Desalination for a Circular Water Economy

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Desalination for a Circular Water Economy

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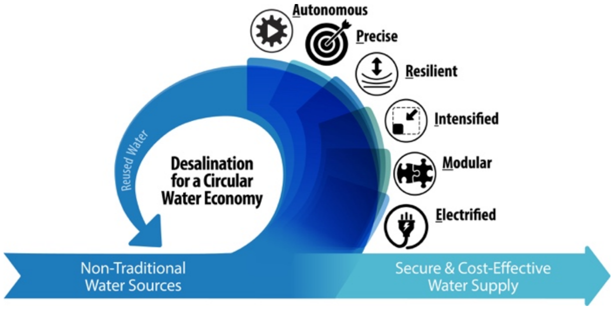
Advancing a circular water economy through autonomous, precise, resilient, intensified, modular, and electrified technologies enabling distributed desalination and fit-for-purpose reuse.



ABSTRACT

Today's water systems are enabled by ample fresh water sources, low-cost centralized treatment, and facile wastewater disposal. Climatic change, aging infrastructure, and source water contamination have exposed the vulnerabilities of this linear water paradigm. While seawater desalination enables coastal communities to augment their supply, more broadly securing water systems for municipal, industrial, and agricultural water users will require distributed desalination and fit-for-purpose reuse of nontraditional water sources. Our linear water economy must evolve into a resilient circular water economy, where water is continuously reused and "contaminants" become the feedstocks for other economically valuable processes. Technology innovation is needed to deliver autonomous, precise, resilient, intensified, modular, and electrified desalination systems that reduce the cost, improve the performance, and enhance the resilience of nontraditional water reuse systems. Meanwhile, strong federal leadership and coordination is needed to accelerate desalination research, promote information gathering efforts to direct technology development, and create an expanded role for non-profit organizations in knowledge dissemination.

BROADER CONTEXT

21st century water demands will not be satisfied using our 20th century paradigm for water supply and water treatment. A century of incremental water efficiency innovations, expansion of reservoir storage, long-distance freshwater conveyance, and a smattering of seawater desalination in our most affluent communities will fail to deliver the resilient, carbon-neutral water supplies the world needs. Augmenting existing systems with an expanding array of diverse, nontraditional water sources that we currently discard (e.g., wastewater, brackish groundwater, produced water, and agricultural drainage) and deploying small-scale desalination and fit-for-purpose water reuse technologies that are autonomous, precise, resilient, intensified, modular, and electrified will be key to stabilizing our water supplies. This Opinion details the technology innovations and policy interventions that will be critical to cost-effectively tapping these new water supplies and highlights a new U.S. Department of Energy investment to move this vision forward.

Water is a linchpin of the economy and critical to the security and prosperity of our communities. The U.S. alone uses more than 1.2 billion m^3 per day,[1] primarily sourced from distant freshwater sources, treated in centralized facilities, used inefficiently, and discharged back into the environment as a waste stream. These 20th century "linear" practices are not sustainable in the 21st century. Climate change, population growth, and depleted groundwater aquifers are exacerbating supply uncertainty;[2, 3] centralized water infrastructure is aging to the point of failure;[4] and wastewater and concentrate discharge is costly to both industry and the environment. Securing water supplies for municipal, industrial, and agricultural end uses will require technology innovation to support a circular water economy where nontraditional water sources—from municipal wastewater, brackish aquifers, or industrial discharges—are treated to fit-for-purpose standards and reused locally.

Desalination, the process of separating ions from water, will be an essential treatment step for tapping and reusing many of these nontraditional water sources. While desalination is most commonly associated with efficiently producing freshwater from the sea,[5] desalination processes are also integral to recycling municipal wastewater, dewatering highly saline produced water, and reusing industrial wastewater. For these high- and low-salinity waters, waters with complex chemistries, and waters with end-uses other than municipal distribution, state-of-the-art desalination technologies are not nearly as thermodynamically efficient. Nontraditional water desalination technologies often operate at 10-100× the thermodynamic limit of separation[6, 7] (Figure 1), and treated water costs are at least an order of magnitude higher than traditional freshwater sources.[8, 9]

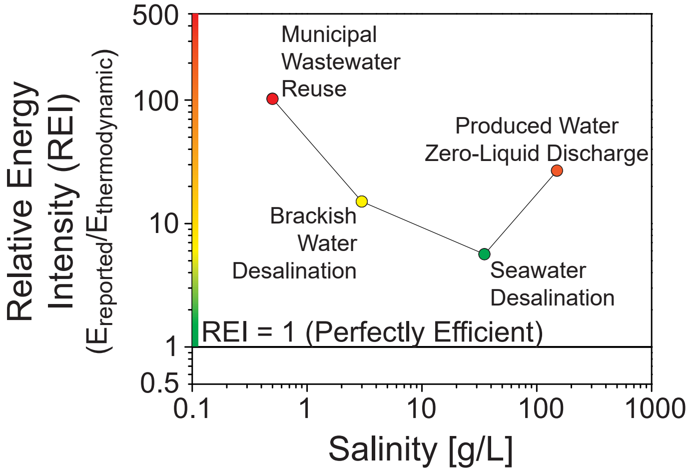


Figure 1. Thermodynamic energy efficiency of select nontraditional water sources treated using state-of-the-art technologies (5-7).

Unfortunately, desalinating nontraditional waters at the thermodynamic limit would not make these sources cost-competitive. Energy consumption accounts for only about one quarter to one half of the typical lifecycle cost of water desalination treatment trains.[10] The remaining treatment costs stem from permitting, capital, and non-energy operational costs that benefit from strong economies of scale (Figure 2). For example, the cost of seawater reverse osmosis scales approximately as treatment capacity to the -0.125 power ($Q^{-0.125}$), meaning that the lifecycle cost of water from a desalination plant designed to treat 10,000 m^3/hr is half that of a plant designed to treat 100 m^3/hr.[8-11]

But large desalination plants also require large distribution systems. Since the unit cost of conveyance (i.e., building and maintaining pipe networks and moving water) scales immutably with distribution system size, total lifecycle unit cost for large scale systems is dominated by conveyance (Figure 2). For the seawater desalination facilities producing greater than 10,000

m^3/hr, we estimate that the costs of transport are greater than the costs of treatment. These conveyance costs limit the cost-optimal size of seawater desalination facilities—most plants are built at the 10's of thousands of m^3 per hr scale—and preclude the existence of large national water grids.

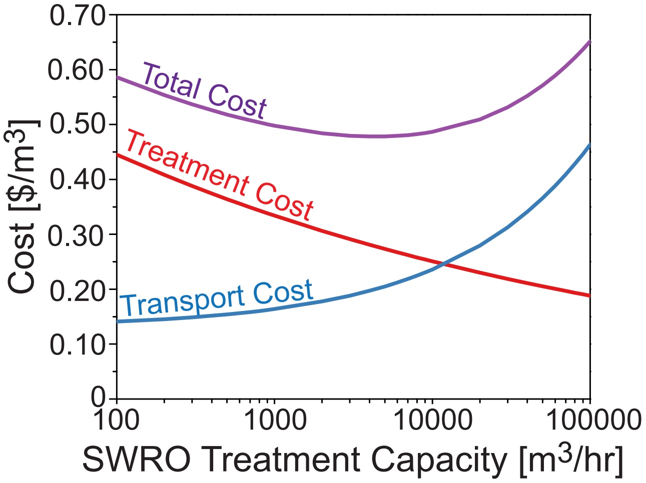


Figure 2. Approximate total lifecycle cost of municipal water from seawater reverse osmosis. Conveyance costs are highly variable and a function of topography, network size, network age, and failure rates. Here, conveyance is estimated by relating average municipal consumption volumes to distribution area and pipe network size, and by assuming a median pipe cost of $35/linear foot and a lifespan of 75 years (*11-12*).

Cost-effectively tapping nontraditional water sources for enhanced water security necessitates new paradigms for water system design. Most nontraditional water sources are small scale, geographically dispersed, chemically heterogeneous, and far more temporally varied than traditional freshwater or seawater sources. These nontraditional sources will only be cost competitive if we minimize transport costs and vastly reduce the lifecycle costs of small scale treatment systems. First, we need to evolve toward a circular water economy, in which water is treated locally and to fit-for-purpose standards. Second, we need to replace conventional economies of scale in treatment with economies of scale in device manufacturing, installation, and operation.

Together, these two paradigm shifts in network and system design would enhance water resiliency, minimize the environmental impacts of wastewater discharge, and facilitate water use efficiency across water end users. In the power generation and mining sectors, wastewater could be efficiently dewatered, delivering pure water for process needs, valuable elements to market, and solid wastes for safe sequestration.[13, 14] In the oil and gas sector, locally tailored treatment could desalinate produced water for beneficial reuse, while concentrate streams could be transformed into valuable oilfield chemicals such as caustic soda and sulfuric acid.[15] Small desalination plants may leverage the revolution in affordable, but intermittent, renewable energy resources to deliver sustainable water supply[16-20] and provide demand response services that enhance grid stability. And in small and medium-size manufacturing operations, wastewater could be retreated and reused onsite by autonomous water treatment “appliances” that would be serviced by a growing “Bluetech” workforce. The wide ranging applications for desalination technologies extend far beyond sourcing water from the sea.

While the cost savings from minimizing water conveyance through local reuse will be greatest for water end users who have not already invested in building and maintaining conveyance infrastructure, this paradigm shift also benefits existing water systems. First, distributed water reuse could complement our traditional water supply systems in municipal settings. Building scale and industrial water reuse would minimize demand for new freshwater resources or provide critical reserve capacity during periods of drought. Second, the manufacturing, installation, and operations innovations that are essential to reducing costs in small scale systems will also generate cost savings for large scale systems. We need look no further than the thousands of stacked membrane modules in today's large seawater desalination facilities for early support of this concept, though some of the greatest benefits of modularity may actually be realized in the facile permitting, faster deployment, and enhanced resiliency of modular systems that are not captured in generic technology capital and operational cost assessments.

But today's technologies cannot fully support this vision. We need a new generation of low-cost processes that are inexpensive to customize, manufacture, operate, and maintain. The transition from designing large, centralized, custom-built, and manually operated facilities to manufacturing small, decentralized, modular, and smart water treatment systems cannot be achieved by simply scaling down existing treatment plant designs or introducing marginal improvements to current treatment processes. Instead, we need a suite of next generation desalination technologies that autonomously optimize process performance, precisely and efficiently remove trace constituents of concern, are robust to variable water quality, desalinate water and concentrate brines in as few, modular units as possible, are readily manufactured, and do not require a constant resupply of consumable chemical reagents. In short, the next revolution in distributed desalination and reuse can only be realized by developing a suite of **a**utonomous, **p**recise, **r**esilient, process-**i**ntensified, **m**odular, and **e**lectrically powered technologies (A-PRIME) that support locally tailored treatment at a cost comparable to other inland and industrial sources (Table 1).

Table 1: Technology innovations for a circular water economy.

Attribute	**Current Systems**	**Future Systems**	**Research Needs**
Autonomous *Sensor networks and adaptive process control for efficient and secure water treatment systems.*	Treatment systems operate at nominally steady-state conditions, relying on human intervention to adapt to variations in water quality and correct failures in process performance.	Simple, robust sensor networks coupled with sophisticated analytics and controls systems enhance performance efficiency, process reliability, and treatment train adaptability while minimizing the need for onsite, manual interventions.	Internet of things infrastructure for water that is generalizable, secure, and resilient to sparse data and sensor calibration errors. Reduced order models for closed loop feedback control and optimization.
Precise *Targeted removal of trace solutes for regulatory compliance, enhanced water recovery, and resource valorization.*	Treatment systems rely on inefficient bulk separation processes to remove solutes that occur at trace levels (e.g., boron, hexavalent chromium, lead, nitrate, perchlorate, selenium, uranium, lithium, iodide). Separation processes rarely selective.	Targeted trace contaminant removal minimizes treatment cost and energy intensity, while reducing system complexity and residual disposal costs. Precise separation or transformation of constituents enables valorization of waste streams, offsetting the lifecycle costs of desalination.	Rational materials design coupled with high throughput materials screening yields materials and processes with high removal efficiency for hard-to-treat or valuable-to-extract compounds.
Resilient *Adaptable water supply networks, flexible treatment processes, and robust materials.*	Treatment trains are coupled to rigid networks. Processes not designed for highly variable feedwater volume and composition. Storage and distribution systems are corroding, leaking, and costly to replace.	Optimized network designs enable flexible, fit-for-purpose reuse. Operando characterization of materials and processes inform adaptive process control and extend materials lifespan in challenging environments.	Computationally efficient multiscale modeling and multi-objective optimization platforms for materials, processes, and networks.
Intensified *Energy efficient concentrate management by eliminating first order phase transitions.*	Thermal brine management technologies are energy intensive, complex, and poorly suited for the modest flows of small-scale desalination systems.	Waste heat driven or non-thermal technologies for brine concentration reduce dependence on finite injection well capacity, minimize brine conveyance, lower concentration energy intensity, and enhance water recovery from nontraditional sources.	Models of nucleation and crystalline phase growth for precise control of precipitation. Processes that leverage multiple driving forces. Topology optimization and precision manufacturing for improved process performance.
Modular *Materials, manufacturing, and operational innovations that propel modular membrane systems into new treatment applications.*	Fouling and scaling of membrane systems, poor removal of low molecular weight and neutral compounds, membranes are not customized for specific feedwater compositions.	Customizable, mass-manufactured modular treatment systems (including membranes) enable tailored water reuse of high fouling and scaling potential waters.	Next generation membrane materials and processes through manufacturing innovation for customization and scalable deployment.
Electrified *Electrifying water treatment processes and facilitating their integration with a clean energy grid.*	Treatment trains use large volumes of energy intensive commodity chemicals. Processes are designed for steady-state operation, reducing their ability to ramp in response to fluctuations in water quality and the price of electricity.	Electrified water treatment processes and optimized pumping schedules reduce water costs while stabilizing the energy grid.	High-fidelity simulation models and operando characterization of electrochemical processes that include chemical, flow, faradaic, and non-faradaic effects in complex fluid compositions. Integrated energy-water economic models to quantify stability, reliability, and flexibility derived from water sector electrification and demand response.

Fortunately, the same technology innovations that are critical to expanding the distributed desalination and fit-for-purpose reuse of nontraditional waters will also address many of the ongoing challenges faced by centralized municipal systems that will continue to supply the majority of our clean water. Municipal water treatment systems will benefit tremendously from more widespread automation with active fault detection, from an ability to precisely remove problematic contaminants like PFOS/PFOA and arsenic, from more robust materials to prevent corrosion and intensified processes to save energy and shrink plant footprints. Modularity may accelerate the permitting and approval process in municipal systems, while process electrification is essential to broader scale decarbonization efforts and enhancing the potential for water treatment systems to provide energy services to the electric power grid.[21]

Realizing this A-PRIME vision will require a focused and integrated *science-to-systems* research program to accelerate the timeline from discovery to process validation to device commercialization to system-level adoption. We need novel tools for data acquisition, analysis, and techno-economic assessment that provide quantitative comparisons of the levelized cost of water, energy intensity, life cycle impacts, water intensity, robustness, and resilience of nontraditional water desalination systems to the R&D and industrial desalination communities. We need innovations in multiscale modeling and simulation of desalination processes that allow researchers to optimize entire treatment trains in a virtual environment and accelerate the design of desalination processes and materials that are cost competitive. We need new desalination technologies that use multi-physics driving forces, intensified process concepts, and advanced algorithms to desalinate close to the thermodynamic limit in modular, manufactured, autonomously operated devices. Finally, we need new approaches to materials discovery, synthesis, and high throughput characterization that are synchronized with precision manufacturing methods to lower the cost of high performance materials and processes.

Technology innovations to deliver cost-competitive, distributed desalination and water reuse must go hand in hand with policy innovations at the federal, state, and local levels. In response to the 1970’s energy crisis, the U.S. Congress created the Energy Information Administration to gather and verify energy generation, transmission, and demand data across the U.S. economy. The absence of an equivalent authority for systematically gathering water quality, treatment, use, or cost data—a “Water Information Administration”—leaves engineers and policy makers unable to quantitatively assess the impact of technology or policy innovations for managing our water.[22] A Water Information Administration would provide robust scientific and economic information to foster a comprehensive and systemic understanding of the country's changing water needs, including supply, demand by sector and end use, and flows.

Data collection efforts must be paired with data dissemination policies. Over the past two decades, access to location specific information about critical water infrastructure has been severely curtailed. Secure data sharing platforms and clear policies around removing identification data in publications would allow academic and national laboratory researchers to access sensitive information about water treatment sources and distribution systems without jeopardizing national security or citizen well-being. Anonymized water data would also facilitate active participation from industrial partners who fear that exposing shortcomings of treatment processes or vulnerabilities in systems design will spark regulatory intervention.

Fostering a water research ecosystem will also require prioritized and sustained R&D investment. U.S. federal statutory authority over water is highly disjointed, leading to conflicting, duplicative, and inconsistent investment. Current desalination research funding is primarily structured as very small basic research grants to universities, industrially driven pilot demonstration projects with large cost-share requirements, or one-off water prizes. None of these models promotes science-to-systems research or sustained investment conductive to innovations for the public-good. Past efforts to establish an interagency framework to coordinate policy and research investments at the energy-water nexus[23] should be expanded and special focus should be paid to shepherding early stage research successes through the demonstration and commercialization phases. As sponsors of the Nexus of Energy and Water for Sustainability (NEWS) Act originally proposed in 2014, federal R&D investments will benefit from innovative financing mechanisms, public private partnerships, and collaboration with state and local agencies who also have a vested interest in water security.

At the state and local level, researchers and consultants have long collaborated with water utilities and industrial water users to provide valuable design knowledge and technical support for operational challenges. Consulting engineers have also been the primary conduits of knowledge, though translating success from one facility to the next remains far too slow. Adoption of appliance-like water treatment solutions in nontraditional applications would shift the role of consulting engineers from unit process designers to innovative system optimizers and raise the importance of professional societies and independent research organizations in disseminating knowledge and communicating future research needs.

A-PRIME technology innovations coupled with policy changes will enable the evolution of a linear water economy into an energy-integrated circular water economy where water is continuously used and reused and "contaminants" become the feedstock for other economically valuable processes. However, establishing a new paradigm of distributed water treatment alongside the existing framework of centralized systems will be a multi-decadal campaign. The U.S. Department of Energy's recent investment supporting desalination research through the National Alliance for Water Innovation is a strategic investment in low technology readiness level innovation, but additional support from other federal, state, and private sources will be essential to translating early stage applied research into commercial products.

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Disclaimer: The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Supplementary Information: Description of Water Treatment Cost Calculations (Section 1), Water Distribution Cost Calculations (Section 2), and References (Section 3).

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