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Desalination and Membrane Technologies: Federal Research and Adoption Issues

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January 2, 2015

Congressional Research Service
7-....
www.crs.gov
R40477

CRS REPORT
Prepared for Members and
Committees of Congress

Summary

In the United States, desalination and membrane technologies are used to augment municipal water supply, produce high-quality industrial water supplies, and reclaim contaminated supplies (including from oil and gas development). Approximately 2,000 desalination facilities larger than 0.3 million gallons per day (MGD) operate in the United States; this represents more than 2% of U.S. municipal and industrial freshwater use. At issue for Congress is what should be the federal role in supporting desalination and membrane technology research and facilities. Desalination issues before the 114th Congress may include how to focus federal research, at what level to support desalination research and projects, and how to provide a regulatory context that protects the environment and public health without disadvantaging desalination's adoption.

Desalination processes generally treat seawater or brackish water to produce a stream of freshwater, and a separate, saltier stream of water that requires disposal (often called waste concentrate). Many states (e.g., Florida, California, and Texas) and cities have investigated the feasibility of large-scale municipal desalination. Coastal communities look to seawater or estuarine water, while interior communities look to brackish aquifers. The most common desalination technology in the United States is reverse osmosis, which uses permeable membranes to separate freshwater from saline waters. Membrane technologies are also effective for other water treatment applications. Many communities and industries use membranes to remove contaminants from drinking water, treat contaminated water for disposal, and reuse industrial wastewater. For some applications, there are few competitive technological substitutes.

Wider adoption of desalination is constrained by financial, environmental, and regulatory issues. Although desalination costs have dropped in recent decades, significant further decline may not happen with existing technologies. Electricity expenses represent one-third to one-half of the operating cost of many desalination technologies. The energy intensity of some technologies raises concerns about greenhouse gas emissions and the usefulness of these technologies for climate change adaptation. Concerns also remain about the technologies' environmental impacts, such as saline waste concentrate management and disposal and the effect of surface water intake facilities on aquatic organisms. Construction of desalination facilities, like many other types of projects, often requires a significant number of local, state, and federal approvals and permits. Emerging technologies (e.g., forward osmosis, capacitive deionization, and chlorine resistant membranes) show promise for reducing desalination costs. Research to support emerging technologies and to reduce desalination's environmental and human health impacts is particularly relevant to future adoptions of desalination and membrane technologies.

The federal government generally has been involved primarily in desalination research and development (including for military applications), some demonstration projects, and select full-scale facilities. For the most part, local governments, sometimes with state-level involvement, are responsible for planning, testing, building, and operating desalination facilities. Some states, universities, and private entities also undertake and support desalination research. While interest in desalination persists among some Members, especially in response to drought concerns, efforts to maintain or expand federal activities and investment are challenged by the domestic fiscal climate and differing views on federal roles and priorities.

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A Primer on Desalination

Interest in using desalination technologies to treat seawater, brackish water,[1] wastewaters, and contaminated sources has increased globally and in the United States, as costs have fallen and pressure to develop drought-proof water supplies has grown. Adoption of desalination, however, remains constrained by financial, environmental, regulatory, and social factors. At issue is the role Congress establishes for the federal government in desalination, particularly in desalination research and development and the federal regulatory environment for desalination projects. Also of congressional interest is what role desalination may play in meeting water demands.

Desalination processes generally treat saline or impaired waters to produce a stream of freshwater, and a separate, saltier stream often called *waste concentrate* or *brine*. The availability and regulation of disposal options for waste concentrate can limit adoption in some locations; this is a particular challenge for large-scale inland facilities. For seawater desalination, the impacts of intake facilities on marine life also often are raised as concerns.

Desalination's attractions are that it can create a new source of freshwater from otherwise unusable waters, and that this source may be more dependable and drought-proof than freshwater sources that rely on annual or multi-year precipitation, runoff, and recharge rates. Another significant application of desalination technologies is for treatment of contaminated waters or industrial water or municipal wastewater. Some communities and industries use desalination technologies to produce drinking water that meets federal standards, to treat contaminated water supplies to meet disposal requirements, or to reuse industrial wastewater. Many of the technologies developed for desalination also can produce high-quality industrial process water. For many of these applications, there may be few technological substitutes that are as effective and reliable as desalination technologies.

There are multiple desalination methods. Two common categories of desalination technologies—thermal (e.g., distillation) and membrane (e.g., reverse osmosis)—are the most common, with reverse osmosis technologies dominating in the United States. For more information on traditional and emerging technologies, see **Appendix A**.

Desalination treatment costs have dropped in recent decades, making the technology more competitive with other water supply augmentation and treatment options. Electricity expenses vary from one-third to one-half of the cost of operating desalination facilities.[2] A rise in electricity prices could reverse the declining trend in desalination costs; similarly, drops in electricity costs improve desalination's competitiveness. Costs and cost uncertainties remain among the more significant challenges to implementing large-scale desalination facilities, especially seawater desalination plants.[3] Desalination's energy intensity also raises concerns about the greenhouse gas

[1] For more on brackish groundwater, see National Ground Water Association, *Brackish Groundwater*, NGWA Information brief, Westerville, OH, July 2010, http://www.ngwa.org/Media-Center/briefs/Documents/Brackish_water_info_brief_2010.pdf.

[2] S. Chaudry, "Unit cost of desalination," California Desalination Task Force, California Energy Commission, 2003.

[3] A survey of municipal desalination facilities in Texas found the cost for brackish desalination ranged from $410 to $847 per acre-foot, and for seawater desalination ranged from $1,168 to $1,881 per acre-foot. (J. Arroyo and S. Shirazi, *Cost of Water Desalination in Texas*, Texas Water Development Board, Austin, TX, October 2009, p. 6). Water produced from proposed seawater desalination facilities in California is estimated to range from $1,900 to $3,000 per acre-foot (H. Cooley and N. Ajami, *Key Issues for Desalination in California: Cost and Financing*, Pacific Institute, November 2012, p. 5). Costs may be lower for larger facilities employing a range of energy-efficient technologies.

emissions emitted and desalination's usefulness as part of a climate change adaptation strategy.[4] Substantial uncertainty also remains about the environmental impacts of large-scale desalination facilities. Social acceptance and regulatory processes also affect the technologies' adoption and perceived risks. Research and additional full-scale facilities may resolve uncertainties, alleviate concerns, and contribute to cost reductions and options for mitigating environmental impacts.

To date, the federal government primarily has supported research and development, some demonstration projects, and select full-scale facilities (often through congressionally directed spending). The federal government also may support construction of municipal desalination facilities through loans or other credit assistance provided through programs of the U.S. Environmental Protection Agency (EPA). For most municipal desalination facilities, local governments or public water utilities (often with state-level involvement and federal construction loans) have been responsible for planning, testing, building, and operating desalination facilities, similar to their responsibility for treating freshwater drinking water supplies.

During recent Congresses, legislative proposals have identified a range of different potential federal roles in desalination. Desalination issues before the 114th Congress may include how to focus federal research to produce results that provide public benefits, at what level to support desalination research and projects, and how to provide a regulatory context that protects the environment and public health without unnecessarily disadvantaging these technologies.

Recent Congressional Consideration

The 113th Congress authorized a new federal credit assistance program, the Water Infrastructure Finance and Innovation Act (WIFIA, 33 U.S.C. §3901), as part of P.L. 113-121. The portion of the program administered by EPA may be used in financing a range of water projects, including desalination projects.[5]

The Water Desalination Act of 1996, as amended (42 U.S.C. §10301), authorized the main desalination research and demonstration outreach program of the Department of the Interior, which is carried out by the Bureau of Reclamation. The 112th Congress extended through FY2013 its annual authorization of appropriations at $3 million. Bills in the 113th Congress proposed another extension, but the 113th Congress did not extend the authorization of appropriations.[6] Although an extension was not enacted, the 113th Congress provided appropriations for these desalination research and demonstration activities (e.g., $1.75 million for FY2015) and for operation and maintenance of the Department of the Interior's operation of the Brackish Groundwater National Desalination Research Facility ($1.15 million for FY2015).[7]

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[4] J. McEvoy and M. Wilder, "Discourse and desalination: Potential impacts of proposed climate change adaptation interventions in the Arizona-Sonora border region," *Global Environmental Change*, vol. 22 (2012).

[5] For information, see CRS Report R43315, *Water Infrastructure Financing: The Water Infrastructure Finance and Innovation Act (WIFIA) Program*, by (name redacted).

[6] In the 113th Congress, H.R. 745 and S. 1245, the Energy and Water Development and Related Agencies Appropriations Act of 2014, would have extended the authorization of appropriations through 2018. Testimony from a May 2013 hearing on H.R. 745 illustrated the range of opinions on the federal role in desalination research, with one witness arguing against further federal support while others discussed research areas warranting federal support (U.S. Congress, House Committee on Natural Resources, Subcommittee on Water and Power, Hearing on H.R. 255, H.R. 745, and H.R. 1963, 113th Cong., 1st sess., May 23, 2013).

[7] The Brackish Groundwater National Desalination Research Facility is a federally constructed research facility focused on developing desalination technologies for brackish and impaired groundwater found in inland states. It is located in Alamogordo, Otero County, NM. The facility opened in August 2007 and is integrated into the Department of the Interior's existing desalination research and development program at the Bureau of Reclamation.

Federal Desalination Research

Research Agenda

Several reports since 2000 have aimed to inform the path forward for U.S. desalination research. The first was the 2003 *Desalination and Water Purification Technology Roadmap* produced by the Bureau of Reclamation and Sandia National Laboratories at the request of Congress. The National Research Council then reviewed the roadmap in a 2004 report, *Review of the Desalination and Water Purification Technology Roadmap*, which called for a strategic national research agenda. To this end, the National Research Council (NRC) convened a Committee on Advancing Desalination Technology. That NRC committee published its own assessment in 2008, *Desalination: A National Perspective*. The NRC concluded that research should focus on reducing desalination costs and that substantial further cost savings were unlikely to be achieved through incremental advances in the commonly used technologies, like reverse osmosis. Consequently, the report recommended that federal desalination research funding be targeted at long-term, high-risk research not likely to be attempted by the private sector that could significantly reduce desalination costs. It also recommended a line of research on minimizing or mitigating the environmental impacts of desalination. The NRC specifically identified for federal investment research that had potential for widespread benefit and that the private sector had little willingness to perform. (See "National Research Council 2008 Desalination Research Recommendations" box for more details.)

National Research Council 2008 Desalination Research Recommendations

The NRC in 2008 identified topics for a research agenda of interest both for public and private sector investment. The topics considered by NRC to be the most appropriate for federal support are identified below in italics.

The NRC recommended steps to reduce the financial cost of desalination with research to

- improve pretreatment for membrane desalination;
- improve membrane system performance;
- develop improved energy recovery technologies and techniques;
- reduce existing desalination approaches' primary energy use by integrating desalination and renewable energy, understanding energy pricing impacts, and identifying opportunities to use low-grade and waste heat; and
- develop novel desalination processes or approaches that reduce primary energy use

The NRC identified the following priority research areas to address environmental concerns:

- assess environmental impacts of desalination intake and concentrate management approaches, and synthesize results in a national assessment;
- improve intake methods at coastal facilities to minimize harm to organisms;
- develop cost-effective approaches for concentrate management that minimizes environmental impacts; and
- develop monitoring and assessment protocols for evaluating the potential ecological impacts of surface water concentrate discharge.

Additionally, the NRC identified the following cross-cutting research activity:

- develop cost-effective concentrate management that minimizes environmental impacts.

Source: NRC, *Desalination: A National Perspective*, 2008.

In 2010, the Water Research Foundation, WateReuse Foundation, and Sandia National Laboratories published a report on how to implement the 2003 roadmap.[8] The report identified research agendas for a range of topics—membrane and alternative technologies, concentrate management, and institutional issues such as energy cost reduction and regulatory compliance.

Evolution of Federal Research Funding

No single federal agency has responsibility for all federal desalination and membrane research; instead numerous agencies and departments are involved in research based on their specific missions. In FY2005, FY2006, and FY2007, federal desalination research totaled $24 million, $24 million, and $10 million, respectively.[9] (These are the most recent comprehensive data on federal desalination funding.) The Bureau of Reclamation was responsible for half or less of that spending at $12 million, $11 million, and $4 million, respectively. Other agencies and departments with spending on desalination research included the Army, National Science Foundation, Office of Naval Research, U.S. Geological Survey, and four of the Department of Energy's National Laboratories. Sandia National Laboratory has had the largest role among the national laboratories. In FY2005 and FY2006, much of the federal desalination research was congressionally directed to specific sites and activities. The level of funding fell after FY2006, when the appropriations process began to include less congressionally directed spending.

The optimal level and type of federal support for desalination research is inherently a public policy question shaped by factors such as fiscal priorities and views on the appropriate role of the federal government in research, industry development, and water supply.[10] Federal support for desalination research raises questions, such as what should be the respective roles of federal agencies, academic institutions, and the private sector in conducting research and commercializing the results, and should federal research be focused on basic research or promoting the use of available technologies? In addition to federal and private research activities, some states, such as California and Texas, also have supported desalination research.[11]

[8] Water Research Foundation, WateReuse Foundation, Sandia National Laboratories, *Implementation of the National Desalination and Water Purification Technology Roadmap*, January 2010.

[9] National Research Council, *Desalination: A National Perspective*, 2008, p. 228. Hereinafter NRC 2008.

[10] For more information on the general discourse about federal funding for research and development, see CRS Report R43086, *Federal Research and Development Funding: FY2014*, coordinated by (name redacted) Part of the debate about the level of desalination research to support in the United States is related to how much desalination research is occurring outside of the United States. While U.S. research previously was significant in the development of desalination especially membrane desalination, the United States now is less prolific than other nations. For example, in a 2011 article analyzing the research institutes producing journal articles on desalination, no U.S. entity was in the top 10; the leading institutes in terms of publications were in Australia (1), China (3), India (1), Jordan (1), Kuwait (2), Oman (1), Poland (1), and Singapore (1) (H. Tanaka and Y. Ho, "Global trends and performance of desalination research," *Desalination and Water Treatment*, vol. 25 (January 2011). Whether this shift signals a reason for more support for U.S. desalination research or for less since other nations are investing depends on one's views on research to support industry and whether the internationally conducted research is meeting U.S. needs.

[11] For example in 2003, House Bill 1370 of the 78th Texas Legislature directed the Texas Water Development Board to participate in research, studies, investigations and surveys to further the development of cost-effective water supplies from seawater desalination. As of May 2012, the Board has spent $4.2 million on 18 brackish and seawater desalination demonstration projects and related activities since 2004.

In 2008, the National Research Council recommended a federal desalination research level of roughly $25 million, but recommended that the research be targeted strategically, including being directed at the research activities described above.[12] The NRC drew the following conclusion:

> There is no integrated and strategic direction to the federal desalination research and development efforts. Continuation of a federal program of research dominated by congressional earmarks and beset by competition between funding for research and funding for construction will not serve the nation well and will require the expenditure of more funds than necessary to achieve specified goals.[13]

No recent authoritative estimate of all federal desalination spending is available. Data for Reclamation indicate a reduction in federal desalination spending. Reclamation's desalination funding has declined from $11 million in FY2006 to between $2 million and $4 million in recent years, with FY2015 funding at $3 million. While some traditional avenues for federal desalination research may be receiving less support, new avenues of support may be opening. Two of these are the Advanced Research Projects Agency-Energy (ARPA-E) and the National Science Foundation's Urban Water Engineering Research Center, which was initiated in 2011.

Desalination Adoption in the United States

Desalination and membrane technologies are increasingly investigated and used as an option for meeting municipal and industrial water supply and water treatment demands. The nation's installed desalination capacity has increased in recent years, reflecting the technology's growing competitiveness and applications and increasing demands for reliable freshwater supplies. As of 2005, approximately 2,000 desalination plants larger than 0.3 million gallons per day (MGD) were operating in the United States, with a total capacity of 1,600 MGD.[14] This represents more than 2.4% of total U.S. municipal and industrial freshwater withdrawals, not including water for thermoelectric power plants. Two-thirds of the U.S. desalination capacity is used for municipal water supply; industry uses about 18% of the total capacity.[15]

Municipal use of desalination for saline water and wastewater treatment in the United States expanded from 1990 to 2010; the number of facilities rose from 98 facilities with a total capacity of 100 MGD in 1990 to 324 facilities with 1,100 MGD of capacity in 2010.[16] By 2010, 32 states had municipal desalination facilities.[17] Florida, California, and Texas have the greatest installed desalination capacity and account for 68% of the municipal desalination facilities.[18] Florida dominates the U.S. capacity, with the facility in Tampa being a prime example of large-scale desalination implementation (see box); however, Texas and California are bringing municipal plants online or are in advanced planning stages. Several other efforts also are preliminarily investigating desalination for particular communities, such as Albuquerque.

[12] NRC 2008. According to the 2004 NRC report, *Confronting the Nation's Water Problems: The Role of Research*, in the past the federal government invested more in this area; in the late 1960s, federal research in desalination and other saline water conversion activities exceeded $100 million annually.

[13] NRC 2008.

[14] H. Cooley et al., *Desalination, With a Grain of Salt: A California Perspective*, Pacific Institute (June 2006).

[15] Ibid.

[16] M. Mickley, "US Municipal Desalination Plants: Number, Types, Locations, Sizes, and Concentrate Management Practices," *IDA Journal of desalination and Water Reuse*, First Quarter 2012, pp. 44-51. Hereafter Mickley 2012.

[17] Ibid.

[18] Ibid.

Tampa's and San Diego's Desalination Experiences and Lessons

The desalination plant in Tampa, Florida, is the largest operating seawater facility in North America at 25 million gallons per day (MGD). The plant's initial planning in the late 1990s was thought of as a signal of desalination becoming a cost-effective supply option. However, the Tampa plant, a facility to desalinate heavily brackish estuarine water, encountered technical and economic problems (e.g., less freshwater produced than anticipated, fouling of reverse osmosis membranes, financing issues) during construction and start-up, driving up the cost of the freshwater produced. In the view of desalination industry observers, the lessons to be learned from Tampa are that (1) good design suited to the local conditions and (2) a thorough pilot-study are critical for a desalination facility to function properly. For other observers, the Tampa project illustrates some of the risks of working with private water developers and lowest-bid contracts without sufficient external review and accountability mechanisms. Private developers, however, remain attractive for some communities because of their role in financing the capital cost of constructing a large-scale desalination facility.

In 1998, just north of San Diego in Carlsbad, California, a private joint venture, Poseidon, initiated its effort to build a 50 MGD seawater desalination facility to sell water to San Diego's water system, In November 2009, Poseidon received all of the permits for the Carlsbad project. In November 2012, the San Diego County Water Authority approved the purchase of the desalinated water for 30 years. Project costs in 2012 were estimated at $1 billion, which represented a significant increase from the $270 million estimated a decade earlier. The cost for delivered desalinated water from the plant is estimated at $1,600 per acre-foot. The plant is expected to complete construction and begin water deliveries in 2016. The extended negotiation and approval process illustrated some of the tensions and concerns that arise during private-sector engagement in provision of municipal water. While Poseidon owned a prime location site for a desalination facility, the water authority and public were hesitant about the arrangement because of concern over profit-taking by a private entity engaged in the provision of a public service. After more than a decade, this concern and other concerns (e.g., environmental impacts) were overcome and mitigated. The Poseidon Carlsbad experience has yielded lessons about the public's expectations for transparency and protections when the private sector is involved in desalination or other aspects of public services and infrastructure. Desalination stakeholders continue to watch the Poseidon Carlsbad facility and arrangement for lessons and precedents.

The saline source water that is treated using desalination technologies varies largely on what sources are available near the municipalities and industry with the demand for the water. In the United States, only 7% of the existing desalination capacity uses seawater as its source. More than half of U.S. desalinated water is from brackish sources. Another 25% is river water treated for use in industrial facilities, power plants, and some commercial applications. Globally, seawater desalination represents 60% of the installed desalination capacity.[19]

While interest in obtaining municipal water from desalination is rising in the United States, desalination is expanding most rapidly in other world regions, often in places where other supply augmentation options are limited by geopolitical as well as natural conditions, such as arid conditions with access to seawater. The Middle East, Algeria, Spain, and Australia are leading in the installation of new desalination capacity,[20] with Saudi Arabia and the United Arab Emirates leading in annual production of desalinated water. Roughly 98% of the desalination capacity worldwide is outside of North America, with 65% in the Middle East.[21]

[19] Ibid.

[20] J. Hughes, "Seawater Desalination Leads Response to Global Water Crisis," *AWWA Streamlines*, Nov. 10, 2009.

[21] M. Shatat, M. Worall, and S. Riffat, "Opportunities for solar water desalination worldwide: Review," *Sustainable Cities and Society*, March 30, 2013. Hereinafter Shatat, Worall, and Riffat 2013.

Energy Concerns and Responses

Reducing Energy Intensity To Reduce Cost Uncertainties

The cost of desalination for municipal water remains a barrier to adoption. Like nearly all new freshwater sources, desalinated water comes at substantially higher costs than existing municipal water sources.

Much of the cost for seawater desalination is for the energy required for operations; in particular, the competitiveness of reverse osmosis seawater desalination is highly dependent on the price of electricity. Reverse osmosis pushes water through a membrane to separate the freshwater from the salts; this requires considerable energy input. Currently the typical energy intensity for seawater desalination using reverse osmosis with energy recovery devices is 3-7 kilowatt-hours of electricity per cubic meter of water (kWh/m^3).[22] The typical energy intensity of brackish reverse osmosis desalination is less than seawater desalination, at 0.5-3 kWh/m^3, because the energy required for desalination is a function of the salinity of the source water.[23]

Uncertainty in whether electricity prices will rise or fall creates significant uncertainty in the cost of desalinated water. If electricity becomes more expensive, less electricity-intensive water supply options (which may include conservation, water purchases, and changes in water pricing) become comparatively more attractive.

Cost-effectively reducing desalination's energy requirements could help reduce overall costs. In recent decades, one of the ways that desalination cost reductions were achieved was through reduced energy requirements of reverse osmosis processes. Now the energy used in the reverse osmosis portion of new desalination facilities is close to the theoretical minimum energy required for separation of the salts from the water.[24] Therefore, although there still is some room for energy efficiency improvements in using desalination as a water supply, dramatic improvements are not likely to be achieved through enhancements to standard reverse osmosis membranes. Instead energy efficiency improvements are more likely to come from other components of desalination facilities, such as the pretreatment[25] of the water before it enters the reverse osmosis process, enhanced facility and system design, or the use and development of a new generation of technologies (see **Appendix A**).

For example, energy efficiency advances in the non-membrane portions of water systems and the use of energy recovery technologies are reducing energy use per unit of freshwater produced at desalination facilities. Pumps are responsible for more than 40% of total energy costs at a desalination facility.[26] Energy efficiency advances in a type of pump that is useful for smaller

[22] NRC 2008, pp. 74-75, and 77.

[23] Ibid. p. 77.

[24] M. Elimelech and W.A. Phillip, "The Future of Seawater Desalination: Energy, Technology, and the Environment," *Science*, vol. 333 (August 5, 2011), pp. 712-717.

[25] Pretreatment is necessary in order to avoid fouling and harm to the reverse osmosis membranes.

[26] A. Subramani, "Energy minimization strategies and renewable energy utilization for desalination: a review," *Water Research*, vol. 45, no. 5 (February 2011), pp. 1907-1920.

applications (called a positive displacement pump) have made desalination more cost-effective for some applications and locations and less sensitive to electricity price increases.[27]

The Affordable Desalination Collaboration is an example of combining federal, state, local, private, and other financial resources to support research; funding from these sources was combined to build and operate a demonstration plant at the U.S. Navy's Desalination Test Facility in Port Hueneme, California. The plant tests the combined use of commercially available reverse osmosis technologies, energy recovery devices and practices, and other energy-efficient technologies to reduce the energy inputs required for seawater and brackish desalination. According to the researchers involved, the energy-efficient demonstration facility has the equivalent energy input per unit of freshwater produced as water imports into southern California from northern California and the Colorado River.[28]

While this research is an example of reducing energy demand, other efforts are looking to substitute the type of energy used for desalination from fossil fuels to renewable energy or waste heat. The use of desalination as a climate change adaptation strategy is questioned because of its potential fossil fuel intensity relative to other adaptation and water supply options.[29] Electricity price uncertainty and emissions considerations have driven some desalination proponents to investigate renewable energy supplies and co-location with power plants and industrial facilities to reduce electricity requirements and costs.[30]

Renewable and Alternative Energy Opportunities

The extent to which desalination technologies can be coupled with intermittent renewable or geothermal electric generation,[31] use off-peak electricity or waste heat, and operate in areas of limited electric generation or transmission capacity but with renewable energy resources is increasingly receiving attention. Desalinating more water when wind energy is available (which requires facilities that can operate with a variable water inflow) and storing the treated water for when water is demanded can almost be viewed as a means of electricity storage and reduction of peak demand.[32] Efforts to jointly manage water and energy supply and demand and to integrate renewable energy with desalination may bolster support for desalination. The first large-scale photovoltaic-powered reserve osmosis seawater desalination facility is in Saudi Arabia, with multiple additional facilities planned in the country before 2018. Concern over declining aquifer

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[27] A. Bennett, "Innovation continues to lower desalination costs," *Filtration+Separation*, July/August 2011. Packaging of pre-engineered membrane-based desalination plants also have reduced the upfront capital costs for some desalination applications.

[28] The demonstration facility achieved energy consumption levels of 2.75 to 2.98 kWh/m^3 at a cost around $2,000 acre-foot of drinking water produced. Affordable Desalination Commission, *Optimizing Seawater Reverse Osmosis for Affordable Desalination*, Bureau of Reclamation, Proposition 50 6a Desalination Final Report Pilot Demonstration, August 30, 2012, http://www.usbr.gov/research/AWT/reportpdfs/ADC-Final-Report-8-2012.pdf. The facility also has been used to test forward osmosis technologies (see **Appendix A**).

[29] J. McEvoy and M. Wilder (2012).

[30] A major benefit of co-location is using the cooling water from the power plant for desalination; this water has been warmed by the power plant which reduces the energy requirements for desalinating it. Also, the desalination facility may avoid construction costs by sharing intake and discharge facilities.

[31] Ibid.

[32] For example, M.S. Miranda and D. Infield, "A wind-powered seawater reverse-osmosis system without batteries," *Desalination*, vol. 153 (2002); D. Weiner et al., "Operation experience of a solar- and wind-powered desalination demonstration plant," *Desalination*, vol. 137 (2001).

levels in Saudi Arabia was one driver for these investments. With demand for desalination increasing in energy-importing countries like India, China, and small islands, there may be particularly strong interest in facilities combining desalination with renewable energy. Some research also is being directed at opportunities for direct solar distillation desalination technologies, particularly smaller-scale production units in solar-abundant remote areas with available land and low-cost labor.[33]

Health and Environmental Concerns

From a regulatory, oversight, and monitoring standpoint, desalination as a significant source of water supply is relatively new in the United States, which means the health and environmental regulations, guidelines, and policies regarding its use are still being developed. Existing federal, state, and local laws and policies often do not address unique issues raised by desalination. This creates uncertainty for those considering adopting desalination and membrane technologies.

Environmental and human health concerns often are raised in the context of obtaining the permits required to site, construct, and operate the facility and dispose of the waste concentrate. A draft environmental scoping study for a facility in Brownsville, TX, identified up to 26 permits, approvals, and documentation requirements for construction and operation of a seawater desalination facility.[34] According to the Pacific Institute's report *Desalination, With a Grain of Salt*, as many as 9 federal, 13 state, and additional local agencies may be involved in the review or approval of a desalination plant in California. For example, during the Corps' process for issuing a seawater desalination facility permits for placing structures in waterways and dredging and filling in navigable waters, the U.S. Coast Guard would consult with the Army Corps of Engineers on whether an intake facility would be a potential navigation hazard and the National Oceanic and Atmospheric Administration would consult on whether intake facilities and discharge of waste concentrate may affect marine resources.

As previously noted, most states do not have policies and guidance specifically for desalination facilities, and instead deal with each project individually. California, through its State Water Resources Control Board, is working toward statewide guidance in order to improve statewide consistency in review and permitting of seawater desalination facilities.

Some of the regulatory requirements are not seen as particularly onerous; others may be seen as challenging depending on the location and size of the facility. Some stakeholders view the current permit process as a barrier to adoption of desalination. Other stakeholders argue that rigorous review and permitting is necessary because of the potential impact of the facilities on public health and the environment. Particular attention often is paid during permitting to the impingement and entrainment of aquatic species by intake structures for coastal and estuarine desalination facilities and the disposal of waste concentrate.

[33] Shatat, Worall, and Riffat 2013.

[34] Texas Water Development Board, *The Future of Desalination in Texas: 2010 Biennial Report*, Austin, TX, Dec.2010, p. 8, http://www.twdb.state.tx.us/innovativewater/desal/doc/2010_TheFutureofDesalinationinTexas.pdf. The report includes a table listing the permits, approvals, and environmental documentation compliance requirements, and estimates of the cost for obtaining each. To reduce the time and expense of the project development process, the Board has supported a study to develop a permitting and decision model for desalination projects in Texas.

Evolving Drinking Water Guidelines

While the quality of desalinated water is typically very high, some health concerns remain regarding its use as a drinking water supply. The source water used in desalination may introduce biological and chemical contaminants to drinking water supplies that are hazardous to human health, or desalination may remove minerals essential for human health.

For example, boron, which is an uncommon concern for traditional water sources, is a significant constituent of seawater and can also be present in brackish groundwater extracted from aquifers comprised of marine deposits. Boron levels after basic reverse osmosis of seawater commonly exceed current World Health Organization health guidelines and the U.S. Environmental Protection Agency (EPA) health reference level.[35] While the effect of boron on humans remains under investigation, boron is known to cause reproductive and developmental toxicity in animals and irritation of the digestive tract, and it accumulates in plants, which may be a concern for agricultural applications.[36] Boron can be removed through treatment optimization, but that treatment could increase the cost of desalted seawater.

EPA sets federal standards and treatment requirements for public water supplies.[37] In 2008, EPA determined that it would not develop a maximum contaminant level for boron because of its rare occurrence in most groundwater and surface water drinking water sources; EPA has encouraged affected states to issue guidance or regulations as appropriate.[38] Most states have not issued such guidance. Therefore, most U.S. utilities lack clear guidance on boron levels in drinking water suitable for protecting public health. The National Research Council recommended development of boron drinking water guidance to support desalination regulatory and operating decisions; it recommended that the guidance be based on an analysis of the human health effects of boron in drinking water and other sources of exposure.

Similarly, the demineralization (particularly the removal of the essential minerals calcium and magnesium) by desalination processes also can raise health concerns.[39] This has prompted researchers to promote the remineralization of desalinated water prior to the water entering the distribution system in communities that are highly dependent on desalinated water.[40] Another

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[35] The EPA Longer Term Health Advisory level for boron is 2.0 milligram-per-liter (mg/L). Boron occurs in oceans at an average concentration of 4.5 mg/L. Concentrations in water derived from basic reverse osmosis of seawater often are near but necessarily below the EPA Advisory level (NRC 2008). A second pass through reverse osmosis membrane with a pH adjustment can effectively remove the boron; boron removal increases with pH. Some states have drinking water standards or guidelines for boron (California, Florida, Maine, Minnesota, New Hampshire and Wisconsin); these range from 0.6 to 1 mg/L. (USEPA, *Summary Document form the Heath Advisory for Boron and Compounds*, Doc. No. 822-S-08-003, 2008.)

[36] According to the NRC 2008, while boron is recognized to have a beneficial role in some physiological processes in some species, higher exposure levels may cause adverse human health effects. EPA has concluded there is inadequate data to assess the human carcinogenicity of boron. Most of the boron toxicity data come from studies in laboratory animals.

[37] For more information on EPA's role in protecting drinking water, see CRS Report RL31243, *Safe Drinking Water Act (SDWA): A Summary of the Act and Its Major Requirements*, by (name redacted).

[38] EPA, *Regulatory Determinations for Priority Contaminant s on the Second Drinking Water Contaminant Candidate List*, available at http://www.epa.gov/OGWDW/ccl/reg_determine2.html.

[39] Fluoride is low in seawater and is further depleted by desalination; communities can choose to add fluoride to treated water consistent with their health goals.

[40] J. Cotruvo, "Health Aspects of Calcium and Magnesium in Drinking Water," *Water Conditioning and Purification*, June 2006. Remineralization would also help reduce the corrosion of piping by desalinated water.

health-related concern is the extent to which microorganisms unique to seawater and algal toxins may pass through reverse osmosis membranes and enter the water supply, and how facilities may need to be operated differently when these organisms and algal toxins are present. Algal toxins are a consideration for desalination facilities in locations affected or potentially affected by harmful ocean algal blooms that can produce a range of substances, including neurotoxins (e.g., domoic acid). How to effectively manage desalination facilities in order to avoid public health threats from algal blooms is an emerging area of interest and research.[41]

Some of the coastal facilities contemplated in the United States would treat estuarine water. Estuarine water, which is a brackish mixture of seawater and surface water, has the advantage of lower salinity than seawater. The variability in the quality and constituents in estuarine water, as well as the typical surface water contaminants (e.g., infectious microorganisms, elevated nutrient levels, and pesticides), may complicate compliance of desalinated estuarine water with federal drinking water standards.

Concentrate Disposal Challenges and Alternatives

Unlike desalination treatment costs, concentrate disposal costs generally have not decreased. For inland brackish desalination, significant constraints on adoption of the technologies are the uncertainties and the cost of waste concentrate disposal. For coastal desalination projects, the concentrate management options are often greater because of surface water disposal opportunities. EPA is authorized to manage the disposal and reuse of desalination's waste concentrate.[42] The disposal option selected largely is determined by which alternatives are appropriate for the volumes and specific characteristics of the concentrate and the cost-effectiveness of the alternatives, which is largely shaped by the proximity of the disposal option and the infrastructure, land, and treatment investments required.

The dominant concentrate disposal options for municipal desalination facilities are surface and sewer disposal; in 26 of the 32 states with municipal desalination facilities, only surface and sewer discharge are used for concentrate disposal.[43] Surface water disposal of waste concentrate is permitted on a project-specific basis based on predicted acute and chronic effects on the environment.[44] Inland surface water disposal is particularly challenging because of the limited

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[41] According to a 2009 article, "there are no published reports on the effectiveness of reverse osmosis for removing dissolved algal toxins from seawater. Some of these toxin molecules (e.g., domoic acid) are near the theoretical molecular size of molecules rejected by reverse osmosis membranes, but experimental studies are required to validate the effective (sic) of this process on toxin removal" (D.A. Caron et al., "Harmful algae and their potential impacts on desalination operations off southern California," *Water Research*, 2009). Coastal algal blooms known as red tides were the subject of a 2012 expert workshop ("Red Tide and HABs: Impact on Desalination Plants," Expert Workshop, Muscat, Sultanate of Oman, Feb. 2012), http://www.medrc.org/index.cfm?area=about&page=expert_workshop_download.

[42] EPA's authority is derived primarily from the Safe Drinking Water Act and the Clean Water Act. For a CRS report on the Safe Drinking Water Act, see CRS Report RL31243, *Safe Drinking Water Act (SDWA): A Summary of the Act and Its Major Requirements*, by (name redacted). The sections of the act most significant to disposal of waste concentrate create the underground injection control (UIC) program; this is in Part C, Protection of Underground Sources of Drinking Water, §§1421-1426 (42 U.S.C. §§300h-300h-5). The Clean Water Act establishes the federal standards for surface water disposal and requirements for obtaining permits for these discharges. For more on the Clean Water Act, see CRS Report RL30030, *Clean Water Act: A Summary of the Law*, by (name redacted).

[43] Mickley 2012.

[44] N. Voutchkov, *Management of Desalination Plant Concentrate*, SunCam, 2011, http://s3.amazonaws.com/suncam/npdocs/113.pdf.

capacity of inland water bodies to be able to tolerate the concentrate's salinity. Limited amounts of concentrate also may be sent through sewer systems with large-volume wastewater treatment facility. As of 2010, deep well injection for municipal concentrate disposal had been used primarily in Florida.[45] For injection, EPA generally classifies waste concentrate as an industrial waste, thus requiring that the concentrate be disposed of in deep wells appropriate for industrial waste. Desalination proponents argue that desalination's concentrate is sufficiently different from most industrial waste that it should be reclassified to increase the surface and injection well disposal opportunities. Some states have made efforts to promote the beneficial use of waste concentrate (e.g., use as liquids in enhanced oil and gas recovery) and facilitate its disposal including land application techniques.[46] Notwithstanding these state efforts, land application[47] and evaporation ponds[48] are seldom and decreasingly used disposal options.[49] While states can have such policies and programs in place, federal environmental regulations administered by EPA for the most part define the regulatory context of concentrate disposal.

Concluding Remarks

Desalination and membrane technologies are playing a growing role in meeting water supply and water treatment needs for municipalities and industry. The extent to which this role further expands depends in part on the cost-effectiveness of these technologies and their alternatives. Desalination's energy use, concentrate disposal options, and environmental and health concerns are among the top issues shaping the technology's adoption. How to focus federal desalination research and support to produce results that provide public benefits, and how to provide a regulatory context that protects the environment and public health without unnecessarily disadvantaging these technologies, are among the desalination issues before the 114th Congress.

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[45] While 50 municipal facilities in Florida use injection, only 1 facility in each of California, Kansas, and Texas use injection for municipal concentrate disposal (Mickley 2012).

[46] For example, House Bill 2654 passed by the 80th Texas Legislature provided for a general permit for Class I injection wells that can be used to dispose of brine concentrate from a municipal desalination plant. Also, the Texas Water Development Board undertook a study with the intent of showing that oil and gas fields can physically and chemically accept desalination waste concentrate and to recommend changes to statutes and rules to facilitate waste concentrate disposal in oil and gas fields (R. E. Mace et al., *Please Pass the Salt: Using Oil Fields for the Disposal of Concentrate from Desalination Plants*, Texas Water Development Board, Austin, TX, April 2006, http://www.twdb.state.tx.us/publications/reports/numbered_reports/doc/Report366.pdf). Since publication of that report, more questions have arisen related to induced seismic activity from deep well injection; these concerns may affect views of the risks and attractiveness of concentrate brine injection as a disposal method among some stakeholders.

[47] Land application can include spraying concentrate on salt-tolerant plants or infiltration; land application typically is used for small volumes of brackish water concentrate.

[48] Evaporation ponds use solar radiation to precipitate salt crystals, which are then harvested and typically disposed; in some cases the salts or other constituents may be beneficially reused.

[49] Mickley 2012.

Appendix A. Traditional and Emerging Desalination Technologies

There are a number of methods for removing salts from seawater or brackish groundwater to provide water for municipal and agricultural purposes. The two most common processes, thermal distillation and reverse osmosis, are described below; their descriptions are followed by descriptions of some of the more innovative and alternative desalination technologies. The earliest commercial plants used thermal techniques. Improvements in membrane technology have reduced costs, and membrane technology is less energy-intense than thermal desalination (although it is more energy-intense than most other water supply options). Reverse osmosis and other membrane systems account for nearly 96% of the total U.S. desalination capacity and 100% of the municipal desalination capacity.

Reverse Osmosis

Reverse osmosis forces salty water through a semipermeable membrane that traps salt on one side and lets purified water through. Reverse osmosis plants have fewer problems with corrosion and usually have lower energy requirements than thermal processes.

Examples of how research advances in the traditional desalination technologies of reverse osmosis have the potential for improving the competitiveness and use of desalination are: nanocomposite and nanotube membranes and chlorine resistant membranes. Nanocomposite membranes appear to have the potential to reduce energy use within the reverse osmosis process by 20%, and nanotube membranes may yield a 30%-50% energy savings.[50]

Membranes are susceptible to fouling by biological growth (i.e., biofouling), which reduces the performance of the membranes and increases energy use. The most widely used biocide is chlorine because it is inexpensive and highly effective. The most common membranes used in reverse osmosis, however, do not hold up well to exposure to oxidizing agents like chlorine. Advancements in chlorine resistant membranes would increase the resiliency of membranes and expand their applications and operational flexibility.[51]

Distillation

In distillation, saline water is heated, separating out dissolved minerals, and the purified vapor is condensed. There are three prominent ways to perform distillation: multi-stage flash, multiple-effect distillation, and solar distillation. In general, distillation plants require less maintenance and pretreatment before the desalination process than reverse osmosis facilities.

While solar distillation is an ancient means for separating freshwater from salt using solar energy, research into improving the technology is increasing.[52] In large part the interest stems from the

[50] A. Subramani (2011).

[51] H,B. Park et al., "Highly Chlorine-Tolerant Polymers for Desalination," *Angewandte Chemie*, vol. 120 (July 2008), pp. 6108-6113.

[52] H. Tanaka and Y. Ho, "Global trends and performance of desalination research," *Desalination and Water Treatment*, (continued...)

potential application for the technology to supply freshwater to small remote settlements where saline supplies are the only source and power is scarce or expensive.

Innovative and Alternative Desalination Processes

Capacitive Deionization

Capacitive deionization desalinates saline waters by absorbing salts out of the water using electrically charged porous electrodes. The technology uses the fact that salts are ionic compounds with opposite charges to separate the salts from the water. The limiting factor for this technology is often the salt absorption capacity of the electrodes. Flow-through capacitive deionization shows promise for energy-efficient desalination of brackish waters.

Electrodialysis

Electrodialysis and capacitive deionization technologies depend on the ability of electrically charged ions in saline water to migrate to positive or negative poles in an electrolytic cell. Two different types of ion-selective membranes are used—one that allows passage of positive ions and one that allows negative ions to pass between the electrodes of the cell. When an electric current is applied to drive the ions, fresh water is left between the membranes. The amount of electricity required for electrodialysis, and therefore its cost, increase with increasing salinity of feed water. Thus, electrodialysis is less economically competitive for desalting seawater compared to less saline, brackish water.

Forward Osmosis

Forward osmosis is an increasingly used but relatively new membrane-based separation process that uses an osmotic pressure difference between a concentrated "draw" solution and the saline source water; the osmotic pressure drives the water to be treated across a semi-permeable membrane into the draw solution. The level of salt removal can be competitive with reverse osmosis, and forward osmosis membranes may be more resistant to fouling than reverse osmosis membranes. A main challenge is the selection of a draw solute; the solute needs to either be desirable or benign in the water supply, or be easily and economically separated out. Research is being conducted on whether a combination of ammonia and carbon dioxide gases or polymers can be used in the draw solution, and on the effects of marine biology on the membranes. The attractiveness of forward osmosis is that when combined with industrial or power production processes that produce waste heat, its electricity requirements can be significantly less than for reverse osmosis.[53] Potential disadvantages of forward osmosis are a lower quantity of freshwater per unit of water treated and a larger quantity of brine requiring disposal.[54]

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vol. 25 (Jan. 2011).

[53] R. L. McGinnis, and M. Elimelech. "Energy requirements of ammonia carbon dioxide forward osmosis desalination," *Desalination* (2007) 207, pp. 370-382.

[54] A. Bennett, "Innovation continues to lower desalination costs," *Filtration+Separation*, July/Aug. 2011.

Freezing Processes

Freezing processes involve three basic steps: (1) partial freezing of the feed water in which ice crystals of fresh water form an ice-brine slurry; (2) separating the ice crystals from the brine; and (3) melting the ice. Freezing has some inherent advantages over distillation in that less energy is required and there is a minimum of corrosion and scale formation problems because of the low temperatures involved. Freezing processes have the potential to concentrate waste streams to higher concentration than other processes, and the energy requirements are comparable to reverse osmosis. While the feasibility of freeze desalination has been demonstrated, further research and development remains before the technology will be widely available.

Ion Exchange

In ion exchange, resins substitute hydrogen and hydroxide ions for salt ions. For example, cation exchange resins are commonly used in home water softeners to remove calcium and magnesium from "hard" water. A number of municipalities use ion exchange for water softening, and industries requiring extremely pure water commonly use ion exchange resins as a final treatment following reverse osmosis or electrodialysis. The primary cost associated with ion exchange is in regenerating or replacing the resins. The higher the concentration of dissolved salts in the water, the more often the resins need to be renewed. In general, ion exchange is rarely used for salt removal on a large scale.

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