J-WAFS

Abdul Latif Jameel
World Water and Food Security Lab

Low Carbon Desalination

Status and Research, Development, and Demonstration Needs

Report of a workshop conducted at the Massachusetts Institute of Technology in association with the Global Clean Water Desalination Alliance

October 17-18, 2016

MIT

Global Clean Water Desalination Alliance
"H_2O minus CO_2"

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The full text of the preliminary workshop report is available at http://web.mit.edu/lowcdesal/

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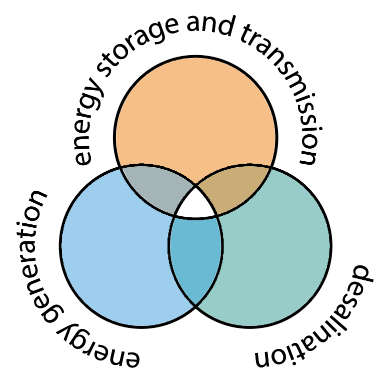
Preliminary Report Executive Summary



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About the workshop:

This invitation-only workshop brought together a small group of academic, industry, and government experts from across the globe to discuss the future R&D needed to drive down the carbon footprint of desalination. Organized at the request of the Global Clean Water Desalination Alliance, which was formed at COP21, and sponsored by the MIT Abdul Latif Jameel World Water and Food Security Laboratory, the workshop produced a white paper giving a high-level overview of the research needed to make low carbon desalination a reality. Our findings will be presented at the COP22 meetings in Marrakech, Morocco during November 2016, and they will serve as a guide for further research and development aimed at sustainable solutions for the world's growing water challenges.

About the MIT Abdul Latif Jameel World Water and Food Security Laboratory (J-WAFS)

The Abdul Latif Jameel World Water and Food Security Lab (J-WAFS), was established by MIT in the fall of 2014 as an Institute-wide effort to bring MIT's unique strengths to bear on the many challenges of food and water supply. J-WAFS spearheads research that will help humankind adapt to a rapidly growing population and a changing climate, through science, engineering, business, and policy. J-WAFS believes in the power of innovation, collaboration, and problem-focused research, and it operates with a combination of on-campus research, international partnerships, and technology development and transfer. J-WAFS aims to improve the security, safety, and efficiency of the water and food supplies and works to reduce environmental impact of water and food systems. Further detail on J-WAFS, including current research projects, is available at: jwafs.mit.edu.

About the Global Clean Water Desalination Alliance (GCWDA)

The Global Clean Water Desalination Alliance – H_2O minus CO_2, was launched at the 2015 United Nations Climate Change Conference (COP21) in December 2015 in Paris. The Lima Paris Action Plan (LPAA) gathered a number of Initiatives, in which alliances of non-governmental actors of all categories and governments engage in actions to foster technology development and solutions sharing in order to drastically reduce CO_2 emissions in their field of intervention. The Alliance is one of those initiatives under the LPAA, focusing on CO_2 emission reductions in the desalination industry. The Alliance is open to all categories of actors, such as utilities, industries, research organizations, universities, NGOs, associations, local authorities, and governments. Beyond the presentation of the workshop's findings at COP22, GCWDA will also be hosting a side event on November 16th in Marrakesh. More information on the burgeoning alliance available at: tinyurl.com/GCWDA-Site.

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Executive summary

"Energy consumption is the major cost of desalination, accounting for more than 1/3 of the cost of water in modern plants, and energy use also represents the major environmental impact of desalination."

Water demand is increasing worldwide as a result of growing populations and rising standards of living. Further, increasing climate variability is disrupting historical patterns of precipitation and water storage. While conservation and reuse efforts have helped to moderate demand for new freshwater resources in some locations, desalination technology is increasingly being used to meet demand worldwide. Currently installed capacity is almost 90 million m^3/day (90 billion liters per day) of desalinated water, a value that has been growing rapidly, with growth projected at 12% over the next five years. Energy consumption is the major cost of desalination, accounting for more than 1/3 of the cost of water in modern plants, and energy use also represents the major environmental impact of desalination. Thus, desalination using low-cost energy sources that have low greenhouse gas emission is highly desirable.

During 17-18 October 2016, MIT brought together an international panel of experts from academia, industry, and government for a workshop on driving down the carbon footprint of desalination systems. Organized at the request of the Global Clean Water Desalination Alliance and sponsored by the MIT Abdul Latif Jameel World Water and Food Security Laboratory[1], the workshop produced this report.

Participants in the workshop contributed prewritten material on research and development needs that they regarded as critical to the reduction of the global warming potential (GWP) of desalination. These inputs form the bulk of this report. The workshop itself was devoted to a vigorous and wide-ranging discussion of the opportunities and priorities for powering desalination systems with low-carbon energy in the context of current and emerging trends in desalination and energy production. The report summarizes the experts' assessment of available technologies and their recommendations for research, development, and demonstration (RD&D) of low carbon desalination. A major conclusion of this workshop is that currently available energy and desalination technologies can be effectively combined to reduce desalination's GWP in the near term.

This report was produced on a compressed timetable, with the aim of having results to share at COP22 in Marrakech, Morocco on 16 November 2016. A more in depth study is planned as a follow on to this initial effort.

Desalination technologies by type and scale

Desalination systems may be loosely classified as membrane or thermal technologies and as large-scale or small-scale systems. For large scale, we may think of fresh water production capacities above 100,000 m^3/day. Small-scale systems may extend well below 10,000 m^3/day.

The dominant thermal technologies are multistage flash (MSF) and multi-effect distillation (MED), usually with thermovapor compression (MED-TVC). MSF is almost exclusively applied at very large scale, and both MED and MSF are generally configured as water-power co-production systems. These systems take fossil fuel as primary energy, but also use significant amounts of electrical energy for water circulation. Some MED systems, at refineries for example, may not include power generation and may take lower grade thermal energy from other process steps. The heat used by these systems must usually be supplied at relatively low temperatures for reasons related to scaling and corrosion of the equipment. As such, this energy has less capacity to produce electricity than the high temperature heat used to generate electrical power.

Membrane technology is dominated by reverse osmosis (RO), which is a highly scalable process used in applications ranging from systems small enough to fit under a kitchen counter to as large as 600,000 m^3/day. RO is driven by electrical energy. Relative to other commonly deployed desalination systems, today's large RO plants have the highest thermodynamic efficiencies when considered in terms of either primary (fuel) energy or the thermal and/or electrical energy input to the desalination plant itself.[2]

A wide variety of additional desalination technologies exists, at varying stages of maturity. Electrodialysis has been in use for brackish water for decades. Membrane distillation, thermolytic forward osmosis, and humidification-dehumidification are in early stages of industrial development, with advantages in important niche applications. None of these have been deployed for large-scale seawater desalination, and in most cases the target applications are quite different; however, hybrid systems that combine two or more desalination technologies have potential to increase water recovery and consequently reduce brine management costs or lower energy requirements per unit water production. Research in this area is quite active.

Desalination: energy requirements and carbon footprint of current systems

The energy required to desalinate water varies depending upon the technology used and system details, as well as the salinity of the water being desalinated. Current state-of-the-art RO plants for desalinating seawater may consume approximately 3.5 kWh_e/m^3 when all unit operations of the overall system are considered. Older plants, and especially thermal desalination plants, are less energy efficient when measured in terms of either effective electrical energy or primary energy. The direct carbon footprint of a desalination plant will depend upon the source of energy that drives it, in addition to the efficiency of the plant. As in most industries, desalination plants produce indirect greenhouse gas (GHG) emissions as well.

Representative Direct GHG Footprint kg CO_2 per m3 (1000 L) fresh water	
Reverse Osmosis (RO)	2.1 – 3.6
Multi-effect Distillation with Thermovapor Compression (MED-TVC)	8 – 16
Multistage Flash (MSF)	10 – 20

As a fraction of the world's energy consumption and GHG emissions, desalination is small – less than 0.2% of worldwide energy consumption in 2013. Top-down estimates place equivalent electric energy consumption of current online capacity at about 200 TWh_e/yr, or an average power demand around 23 GW_e, and preliminary estimates show a direct carbon footprint of about 120 million metric tons annually.[3] About 41% of this energy is consumed as electricity; the remainder is heat used to drive thermal desalination plants, typically in the form of steam at temperatures between 65 and 130°C depending upon the technology.[4] With RO, about 2.1–3.6 kg CO_2 are produced per m^3 (1000 liters) of fresh water, depending strongly on the fuel used to produce the electricity. The less efficient thermal desalination technologies generally emit 8–20 kg CO_2/m^3, with the exception of stand-alone MED at 3.4 kg CO_2/m^3. As small as these numbers may appear through a global lens, they can be large in regional grids and ecosystems.

Desalination can never be done with "zero energy." The minimum amount of energy to separate water from salt water depends upon the salinity of water and the percentage of fresh water to be recovered. For average seawater desalination conditions, this thermodynamic minimum energy is about 1 kWh_e/m^3 of fresh water produced,[5] when expressed in terms of electrical energy (or what a thermodynamicist would call "work"). Real systems are not this efficient, as a result of losses in components and deliberate design choices made to reduce a system's capital cost. Further, additional energy is required for intake pumping, pretreatment, and plant operations. Even so, process improvements that bring the actual energy consumption closer to the minimum possible energy consumption do lower the carbon footprint of a desalination plant, if only by increments.

Desalination plants can be operated using electrical energy ("work") or thermal energy ("heat") or even a combination of the two. For a given type of water and fresh water recovery, the thermodynamic limits of performance are the same for every desalination technology irrespective of how

the plant is operated. The source and cost of energy may differ, however. For example, a plant might use grid electricity to drive pumps but use solar thermal energy to distill water. The electricity is delivered at grid prices, which can vary, whereas the fuel for solar energy is free but requires an upfront capital expense for the solar collectors. Consequently, a present-value techno-economic analysis is required to compare the cost of water produced by different means. The overall energy efficiency of a plant may be determined using thermodynamic methods, as described in this report.

Different processes for desalination have been implemented around the world depending upon the technologies that were available at the time of installation and in consideration of the types and availability of energy to drive them. Because of current and foreseen advances in both energy and desalination technologies, the opportunity exists to guide future developments in ways that minimize energy use and greenhouse gas emissions.

"The estimated direct carbon footprint of desalination worldwide is roughly 120 million metric tons annually and is expected to grow unless low-carbon options are implemented."

Low carbon energy: status and developments

This report is not focused on reviewing the full scope of low carbon energy research and development needs, which has been considered in depth elsewhere,[6] but rather only on those aspects of direct relevance to reducing the global warming potential of desalination. As such, greater attention is given to driving desalination with low-carbon energy technologies that are at advanced states of development.

Renewable energy sources can be distinguished from other low-carbon sources that are not renewable. For renewable sources, fuel cost is replaced by increased upfront capital cost. Generally, if a desalination system is more energy efficient, a small renewable power source is needed, thus leading to reduced capital cost for energy supply and a lower average total (or levelized) cost of water.

Renewable sources available at large scale and with affordable cost include wind power, photovoltaic power (PV), and concentrating solar power (CSP). Wind and solar energy each have much better availability in some geographic regions, and both operate intermittently unless investment is made in energy storage. For wind and PV, battery storage remains costly; for CSP, thermal energy can be stored relatively inexpensively. Intermittent operation is a particular concern when dispatchable power is required. For water production, the situation is more complicated. While water storage is relatively inexpensive, intermittent use of a desalination plant to meet baseload water demand requires oversizing the plant relative to what would be needed under steady operation. On the other hand, when power tariffs vary during the day, energy cost savings through intermittent operation may offset the high capital cost of a larger plant.

Recently, a number of utility-scale solar photovoltaic (PV) projects in high insolation regions have been bid at prices ranging from \$0.03 to \$0.06/kWh$_e$,[7] and further price decreases are expected.

"...available energy and desalination technologies can be effectively combined to reduce desalination's GWP in the near term."

These systems do not include storage and are not designed to be dispatchable. Utility-scale solar PV systems at a scale of hundreds of megawatts are situated in arid regions with high insolation and relatively flat, inexpensive land. While a number of favorable local factors, including financing, have enabled this pricing, the potential opportunity to use this technology to cost-effectively, if intermittently, desalinate water with a near-zero carbon footprint is promising.

Utility-scale wind projects (both off shore and on shore) are another promising source of low-carbon, cost-effective power. The global installed capacity of wind is expected to continue its rapid growth, and over the next five years the cost of wind projects is projected to drop by 14% as the industry continues along the learning or experience curve.[8] For example, US-based wind power prices have dropped from approximately \$0.055/kWh$_e$ in 2009 to under \$0.02/kWh$_e$ in 2016.[9] Again, the ability to leverage this intermittent, cost-effective source of low-carbon energy for desalination is promising.

Electrical energy storage for renewables remains costly, with representative Li-ion battery pricing of \$220 - \$350/kWh$_e$.[10]

CSP power production has a representative price of \$0.13/ kWh$_e$ at present,[11] which has declined from just a few years ago.[12] Some requested bids are as low as \$0.08/ kWh$_e$ and one project has been bid at \$0.063/kWh$_e$.[13] CSP power is dispatchable. Thermal energy storage is accomplished with molten salts, which currently cost about \$39/kWh$_t$ stored.

The principal non-renewable low-carbon power source is nuclear energy, which is proven at large scale as baseload generation. Capital costs vary greatly, depending primarily upon project risk factors, but in the best cases, low cost power is possible. The average production cost of electricity from the (fully-amortized) U.S. nuclear fleet is currently \$0.024/kWh$_e$.[14] Non-amortized costs are \$0.09-0.10/kWh$_e$.[15] Nuclear energy, however, faces political and social challenges in relation to long term disposal of radioactive waste, public opposition in certain countries, and proliferation concerns.

In addition to solar and wind, enhanced geothermal energy may be useful for thermal desalination in some localities. A wide range of other renewable power resources have also been proposed, such as salinity gradient, marine hydrokinetic, and ocean thermal energy conversion; however, most these technologies have not yet been developed broadly or at scale. Consequently, they are not considered in any detail herein.

Finally, considerable interest surrounds so-called "waste heat," which is thermal energy rejected at low temperature by some thermal generators and industrial processes. The use of waste heat requires capital investments for heat exchange processes (i.e., waste heat is not "free"); in many cases its use for desalination would require modification of the upstream process to account for differences in temperature or heat load. While the potential for use of such low temperature energy is substantial, its systematic exploitation for water purification is not straightforward and can lead to operability challenges. For example, many Middle Eastern utilities operate integrated systems that produce power from thermal generation (typically using oil or gas to drive a steam turbine) and water from closely coupled MED or MSF thermal desalination systems. Due to increasingly disproportional needs for water and electricity, however, there is, a growing trend of shifting from these closely coupled systems to more efficient RO systems that operate independently.

Large-scale desalination: grid-electricity driven and thermal power-water hybrids

For large-scale electrically driven desalination systems (i.e., RO), the power requirements for the plant are typically in the tens of MW_e. The largest seawater reverse osmosis plant in the world, the new Sorek plant in Israel, produces 627,000 m^3/day, enough for 1.5 million people, with a demand just under 100 MW_e (specific power consumption of 3.5 kWh_e/m^3). Seawater desalination plants are located near the coast, where land can be difficult to acquire and where conditions for solar or wind power may be suboptimal. In these cases, the preferred approach to decarbonizing the power supply may be to locate a renewable power plant away from the coast (inland or offshore) and to transmit electricity to the desalination systems or simply to purchase power credits attributable to the renewable source. No direct energetic advantage comes from co-locating power and reverse osmosis plants, other than reduction in electricity transmission losses. Similar ideas apply to using nuclear electricity for RO.

Service	Description
Regulation	Respond to random unscheduled deviations in the load
Flexibility/Renewable	Provide load-following reserve for unforcasted win/solar ramps integration
Contingency	Respond to sudden loss in supply/ generation.
Energy	Shift enegy comsumption from high-priced to low-price items
Capacity	Serve as an alternative to generation/reduce peak load

The integration of non-dispatchable, intermittent sources of renewable energy can pose challenges for grid operators, particularly when the percentage of power produced by wind or solar becomes a substantial part of the generation mix. Properly designed desalination systems can provide value to the grid or associated microgrid by flexibly varying load to shift demand to times of lower generation costs, reduce peak load and flatten aggregate demand, and mitigate the integration challenges associated with intermittent renewables. Designing and operating these systems in an integrated fashion can reduce the overall cost of electricity generation and water treatment. Desalination systems can be designed with the flexibility and water storage required to meet aggregate demand while providing valuable grid services. The associated grid or microgrid can be designed to take advantage of the flexibility of desalination systems, and thus can maintain power quality without the costs associated with additional generation, storage, or excess spinning reserves.

CSP and nuclear power both generate electricity and rejected waste-heat as part of their thermal cycle. Much like traditional water-power coproduction, CSP and nuclear power may be combined or hybridized with desalination processes. Nuclear-powered desalination has been demonstrated at scales of up to 135 MW_e and 80,000 m^3/day using MED, and at smaller scales using RO and RO-thermal hybrids.[16] Relatively few examples of CSP and nuclear powered desalination have been built to date, but a number of design studies have shown potential for combinations of, typically, MED with RO that can desalinate water and produce electricity for sale. One major research need in this direction is lower cost storage for thermal energy in CSP. Other opportunities may be to couple a coastal desalination plant to thermal energy produced at some distance inland or to couple MED by a water loop to trough solar collectors.

Stand-alone, small-scale desalination

Many areas of great water scarcity also have minimal or inadequate water and power infrastructure. Such water scarcity may be sustained, or temporary as in the case of natural disasters. Small-scale, rapidly deployable, point-of-use desalination systems require no grid connection, and therefore have a significant role to play in mitigating such scarcity with minimal global warming impact. RO membranes perform similarly over wide ranges of scale, but many auxiliary components do not.

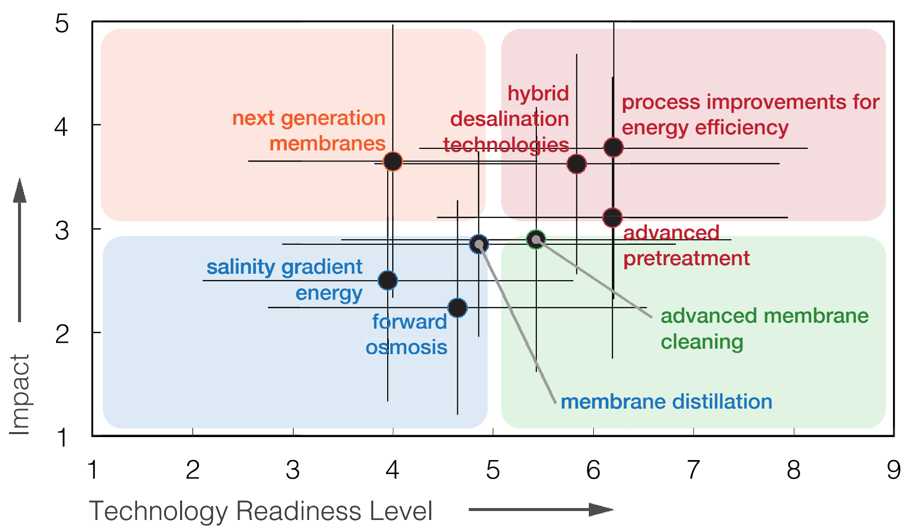
Consequently, existing small-scale systems tend to be more costly (1.5 to 3 times on a unit water basis), and less efficient than large systems. However, the sharp price decline of photovoltaic panels in recent years[17,18] has served to improve the cost competitiveness of small-scale standalone systems, such as PV-RO and PV-ED. Closed cycle RO systems (CCRO) may also have potential to reduce costs of PV- or wind-driven RO, in review of demonstrated high energy efficiency and high water recovery.

In particular, RD&D activities are required to improve the performance and lower the specific cost (per m^3 of capacity) of small-scale, high-efficiency, high-pressure pumps, the component consuming the greatest energy in RO systems. The efficiency of a large-scale pump may be around 89%. High performance, small-scale pumps can reach 85%, but less expensive small pumps may perform considerably less well. More long-term performance demonstrations of small-scale RO driven by intermittent power sources are also needed.

Recommendations for research, development, and demonstration

Workshop participants were asked to rank key RD&D segments in terms of their technology readiness level (TRL) and impact on GHG emissions. TRL reflects technological development on a scale from 1 (basic principles observed) to 9 (proven in operating environment).[19] Impact was rated on a scale from 1 (no reduction in associated GHG emissions) to 5 (all associated GHG emissions eliminated).

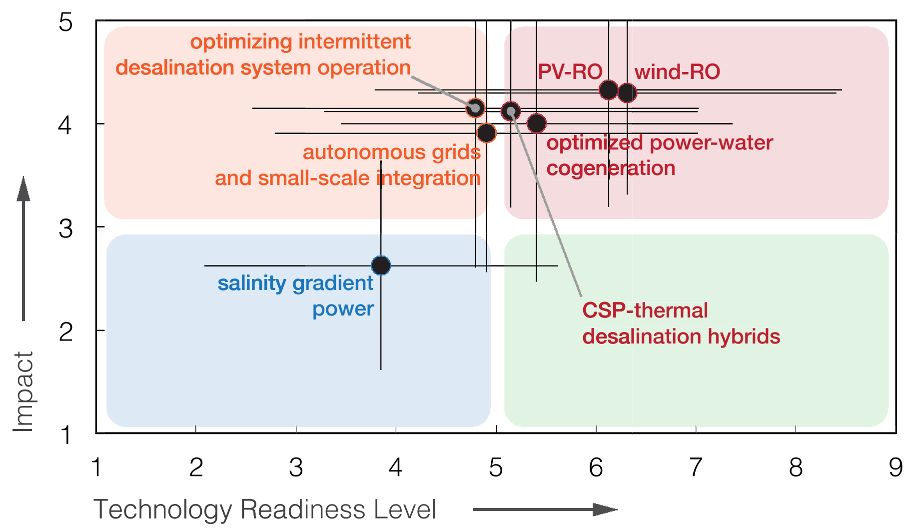
Figure 1: GHG Reduction versus Technology Readiness Level for Desalination Technologies



Average scores for technologies that reduce the carbon footprint of the desalination system itself are shown in Figure 1. On average, process improvements for energy efficiency, hybrid desalination technologies, and advanced pretreatment technologies were rated as high impact, high TRL. Salinity gradient energy recovery, forward osmosis, and membrane distillation were rated as relatively low-priority.

Average scores for RD&D needs in integrating desalination systems with low-carbon are shown in Figure 2. Four areas were ranked high TRL, high impact: PV-RO, wind-RO, CSP-thermal desalination hybrids, and optimized power-water cogeneration. Indirectly coupled arrangements or

Figure 2: GHG Impact versus Technology Readiness Level for Several Low Carbon Desalination Systems



PV- and wind- RO were viewed as higher TRL than directly coupled arrangements. Salinity gradient power was viewed as relatively low priority in terms of impact and TRL. Nuclear-RO combinations (either grid-driven or perhaps stand-alone with micro or small modular reactors below 10 or 300 MW_e respectively) were also recognized to have high potential impact on GHG, and a generally high TRL. Nuclear-thermal hybrids have similar impact, but lower TRL.

Summary of current status

- Desalination capacity is growing rapidly worldwide, reaching nearly 90 million m^3/day in 2016.
- Desalination systems are needed in many areas with excellent access to renewable energy resources, such as the Middle East and North Africa, and parts of China.
- State-of-the-art, large-scale seawater reverse osmosis plants consume about 3.5 kWh_e/m^3 of fresh water at representative ocean salinities and water recovery rates. The associated carbon footprint is around 2.1 to 3.6 kg CO_2/m^3, depending on the fossil fuel source.
- Average power-equivalent demand for all desalination worldwide is estimated at around 23 GW_e.
- The estimated direct carbon footprint of desalination worldwide is roughly 120 million metric tons and is expected to grow unless low-carbon options are implemented.
- The theoretical minimum energy required to desalinate seawater is about 1 kWh_e/m^3 fresh water at 50% recovery and a seawater salinity of 35 g/kg. Economical designs are unlikely ever to reach this thermodynamic limit, but with progress desalination energy can perhaps come within a factor of 1.5 to 2. In addition to the desalination energy, further energy will usually be needed for intake, pretreatment, post-treatment, and product delivery.
- Recent utility-scale solar PV bids, without storage, are \$0.03–0.06/kWh_e, depending greatly on location; current wind power costs as little as \$0.02/kWh_e for land-based wind with access to the best wind resources.

Summary of research, development, and demonstration needs

> "Integrating desalination with renewables-powered grids at large-scale can provide grid services, such as significant flexible load or demand response, possibly helping to flatten demand and act as a counterpoint to intermittent supply."

- Significant opportunity exists to couple existing large-scale renewable power systems, such as wind and photovoltaic systems, to existing large-scale reverse osmosis systems to provide low carbon desalination at low energy prices. Better understanding is needed around system integration and cost optimization relative to intermittent operation and/or energy and water storage options.

- Integrating desalination with renewables-powered grids at *large-scale* can provide grid services, such as significant flexible load or demand response, possibly helping to flatten demand and act as a counterpoint to intermittent supply.

- Integration of desalination and renewable energy at *small-scale* can provide clean water in areas of transient or sustained water scarcity with limited or non-existent grids. These desalination systems can also provide the dump load or demand response needed to maintain the stability of an associated microgrid.

- For desalination systems specifically, the preliminary survey results indicate workshop participants rated process improvements for energy efficiency, hybrid desalination technologies, advanced pretreatment, and fouling control methods as areas of highest current TRL and potential impact. These combinations are candidates for development and demonstration. Next generation membranes were considered to have high potential impact, but lower TRL, suggesting value for additional research and development. Salinity gradient energy recovery, forward osmosis, and membrane distillation were rated as relatively lower TRL and impact.

- For integration with low-carbon power sources, participants rated PV-RO and wind-RO (at large scale) as having highest potential impact and technology readiness, suggesting that demonstration at scale may be timely. CSP-thermal desalination hybrids, optimized power-water cogeneration, system optimization with intermittency, and autonomous grids and small-scale integration were considered to have lower technology readiness but significant potential impact; these technologies may be considered for further research and demonstration. Salinity gradient power was rated as a low priority.

- Further research should examine the long-term reliability of desalination systems when operated intermittently with renewable energy.

- Further research should be done to develop the TRL and impact scores systematically. This work should include life-cycle analysis of GWP for each technology.

Endnotes

[1] http://jwafs.mit.edu/

[2] Emerging technologies, both membrane and thermal, are hoped to have greater energy efficiency, as discussed at several points in this report. Even current technologies can be designed for greater energy efficiency, but with increased capital costs can render such designs impractical. In general, systems are designed to limit the average (or levelized) cost of water, taking capital costs and operating costs into consideration, as opposed to designing for high energy efficiency alone.

[3] For methodology used to create these estimates, see Chapter 1 of this report.

[4] The steam is typically backpressure steam from a power plant's turbine. For MSF and used to drive thermal desalination plants, a typical steam condition is 2.7 bar absolute at 130°C. This produces a top brine temperature of 105-110°C for MSF and 64-70°C for MED-TVC.

[5] This value is for a typical seawater salinity of about 35 g/kg and about 50% recovery of fresh water from seawater. Figure 1.2 in this report shows the variation with salinity and water recovery. The theoretical limit is based on well-established thermodynamic principles that have been in the literature for many decades. For details, see J.H. Lienhard V, K.H. Mistry, M.H. Sharqawy, and G.P. Thiel, "Thermodynamics, Exergy, and Energy Efficiency in Desalination Systems," in *Desalination Sustainability: A Technical, Socioeconomic, and Environmental Approach*, Chpt. 5, H.A. Arafat, ed. Elsevier Publishing Co., 2017.

[6] "The future of solar energy," MIT Energy Initiative Report. Massachusetts Institute of Technology, Cambridge MA, 2015. https://energy.mit.edu/publication/future-solar-energy/

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[9] Wiser et al., 2015 *Wind Technologies Market Report*, U.S. Department of Energy, 2016.

[10] Chung et al., National Renewable Energy Laboratory, Technical Report NREL/TP-6A20-66086, April 2016. http://www.nrel.gov/docs/fy16osti/66086.pdf

[11] This levelized cost of electricity (LCOE) value is from http://energy.gov/eere/sunshot/concentrating-solar-power .

[12] http://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-csp.pdf

[13] http://social.csptoday.com/markets/dubai-set-hit-record-low-middle-east-csp-price-its-first-project

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[15] US Energy Information Administration, *2015 Energy Outlook of the EIA*.

[16] "Nuclear Desalination", Information Library of the World Nuclear Association http://www.world-nuclear.org/information-library/non-power-nuclear-applications/industry/nuclear-desalination.aspx, 2016.

[17] Fu et al., "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016," National Renewable Energy Laboratory (NREL). http://www.nrel.gov/docs/fy16osti/66532.pdf

[18] http://analysis.pv-insider.com/innovations-solar-plant-assembly-drive-costs-towards-1-watt-2017

[19] https://en.wikipedia.org/wiki/Technology_readiness_level - European_Commission_definition

Acknowledgments

Sponsoring Organizations

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Global Clean Water Desalination Alliance
"H_2O minus CO_2"

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