D technologies or practical minimum (PM). A fourth theoretical minimum (TM) energy consumption band can also be estimated. The **bandwidth**—the difference between bands of energy consumption—is used to determine the potential energy savings opportunity. The impact on total cost of water attributable to the reduction in energy intensity for each band can also be estimated. The concept of energy **bands** and **bandwidths** are illustrated graphically in Figure 1.1.3; additional details for the Desalination Bandwidth Studies can be found in the references in Table 1.1.1.

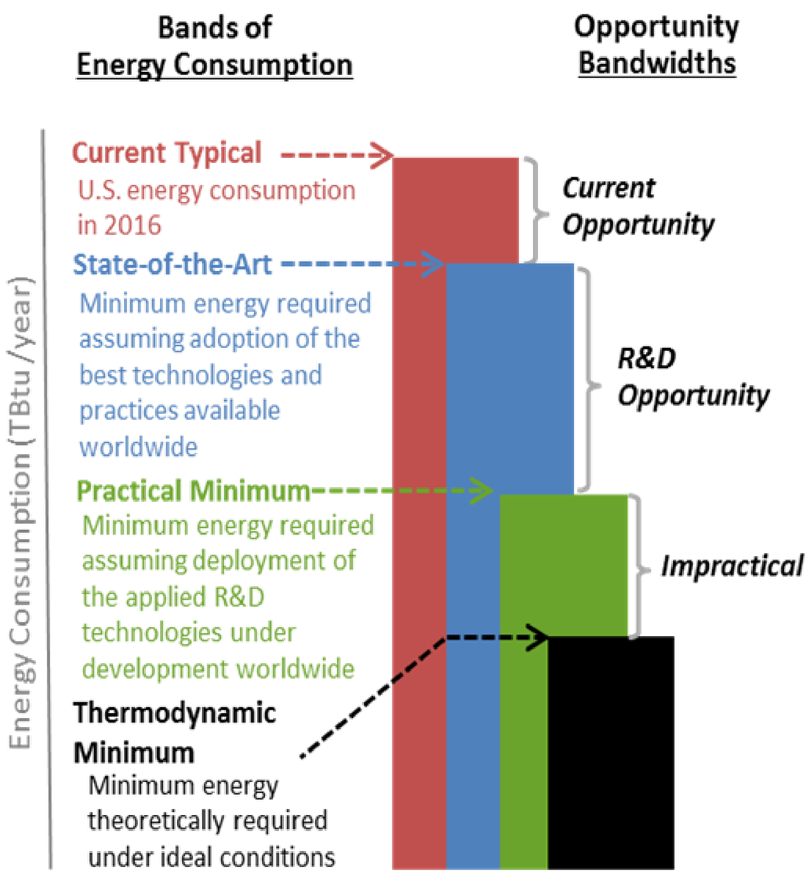


Figure 1.1.4 Energy Consumption Bands, and Energy Savings Opportunity Bandwidths

[5] https://energy.gov/eere/amo/energy-analysis-sector

Table 1.1.1 Contents of the Volume 1 and Volume 2 Bandwidth Studies[6]

Volume 1: Survey of Available Information in Support of the Energy-Water Bandwidth Study of Desalination Systems	• Boundary Analysis Framework • Energy Intensities for Five Desalination System Unit Operations • Framework for Establishing Desalination Uptake Scenarios

Volume 2: Energy-Water Bandwidth Study of Seawater Desalination Systems	• Energy Consumption for Seawater to Municipal Potable Water Evaluated at:
	    ○ CT Energy
	    ○ SOA Energy
	    ○ PM Energy
	    ○ TM Energy
	• Energy Consumption for Brackish Water to Municipal Water at CT Energy
	• Energy Savings from Current and R&D Advancements Opportunity

Results from the Desalination Bandwidth Study are shown below. Figure 1.1.5 compares the onsite energy consumption for membrane and thermal seawater desalination. Membrane #1 and Membrane #2 both implement RO desalination with the same post-treatment (remineralization and disinfection) and concentrate management (surface water discharge), but use different intake and pre-treatment methods:

- Membrane #1 intake and pre-treatment processes are sub-surface intake and cartridge filtration, respectively.
- Membrane #2 intake and pre-treatment processes are open-ocean intake and flocculation, coagulation, sand filtration, and cartridge filtration pre-treatment, respectively.

The energy consumption for sourcing the same volume of water from freshwater instead would be 145 billion Btu (BBtu), assuming a national energy intensity for freshwater extraction, conveyance, and treatment of 0.29 kilowatt-hours per cubic meter (kWh/m^3). This intensity varies throughout the U.S. For example, in Southern California, it is 2.6 kWh/m^3 and the resulting energy consumption for sourcing the same volume of potable water from freshwater in Southern California is 1,285 BBtu.

[6] The Seawater Desalination Bandwidth Study is available at: https://energy.gov/eere/amo/energy-analysis-sector ; a Volume 1 DOE review of desalination background data and information is available at: https://eta.lbl.gov/publications/volume-1-survey-available-information

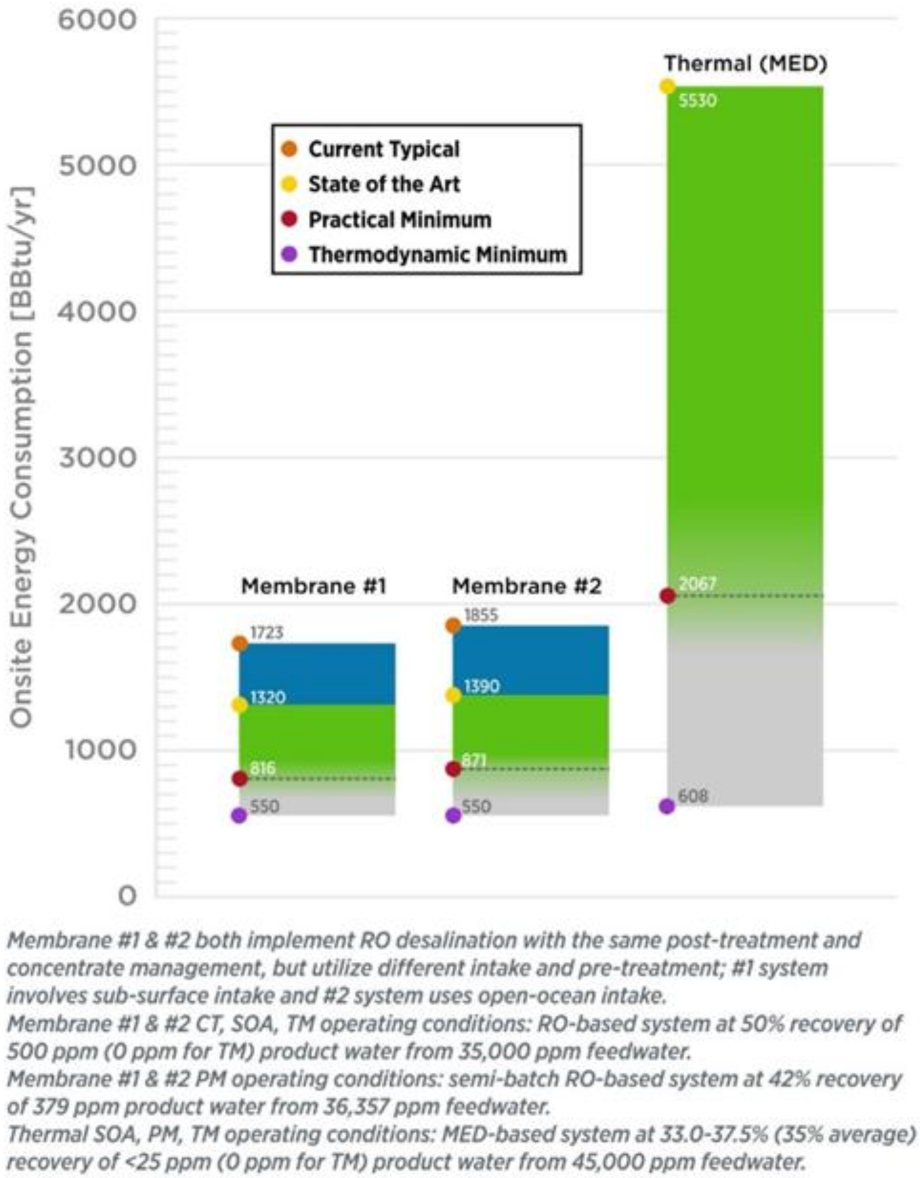


Figure 1.1.5 Preliminary results for Membrane and Thermal Processes, from the Desalination Energy Bandwidth Study. The thermal (MED) system does not have a CT value as it is not currently used for seawater desalination in the U.S.

Figure 1.1.6 shows the energy consumption from thermal Multi-Effect Distillation (MED) if it were used in the U.S.; however, there were no known thermal seawater desalination installations in the U.S in 2016 (the baseline year for this study). As such, a CT value for thermal MED is not shown, since seawater desalination processes in the U.S. typically utilize RO. While the energy consumption of thermal systems is significantly higher than membrane systems, use of waste heat from other processes and/or renewable thermal energy may provide a low-cost and clean source of energy to power thermal desalination plants. Figure 1.1.6 also shows the breakdown of thermal desalination energy savings by electrical and fuel sources. This indicates that energy savings in thermal desalination is heavily reliant on minimizing consumption of fuel. Fuel sources in thermal desalination accounted for approximately 89% of the total energy savings for the R&D opportunity (i.e., the difference between SOA and PM).

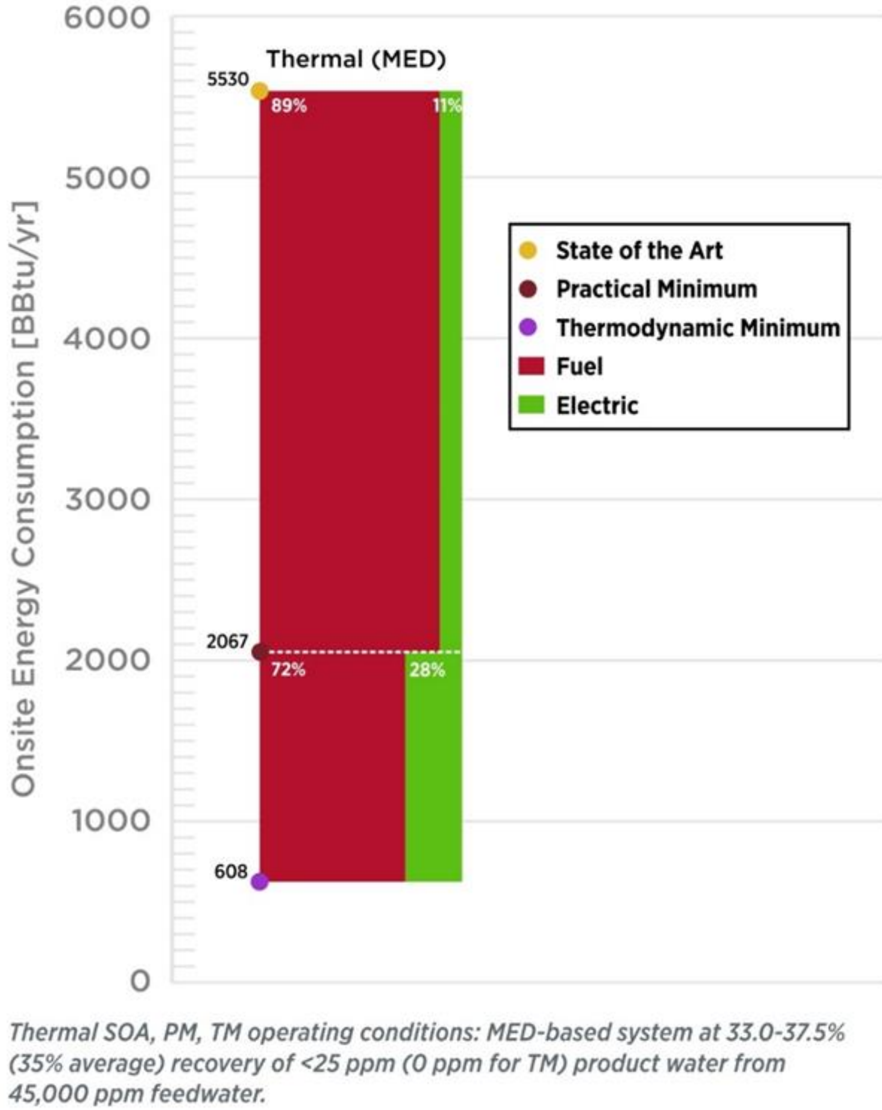


Figure 1.1.6 Preliminary results from the Desalination Bandwidth Study indicate opportunity for waste heat or renewable thermal energy to offset direct fuel use in thermal MED.

Figure 1.1.7 shows the estimated *current* and *R&D* energy savings opportunities for individual desalination system unit operations for the Membrane #2 system (RO desalination with an open-ocean intake); this Figure gives an additional level of granularity beyond the information shown in Figure 1.1.6.

Based on the results of this study:

- An estimated annual energy savings of 465 BBtu could be expected if capital investments in the best technologies and practices available worldwide were used to upgrade the desalination system unit operations studied as applicable (*Current Opportunity*);
- An additional 519 BBtu could be saved through the adoption of applied R&D technologies under development worldwide (*R&D Opportunity*). Adoption of applied R&D technologies to current U.S. seawater desalination systems could realize a 7% reduction in water cost based on national average electricity prices.

The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading to represent the increased uncertainty in a PM point, because the PM energy savings impacts are based on research at the laboratory scale that is currently being demonstrated; emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption. For the unit operations studied, the greatest *current* and *R&D* energy savings opportunity for seawater desalination comes from upgrading the desalination unit operation – this is largely due to the fact that a significant amount of energy consumed in seawater desalination occurs in this step.

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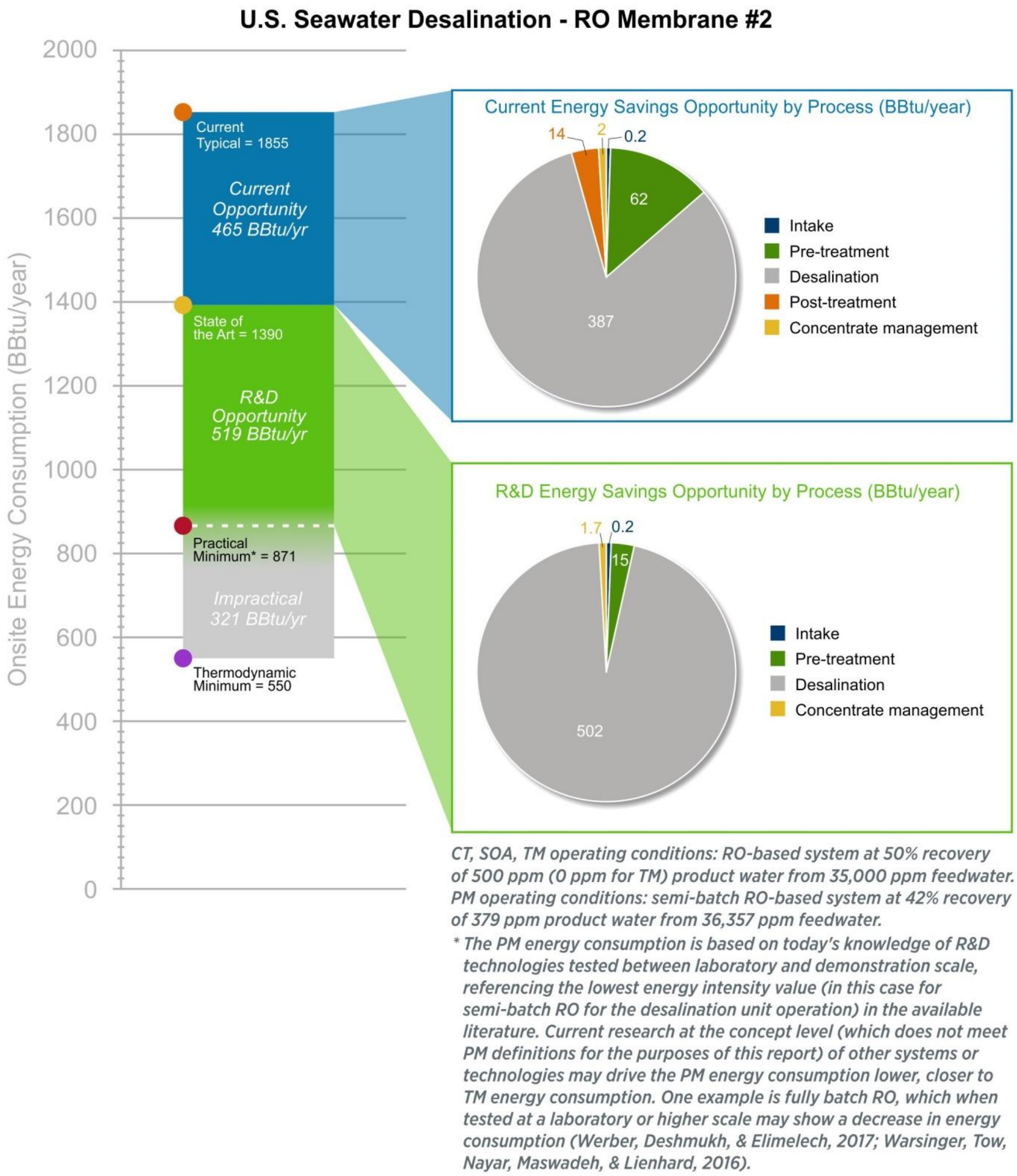

Figure 1.1.7 Preliminary results from the desalination bandwidth study indicate the current and future energy savings opportunities for RO-based seawater desalination in the U.S.

1.2 Overview of R&D Needs and Process Improvement Opportunities

This section highlights some of the technological challenges and hence efficiency improvement opportunities associated with clean water production from a variety of sources, with an emphasis on desalination. The discussion focuses on issues related to improvements in the overall system, operations, energy and water source flexibilities, as well as process level and system integration improvements opportunities.

Depending on source and use, production of clean water includes several steps connected in series, such as water intake (pumping, storage, pipe transport etc.) followed by a set of purification steps (e.g., screening, filtration, desalination, sedimentation, and coagulation/flocculation) and treatment steps (e.g., disinfection), then waste processing (from each purification step), and transport and integration to the target water system. Figure shows a Block Flow Diagram (BFD) that illustrates the different stages of a typical clean water production system. Processes associated with those stages are shown in Table .

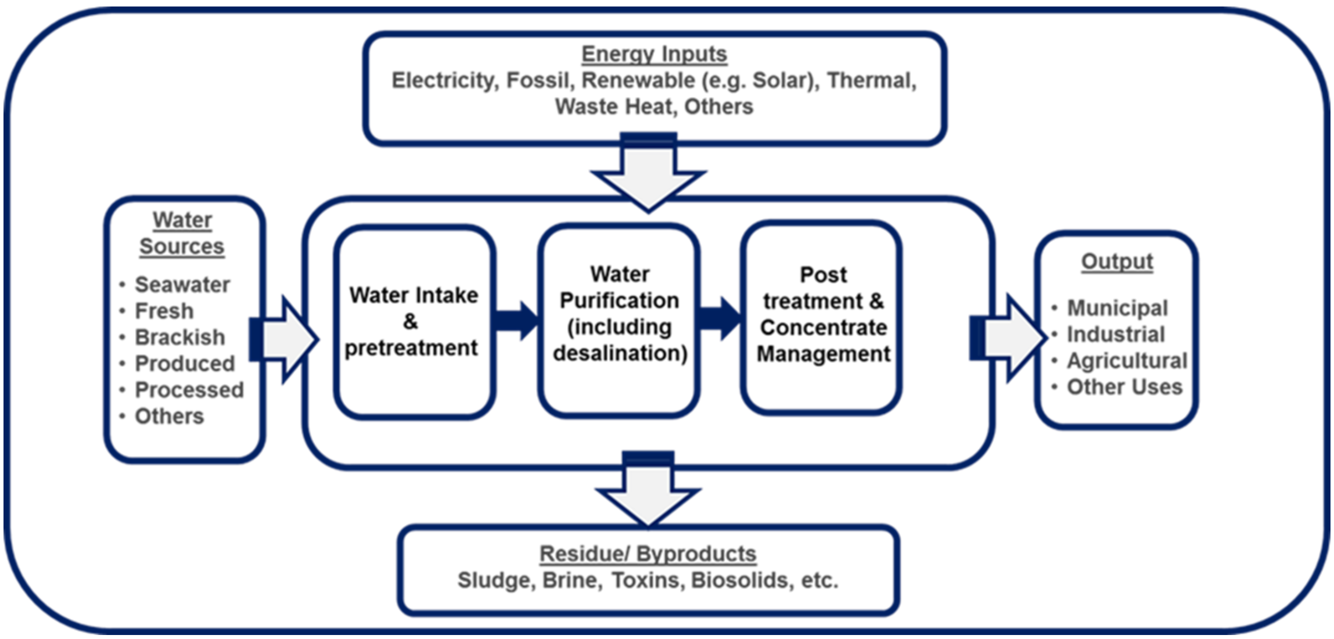

Figure 1.1.8 A block flow diagram of a typical water production system along with its components

Table 1.1.2 Desalination System Unit Operations[7]

Unit Operation	Processes

Intake	Open-ocean intake
	    Screened
	Subsurface intake
	    Beach wells
	    Offshore radial collector wells

Pre-treatment	Membrane filtration
	    Microfiltration
	    Ultrafiltration
	Pressure sand filtration
	Cartridge filtration
	Disc filtration
	Granular media filtration
	Dissolved air flotation (DAF)
	Flocculation
	Coagulation
	Sedimentation
	Chlorination

Desalination	Reverse osmosis
	Multi-stage flash distillation
	Multi-effect distillation
	Vapor compression
	    Mechanical vapor compression
	    Thermal vapor compression

Post-treatment	Remineralization Disinfection Boron removal
Concentrate Management	Surface water discharge Brine concentration Crystallizers

Fundamental materials discovery has the potential to improve various components including membranes, pipes, tanks and pumps. For example, membranes with high permeability that do not sacrifice water quality (i.e., highly selective membranes) and are resistant to fouling are needed. Additional material needs are for pipe, tank and pump materials that do not corrode and can withstand higher pressures and offer lower friction. Molecular modeling may be employed for materials discovery.

Better components (membranes, pumps, evaporators, heat exchangers, etc.) that can operate more efficiently, without interruptions, and dynamically adapt to changing conditions (salinity, bio-organisms, pH, temperature, etc.) are required. Multi-scale models to simulate processes need to be developed to predict performance and optimize design; this will ultimately provide feedback that enables better quality and more cost effective component manufacturing processes.

Unit operation optimization can lower the energy/economic impact of water transport, treatments, waste recovery, and dynamic adaptation, such that components (e.g., intake, filtration, and desalination) are integrated with one another in a single unit operation. The value of chemicals or embedded chemical energy from waste/residuals from each operation also need to be identified and extracted, at least for seawater. Furthermore, there is need for intake structures that cost less and are less harmful to bio life for seawater

[7] https://eta.lbl.gov/publications/volume-1-survey-available-information

installations as well as a need for reduced energy intensity and disposal costs for concentrate management for brackish facilities.

1.2.1 Improvement Opportunities in Water Intake and Pre-treatment[8]

Pre-treatment before desalination may involve chemical and non-chemical methods to contain non-TDS (Total Dissolved Solids) impurities. When determining the total cost and energy intensities of water processing and purification, material replacement/shut down due to environmental degradation and containment of bio-fouling elements needs to be considered, especially for pre-treatment of salt and brackish water, which may share commonalities with purification of fresh water. Advances in water pre-treatment in conjunction with RO, can improve the bio-environment, helping to contain and control health hazardous contaminants. These improvements also benefit downstream membranes and their auxiliary systems (filters, pipes, storage tanks, pumps, etc.).

The water intake infrastructure can be improved by enhancing the pumping system efficiency (e.g., variable speed drives for motor-driven systems), and the use of low friction and fouling/corrosion-resistant pipes and other components (e.g., pipes-to-pipes, pipes-to-pumps joining components). The energy to transport water, especially at higher elevations, may exceed the energy cost for purification, solutions may be found in improvements in pump efficiency and friction reduction as well as in plant design in terms of optimizing locations and modularity.

1.2.2 Improvement Opportunities for Purification/Treatment

Water purification technologies can be classified as membrane-based, thermal and hybrid/emerging processes. Membrane processes include RO and electrodialysis. Thermal processes include distillation such as multi-stage flash (MSF) and multi-effect distillation (MED) and hybrid/emerging technologies include processes like FO in combination with distillation, membrane distillation (MD) and ion exchangers. RO is the dominant method used to desalinate water in the U.S. as mentioned before. Technical challenges can either relate to the variety of water input feeds (Figure 1.1.1) or can be process/step/technology related issues (Figure). Discussion here is limited to desalination for seawater and produced water[8].

The following two sub-sections provide an overview of improvement opportunities for common membrane and non-membrane based technologies primarily for seawater/brackish water and produced water desalination.

Membrane Desalination

When determining the cost and energy intensities of water processing and purification, desalination is known to be an energy intensive step, contributing significantly to the overall operating cost. RO is considered to be a mature membrane technology for seawater desalination. Two particular concerns, however, have developed in the last few years. The first is energy use and the second is bio-fouling, which increases both energy use and chemical cleaning frequency, as well as creating a waste sludge for disposal. Literature studies suggest that there is little room for improvement of the energy efficiency when applying state-of-the-art RO membranes for desalination but there are significant opportunities to improve the robustness of the membranes, optimize their performance, and extend membrane lifetime[9]. Frequent cleaning, for example, can reduce membrane life and impair performance, making replacements more frequent and increasing costs. Bio-fouling is a challenging issue, experienced routinely offshore, necessitating bio-fouling prevention strategies.

Produced water purification is much more complex than brackish water/seawater, primarily due to the presence of a wide variety (temporally and spatially) of impurities and the high concentration of salts. Produced water salinity can reach as high as 30% and may contain as high as 180,000 ppm of TDS. Heavy metals, other metals, dissolved and suspended materials that include fatty acids, dissolved gases and hydrocarbons, and NORM may also be present. Produced waters are currently re-introduced to the environment at a very high

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[8] https://eta.lbl.gov/publications/volume-1-survey-available-information
[9] https://energy.gov/eere/amo/energy-analysis-sector

cost, and the re-injection inland has been associated with seismic activities[10]. Water quality for produced water varies by basin, location, depth and time – and this variability adds complexity to water monitoring and quality analyses. If alternative uses for produced water from diverse sources (e.g., agriculture, municipal, manufacturing, etc.) are to be developed, new technologies are needed to increase produced water monitoring, analysis, and purification efficiency, leading to reduced costs and lower energy intensity.

Current produced water monitoring technologies implemented offshore are either labor intensive or are not robust in the offshore environment. This presents an opportunity to pursue measurement improvements, even for common measurements (e.g., SDI (Silt Density Index) and TSS (Total Suspended Solids)). Technological and practical limitations of current purification approaches (e.g., seawater desalination challenges described earlier) also need to accommodate the complex composition of the produced water.

New cost effective and energy efficient desalination approaches may be necessary for desalination of produced waters (or any type of water) if existing technologies cannot meet cost and energy reduction targets. AMO's approach is to identify opportunities to narrow the gap in energy consumption between the current state-of-the-art, and what is practically achievable with technologies under R&D globally. This may include, for example, opportunities for advanced materials and improved systems design to increase salt and other impurity rejection, and increase in water recovery percentage. Energy bandwidth studies described earlier can aide in this respect.

Thermal Desalination

Thermal desalination accounts for nearly 50% of current global seawater desalination installed capacity, with 42% coming from multi-stage flash desalination, and 8% from MED[11]. Thermal technologies use phase change to separate salts from the feed water. Vacuum components are sometimes incorporated as well to increase evaporation at lower temperatures. In thermal technologies, the seawater is heated using thermal energy and is then exposed to partial vacuum. The combination of the thermal energy and the partial vacuum will cause pure water to flash (vaporize); freshwater is produced by condensing the resulting water vapor. The thermal energy extracted from the vapor during condensation is then reused to pre-heat the incoming feed water.

MED, MSF, mechanical vapor compression (MVC), and thermal vapor compression (TVC) are all applications of this technology. Steam, low-grade heat, or waste heat is typically the source of energy as well as mechanical energy for pumping.

Thermal technologies are in general more energy intensive than membrane processes, owing in part to large losses due to entropy generation and the need to change phases. Despite having significantly lower product water salinities, thermal systems also tend to operate at lower recoveries than membrane technologies; however, these technologies are most effective for high ppm water feeds/sources. The potential applications where thermal desalination technologies might compete with RO based technologies must be assessed on either cost of treated water or total energy consumption.

Materials innovations could enable more efficient (higher temperature) thermal desalination. Opportunities to develop next-generation heat exchanger materials could use lower cost materials (e.g., polymers) leading to lower-cost compact heat exchangers, as well as innovations to reduce chemical scaling on heat exchanger surfaces.

It is worth mentioning here that the energy footprint of reverse osmosis processes is the current state-of-the-art for desalination of seawater. However, if there are significantly higher levels of TDS, other chemical contaminants, etc. this may be the preferred method for cleaning up the water to a high standard (boiling off the water leaves all the contaminants behind). This exemplifies that the best choice of processing water will be

[10] https://www.eia.gov/conference/2017/pdf/presentations/meg_coleman.pdf
[11] https://eta.lbl.gov/publications/volume-1-survey-available-information

strongly dependent on the properties of the feed water as well as the desired characteristics (or applications) of the processed water. Thermal technologies for desalination of seawater are an opportunity for power integration, but the need for higher temperatures/high quality waste heat remains a challenge to address; one potential opportunity for R&D is bottom-cycle Concentrated Solar Power (CSP) (waste heat to power) at large industrial sites.

1.2.3 Improvement Opportunities for Post Treatment, Transport and Treatment/ Handling of Residue

Residue properties can vary in terms of TDS levels, presence of other contaminants, etc., depending on water sources used (e.g., seawater, produced water or brackish water). This implies there will be different disposal practices and environmental consequences when determining efficiency improvement opportunities.

The handling, transport and disposal of desalination effluents (sludge, concentrate, etc.) can add significant costs to the overall water processing costs, and must be considered when evaluating the total cost. Improved practices include recovery of valuable elements, as well as technologies available that may result in an entirely solid residue. Also, like water intake and transport, the transport of the effluent to the disposal site may constitute a significant part of the energy footprint. Structural materials concerns are also anticipated as a result of potential corrosion and fouling for storage and transport of concentrate.

Other issues related to clean water delivery exist, such as water loss upstream of the desalination process. Opportunities include efficient pressure management techniques, leak detection, and increased in-situ pipe repair/replacement.

1.2.4 Improvement Opportunities in Operational Flexibility and System Integration

There are several costs and energy benefits associated with having a water purification facility that can operate flexibly including tolerance and adjustment to operating conditions, and accommodating a variety of water qualities or energy sources. Since water is relatively easily stored, desalination plants can potentially provide services to the electricity grid through time-shifting of electricity consumption, demand response, ancillary services, and potential utilization of over generation by variable energy resources. A flexible purification facility would need to vary its operations depending on current conditions and successfully balance input and output flows of water, electricity, and wastes, while addressing water demand, electricity system services, market opportunities, and environmental goals.

R&D is needed to evaluate the technical potential for design and implementation of water processing and purification technologies directly integrated with renewable and waste energy sources. Costs of operating these systems may be reduced via the use of renewables, either in conjunction with or independent of the grid. DOE is interested in innovations to utilize solar thermal resources for desalination technologies as well as modular technologies. Several analysis efforts, however, are required to show whether thermal desalination technology based on renewable heat (e.g., solar thermal) would be competitive with current membrane-based technologies (i.e., cost, performance and market metrics need to be defined). Other desalination systems of interest include those that can be powered directly by wave energy, geothermal energy, wind energy and/or waste heat from other energy sources (hybrid systems). Technical and practical challenges related to cost, performance, energy source variability, competitiveness, and market need to be addressed.

1.2.5 Improvement Opportunities in Process Sensors, Monitoring and Control

Process control and monitoring are essential to enable optimal system-wide performance (intake, purification, and power supply), cost-effective, real-time, in-situ monitoring and control of water at all processing stages. Sensing of contaminant levels and types, temperature, pressure, etc., is critical to improve component resilience towards fouling, corrosion, clogging, etc., and allows for operating under optimized conditions for a given location, time or water source (e.g., seawater, brackish water, produced water, etc.).

Sensing and control could also be a vital tool for optimizing performance and energy consumption. For example, if multiple energy sources are used (solar, waste heat, grid, etc.), the variability may need to be compensated for in a smart way (e.g., sensing to schedule maintenance and part replacement resulting in more efficient operations and reduced down time).

1.2.6 Other Improvement Opportunities

Other improvement opportunities do exist. PI, for instance, and as detailed in the DOE Process Intensification Technology Assessment,[12,13] "targets dramatic improvements in manufacturing and processing of chemical products by rethinking existing operation schemes into ones that are both more precise and more efficient. PI frequently involves combining separate unit operations such as reaction and separation into a single piece of equipment, resulting in a more efficient, cleaner, and more economical manufacturing process. At the molecular level, PI technologies significantly enhance mixing, which improves mass and heat transfer, reaction kinetics, yields, and selectivity. These improvements translate into reductions in equipment numbers, facility footprint, and process complexity, and, thereby, minimize cost and risk."

Commercial applications of PI in the petrochemical industries, for example, have demonstrated capital cost reductions of 10-80% as well as energy reductions in the same range. PI approaches for industrial water treatment is estimated to reduce energy consumption by more than 50%[12].

Materials and minerals co-production is another area of interest. Water sources can contain significant quantities of minerals and other materials, both chemical and biological. At large volumes of water processing, these components can become significant byproducts requiring either disposal or recovery (if economically viable).

1.3 Benefits

Water demand in the U.S. is projected to increase over the next several decades, the use of nontraditional waters in major water-using sectors has the potential to mitigate freshwater shortages, but technological and cost barriers need to be overcome[14]. Advanced water processing technologies has the potential to improve efficiency, lower energy consumption and cost of water purification from a variety of sources.

Figure 1.1.3 shows the energy and water flows in the U.S. (Sankey Diagram) highlighting subsystems of key interest (e.g., desalination for potable water), along with technical barriers that cross-cut all systems, and where advancements would improve overall systems efficiency (in addition to what was shown previously in Figure 1.1.1)

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[12] https://energy.gov/sites/prod/files/2015/11/f27/QTR2015-6J-Process-Intensification.pdf
[13] https://energy.gov/sites/prod/files/2017/01/f34/Draft%20Advanced%20Manufacturing%20Office%20MYPP_1.pdf
[14] https://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities

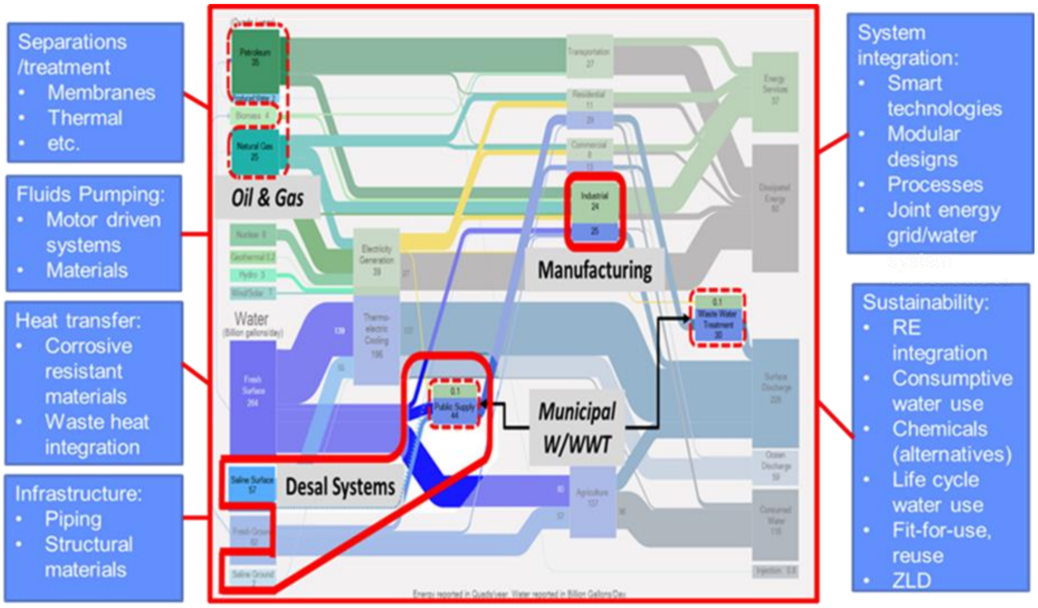

Figure 1.3.1 The energy and water flow Sankey diagram highlighting cross-cutting technical opportunities for key subsystems [15]

Materials innovations for the key subsystems highlighted in Figure 1.3.1 can enable emerging technological advancements. For example, synthesis of novel membrane materials that have high permeability and selectivity and resist fouling, corrosion and clogging is needed. Furthermore, membrane module designs need to mitigate issues related to Concentration Polarization (CP) and allows for higher water recovery. Other needs include low cost and novel catalysis that can replace precious or expensive metal catalysts for use in treating/deactivating/destroying contaminants.

Advanced manufacturing technologies can be implemented to produce low cost and reliable water purification components. Reliable structural materials are needed, such as piping systems that are lighter, stronger, and longer-lasting; that eliminate or greatly reduce the development of biofilms, corrosion, and scaling; and that cost less than currently used technologies. There are several technologies being investigated to enable this, some of which were highlighted in the MYPP published by the DOE Advanced Manufacturing Office[16]. These technologies include roll-to-roll processing, smart manufacturing, electrotechnologies, additive manufacturing, materials for harsh service conditions and others.

1.4 Workshop Series Overview

DOE's Advanced Manufacturing Office and Office of Fossil Energy held a series of three desalination/clean water processing technologies workshops between 2015 and 2017. Representatives from industry, academia, DOE national laboratories, and non-governmental organizations gathered to hear keynote addresses, expert panel discussion, and participate in workshop series breakout sessions. Discussion topics focused on challenges and opportunities for development of new technologies that will enable energy efficient and cost effective clean water processing from variety of sources.

The AMO within DOE's Office of Energy Efficiency & Renewable Energy (EERE) partners with private and public stakeholders to improve U.S. competitiveness, Improve energy productivity, create high-quality

[15] https://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities
[16] https://energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017

domestic manufacturing jobs and ensure global leadership in advanced manufacturing and clean energy technologies. AMO invests in cost-shared research, development and demonstration (RD&D) of innovative, next generation manufacturing processes and production technologies that will improve energy productivity, reduce industrial waste, and reduce the life-cycle energy of manufactured products. AMO is particularly interested in the challenges associated with advanced manufacturing technology that might be overcome by pre-competitive collaborations conducted via a consortium approach.

Through the workshops, AMO sought to gather input from stakeholders on the vision of future opportunities and technical challenges facing development and scale-up of sensors, process, and equipment that can make step-changes to improve yields while maintaining quality of clean water processing technologies. AMO also sought individual input on challenging performance metrics and identification of key problem sets to be addressed. During these workshops, participants identified low Technology Readiness Level (TRL) R&D needs, market challenges, metrics and impacts, and other considerations for clean water processing. These workshops identified critical crosscutting problems/barriers that if successfully addressed represent a step change beyond current state-of-the-art.

As the consequences of stressed water supplies and degraded quality of clean water become more pressing, it is becoming increasingly important to be able to ensure sufficient supplies of water are available at a reasonable cost and adequate purity for a variety of uses. DOE's report on the Energy-Water Nexus[17] identified the importance of research and development in developing technologies to provide water from a wide range of sources for diverse end uses, including industrial, agricultural, and municipal applications.

The purpose of the workshop series is to discuss opportunities for major advancements in science and technology for processing of clean water. This includes, but is not limited to the fields of:

- Process, Materials discovery and component structures for medium to high TDS waters, silts, brines and other contaminant removal, at low energy, low cost, and improved reliability of existing and future advanced manufacturing process technologies.
- Effective and energy-efficient pre-treatment processes of feedstock and post-process transport, storage, injection of water, processed water and effluent processing.
- Cost-effective energy resources for the water purification and the potential of co-production processes to recover and manufacturer other valuable minerals and elements.
- Systems integration technologies that incorporates smart sensors and actuators as well as modular integration and other process intensification approaches.
- Strategize how best to leverage R&D among the U.S. DOE and other Federal agencies.
- Encourage discussion and networking among leaders in the field.

1.5 Plenary Discussions

A panel of subject matter experts (SME) provided their insights on the capability needs and research trends on process intensification. The panel on the first day composed of experts from non-government organizations (NGO) while the panel on the second day drew from industry experts. Biographies of the panelists can be found in Appendix C.

[17] https://energy.gov/under-secretary-science-and-energy/downloads/water-energy-nexus-challenges-and-opportunities

1.5.1 Energy Optimized Desalination Technology Development Workshop (San Francisco, CA)

Several subject matter experts provided their insights on water markets and desalination opportunities. Highlights of the plenary presentations include[18]:

- Dr. Peter Gleick, President Emeritus and Co-Founder of the Pacific Institute, started his discussion by reviewing the future challenges of water management, such as water quality, water scarcity, and political conflict. Dr. Gleick emphasized the need to respond to these challenges by increased investment and water policies for foreign and domestic sources. Dr. Gleick stated that these investment and water policy strategies are particularly important for combating future risks associated with "Peak Water," the point in which traditional approaches are not considered optional. Dr. Gleick concluded that rethinking water supply, water demand, and water management can enable increased water productivity and efficiency, and decreased waste. In addition, this can be an interdisciplinary effort if increased public awareness, and institution involvement occurs.

- Mr. Tom Pankratz, an independent consultant and editor of the Water Desalination Report, began his presentation by discussing the history of RO desalination and its subsequent improvements over time. These improvements have enabled RO for seawater and brackish water sources to currently be the most implemented desalination technology in the world. Mr. Pankratz stated that the current RO desalination is expensive because of the high energy requirements for equipment, such as pumps, and piping, as well as intake, pretreatment, outfall and pressure vessel desalination stages. Therefore, Mr. Pankratz expressed that on-going R&D is continuing for RO desalination, especially for seawater and brackish water sources. He concluded that these on-going research efforts for brackish water and seawater RO desalination are important to increase potable water source diversification and availability, as well as potentially decrease water costs.

- Dr. John Lienhard, Professor of Mechanical Engineering at Massachusetts Institute of Technology (MIT), began his discussion by introducing the basic energy requirements for current desalination systems, such as reverse osmosis and thermal distillation, as well as their thermodynamic considerations. Dr. Lienhard emphasized the importance of the gained output ratio (GOR) as a means of determining thermal desalination plant efficiency. Increasing a thermal plant's GOR reduces both steam requirements, and total land footprint. Dr. Lienhard also indicated that these thermal facilities will have high future impact when combined with power plants, which significantly lowers energy costs. Dr. Lienhard concluded that optimizing thermal desalination performance (in terms of temperature, heat recovery, and water composition) and water transportation distances will enable lower energy costs.

- Mr. Rob Oglesby, an Executive Director at the California Energy Commission, started his discussion on the current major water projects at the federal, state, and local levels. Mr. Oglesby stated that in order to combat issues of water scarcity with respect to future population growth and weather patterns, seawater and brackish water desalination can provide an answer. Desalination technologies have significantly decreased energy requirements since the 1980s, so more facilities are being constructed. California legislation has enacted policies, such as the California Water Action Plan, that heavily invest in desalination technologies while promoting conservation efforts. For example, desalination-specific conservation efforts involve regulations on source water intake and concentrate discharge to both monitor and minimize environmental impacts from releasing higher toxicity and salinity streams. He also indicated that desalination costs are significantly higher than traditional water supplies because of higher energy requirements. However, Mr. Oglesby also concluded that excess renewable energy generation in California could be used to help power desalination facilities, which can lower energy and water production costs.

[18] For presentation slides, please visit https://energy.gov/eere/amo/downloads/energy-optimized-desalination-technology-development-workshop-november-5-6-2015

1.5.2 Clean Water Processing Technologies Research & Development Workshop (Dallas, TX)

Several subject matter experts provided their insights on clean water processing opportunities. Highlights of the plenary presentations include[19]:

- Dr. Linda Capuano, Fellow in Energy Technology at the Baker Institute discussed water resource sustainability issues, challenges and the interconnected relationship between water and energy. She highlighted the potential for non-traditional waters to close the demand-supply gap governed by the limited availability of fresh water supplies. Dr. Capuano also discussed water demand and supply trends as well as the priority challenges that need to be addressed. Those include the need for (1) standardized approaches to verify and test new water analysis and treatment technologies supported by impartial and objective guidelines, (2) Comprehensive modeling methods to calculate and compare relative environmental impact, carbon intensity, risk, costs and other characteristics of using produced water when compared to other fresh and non-fresh water sources, and (3) Clarification of produced water ownership and liability as it is treated and put to beneficial use. Dr. Capuano gave several examples, case studies and work groups findings related to produce water and has concluded her talk by highlighting several recommendations from those activities.

- Mr. Rick McCurdy, Manager - Chemicals & Water Reclamation at Chesapeake Energy started his talk by highlighting the relationship between water processing cost per unit volume and total dissolved solids in water resources along with the technologies that are currently implemented. Mr. McCurdy gave specific examples of power demands for processing water using a few of the current technologies. A few promising technologies to reduce the cost/energy intensity were also highlighted. Those included acid base generation, MD and plasma arc. Mr. McCurdy concluded the talk by discussing hindrances to beneficial reuse of water.

- Dr. Diego Rosso, Director at the Water-Energy Nexus Center and Associate Professor, Civil and Environmental Engineering and Chemical Engineering and Materials Science, University of California, Irvine, discussed Water Processing Dynamics, Metrics, and Sensors. Dr. Rosso highlighted several aspects related to energy and water processes. He started by pointing out the energy intensity in water reuse and how carbon and energy footprints are dependent on the water purification method. Dr. Rosso also discussed the differences between energy consumption and energy cost and whether other metrics should be considered such as power density and overall energy cost as opposed to only considering the energy intensity. Dr. Rosso emphasized on the need for extensive process analysis and audits to improve water reuse and processing efficiencies.

- Dr. Michael E. Webber, Deputy Director of the Energy Institute and Professor of Mechanical Engineering, University of Texas, Austin started his presentation by highlighting the interconnected relationship between water and energy. Dr. Webber mentioned that water problems becomes energy problems and vice versa as a result of this interconnected relationship and that cross-cutting solutions could exist for both water and energy. Dr. Webber then highlighted a few examples of energy use for water processing such as for conveyance, pumping, treating, heating, pressurizing and chilling. Dr. Webber also discussed the variability of energy intensity for water desalination across the U.S. emphasizing that about 80% of specific energy consumption is determined by source water salinity and first year of operation. Dr. Webber then moved to discussing some policy and technical solutions to address the water-energy problems, those included energy recovery from wastewater treatment plants, integrating renewables with water treatment and desalination and using excess flared gas from shale production for waste water treatment. Dr. Webber then mentioned the need for smarter water systems as well as the need for water use data as those can set the path for identifying energy savings opportunities.

[19] For presentation slides, please visit: https://energy.gov/eere/amo/downloads/workshop-clean-water-processing-technology-research-and-development-july-10-11

1.5.3 Clean Water Processing Technologies Research & Development Workshop (Cleveland, OH)

Several subject matter experts provided their insights on clean water processing opportunities. Highlights of the plenary presentations include[20]:

- Mr. Snehal Desai, Global Business Director at Dow Water and Process Solutions, started his presentation by highlighting some of the technical challenges in clean water processing. Those included the increasing cost of water processing and reuse owing in part to the varying salinity and impurities of feed water. Mr. Desai mentioned that the cost of water recovery can be reduced by up to 60% by taking incremental efficiency improvements to Zero Liquid Discharge (ZLD). This could be accomplished by implementing Minimal Liquid Discharge (MLD) step prior to ZLD. Mr. Desai showed graphical representation of how MLD has the potential to get water recovery from the average primary wastewater reuse rate of 70% all the way up to 95% with minimal cost impact.

- Mr. Andrew Flowers, Filtration Systems R&D Engineer at PPG industries gave an overview of PPG's membrane filtration technology which is based on using membrane materials composed of polymeric matrix with incorporated inorganic filler. Mr. Flowers mentioned that this would create hydrophilic/hydrophobic hybrids that would result in capillary forces. Mr. Flowers indicated that such a hybrid feature would also allow for membranes to possess high flux and selectivity and consequently lower energy and operating costs. Mr. Flowers discussed several case studies where such membranes were tested in variety of applications to Seawater Reverse Osmosis Pre-Filtration, Gray Water Filtration – RO Pre-filtration, Filtration for Industrial Water, Waste Silica Slurry Concentration, High Solids Paint Filtration and Filtration for Industrial Paint Production. Mr. Flowers concluded his talk by discussing the needs and approaches to further lower filtration costs through high flux and longer filter life. Mr. Flowers mentioned that this can be accomplished by the development of appropriate coatings materials as well as performing fluid dynamics modeling to better understand some of the fundamentals involved in that work.

- Mr. Adrien Moreau, Global Support Engineer and MIT System Design and Management Fellow, Veolia Water, has discussed the needs for next generation technologies to address the Energy-Water Nexus challenges. Mr. Moreau emphasized the need for understanding the Energy-Water Nexus from a system perspective and that water management is now part of the whole manufacturing/production cycle. Mr. Moreau concluded his talk by discussing some of the technological needs/gaps for clean water technologies which included Selective Separation Processes, Selective Biological Processes, Cost effective ZLD treatment line, Digitalization (Performance optimization, Reliability & Robustness), and Continuous monitoring & Control.

- Dr. Seth W. Snyder, Water Research Leader at Argonne National Laboratory has started his talk by discussing key elements needed to develop new water namely Technology, Policy, Social tools and Efficiency, Alternative water sources, and Fit-for-purpose. Dr. Snyder discussed the challenges and dominant technologies for processing sweater brackish water. Technologies highlighted included RO for seawater and Capacitive Deionization (CDI) as an emerging technology. Dr. Snyder discussed Energy cost as function of feed salinity for both technologies. Dr. Snyder concluded his talk by highlighting Water Electrodeionization (EDI) as an emerging technology that has applications in cooling towers, brackish, produced water, industrial water processing. According to Dr. Snyder, this technology has the potential to reduce energy intensity compared to RO for brackish water and possess high recovery rates (>90%).

[20] For presentation slides, please visit: https://energy.gov/eere/amo/downloads/workshop-clean-water-processing-technology-research-and-development-august-23-24

- Dr. Seth Darling, Director, Institute for Molecular Engineering & Scientist at Argonne National Laboratory discussed priority research directions for clean water processing. Those included predicting static and dynamic properties of multicomponent fluids, achieving mechanistic control of interfaces and transport in complex and extreme environments, exploiting specific material-fluid interactions to design and discover innovative fluids and materials, and advancing science to harness the subsurface for a transformational impact on water. Dr. Darling concluded his talk by emphasizing that basic science will lay the groundwork for ensuring robust and secure energy water systems in both natural and manufactured environments.

1.6 Workshop Series Discussions and Breakout Sessions

The workshop series discussions provided AMO with further information on both crosscutting and specific technology research and development challenges. Additional discussions on basic rationale for an innovation institute, consistent with the missions of the DOE, also took place at the workshop. Presentations given at the workshops are available at https://energy.gov/eere/amo/workshops. Several breakout sessions were conducted, as shown below for the three workshops.

1.6.1 Energy Optimized Desalination Technology Development Workshop (San Francisco, CA)

- **Markets –** state of market and challenges/opportunities in the following areas:
- Municipal Water
- Agricultural Water
- Industrial Water
- Produced Waters

- **Technology Priorities –** priorities for desalination technology to meet the identified challenges and opportunities; focusing on the current state of both deployed and emerging desalination technologies and innovations necessary to reach full technical potential in the following areas:
- Thermal Technologies
- Pressure-Based Technologies
- Emerging Technologies
- Concentrate Management Technologies

- **System Integration Challenges –** technical integration challenges for desalination in the following areas:
- Environmental, Health, and Safety Challenges
- Intake/Outfall Management
- Energy Network Integration
- Water Network Integration

1.6.2 Clean Water Processing Technologies Research & Development Workshop (Dallas, TX)

- **Water Purification Technologies –** priorities for clean water processing technologies to meet the identified challenges and opportunities; focusing on the current state of both deployed and emerging technologies and innovations necessary to reach full technical potential in the following areas:
- Membrane-based Technologies
- Non-Membrane Technologies
- Thermally-Powered Desalination Technologies
- Integration of Solar-thermal power with desalination
- Pre-treatment Processes

- **Water Systems Integration–** technical integration challenges for clean water processing in the following areas:
- Sensors and Controls
- Water intake, transport engineering and effluent handling and concentration
- Water purification plant design and Operation and Maintenance (O&M)

1.6.3 Clean Water Processing Technologies Research & Development Workshop (Cleveland, OH)

- **Water Purification Technologies –** priorities for clean water processing technologies to meet the identified challenges and opportunities; focusing on the current state of both deployed and emerging technologies and innovations necessary to reach full technical potential in the following areas:
- Membrane-based Technologies
- Non-Membrane Technologies
- Technologies for variable water quality

- **Water Systems Integration–** technical integration challenges for clean water processing in the following areas:
- Sensors and Controls
- Water technologies in the energy systems
- Water purification plant design and O&M

- **Cross-Cutting Water Processing–** technical cross-cutting technologies challenges for clean water processing in the following areas:
- Process Intensification
- Integration of Renewable Energy with Desalination
- Materials and Minerals Co-production

Participants in each breakout session answered a different set of questions that were appropriate for the topic. Summaries of the breakout group discussions and questions posed are outlined in Chapter 2. The Appendices include the meeting Agenda, detailed workshop series outcomes and lists of participants for all the three workshops.

1.7 Collaboration / Partnerships

The participants identified that a hub or R&D consortia (building a multidisciplinary innovation ecosystem to accelerate tech development that then industry implements) would be advantageous to advancing clean water technologies, because single entities do not have the financial means nor technical breadth to undertake such a large effort individually. Further, they identified the need for an environment where shared resources such as supercomputing capability and subject matter experts are accessible by industry and researchers. Multiple partners would be involved, including industry, government, academia, non-profit, and national laboratories. The result of this collaboration is an environment that supports early stage R&D of Clean Water Processing Technologies to enable the development of next generation technologies.

2. Summary of Workshop Series Results

This chapter provides a comprehensive summary of the outcomes of the three workshops. The first section is devoted to summarize the results from the Energy Optimized Desalination Workshop (San Francisco, CA) while the second section provides a consolidated summary of the Clean water Processing Technologies Research & Development Workshops (Dallas, TX and Cleveland, OH).

2.1 Energy Optimized Desalination Workshop (San Francisco, CA)

This subsection provides a summary of water market and desalination challenges for municipal, agricultural, industrial, produced water. It also highlights R&D priorities and system integration challenges for the desalination technologies.

2.1.1 Water Market

Below is a summary for water markets and desalination challenges for municipal, agricultural, industrial and produced water. Each subsection covers state of the market as well as challenges and opportunities.

Municipal Water Markets and Desalination Challenges

Municipal water markets state and challenges and opportunities were discussed and the following is a summary of the outcomes.

State of the Market

On the discussion of state of the market, key themes are highlighted below.

Municipal water utilities are increasingly looking to diversify their water supplies:

- But decision-making and competing water source costs are specific to the local area.
- Pricing considerations should address both source and treatment costs.
- In particular, water supply challenges in California were discussed extensively.

- Planning and modeling are significant challenges:
  - While tools exist, planning based on historical knowledge may not mesh well with future water demands.
  - There may be an opportunity to have better sharing of modeling tools and resources.

Challenges and Opportunities

On the discussion of challenges and barriers, key themes are highlighted below

- Opportunity discussion focused on certain advanced technology options and their associated challenges:
  - RO is fairly well known, and would be appropriate to compare advanced technology against.
  - CDI is potentially viable and has some advantages, but also some disadvantages.
  - Thermal technology options include humidification-dehumidification (HDH), though scalability could be a challenge compared to existing reverse osmosis technology.
- Financing mechanisms and risk considerations are major concerns for water utilities:
  - Alternative financing structures should be evaluated.
  - Small municipal utilities face particular challenges.
  - Risk aversion may limit new technology deployment.
  - All cost considerations should be fully incorporated in determining the price for water.
- Optimization of energy costs and desalination plant impact overall cost:
  - An example opportunity is to take maximum advantage of off-peak power prices.
  - Modeling and controls can be used to improve productivity.

Agricultural Water Markets and Desalination Challenges

The following is a summary of the outcomes from the Agricultural Water Markets State and Challenges and Opportunities.

State of the Market

On the discussion of state of the market, key themes are highlighted below.

- Costs are highly variable based on location and water rights.
- Water use efficiency in irrigation could be increased.
- Generally speaking, water reuse could be increased:
  - Has potential impacts on soil salinity and aquifer levels.
- Models can be improved and better incorporate available data:
  - Expand capabilities and tools.
- Concentrate management is a significant issue, particularly in California:
  - Address challenges for salt/brine.

Challenges and Opportunities

On the discussion of challenges and barriers, key themes are highlighted below.

- Agricultural water really need to consider the concentrate:
  - Brine and drainage.
- Financing is a challenge without readily available mechanisms.
- Techno-economic feasibility needed.
- Distributed vs centralized; advantages and disadvantages.
- Multitude of energy options for distributed operation.
- Various approaches to address concentrate separation and management.

Industrial Water Markets and Desalination Challenges

Industrial water markets state and challenges and opportunities were discussed and the following is a summary of the outcomes.

State of the Market

On the discussion of state of the market, key themes are highlighted below.

- High level of variability in cost across different industrial subsectors:
  - Regulations and permitting greatly influence.
- Consider a systems approach, ensuring appropriate boundaries.
  - But may be hard to standardize as each industry has own requirements.
- Develop specific water bandwidth studies for individual sectors.
  - Better tools for optimization.

Challenges and Opportunities

On the discussion of challenges and barriers, key themes are highlighted below.

- Challenges:
  - Reverse osmosis may be nearing technical limits.
  - Waste management (with suggestion to take a systems approach).
- Opportunities:
  - Improvements for utilization of brackish water.
  - Use of or integration of technology with renewable energy resources.
  - Develop technology capable of utilizing low temperature waste heat technology.

- Microbial electrochemical cells.
- Systems level optimization.

Produced Water Markets and Desalination Challenges

Produced water markets state and challenges and opportunities were discussed and the following is a summary of the outcomes.

State of the Market

On the discussion of state of the market, key themes are highlighted below.

- The vast majority of produced water is currently reinjected into underground injection control (UIC) wells or recycled within the industry as either hydraulic fracturing fluid injected for enhanced oil recovery.
  - Neither of these uses typically requires desalination.
  - The industry focus is on minimizing risk (financial, regulatory, and operational).
- In a few niche areas desalination has been deployed in the treatment of produced water
  - Reverse osmosis, mechanical vapor compression, carrier gas extraction technologies have all been deployed in the oil industry.
  - Desalination of produced water typically has high and variable pretreatment requirements.
- Adoption of desalination is sensitive to costs, regulation, water quality, and risks
  - Costs for desalination must be cheaper than alternative recycling or disposal methods.
  - Regulations can either encourage or discourage desalination and reuse.
  - Produced water quality varies significantly across and throughout plays which can have a significant impact on desalination costs and final use options.
  - The industry is sensitive to risks such as NORM in concentrate or solids, organics removal, liability for above ground water management, and public perception challenges with reuse outside the oil patch.
- Innovation can help improve the adoption of desalination for produced water.
  - New technology can drive down costs.
  - System optimization for oilfield applications.
  - Use of renewables or waste heat.

Challenges and Opportunities

On the discussion of challenges and barriers, key themes are highlighted below.

- Coal fired generators with carbon capture will increase their water use.
- Possible alternative sources of water for coal generation:
  - Acid mine drainage.
  - Coal bed methane produced water.
  - Water extracted from carbon storage reservoirs.
  - All sources have risks and potential high transportation and treatment costs.
- Combined heat and power (CHP) represents a potentially low cost energy source for desalination:
  - MED, FO, and MD all potential options for using of CHP.
- Material recovery may be possible from produced waters, but there are high financial, technological, and regulatory risks involved.
- There are significant challenges with applying desalination in the oil and gas industry:
  - Costs and reliability of water treatment are not competitive with disposal.
  - The economies of scale and transportation challenges are not in favor of desalination.
- NORM is a significant challenge for concentrate and solids management from desalination, especially if ZLD is desired.
- There are opportunities to make significant energy efficiency improvements in desalination:

- Use of renewables, locally produced fuels (e.g. flare gas), and waste heat (e.g. natural gas compression).
- Power system integration can be significantly improved.
- Emerging systems such as FO and carrier gas extraction show potential for efficiency improvements.
- Hybrid systems combining multiple units through integration and optimization can potentially improve efficiency.

2.1.2 R&D Priorities for Desalination Technology

Below is a summary of R&D priorities for desalination technologies including thermal, pressure-based, emerging and concentrate management technologies.

Thermal Technologies

On the discussion of thermal technologies, key themes are highlighted below.

Conventional:

- **Materials** improvements were another main topic of discussion for conventional thermal distillation technologies; participants noted that materials challenges, though they would take a concentrated effort to solve, would be a "game changer" for the desalination community. Scaling, fouling, and corrosion in these systems could be addressed with new coating such as titanium. Improvements in tube materials could include research into scale rejection and surface morphology to improve film adhesion for anti-scaling, reducing thickness of tubes with increased strength materials, and addressing easily contaminated coatings. There are numerous other research opportunities for materials, including polymer heat exchangers to help reduced the cost of thermal desalination or reducing the size of hydrophobic condensers.

Novel:

- **Membrane distillation (MD)** is considered a commercially available technology yet there are no large plants in operation and membranes are not produced in large quantities like those for RO so it is considered a newer technology with less data to use for comparison. The technology is more ideal for small applications, possibly such as small-scale power generation for island locations, solar integration, or RO waste management. Challenges that must be addressed with the technology include improving membrane hydrophobicity, developing membranes for higher temperature (>80°C) processes, increasing the membrane module length above 20 inches, and achieving the desired thermal cycle.
- Target markets for **humidification-dehumidification (HDH) desalination** include the produced water sector (oil and gas, mining water, wastewater) or drinking water if inexpensive solar power is available. The key is to have a cycle with high thermal performance with a low-cost collector. Currently the technology is demonstrated as inefficient (maximum GOR of four). Challenges include heat recovery, nonlinearity of the vapor pressure curve as a function of temperature, and the larger amounts of fluid that must be pumped for minimum production. However, there are opportunities to improve the efficiency of the process, whether it may be from system balancing, heat recycling at higher temperature operation when driven by variable input solar, developing better direct contact heat transfer modeling, or using advanced manufacturing techniques such as additive manufacturing to realize novel designs that maximize pressure drop and mass transfer.
- There has been a great deal of interest in **thermally driven forward osmosis** but there are still challenges to address, especially in terms of picking a suitable draw solution and ensuring a high temperature heat source is available. The draw solution must not leak (need to avoid back diffusion) and there are challenges with membrane fouling.
- **Other** types of R&D priorities for thermal technologies were also discussed and it was noted that beyond the conventional and novel technologies discussed there is room for innovative thinking on

new cycles. Ideas include selective absorbents, gas hydrate combined with a separation process, freeze desalination combined with a cooling room, cryogenic capture, directional solvent extraction, and supercritical oxidation.

Pressure-Based Technologies

On the discussion of pressure-based technologies, key themes are highlighted below.

Technology gaps:

- **Lack of big data collection and utilization for RO desalination systems** is a major consideration in future R&D, especially in terms of utilizing all data readily available from plants. Minimizing gaps in big data collection for commercial RO plants is accomplished by installing the right sensors around facilities, determining plant design with respect to water salinity and temperature, and developing models and tools capable of making real-time system characteristic decisions. This type of big data collection can lead to improved plant performance, desalination cost benefits, and load balancing across membranes.
- There is great interest in **optimizing element density and characteristics across desalination membrane pressure vessels**. Current manufacturing of these membranes is very sophisticated, especially for newer technologies and specialty materials. Other challenges for optimizing these elements include determining how to handle membrane fouling and scaling and monitoring the pressure for each individual element.
- **Membrane fouling and scaling** (particularly **algal blooms and biofouling**) is a major challenge in desalination systems. Algal blooms occur near the surface and contain harmful toxins. Dealing with these issues requires extensive membrane development and pre-treatment and demonstrated ability to continue water production through algal blooms. Utilization of more sea-floor intake systems and installation of better pre-treatment could minimize biofouling issues.

Test facilities:

- Certain test facilities are in use today internationally (Spain, Singapore, Saudi Arabia) and domestically (Alamogordo, NM, El Paso, TX, West Center in Tucson, AZ). There has been significant interest in determining **test facility locations** best suited for technological development, especially those accessible to different water types (brackish, seawater, etc.). New facilities would not be necessary for proven technologies that have existing pilots, but for emerging membrane and process technologies where they could be easily dropped in and tested.

Collaboration:

- Collaboration between large companies would help further pressure-based desalination technology R&D. Possible collaborations include direct engagement of companies working on new membrane technologies and funding opportunities for middle-level research (applied research to demonstration-scale technologies).

Emerging Technologies

On the discussion of emerging technologies, key themes are highlighted below.

- Different types of **emerging technologies** were discussed for desalination R&D priorities. It was unclear to the group what concrete opportunities high performance computing might have in desalination. Additionally, other technologies, such as smart sensors, have been well-developed in other fields but may not yet necessarily have been applied in water purification. One reason includes the lack of available pilots.
- **Collaboration** through consortia could provide numerous benefits including opening marketplace pathways, connecting technology developers and stakeholders, providing a down-select filter, driving self-sustainability, and overall developing technical criteria and standard testing

protocols. Existing consortia (such as the Electric Power Research Institute (EPRI)) could be built upon or leveraged with test bed capabilities. Investment in consortia capabilities and ensuring sustained commitment would be critical to success

Concentrate Management Technologies

On the discussion of concentrate management technologies, key themes are highlighted below.

Technology gaps:

- There has been significant interest in **concentrate management techniques from different separation technologies**. Ideas that were considered to utilize desalination concentrate included using concentrate feeds from CDI, electrosorption, and other separations technology, as well as creating markets for concentrate use in commercial end products.
- Finding **low-risk financing** for commercialization is also important for effective concentrate management, but methods of determining these options are currently unknown.
- **Solar gradient ponds** are a possible alternative identified for concentrate management. Facility benefits include energy production potential, brine collection areas, and dispatchability. In addition, these facilities can use solar thermal energy to run Rankine cycle and store solar energy at 70-90°C. However, one of the current challenges that affect solar pond development is their large land footprint as they require tens of acres. Pilot demonstrations (tied to geothermal) have been completed in the Middle East and Texas.

Collaboration:

- Collaboration through a **desalination hub/consortia** would be very helpful for companies and national laboratories as these programs exist internationally (e.g., Singapore). GE has been successful in public private partnerships. In addition, national laboratories are excellent independent testing entities. This could provide an opportunity for marketing of laboratory resources as available for industry to leverage.
- There is also a great deal of interest in more **tech-to-market assistance**. However, prize sizes would have to be defined based on metrics such as market size, cost reduction, and financial modeling for water production. Also, small company refereeing/vetting is needed and can lead to more productive breakthroughs/scale-ups, open door testing/technology evaluations, standardization, and coeds/standards of desalination performance. Guidance and/or review publications on physical limitations and state of the art would also be needed. A soft-cost of legislator/policymaker education may also be incurred.

Modeling tools/test facilities:

- New modeling tools and test/pilot facilities (especially for TRL pipelining) are increasingly needed. There is also extensive interest in modeling the 20 year need for water, particularly local predictions, contaminates, and wasted generation. These models can be leveraged from the mining and chemical industries. In addition, these models can include market value, cost comparison, and logistics analyses as well as experimental design and strategy optimization.

2.1.3 System Integration Challenges

This set of breakout sessions focused on four key topic areas:

- Topic 1: Environmental, Health, and Safety
- Topic 2: Intake/Outfall Management
- Topic 3: Energy Network Integration
- Topic 4: Water Network Integration

For each area, several focus questions were posed. Individual participant's views and responses were captured using a brainstorming process. Highlights of discussions are outlined below.

Environmental, Health, and Safety

On the discussion of environmental, health, and safety, key themes are highlighted below.

- General themes:
  - Pre-treatment and post requirements vary for different technologies, water sources.
  - Bacteria and other biological contaminants a concern.
  - Chaining technologies to minimize concentrate and maximize recovered water.
  - Desalinated water can sometimes be "too clean" and may need to re-mineralize for some uses and cool the water in the case of many thermal treatment methods.
- Concentrate disposal:
  - Dispose of concentrated brine vs. dry solids.
  - Dry solids a challenge if NORM is present.
  - Are there minerals in the waste stream that can be removed economically?
  - Disposal challenges expected to be less than some other industries such as semiconductors and petrochemicals.
  - Concerns about closed loop systems due to buildup of contaminants such as pharmaceuticals.
  - Under what conditions can it be blended and used in agriculture?
- Greenhouse gas minimization and tools:
  - Localize treatment to minimize transportation energy costs.
  - Use of clean energy or waste heat.
  - Possible use of concentrated brine for CO_2 mineralization.
  - Explore opportunities to utilize salinity gradient from concentrate.

Intake/Outfall Management

On the discussion of intake/outfall management, key themes are highlighted below.

- Environmental concerns:
  - Impingement and entrainment a major concern with intake from seawater sources.
    - Clean Water Act (CWA) Section 316b addresses this issue.
    - Below seabed intakes a possible solution.
  - Environmental concerns from inland groundwater:
    - Salt-water intrusion or subsurface flow issues.
    - Aquifer structural integrity, subsidence.
  - Use of produced water complicated by transportation and potential for NORM.
  - Overall there are significant uncertainties due to limited/poor data on environmental impacts.
  - High risks associated with transporting concentrate.
- Cost parameters:
  - Seawater:
    - Data from CWA 316b for power plants relevant for seawater intake structures.
  - Offshore:
    - Desalination on barges/ships likely impractical beyond emergency situations.
    - Pipelines potentially costly.
    - Pretreatment is costly.
  - Pumping seawater inland:
    - Challenges with obtaining rights of way.
    - Carlsbad pipeline, 10 miles, cost $200 million.
    - Overall cheaper and easier to desalinate near the coast and pump clean water than to pump seawater inland for desalination.
  - Inland:
    - Availability and lifetime of disposal wells variable with a high impact on cost.

    - Local regulations important.
- Opportunities:
  - Combine concentrate with wastewater flows to take advantage of potential energy recovery opportunities through capturing the energy of mixing and reduce outfall impacts due to salinity.
  - Offshore desalination:
    - Lower concerns about impact on marine life
    - Regulatory concerns
  - Zero liquid discharge (ZLD):
    - Increase water recovery, and reduce intake requirements.
    - ZLD is typically regulation driven.
    - Potential for mineral recovery, but economics unknown.
    - NORM a potential risk depending on source.

Energy Network Integration

On the discussion of energy network integration, key themes are highlighted below.

- **General themes**: There is a great opportunity to better integrate water desalination into the electric grid of the future, helping to provide benefits to the grid by integrating with distributed energy resources, as well as other grid management techniques such as demand response and time-of-use electricity pricing. In order to optimize this energy network integration, powerful new modeling tools will need to be developed in order to better understand potential grid impacts.
- **Energy cost parameters**: According to some workshop participant, power cost is estimated to account for approximately 50% of a desalination plant's operational expenses and 25% of the overall water price. Other factors that impact the cost include the total dissolved solids, disposal and waste treatment,
- **Optimization opportunities**: Demand response integration, distributed energy resources integration, water storage, waste heat recovery integration, co-location opportunities with power plants, using power purchase agreements to de-risk the cost of electricity. For example, if water storage capacity is available, can take advantage of hourly pricing to only produce water when electricity is cheap. Providing ancillary services.
- **Research opportunities**: Modeling was identified as a key R&D opportunity. Modeling will help decision makers and analysts to better understand:
  - The role water desalination facilities can play in optimizing electric grid stability by developing modeling tools for the water grid that are as powerful as the modeling tools available for the electricity grid
  - The interlinkages between water and electricity e.g., modeling of how water storage and demand response can help to strengthen the electricity grid, how water desalination can best integration with renewable resources (e.g., solar, wind)
- In addition to modeling, other R&D identified priorities include materials research to develop materials with high thermal conductivity and resistance to corrosive environments, integration of sensors and advanced process control, waste heat recovery, and integrating solar thermal into desalination processes.

Water Network Integration

On the discussion of water network integration, key themes are highlighted below.

- **General themes**: Desalination can play a central role in strengthening integration with water networks, however several challenges must be mitigated. It is currently expensive to connect a desalination plan to the water utility network, so opportunities to decrease this cost must be explored. Building a large desalination facility is expensive and often considered to be financially viable only during droughts, so novel financial models can be explored to develop a more stable financial approach.

- **Cost parameters**: There are significant costs associated with integrating desalination plant water into water networks. These costs include: the need to transport water uphill to connect to the gravity fed distribution system, ensuring the appropriate water quality from the desalination plant,
- **Investment challenges**: Water networks can be more intelligently designed, using novel financial models, to be financially viable regardless of any particular drought cycle. One challenge with RO facilities is that the RO membranes need to be maintained under pressure, or there are fouling issues that will result. Maintaining the membranes under pressure uses the majority of electricity consumption.
- **Design and distribution opportunities**: Decentralized systems can help to reduce costs, however there are concerns that distributed systems would have increased O&M costs. There could be specific opportunities to take advantage of oil and gas (produced) waters. And desalination may be able to help enable "one water" systems that enable water reuse in the system through multiple cycles. Desalination is expected to help enable more use of water local to the supply, such as sustainable agriculture from existing local surface and ground water supplies. Lastly, coastal desalination can play a special role in helping to rebalance water networks, by enabling more local use of local water supplies.
- **Sustainability aspects**: More understanding is needed on how to more sustainably tap into saline groundwater aquifers without adversely impacting water quality and the hydrology system. Concentration management is also a critical consideration to ensure desalination sustainability.

2.2 Clean Water Processing Technologies Research & Development Workshops (Dallas, TX and Cleveland, OH)

This subsection provides a combined summary from both workshops where three major topics were discussed. Those included Water purification technologies, water systems integration as well as cross cutting water processing. The first two topics were addressed at both workshops, while the topic of cross-cutting water processing was only discussed during the Cleveland workshop.

2.2.1 Water Purification Technologies

On the discussion of water purification, several technologies were considered. Those included membrane-based technologies, non-membrane based technologies (including thermally-powered desalination) and technologies for variable water quality (including pre- and post-treatment processes).

Membrane-based Technologies

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below. Bullets that appear in **bold are common outcomes from both workshops**.

Future Capabilities and Opportunities

- Membranes with higher selectivity for specific ion/contaminant removal and with higher recovery to reduce waste stream.
- Fouling and scaling resistant; Surface modification of membranes for anti-fouling.
- Stable operation in harsh conditions (tolerant to temperatures and pressures and their changes) or other extreme environments (chemistry – oxidants/chlorine, pH, organics).
- Contaminant resistant (e.g., chlorine, bromine).
- Easily regenerated and atomically thin membranes but also mechanically robust membranes with higher permeability.
- Self-cleaning membranes and manufactured in situ.
- Multiple usage and capable of dry storage between deployments.
- Real-time monitoring and automatic defect detection.

- Chemically active composite membranes (redox – sequestration); catalytic membranes for concentration (pollution and fouling control).

Identified Metrics

- 99.99% salt reduction.
- 75% increased efficiency of water.
- High-flux, low energy chlorine tolerant (>1 ppm) materials for brackish potable water.
- Technology to remove last 1% bromide in seawater and boron in source water (iodide).
- Cost [Target]: Moving target such as $500 acre-foot; up to four times reduction of cost compared to what is presently available.
- Energy [Target]: Up to three times reduction of electricity use compared to what is currently achievable.
- Environmental [Target]: Up to two times reduction of greenhouse gas emissions compared to what is currently achievable.

Technology Barriers / Challenges

- **Manufacturing complexity; uniformity control of mass production.**
- **Multiple foulants and foulants modes; selectivity of ions, contaminants (e.g., monovalent vs. divalent ions).**
- Biofilms.
- **Multifunctional systems – organic versus analytical TDS; understanding trade-offs in TDS/pathogens/chemicals by application**
- Coating technologies for low-cost ultrathin membranes with low defect concentration
- Pilot-scale test beds.
- Misaligned incentives between academic innovators and industry.
- Fundamental understanding of transport incomplete.
- Overall energy use.

Prioritized R&D Needed for Technologies or Applications

- **Membranes with tunable selectivity/permeability and responsive to environmental/operating conditions (pH, light, salinity); Flexibility of material properties tolerant to organics, hydrocarbons, high temperature, and ions.**
- **Molecular modeling and characterization to understand membrane formation and structure; Better understanding of solute interactions with membranes surface and pores, e.g., ion transport/storage, chemical interactions, and interfacing confined spaces and pores.**
- Molecular modeling to understand behavior of water in confined spaces.
- Techno-economic consistency (e.g., well-defined metrics: what's included in energy and cost?)
- Collaboration between materials, process, and testing experts, as well as industry and academia
- Brine management including fixation and stabilization.
- New materials for CDI and membrane capacitive deionization (MCDI) including brackish water.
- Multi-functional and multi-scale new materials.
- High-throughput membrane testing and preparation.
- Characterization to understand membrane formation and structure (imaging/spectroscopy).

Non-Membrane Technologies; Thermally-Powered Desalination Technologies

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below. Bullets that appear in **bold are common outcomes from both workshops**.

Future Capabilities and Opportunities

- **Selective and reusable sorbents; reusable materials capable of selective ion removal.**
- Electrochemical recovery of valuable components.

- Ion exchange.
- Scaling-resistant technologies.
- Electrokinetic separation.
- Thermal system integration with existing processes (e.g., low-grade heat recovery).
- Membrane distillation.
- 3-D printed novel heat exchangers.
- Bio-derived organism treatment.
- Evaporation and subsets.
- Waste nuclear heat utilization for desalination.
- Freeze separation.
- Brine management (also identified as an R&D need).
- Supercritical processes.

Identified Metrics

- Performance: kWh/m^3, cubic meter per hour per dollar, low and high salinity capability (kW/mol salt removed).
- Cost: Capital expenditure/operating expenditure, levelized cost of water purification
- Environmental impacts, human health impacts.

Technology Barriers / Challenges

- **Scalability up; distributed/modular approaches.**
- Inexpensive material for selective ion removal.
- Techno-economic analysis.
- Improved inhibition of scaling.
- CDI – materials barrier.
- Pilot plant access.
- Ability to efficiently recover low temperature gradient heat.
- Materials resistant to harsh conditions.
- Lack of water and energy metrics.

Prioritized R&D Needed for Technologies or Applications

- Brine management.
- System models and fundamental understanding of interfaces.
- Scaled prototypes.
- Data collection, benchmarking, and data sharing.
- Database of impaired waters and heat sources (geospatial/amounts/quality).
- Hybrid technologies / process intensification (note: This can be grouped with Cross-Cutting Group / PI).
- Highly selective FO membranes / MD membrane optimization.

Technologies for Variable Water Quality (Includes Pre- and Post-Treatment Processes)

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below. Bullets that appear in **bold are common outcomes from both workshops**.

Future Capabilities and Opportunities

- SMART
    - Sensor technology: rapid online sensing methods; technology for automatic adjustment; distributed, variable controls.
    - Computer control: predictive.
    - Cybersecurity.
- Process control improvements: rapid response, treatment cascade, variable flow.

- Note: This has a connection to the Cross-Cutting Group / Process Intensification.
- Differentiation of specifications: Efficient classification of water quality.
- Design Strategies – specialized vs flexible.
- Techniques and standards for biofouling potential and treatment.
- Non-chemical methods of scaling inhibition.
- Dynamic, reusable flocculants.
- Selective contaminant removal: photo and electrolytic processes; adsorption.
- Ability to seasonally adapt: red tide algae bloom, etc.
- Low energy micro-particle removal.

Identified Metrics

- For sensor technology: longevity, need for calibration, accuracy, drift.
- For process control improvements: Meet regulations and standards, process intensification at greater than 95%.
- Treatment costs less than costs of disposal.
- Increase cycles at inland groundwater cooled power plants to greater than 15.
- 100% produced water reuse.
- Target: Geographic Information System (GIS) heat map of injection or evaporation costs.

Technology Barriers / Challenges

- **Foulants: Many types and challenging contaminants; variety of contaminants and reactions; Fundamental understanding of fouling and biofouling, especially biofilms (removal of biodegradable organics).**
- **Development of analytical methods for continuous sensing, i.e., trace levels (sensor response at 1 to 10 seconds); Real-time sensing and pretreatment response.**
- Sensing at membrane levels.
- Stimuli responsive systems (sensor response at 1 to 10 seconds).
- Lack of investment for retrofitting and infrastructure ($1 trillion).
- Data handling and storage (1 terabyte per day of storage and analysis).
- Easy swap modular systems.
- Cybersecurity: need to protect smart sensing systems.

Prioritized R&D Needed for Technologies or Applications

- Biofouling sensing
- Tech-to-market analysis for pretreatment alternatives
- Predictive models that include separation, reaction, fluid mechanics, fouling based on complex water source inputs
- Membranes stable to pH, temperature, oxidant, and organics
- Self-cleaning interfaces
- Standardized fouling/scaling potential tests for emerging membrane technologies
- Fundamentals of DLVO theory in high ionic solutions and organic carbon

2.2.2 Water Systems Integration

On the discussion of water systems integration, several topical areas were considered. Those included sensors and controls, water technologies in the energy system (intake, transport, effluent handling), and water purification plant design and O&M.

Sensors and Controls

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below. Bullets that appear in **bold are common outcomes from both workshops**.

Future Capabilities and Opportunities

- **Sensor durability, sensitivity, drift, fouling, detection range.**
- **Sensor material and design applicable for detecting and measuring range of contaminants; rapid go/no-go to detect composition change, direct new incoming streams.**
- Real-time and reliable coupled sensors capable of pinpointing failure; advanced sensor analysis.
- Sensors, controls, and algorithms/data for renewable/conventional energy integration (real-time simulation).
- Development of / ability to manufacture sensors with advanced materials and scale-up at low cost.
- Techno-economic analysis, supply chain concerns.
- Operator training with new monitoring and control software/program.
- Detection of polysaccharide and organic materials for fouling monitoring.

Identified Metrics

- Measurement speed should match process/equipment dynamics; this will depend upon goals although about 15 minutes of data should be sufficient.

Technology Barriers / Challenges

- Cybersecurity issue: utilities are not encouraged to cloud sourcing.
- Data fusion challenge (data analytical), integrated to enable using of delivered data in water system; processing challenge – fusion of multiple measurements in real-time.
- Sensor cleaning, self-cleaning capability.
- Non-ideal conditions – variability of water quality/mixed streams and interference to the detection
- Low cost sensors; selectivity with different TDS types; self-healing, self-correcting.
- Sensors need to be designed within new components/technologies, as part of manufacturing (to help support troubleshooting more efficiently).

Prioritized R&D Needed for Technologies or Applications

- Renewable energy source integration including solar thermal and photovoltaics (PV), waste heat, wind, hydrogen; load profile modeling and solution deployment.
- Relationship among sensors in a sensor network can more quickly reveal if failure is imminent and define a fault attribution.
- Network design: approaches to design "optimal" sensor network in time and space.
- Need to develop distributed in-situ data and analysis sensing platforms.
- Need strategies for preventing process performance degradation that are caused by many mechanisms (fouling/biofouling, precipitation/scaling, clogging, etc.).
- Advanced synthesis technique to enable advanced material manufacturing; conversion of batch process to continuous or roll-to-roll (R2R) process for low-cost advanced material manufacturing
- Need integrated multiscale strategies for fouling prevention.

Water Technologies in the Energy System (Intake, Transport, Effluent Handling)

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below. Bullets that appear in **bold are common outcomes from both workshops**.

Future Capabilities and Opportunities

- Having a separation system that is both high efficiency and low cost.
- Modularized/distributed vs. centralized systems – cost considerations and economies of scales.
- New multi-functional material for desalination membrane (to address issues such as biofouling).
- Fit for purpose treatment (depending upon industry, crop, etc.).
- Decentralized systems to prevent transport losses; modular systems would reduce need to transport.

Identified Metrics

- [None identified]

Technology Barriers / Challenges

- Operational and political barriers for energy/water system integration, including scale issues (local vs. state), temperature/pressure, and lack of regional coordination.
- Barriers/challenges in manufacturing: return on investment (ROI), system life, adaptability, and cost-effectively manufacturing and deploying to materials and surface textures.
- Identifying leakage points in distribution systems.

Prioritized R&D Needed for Technologies or Applications

- **Flexible, modular systems are needed for distribution/ treatment (plug & play); different technologies for different uses; smart and smaller membrane modules.**
- **Materials for specific adsorption and selective separations; Multi-functional material design based on fluid-solid interactions for fouling /scaling prevention to improve durability.**
- Sensors and telemetry for infrastructure and equipment monitoring/diagnostics.
- Scalable manufacturing approaches for new material testing/performance evaluation.
- Non-membrane technologies for separation from solvents and others; must be cost effective.
- Improve resilience to fouling in filters, pipes, and pumps in water and energy systems.
- Design experiments and test at relevant scale, even for low TRL.
- Develop modeling and analysis framework that integrates surface chemistry/interaction model, unit operation model, process level model, and system level models, to find opportunities to optimize performance.
- Develop system level analysis for performance, cost, trace element analysis (TEA), life-cycle analysis (LCA), water resource, and energy use at regional scale, and factoring temporal considerations for multiple applications and multiple resource qualities; decision support tool.
- Increase performance and cost of auxiliary system.
- User friendly software.

Water Purification Plant Design and O&M

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below. This subsection was only discussed in the Dallas workshop.

Future Capabilities and Opportunities

- Developed cost model for water plants and systems (update old ones, create new ones).
- Co-location with facilities/industries that have excess waste heat (e.g., servers at data centers).
- Fit-for-purpose systems: utilize a "one water approach" where the plant design considers the community being served and other factors.
- Eliminated pre-treatment for RO if possible (through improved membranes, chlorine, etc.).

Identified Metrics

- For pilot plants, candidate metrics will be different than full scale, e.g., lab scale should be 1-4 gallons per minute (GPM), pilot plants 10-40 GPM; pilot goal target should be the current U.S. cost of water (in energy and $) but will vary depending upon application/location.
- Energy efficiency or percent of energy coming from renewables (or other sources).
- Capital provided directly from municipalities versus grants.
- Mean time for system function failure: greater than 20 years.
- Quantifying design capacity versus operational load including peaking.
- ROI: 1 to 2 years for industry; unknown / unspecified for municipalities.
- Smart manufacturing and three-dimensional (3D) printing for skids with 50% reduced material costs.

Technology Barriers / Challenges

- Centralized model limits use – building large plants that may not be needed.
- Size of plant and projections on water availability/demand and population cause uncertainty and affects capital costs.
- Computational modeling at different levels is not being done today.
- Plants have to pay for pilot tests (costing several million dollars); and regulations differ between states.
- Perceived and actual risk of using alternative water sources (e.g., water from waste sources).

Prioritized R&D Needed for Technologies or Applications

- Utilize system analysis to inform the system integration approach to determine research needs (before starting experiments).
- Better mid-scale, Aspen-level process models.
- Validation of design parameters (TDS and temperature) for technologies in test beds.
- Better models for future projections (water availability/demand) that include climate change.
- Overall computational model that connects the entire plant design.

2.2.3 Cross-cutting Water Processing

The topic of cross-cutting water processing was only discussed in the Cleveland workshop, and several sub-topical areas were addressed. Those included process intensification, integration of renewable energy with desalination, and materials and minerals co-production.

Process Intensification

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below.

Future Capabilities and Opportunities

- High thermal conductivity materials for high temperature and hybrid water processing systems (greater than 100^{o}C) to efficiently utilize thermal energy and waste heat recovery.
- Hybrid systems (nanofiltration, reverse osmosis, electro-dialysis, and capacity deionization) and combined technologies/treatment methods to reduce capital expenditures of multi-effect systems through manufacturing innovation.
- Modularization of multiple water treatment operations and off-grid or micro/modular systems.
- Brine waste recovery opportunities including handling and disposal (environmental impact).
- Water supply security including distributed treatment for water system resilience and hardening.

Identified Metrics

- Energy: Mole – salt/kilowatt-hour; Dynamic capacity and rate: [volume/energy]/time.
- Fully renewable energy (solar) cost less than $0.3/m3; ZLD.
- 80% reduction in greenhouse gas emissions; net zero energy.
- Use of exergy coefficient of performance (ECOP).
- Levelized cost of energy (LCOE) versus levelized cost of water (LCOW); develop a ratio.
- System optimized to a specific discount rate.
- Dollars/sustainability (regional deployment).

Technology Barriers / Challenges

- Material cost/lifecycle, appropriate predictive models, degradation due to fouling and side reactions.
- Lack of multi-technology systems integration.
- Large scale testing facilities are scarce.
- Scale-up production of nanostructured membrane or solar-steam generation materials.
- High volume/low total dissolved solids treatment is expensive.
- Thermally-stable polymers or other materials for membrane modules (temperature at 100^{o}C).

Prioritized R&D Needed for Technologies or Applications

- More large-scale test facilities needed including test beds for evaluation at scale with data sharing.
- Fundamental materials design and development including computational materials design and optimization with rigorous validation.
- Renewable energy storage integration with desalination - concentrate on solar power technologies and pair with modular desalination (photochemical/photothermal).
- Organism solutions for brine management and use of bio-solids as an energy source.

Integration of Renewable Energy with Desalination

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below.

Future Capabilities and Opportunities

- More use of thermal solar for RO feed and customizable and flexible, low-temperature (<100°C) solar collectors for desalination.
- Use of waste heat for low temperature water purification operations and technologies for using low-grade heat sources (e.g., cooling towers).
- Integrated solar PV / thermal desalination systems and renewable energy technologies.
- Fresh water/desalination concentrate integrated with grid stabilization.
- Use of alternative energy sources (photo-catalysis for peroxide and ozone for pre-treatment, biosolids, etc.).
- Water storage vs electricity storage.

Identified Metrics

- Capacity value and demand response potential of water infrastructure (in megawatt-hours (MWh))
- Water production 100% focused on below average energy costs.
- Thermal storage density approaching 40 mega joules per kilogram (MJ/kg).
- Water at pipe parity.

Technology Barriers / Challenges

- Renewable energy capacity factors and grid stability challenges.
- Lack of robust and effective in-situ photo-catalysis oxidant production.
- Lack of automation of water technology operations.
- Low power density of low and intermediate temperature thermal storage.
- Modeling of renewables and water management to identify technical and economic drivers.

Prioritized R&D Needed for Technologies or Applications

- New thermochemical storage cycles.
- System models that include a renewable energy technology portfolio for integrated process synthesis
- Heat-to-cold desalination / pretreatment technologies.
- Water treatment technologies that can robustly ramp up and down.
- Metrics-driven modeling for optimization and technology selection.

Materials & Minerals Co-production

Future Capabilities and Opportunities, metrics, technology barriers / challenges and prioritized R&D needed for technologies or applications were discussed and the outcomes are summarized below.

Future Capabilities and Opportunities

- Need for highly selective materials and technologies for recovery of target elements (e.g. lithium, manganese oxide, rare earth elements).
- New recovery methods for Li/Mg for battery materials, nitrates/phosphates/carbon compounds from agriculture, short chain fatty acids in digestion, and low concentrations of rare earths.

- More data and a national resource characterization database.
- Other areas for future opportunities; incinerator ash, mixed metal oxide production, brackish sources, etc.

Identified Metrics

- Reduce cost of mineral recovery from co-produced brine by tenfold.
- Develop technology to recover critical and other minerals from brine concentrate up to 15 weight percent salt (high TDS brine).
- Product metal purity greater than 90% to the customer.
- Performance ratio (like GOR) of integrated thermal systems greater than 20 per dollar capital invested per daily gallon produced.
- Seawater desalination provides all the uranium for reactors.
- Mineral / metal production with an Internal Rate of Return (IRR) greater than 20%.

Technology Barriers / Challenges

- Existing technologies not sufficiently selective given low concentration of target species
- Lack of fundamental understanding on metal interactions with surface.
- Low concentration, large variety of chemicals and variation over time and location.
- Environmental impacts of concentrating contaminants (e.g., selenium in Calif. Central Valley)
- Scalability of extraction approaches.

Prioritized R&D Needed for Technologies or Applications

- Selective separation of materials and processes based upon oxidation state with 90% separation efficiency.
- New low energy and low water use in primary metals production processes.
- Surface functionalization for selective separation in preprocessing.
- Optimal control for flexible operations with dynamic feed properties that are source specific.
- More large-scale and better testing facilities.

Appendix A: Agenda

A.1 Energy Optimized Desalination Workshop (San Francisco, CA)

Thursday, November 5, 2015

8:00-8:30 – Registration and Continental Breakfast

8:30-8:50 – Welcome Presentation

- Mark Johnson, Director, Advanced Manufacturing Office, DOE

8:50 -10:50 – Plenary Presentations

- Peter Gleick, President and Co-Founder, Pacific Institute
- Tom Pankratz, Editor, Water Desalination Report
- Yoram Cohen, Professor, Chemical and Biological Engineering, UCLA
- John Lienhard, Professor, Mechanical Engineering, MIT

10:50-11:00 - Breakout session instructions

11:00-11:15 - Coffee Break

11:15-12:15 - Breakout Session 1: Current desalination markets; discussion of cost/performance for current state of the art. Parallel sessions on the current state of desalination use for:

- Municipal
- Agricultural.
- Industrial
- Produced Waters

12:15-1:15 – Lunch

1:15-2:15 - Breakout Session 2: What are the challenges to deploying desalination into these markets? What opportunities are there for next-generation desalination technologies? Parallel sessions on:

- Municipal

- Agricultural
- Industrial
- Produced Waters

2:15-2:45 – Coffee Break

2:45-3:30 – Report outs from Breakouts 1 & 2

3:30-5:30 – Breakout Session 3: *What are the R&D priorities for desalination technology to meet the identified challenges and opportunities? The discussion will center on the current state of both deployed and emerging desalination technologies and what innovations are necessary to reach their full technical potential. Parallel sessions on:*

- Thermal Technologies
- Pressure-Based Technologies
- Emerging Technologies
- Concentrate Management Technologies

Friday, November 6, 2015

8:00-8:30 – Continental Breakfast

8:30-9:00 – Plenary Presentation

- Rob Oglesby, Executive Director, California Energy Commission

9:00-9:45 - Report outs from Breakout 3

9:45-10:00 – Coffee Break

10:00-12:00 - Breakout Session 4: *System Integration Challenges with parallel sessions on:*

- Environmental, Health, and Safety Challenges
- Intake/Outfall Management
- Energy Network Integration
- Water Network Integration

12:00-12:45 - Report outs from Breakout Session 4; Closing Remarks

12:45 – Lunch

A.2 Clean Water Processing Technologies Research & Development Workshop (Dallas, TX)

U.S. DOE ADVANCED MANUFACTURING OFFICE CLEAN WATER WORKSHOP JULY 10-11, 2017

Hilton Dallas Lincoln Centre
5410 Lyndon B Johnson Freeway, Dallas, TX 75240
(972) 934-8400

AGENDA

<table>
<tr><th colspan="4">Day 1 (July 10)</th></tr>
<tr><td>7:00 – 8:00 am</td><td colspan="3">Registration and Continental Breakfast — Lakeview Room (Lobby Level)</td></tr>
<tr><td>8:00 – 8:10 am</td><td colspan="3">Opening Remarks: <u>Main Session Room – Lincoln East/West (Ballroom Level)</u>
Dr. Mark Johnson, Director, DOE Advanced Manufacturing Office</td></tr>
<tr><td>8:10 – 8:30 am</td><td colspan="3">Keynote
Mr. Rick Perry, Secretary of Energy (Invited)</td></tr>
<tr><td>8:30 – 8:50 am</td><td colspan="3">Opening Session
Chair: Linda Capuano, Fellow in Energy Technology, Center for Energy Studies, Baker Institute
Energy-Water Nexus: Water Resource Sustainability</td></tr>
<tr><td>8:50 – 9:15 am</td><td colspan="3">Michael E. Webber, Deputy Director of the Energy Institute and Professor of Mechanical Engineering, University of Texas, Austin
Energy in Water</td></tr>
<tr><td>9:15 – 9:40 am</td><td colspan="3">Rick McCurdy, Chemicals & Water Reclamation, Chesapeake Energy
Produced Water Treatment: A Look at Current Technologies, Challenges and Opportunities</td></tr>
<tr><td>9:40 – 10:05 am</td><td colspan="3">Yoram Cohen, Director, Water Technology Research Center and Distinguished Professor of Chemical and Biomolecular Engineering, UCLA
The Challenges and Future of Membranes in Water Treatment and Desalination Technologies</td></tr>
<tr><td>10:05 – 10:30 am</td><td colspan="3">Diego Rosso, Director, Water-Energy Nexus Center and Associate Professor, Civil and Environmental Engineering, Chemical Engineering and Materials Science, University of California, Irvine
Water Processing: Dynamics, Metrics, Sensors</td></tr>
<tr><td>10:30 – 10:40 am</td><td colspan="3">Breakout Session Instructions</td></tr>
<tr><td>10:40 – 11:00 am</td><td colspan="3">BREAK (move to breakouts) — Ballroom Foyer</td></tr>
<tr><td rowspan="2">11:00 am – 12:30 pm</td><td>Water Purification (Group 1) Lincoln 1/2/3 Ballroom Level
A. Membrane-based Technologies
B. Non-membrane Technologies; Thermally-Powered Desalination Technologies
C. Pre-treatment Processes</td><td>Water Purification (Group 2) Lincoln 6/7/8 Ballroom Level
A. Membrane-based Technologies
B. Non-membrane Technologies; Thermally-Powered Desalination Technologies
C. Integration of Solar-Thermal Power with Desalination</td><td>Water Systems Integration (Group 3) Jackson/Adams/ Washington Ballroom Level
A. Sensors and Controls
B. Water intake, transport engineering and effluent handling and concentration
C. Water Purification Plant Design and O&M</td></tr>
<tr><td colspan="3">Breakout Session 1: Technology/Process A</td></tr>
</table>

12:30 – 1:30 pm	LUNCH (included in Registration Fee)	Lakeview Room (Lobby Level)
1:30 – 3:45 pm	**Breakout Session 2: Technology/Process B**	
3:45 – 4:10 pm	BREAK (move to Main Session Room)	Ballroom Foyer
4:10 – 5:00 pm	Report Outs (Day 1)	Lincoln East/West (Ballroom Level)
5:00 pm	Adjourn	

Day 2 (July 11)		
7:30 – 8:30 am	Registration and Continental Breakfast	Lakeview Room (Lobby Level)
8:30 – 8:45 am	Welcome and Recap	
8:45 – 9:10 am	**Joe Cresko**, Strategic Analysis Technology Manager, DOE Advanced Manufacturing Office *Foundational Approach and Research for Energy-Water Bandwidth Study of Desalination Systems*	
9:10 – 9:20 am	Move to Breakouts	
9:20 – 11:00 am	**Breakout Session 3: Technology/Process C**	
11:00 – 11:15 am	BREAK (move to Main Session Room)	Ballroom Foyer
11:15 – 12:00 pm	Report Outs (Day 2)	Lincoln East/West (Ballroom Level)
12:00 – 12:15 pm	General Session Closing Remarks	
12:15 pm	Adjourn	

A.3 Clean Water Processing Technologies Research & Development Workshop (Cleveland, OH)

U.S. DOE ADVANCED MANUFACTURING OFFICE CLEAN WATER WORKSHOP AUGUST 23-24, 2017

Wyndham Cleveland at Playhouse Square
1260 Euclid Ave, Cleveland, OH 44115
(216) 615-7500

AGENDA

<table>
<tr><th colspan="4">Day 1 (August 23)</th></tr>
<tr><td>7:00 – 8:00 am</td><td colspan="3">Registration and Continental Breakfast — Palace Foyer</td></tr>
<tr><td>8:00 – 8:15 am</td><td colspan="3">Opening Remarks: — Palace West
Mark Johnson, Director, DOE Advanced Manufacturing Office</td></tr>
<tr><td>8:15 – 10:30 am</td><td colspan="3">Panel Session
Moderator: Seth Snyder, Senior Researcher/Leader for Argonne National Laboratory Water Initiative, Global Security Sciences, Argonne National Laboratory
Panelists
Snehal Desai, Global Business Director, Dow Water & Process Solutions
Dale Keairns, Executive Advisor, Deloitte, former Senior Executive ,Westinghouse
Seth Darling, Nanoscientist, Center for Nanoscale Materials, Argonne National Laboratory
Adrien Moreau, Global Support Engineer, MIT System Design and Management Fellow, Veolia Water</td></tr>
<tr><td>10:30 – 10:40 am</td><td colspan="3">Breakout Session Instructions</td></tr>
<tr><td>10:40 – 11:00 am</td><td colspan="3">BREAK (move to breakouts) — Embassy, Roxy, Hanna Rooms</td></tr>
<tr><td rowspan="2">11:00 am – 12:30 pm</td><td>Water Purification* (Group 1)
A. Membrane-based technologies
B. Non-membrane technologies
C. Technologies for variable water quality
*Includes pre- and post-treatment processes
(Room: Embassy)</td><td>Water Systems Integration (Group 2)
A. Sensors and controls
B. Water technologies in the energy system
C. Water purification plant design and O&M
(Room: Roxy)</td><td>Cross-Cutting Water Processing (Group 3)
A. Process intensification
B. Integration of renewable energy with desalination
C. Materials and minerals co-production
(Room: Hanna)</td></tr>
<tr><td colspan="3">Breakout Session 1: Technology/Process A</td></tr>
<tr><td>12:30 – 1:30 pm</td><td colspan="3">LUNCH (included in Registration Fee) — Palace East</td></tr>
<tr><td>1:30 – 3:45 pm</td><td colspan="3">Breakout Session 2: Technology/Process B</td></tr>
<tr><td>3:45 – 4:10 pm</td><td colspan="3">BREAK (move to Main Session Room)</td></tr>
<tr><td>4:10 – 5:00 pm</td><td colspan="3">Report Outs (Day 1) — Palace West</td></tr>
<tr><td>5:00 pm</td><td colspan="3">Adjourn</td></tr>
</table>

Day 2 (August 24)		
7:30 – 8:30 am	Registration and Continental Breakfast	Palace Foyer
8:30 – 8:45 am	Welcome and Recap	Palace West
8:45 – 9:10 am	**Joe Cresko**, Strategic Analysis Technology Manager, DOE Advanced Manufacturing Office *Foundational Approach and Research for Energy-Water Bandwidth Study of Desalination Systems*	
9:10 – 9:20 am	Move to Breakouts	
9:20 – 11:00 am	**Breakout Session 3: Technology/Process C**	Embassy, Roxy, Hanna Rooms
11:00 – 11:15 am	BREAK (move to Main Session Room)	
11:15 am – 12:00 pm	Report Outs (Day 2)	Palace West
12:00 – 12:15 pm	General Session Closing Remarks	
12:15 pm	Adjourn	

Appendix B: Workshop Participants

B.1 Energy Optimized Desalination Workshop (San Francisco, CA)

Table B.1.1 List of San Francisco's Workshop Participants

Name	Organization
Newsha Ajami	Stanford University
Ken Armijo	Sandia National Laboratories
Lily Baldwin	Chevron
George Barclay	The Dow Chemical Company
Matt Bauer	U.S. Department of Energy
Graham Beatty	Poseidon Water
Kathryn Berchtold	Los Alamos National Laboratory
William Bourcier	Lawrence Livermore National Laboratory
Abhoyjit Bhown	Electric Power Research Institute
Dane Boysen	Gas Technology Institute
Simone Callioni	Aquatech
Linda Capuano	Rice University
Tzahi Cath	Colorado School of Mines
Amy Childress	University of Southern California
Young Chul Choi	RTI
Yoram Cohen	University of California-Los Angeles
Jill Cooper	Anadarko
Joe Cresko	U.S. Department of Energy
Shreya Dave	Massachusetts Institute of Technology
Michael Dean	-
Saied Delagah	Bureau of Reclamation, U.S. Department of the Interior
Ron Durbin	University of California-Merced
Martin Edelstein	Covalent
Ron Faibish	U.S. Department of Energy
David Forrest	U.S. Department of Energy
Carter Fox	Idaho National Laboratory
Patrick Frye	Gas Technology Institute
Peter Fyfe	Southwestern Energy
Ashok Gadgil	Lawrence Berkeley National Laboratory
Robert Gemmer	U.S. Department of Energy
Philip Gleckman	Sunvapor
Peter Gleick	Pacific Institute
William Guiney	Artic Solar
Jyotsna Iyer	Aquas Technologies
Indira Jayaweera	SRI International
Mark Johnson	U.S. Department of Energy
Jennifer Klare	Porifera
James Klausner	U.S. Department of Energy
Hareesh Kommepalli	General Electric
Robert Kostecki	Lawrence Berkeley National Laboratory
Jose Lage	National Science Foundation
Minh Le	U.S. Department of Energy
Robie Lewis	U.S. Department of Energy
Alan Liby	Oak Ridge National Laboratory
John Lienhard	Massachusetts Institute of Technology
Dawson Lindauere	Repsol

Table B.1.1 List of San Francisco's Workshop Participants

Name	Organization
Steve Lindenberg	U.S. Department of Energy
Noam Lior	University of Pennsylvania
Yanbao Ma	University of California-Merced
Bruce Macler	U.S. Environmental Protection Agency
Aaron Mandell	WaterFX
Greg Manuel	Pioneer Natural Resources
Jim Matharu	Aquatech
Charles McCaughey	Bureau of Reclamation, U.S. Department of the Interior
Jan McFarland	Fairhaven Institute
Pete McGrail	Pacific Northwest National Laboratory
Josh Mengers	U.S. Department of Energy
James Miller	Sandia National Laboratories
Mohan Misra	ITN Energy Systems
Shara Mohtadi	White House Office of Management and Budget
David Moore	General Electric
William Morrow	Lawrence Berkeley National Laboratory
Jessica Mullen	National Energy Technology Laboratory
Robin Newmark	National Renewable Energy Laboratory
Karthik Nithyanandam	Virginia Tech University
Steve Obrey	Los Alamos National Laboratory
Rob Oglesby	California Energy Commission
Dana Olson	U.S. Department of Energy
Tom Owens	Pisces Foundation
James Palko	Stanford University
Tom Pankratz	Global Water Intelligence
Shilen Patel	Veolia
Ravi Prasher	Lawrence Berkeley National Laboratory
Prakash Rao	Lawrence Berkeley National Laboratory
Chris Rayburn	Water Research Foundation
Jason Ren	University of Colorado
Jeff Roberts	Lawrence Livermore National Laboratory
Angel Sanjurjo	SRI International
Bhima Sastri	U.S. Department of Energy
Rick Seymour	Sierra Pacific Mortgage
Dev Shenoy	U.S. Department of Energy
Subhash Shinde	Sandia National Laboratories
Abhishek Shrivastava	The Dow Chemical Company
Avi Shultz	U.S. Department of Energy
AJ Simon	Lawrence Livermore National Laboratory
Eric Smistad	National Energy Technology Laboratory
Seth Snyder	Argonne National Laboratory
Michael Stadermann	Lawrence Livermore National Laboratory
Ellen Stechel	Arizona State University
Joe Stekli	U.S. Department of Energy
Ryan Stolley	U.S. Department of Energy
Matthew Stuber	WaterFX
Rich Svindland	American Water
Alan Sweedler	San Diego State University
Xiaowei Teng	University of New Hampshire

Table B.1.1 List of San Francisco's Workshop Participants	
Name	**Organization**
Jeremy Theil	-
Sebastien Tilmans	Stanford University
Craig Turchi	National Renewable Energy Laboratory
Kala Viswanathan	National Resources Defense Council
Armin Volkel	PARC
Hua Wang	General Electric
Aaron Wilson	Idaho National Laboratory
Thomas Wolfe	Toray Membrane
Hongping Yan	SLAC National Accelerator Laboratory

B.2 Clean Water Processing Technologies Research & Development Workshop (Dallas, TX)

Table B.2.1 List of Dallas's Workshop Participants	
Name	Organization
Andrea Achilli	University of Arizona
Dimitri Argyriou,	Ames Laboratory
Bamdad Bahar	Xergy Inc.
Gretelson Baier	
Matthew Bauer	U.S. Department of Energy
Kristin Bennett	KB Science LLC
Brian Berland	
Anima (Ani) Bose	University of Houston
Patrick Campbell	
Linda Capuano	Baker Institute, Rice University
Ryan Cater	Southwest Research Institute
Tzahi Cath	Colorado School of Mines
David Cercone	National Energy Technology Laboratory
Amy Childress	University of Southern California
Yoram Cohen	University of California Los Angeles
Joe Cresko	U.S. Department of Energy
Sujit Das	Oak Ridge National Laboratory
Yifu Ding	University of Colorado at Boulder
Kirk Ellison	EPRI
Ali Fares	Prairie View A&M University
Peter Fiske	Lawrence Berkeley National Laboratory
Robert Gemmer	U.S. Department of Energy
David Ginley	National Renewable Energy Laboratory
David Gotthold	Pacific Northwest National Laboratory
Johney Green	National Renewable Energy Laboratory
William Guiney	Artic Solar, Inc.
Kelsey Hatzell	Vanderbilt University
Marta Hatzell	Georgia Institute of Technology
Zachery Hendren	RTI International
Richard Hess	Idaho National Laboratory
Mike Hightower	University of New Mexico
Kevin Hoopes	Southwest Research Institute
Inez Hua	Purdue University
Brian Hunter	U.S. Department of Energy

Table B.2.1 List of Dallas's Workshop Participants

Name	Organization
Scott Husson	Clemson University
Robert Ivester	U.S. Department of Energy
Kristen Jenkins	Southern Research
Bhavana Karnik	Chevron USA
Neil Kern	Duke Energy
Tamotsu Kitade	Toray Membranes USA, Inc.
Jennifer Klare	Porifera Inc.
Robert Kostecki	Lawrence Berkeley National Laboratory
Manish Kumar	Pennsylvania State University
Stephanie Kuzio	Sandia National Laboratory
David Lampert	Oklahoma State University
Mark LeChevallier	American Water
Robie Lewis	U.S. Department of Energy
Sun Liang	Metropolitan Water District of Southern California
Haiqing Lin	University of Buffalo, SUNY
Yupo Lin	Argonne National Laboratory
Di-Jia Liu	Argonne National Laboratory
Nathaniel Lynd	University of Texas at Austin
Brenna Mannion	
Rick McCurdy	Chesapeake Energy
Peter McGrail	Pacific Northwest National Lab
Elena Melchert	
Mohan Misra	ITN Energy Systems, Inc.
Jeff Mosher	Water Environment & Reuse Foundation
Bruce Moyer	Oak Ridge National Laboratory
Dan Mueller	Environment Defense Fund
Jessica Mullen	National Energy Technology Laboratory
Robin Newmark	National Renewable Energy Laboratory
Michael Nickolaus	Ground Water Protection Council
Stephen Obrey	Los Alamos National Laboratory
Kenan Ozekin	Water Research Foundation
Laurel Passantino	Arizona State University
Pinakin Patel	eT2M
Brian Pianfetti	University of Illinois at Urbana Champaign
Yarom Polsky	Oak Ridge National Laboratory
Zhiyong (Jason) Ren	University of Colorado Boulder
Jeff Roberts	Lawrence Livermore National Laboratory
Diego Rosso	University of California, Irvine
David Sedlak	University of California Berkley
Sridhar Seetharaman	U.S. Department of Energy
Apoorva Sharma	California Resources Corporation
Randy Shaw	Brackish Groundwater National Desalination Research Facility
Abhishek Shrivastava	The Dow Chemical Company
AJ Simon	Lawrence Livermore National Laboratory
Dileep Singh	Argonne National Laboratory
Rajinder Singh	Los Alamos National Laboratory
Seth Snyder	Argonne National Laboratory
Vincent Tidwell	Sandia National Laboratories
Gabriel Levesque Tremblay	American Institute of Chemical Engineers

Table B.2.1 List of Dallas's Workshop Participants	
Name	**Organization**
Costas Tsouris	Oak Ridge National Laboratory
Craig Turchi	National Renewable Energy Laboratory
Michael Webber	University of Texas Austin
John Webley	Trevi Systems Inc.
Brian Weeks	Gas Technology Institute
Aaron Wilson	Idaho National Laboratory
Thomas Wolfe	Toray Membrane USA
May Wu	Argonne National Laboratory
Pei Xu	New Mexico State University
Ngai Yin Yip	Columbia University

B.3 Clean Water Processing Technologies Research & Development Workshop (Cleveland, OH)

Table B.3.1 List of Cleveland's Workshop Participants	
Name	**Organization**
Nirupam Aich	Civil, Structural and Environmental Engineering
Susan Altman	Sandia National Laboratories
Kenneth Armijo	Sandia National Laboratories
Marissa Ballantine	Sandia National Laboratories
Andre Benard	Michigan State University
Craig Blue	Oak Ridge National Laboratory
Michael Bortner	Virginia Tech
William Bourcier	Lawrence Livermore National Laboratory
Anthony Burrell	National Renewable Energy Laboratory
Stephen Butler	NanoRanch UHV Technologies
Malynda Cappelle	The University of Texas at El Paso
Young Chul Choi	RTI International
Joe Cresko	U.S. Department of Energy
Fred Crowson	Energetics Incorporated
Roland Cusick	University of Illinois at Urbana-Champaign
Claus Daniel	Oak Ridge National Laboratory
Seth Darling	Argonne National Laboratory
Snehal Desai	Dow Chemical
Caroline Dollinger	Energetics Incorporated
Laura Fabeny	Allegheny Science & Technology
Wen Fan	Institute for Sustainable Energy and the Environment
Peter Fiske	Lawrence Berkeley National Laboratory
Andrew Flowers	PPG
Steve Frenkel	
Robert Gemmer	Advanced Manufacturing Office, US
Amit Goyal	University At Buffalo, SUNY
David Hardy	Department of Energy/ EERE-AMO
Kerri Hickenbottom	University of Arizona
Jon Holland	Nissan North America, Inc.
Patricia Ignacio-de Leon	Argonne National Laboratory
Mark Johnson	U.S. Department of Energy
Dale Keairns	Deloitte Consulting LLP
Jaehong Kim	Yale University
Greg Krumdick	Argonne National Laboratory
Jackie Kulfan	PPG
Kuldip Kumar	Metropolitan Water Reclamation District
Stephanie Kuzio	Sandia National Laboratories

Table B.3.1 List of Workshop Participants	
Name	**Organization**
David Ladner	Clemson University
Richard Lueptow	Northwestern University
Tengfei Luo	University of Notre Dame
Jordan Macknick	National Renewable Energy Laboratory
Meagan Mauter	Carnegie Mellon University
James McCall	National Renewable Energy Laboratory
Jeffrey McCutcheon	University of Connecticut
Pete McGrail	Pacific Northwest National laboratory
Travis McLing	Idaho National Lab
Sue Mecham	University of North Carolina Chapel Hill
Jeff Moeller	WE&RF
Jaeyun Moon	University of Nevada, Las Vegas
Adrien Moreau	Veolia Water Technologies
Tala Navab-Daneshmand	Oregon State University
Mark Nicholson	Veolia Water
Stephen Obrey	Los Alamos National Laboratory
Aaron Packman	Northwestern University
Brian Pianfetti	University of Illinois at Urbana Champaign
Yarom Polsky	Oak Ridge National Laboratory
Jeffery Preece	Electric Power Research Institute
Jay Renew	Southern Research
Matthew Ringer	National Renewable Energy Laboratory
Douglas Rotman	Lawrence Livermore National Laboratory
Igor Slowing	Ames Laboratory
Michael Stadermann	Lawrence Livermore National Laboratory
Frederick Stewart	Idaho National Laboratory
Matthew Stuber	University of Connecticut
Emmanuel Taylor	Energetics Incorporated
Richard Todaro	Allegheny Science & Technology
David Turpin	Agenda 2020 Technology Alliance
Judith Underwood	Blue Institute at Cape Cod, Inc.
David van der Wiel	B&W Research Center
Jenita Warner	Northeast Ohio Regional Sewer District
Aaron Wilson	Idaho National Laboratory
May Wu	Argonne National Laboratory
Ronggui Yang	University of Colorado
George Zhou	Purdue University

Appendix C: Panelist Biographies

C.1 Energy Optimized Desalination Workshop (San Francisco, CA)

- Dr. Peter Gleick, President Emeritus and Co-Founder of the Pacific Institute. Dr. Gleick is a world-renowned expert, innovator, and communicator on water and climate issues. In 1987 he co-founded the Pacific Institute, which he led as president until mid-2016, when he became president emeritus. Peter developed one of the first analyses of climate change impacts on water resources, the earliest comprehensive work on water and conflict, and defined basic human need and right to water – work that has been used by the United Nations and in human rights court cases. Also, he pioneered and advanced the concepts of the "soft path for water" and "peak water". Peter received the prestigious MacArthur "Genius" Fellowship and was elected to the U.S. National Academy of Sciences. He serves on the boards of numerous journals and organizations, and is the author or co-author of many scientific papers and 11 books. Dr. Gleick holds a B.S. from Yale University and an M.S. and Ph.D. from the University of California, Berkeley.

- Mr. Tom Pankratz, an Independent Consultant. Mr. Pankratz serves as Editor of the Water Desalination Report, a weekly publication at Global Water Intelligence. Mr. Pankratz also serves as an Independent Desalination Consultant and Technical Advisor. He has been involved in the water industry for his entire career and participated in the development of some of the world's largest and most technically advanced desalination and water reuse projects. He was appointed to National Academy of Sciences desalination roadmap review committee, the WHO Desalination Guidelines Technology/Chemistry/Engineering Working Group, and the research advisory council of the Middle East Desal Research Center. His water experience includes international assignments in the Middle East and Europe, and he has written several industry-related books including the "desalination.com", "Dictionary of Environmental Engineering", and "Screening Equipment Handbook". He has also written technical papers on subjects ranging from seawater desalination to water reuse to zero liquid discharge. Mr. Pankratz serves as a Member of Scientific Advisory Board at NanoH2O, Inc.

- Dr. John Lienhard, Professor of Mechanical Engineering at Massachusetts Institute of Technology. Prof. Lienhard V is Abdul Latif Jameel Professor and the Director of the Abdul Latif Jameel World Water and Food Security Lab at MIT. During nearly three decades on the MIT faculty, Prof. Lienhard's research and educational efforts have focused on water purification and desalination, heat and mass transfer, and thermodynamics. He has also filled a number of administrative roles at MIT. Prof. Lienhard received his bachelors (*summa cum laude*) and master's degrees in thermal engineering at UCLA from the Chemical, Nuclear, and Thermal Engineering Department, where he worked on thermal instabilities in solar collectors and evaporating meniscus measurements for desalination systems. He joined MIT immediately after completing his PhD in the Applied Mechanics and Engineering Science Department at UC San Diego, where he did experimental work on thermally stratified turbulent flows. Since coming to MIT, Pr9of. Lienhard has worked on desalination processes, liquid jet impingement, high heat flux engineering, electronics thermal management, and other topics. His research in desalination includes humidification-dehumidification desalination, membrane distillation desalination, forward and reverse osmosis, fouling and scale formation, electrodialysis, nanofiltration, management of high salinity brines, solar-driven desalination, thermodynamic and energy efficiency analysis of desalination cycles, and energy-water nexus issues.

- Mr. Rob Oglesby, an Executive Director at the California Energy Commission. Mr. Oglesby served as Executive Director of the California Energy Commission from 2011 to 2017. The Commission is the state's primary energy policy and planning agency. The Commission also licenses large power plants, sets appliance and building efficiency standards and administers about $750 million annually funding energy efficiency, energy research and development, and alternative fuels and vehicles. Mr. Oglesby began his career under the first Brown Administration Department of Economic and Business

Development, and worked in the private sector for ten years on issues related to public finance, the environmental and economic development. Immediately prior to joining the Energy Commission, Mr. Oglesby held several positions at the California Air Resources Board (ARB) where he served four Governors as an appointee and participated at a high level in virtually all major issues affecting air pollution and global warming over the past two decades. Mr. Oglesby's tenure at the ARB included the inception of the Low and Zero Emission Vehicle standards, adoption of reformulated gasoline and diesel fuel requirements, and development and implementation of the Global Warming Solutions Act (AB 32).

C.2 Clean Water Processing Technologies Research & Development Workshop (Dallas, TX)

- Dr. Linda Capuano, Fellow in Energy Technology at the Baker Institute. Dr. Capuano is the fellow in energy technology at the Baker Institute Center for Energy Studies. She is also on the faculty of Rice University's Jones Graduate School of Business, where she teaches operations strategy for the executive MBA program. Her research interests in the energy-water-food nexus focus on accelerating the treatment and use of non-fresh water sources. Dr. Capuano's career has centered on commercializing technology innovation through a network of contacts and experience in high-tech companies, where she has guided new technologies from design to successful commercialization. She previously served as an officer and company vice president of technology at Marathon Oil Corp.; senior vice president of engineering design at Solectron Flextronics; executive vice president and chief technology officer at Advanced Energy Industries; corporate vice president of technology strategy at Honeywell; general manager of wide body aircraft auxiliary product units at AlliedSignal Aerospace; and manager in computer memory product development at IBM. She co-founded and served as chief financial officer of Conductus, a Silicon Valley start-up that commercialized ceramic superconductor technology discovered in the 1980s. Dr. Capuano received her Ph.D. in materials science and engineering and M.S. in engineering management from Stanford University; an M.S. in chemistry and a B.S. in chemical engineering from the University of Colorado at Boulder; and a B.S. in chemistry from the State University of New York at Stony Brook.

- Mr. Rick McCurdy, Manager - Chemicals & Water Reclamation at Chesapeake Energy. In his current role, Mr. McCurdy is responsible for technical guidance for all chemical programs at Chesapeake Energy and for development of new technologies for chemically-related operational challenges. He is also responsible for development of environmentally friendly hydraulic fracturing fluids. In addition, evaluate and advise on water reclamation and reuse activities throughout Chesapeake's operating area. Prior to joining Chesapeake Energy, Mr. McCurdy worked for BJ Chemicals Services for several years where he was responsible for oversight of Technical Service groups and Laboratory support functions for the Permian Basin and Rocky Mountains. He was also responsible for preparation and presentation of technical and commercial business offerings and for internal and external technical training.

- Dr. Diego Rosso, Director at the Water-Energy Nexus Center and Associate Professor, Civil and Environmental Engineering and Chemical Engineering and Materials Science, University of California, Irvine. Dr. Rosso is an Associate Professor in the Civil and Environmental Engineering Department and is the Director of the Water-Energy Nexus Center at UCI. Since 2000, he has been investigating the water-energy-carbon nexus and water reclamation and reuse processes. His research portfolio, to date exceeding $2M, has been supported by federal and state funding, and from a variety of industrial sources. He is a Chemical Engineering Laureate from the University of Padua in Italy and earned a Ph.D. in Environmental Engineering from UCLA.

- Dr. Michael E. Webber, Deputy Director of the Energy Institute and Professor of Mechanical Engineering, University of Texas, Austin. As a Deputy Director of the Energy Institute, Co-Director of the Clean Energy Incubator, Josey Centennial Professor in Energy Resources, Author, and Professor of Mechanical Engineering, Dr. Webber trains the next generation of energy leaders at the University of Texas at Austin and beyond through research and education at the convergence of engineering, policy, and commercialization. His recent book, “Thirst for Power: Energy, Water and Human Survival”, which addresses the connection between earth’s most valuable resources and offers a hopeful approach toward a sustainable future, is receiving wide praise. His television special Energy at the Movies was in national syndication on PBS stations 2013-2015, and a suite of energy literacy tools titled Energy 101, including videos, online courses, and an interactive ebook, is available globally. He was selected as a Fellow of ASME, has authored more than 300 publications, holds 4 patents, and serves on the advisory board for Scientific American. Webber holds a B.S. and B.A. from UT Austin, and M.S. and Ph.D. in mechanical engineering from Stanford. He was honored as an American Fellow of the German Marshall Fund, an AT&T Industrial Ecology Fellow, and on four separate occasions by the University of Texas for exceptional teaching.

C.3 Clean Water Processing Technologies Research & Development Workshop (Cleveland, OH)

- Mr. Snehal Desai, Global Business Director at Dow Water and Process Solutions. Mr. Desai is the global business director for Dow Water & Process Solutions, a leader in sustainable separation and purification technologies, representing revenue of approximately $1 billion. In his role, Mr. Desai is responsible for developing and implementing the growth strategy for the business and leading the approximately 1,700 employees worldwide. Mr. Desai has more than 25 years of increasing leadership responsibility experience in the sales, marketing and business development of water, plastics, chemicals and renewable materials. From 2008 to 2010, he led commercial and business development for Segetis, a startup focused on developing novel bio-based chemicals, and from 2003 to 2008, served as the vice president and chief marketing officer of NatureWorks LLC, the first company to offer a family of commercially available low-carbon-footprint polymers. Mr. Desai received bachelor’s degrees in chemistry and chemical engineering from the University of Michigan and an M.B.A. from the Kellogg Graduate School of Management at Northwestern University.

- Mr. Andrew Flowers, Filtration Systems R&D Engineer at PPG industries. Mr. Flowers helps industrial water users recover water and valuable byproducts for recycling or reuse, decreasing disposal costs and increasing the profitability of their operations. Once practical recycling/reuse limits are reached, Mr. Flowers then work with clients to achieve effluent quality required by local, state, and federal regulations in order to discharge to surface or ground waters, or their POTW. Mr. Flowers has a Bachelor of Science degree in Chemical Engineering from the University of Pittsburg with 8+ years of industrial water treatment engineering experience, including raw make-up, cooling tower, boiler, process, and wastewater applications.

- Mr. Adrien Moreau, Global Support Engineer and MIT System Design and Management Fellow, Veolia Water. Mr. Moreau has 10+ years of industry experience in product development & technical risk management, technology and product road mapping, technology assessment and validation, and IP strategy. He’s also expert in competitive industry and market analysis, innovation strategy development, stakeholder analysis and engagement. He holds a PhD degree in Water management/sanitary engineering from the Delft University of Technology.

- Dr. Seth W. Snyder, Water Research Leader at Argonne National Laboratory. Dr. Snyder is the leader of Argonne National Laboratory's water initiative. In this role, he coordinates work with other U.S. Department of Energy national laboratories to address the Energy-Water Nexus. He also coordinates a regional initiative in water investment in Chicago. Previously he served as Bioenergy Technology Manager and leader of Process Technology Research. He is a Senior Fellow in the University of Chicago's Energy Policy Institute at Chicago. He is also a Fellow at the Institute of Molecular Engineering and the Northwestern-Argonne Institute for Science and Engineering. He received his PhD degree in Biophysics from the University of Virginia.

- Dr. Seth Darling, Director, Institute for Molecular Engineering & Scientist at Argonne National Laboratory. During his 15-year career at Argonne, Dr. Darling has made a notable impact as a scientist within the Nanoscience and Technology Division (NST) and at the Center for Nanoscale Materials (CNM). He has received numerous awards for his work and has led several strategic efforts. Dr. Darling's research at Argonne has included blending chemistry, physics, materials science and engineering, and nanoscience to create and study materials for energy and water. With colleagues at Argonne, Dr. Darling invented a new materials synthesis technique called sequential infiltration synthesis, which has found applications in areas ranging from nanolithography to optical coatings to advanced sorbents and membranes. Dr. Darling holds a PhD degree in Physical Chemistry from the University of Chicago.

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DOE/EE-1764 ▪ March 2018