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

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/

Low Carbon Desalination

Status and Research, Development, and Demonstration Needs

Report of a workshop conducted at the Massachusetts Institute of Technology
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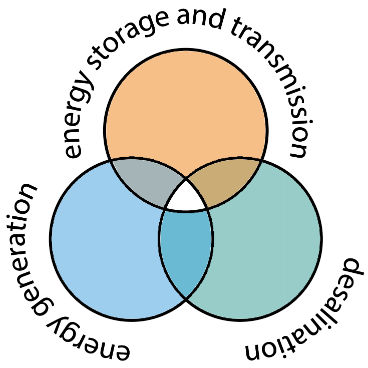
Preliminary Report
Executive Summary

filling the low-carbon desalination R&D gap



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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.

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.

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

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 $\$0.055/\text{kWh}_e$ in 2009 to under $\$0.02/\text{kWh}_e$ 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 $\$220$ - $\$350/\text{kWh}_e$.[10]

CSP power production has a representative price of $\$0.13/\ \text{kWh}_e$ at present,[11] which has declined from just a few years ago.[12] Some requested bids are as low as $\$0.08/\ \text{kWh}_e$ and one project has been bid at $\$0.063/\text{kWh}_e$.[13] CSP power is dispatchable. Thermal energy storage is accomplished with molten salts, which currently cost about $\$39/\text{kWh}_t$ 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 $\$0.024/\text{kWh}_e$.[14] Non-amortized costs are $\$0.09$-$0.10/\text{kWh}_e$.[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.

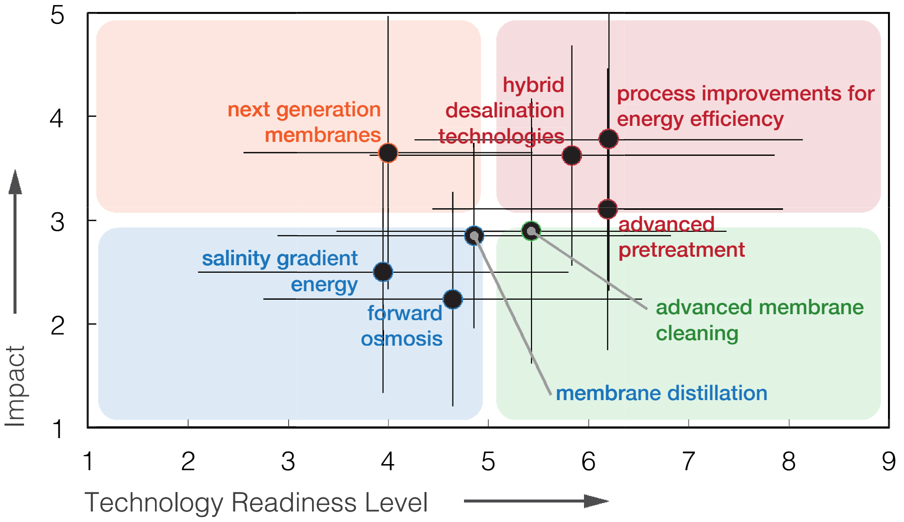
Consequently, existing small-scale systems tend to be more costly (1.5 to 3 times on a unit water basis), and less efficient than large systems. However, the sharp price decline of photovoltaic panels in recent years[17,18] has served to improve the cost competitiveness of small-scale standalone systems, 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).

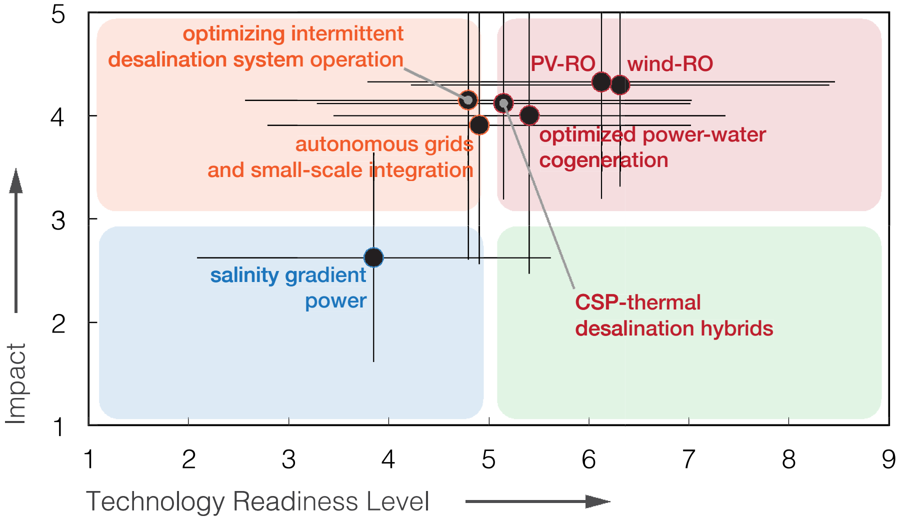
Figure 1: GHG Reduction versus Technology Readiness Level for Desalination Technologies



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.

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[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

J-WAFS

Global Clean Water
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1. Introduction

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1.1 Climate change severity and demand for water

These are troubling times. July 2016 was the warmest July on record, in 136 years of modern record-keeping, according to a monthly analysis of global temperatures[1]. Globally, water demand outstrips renewable fresh water supply for half of the world's population[2], and this mismatch is rising with population growth and more industrialized standards of living[3]. This stress is only worsened as atmospheric CO_2 concentrations increase[4], with historical precipitation patterns shifting and extreme weather events rising. Further, the world's ground water resources are over-tapped, at high levels that have only recently come to light[5].

As the gap between freshwater supply and demand grows, saline and used water sources can be desalinated to provide additional supply. Indeed, almost 50% of Earth's population lives within 100 km of the ocean, and the percentage is increasing. However, relative to the treatment of traditional fresh water sources, desalination is energy intensive. Continued growth of the desalination sector requires new systems that limit (or zero out) the carbon footprint of desalination. This includes continued effort to lower the energy requirements of desalination, continued development of low-cost low-carbon energy systems, and a marriage of the two through system-level engineering. The present report considers these issues in turn, and provides recommendations for future research and development to make zero-carbon desalination a large-scale reality.

1.2 Desalination: global growth, energy consumption, and carbon footprint

Desalination capacity has been growing rapidly worldwide. In 2015, 31.6 billion cubic meters of freshwater were produced using desalination, more than twice the amount produced in 2005. Most of this capacity was produced by reverse osmosis, an electricity-driven membrane-based method of desalination, as illustrated in Fig. 1.1. Just under half of the total capacity, or about 41 million cubic meters per day, is seawater desalination for municipal use[6]. By 2020, an additional 10 million cubic meters is forecasted to come online – nearly all of which will be seawater reverse osmosis, and about half of which will be in the MENA region[7].

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[1] NASA Goddard Institute for Space Studies (2016): http://data.giss.nasa.gov/gistemp/, 2016

[2] C.A. Schlosser et al., The future of global water stress: An integrated assessment, Earth's Future, 2(8), 2014

[3] WWAP (United Nations World Water Assessment Programme), *The United Nations World Water Development Report 2015: Water for a Sustainable World*, 2015.

[4] C.B. Field et al. (eds.), IPCC, 2014: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2014.

[5] A.S. Richey et al., Quantifying renewable groundwater stress with GRACE, Water Resources Research, 51(7), 2016

[6] Global Water Intelligence, desaldata.com.

[7] Global Water Intelligence, desaldata.com.

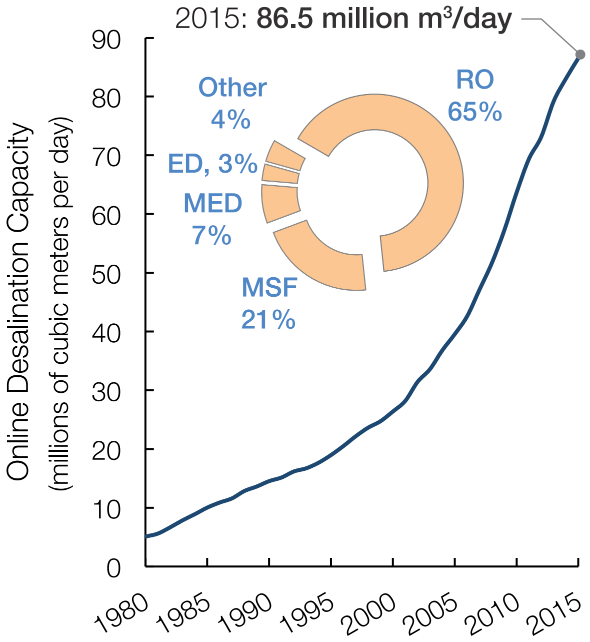

Figure 1.1: Worldwide online desalination capacity, 1980-2014: desalination capacity has more than doubled in the last decade, with reverse osmosis (RO) dominating installed capacity. The inset shows the technology mix by installed capacity: Reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MED), and electrodialysis (ED)[8].

Energy, exergy, and efficiency in desalination

The energy used by desalination systems may be in the form of either work (such as electricity) or heat (normally as low temperature steam). These forms of energy are distinct and cannot simply be added to find a "total" energy requirement[9]. The separation of fresh water from saline water requires a minimum amount of thermodynamic work which depends upon the feed water salinity and the fraction of total water to be separated, the so-called least work of separation (see Fig. 1.2). Typical seawater desalination plants operate at around 50% water recovery with seawater of about 35 g/kg salinity, which translates to a least work around 1 $\mathrm{kWh_e/m^3}$. Lower values exist at lower recovery ratios and for less saline feed waters. All of these factors must be considered when describing the energy requirements and thermodynamic efficiency of a desalination process.

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[8] International Desalination Association, Desalination Yearbook, Section 1. Market Profile 2015-2016, 2016

[9] For a detailed discussion of these issues, 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; or Mistry et al. "Entropy generation analysis of desalination technologies," *Entropy*, **13**(10):1829-1864, Sept. 2011 (http://www.mdpi.com/1099-4300/13/10/1829/).

As a brief elaboration, to generate work from thermal energy (as when electricity generated by fossil fuel combustion or from absorbed solar radiation in CSP) heat must be transferred between a high temperature source to a low temperature sink through a heat engine (such as a steam turbine or gas turbine). The amount of work that can be generated from a given amount of high temperature heat depends upon (and increases with) the ratio of the hot to the cold temperature. The production of a given amount of electrical energy requires two to three times the amount of thermal energy for an ordinary power plant.

For desalination systems, the work done is the work of separation (rather than electrical work). When thermal energy is used to drive distillation, the amount of thermal energy required depends on the temperature of that energy and will very substantially exceed the least work of separation, because the steam temperatures involved are much lower than in power plant combustors. In addition, however, most thermally driven desalination systems also require some amount of electrical work to drive pumps and other processes.

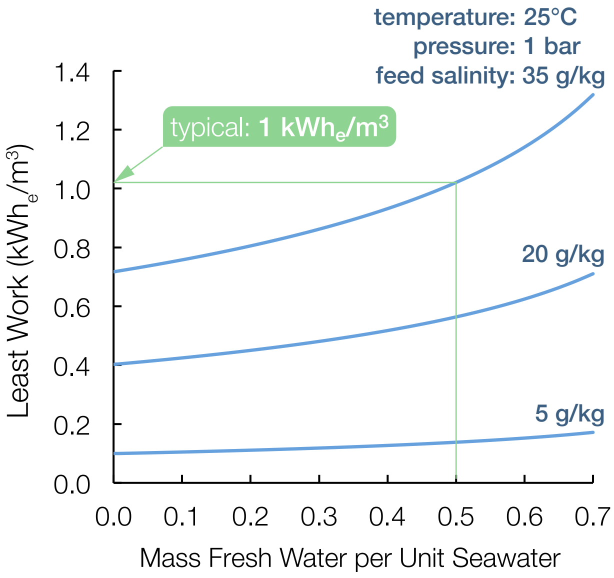

Figure 1.2: Least work of separation as a function of the recovery ratio (the mass of freshwater per unit feed water) for various feed water salinities [Lienhard et al., 2017]. Typical seawater desalination plants operate at 50% recovery, which translates to a least work of about 1 kWh$_e$/m^3. Lower values can theoretically be obtained at lower recovery ratios and for less saline feed waters.

Of the three most common desalination technologies, which account for 93% of installed capacity (Fig. 1.1), one is work-driven and two are thermally driven. Reverse osmosis (RO) desalts using electricity to pressurize seawater above its osmotic pressure, forcing it through a membrane that admits pure water but rejects dissolved salts. Many systems recover the energy associated with depressurizing the high-pressure brine stream that leaves the membrane modules, partially offsetting the energy required to pressurize incoming seawater. The two thermally-driven technologies rely upon the very large difference in volatility between salt and water to effect separation. In multistage flash (MSF), steam heats seawater that cascades through many successive stages of incrementally lower pressure, causing small amounts of pure water to vaporize (or "flash") from the feed with each drop in small pressure. The vapor is condensed using colder incoming seawater, recycling a portion of the energy consumed by evaporation to preheat the seawater feed. Like MSF, multi-effect distillation (MED) produces vapor by flashing, but superimposes thin-film evaporation to generate additional vapor in each stage (or effect). The vapor is again condensed so as to achieve efficient heat (energy) recovery. Part of the vapor is, like MSF, condensed by colder incoming seawater; the balance condenses in the next (lower-pressure) effect to drive the thin-film evaporation.

Table 1.1: Representative electricity, heat, and exergy requirements of common seawater desalination systems (entire plant) after Sommariva, 2010. Electrical and exergetic energy are in units of kWh$_e$ (i.e., work) and thermal energy is in kWh$_t$.

	Specific power consumption	**Thermal energy of steam**	**Steam extraction pressure**[10]	**Equivalent power loss (*exergy* of steam)**	**Total exergy input**
	kWh$_e$/m^3	kWh$_t$/m^3	bar (abs)	kWh$_e$/m^3	kWh$_e$/m^3
SWRO (Mediterranean Sea)	3.5	0	n.a.	0	3.5
SWRO (Arabian Gulf)	4.5	0	n.a.	0	4.5
MSF	4–5	78	2.5–2.2	10–20	14–25
MED-TVC	1.0–1.5	78	2.5–2.2	10–20	11–21.5
MED	1.0–1.5	69	0.35–0.5	3	4–4.5

Representative energy requirements of these desalination processes are given in Table 1.1[11]. Energy consumption and cost must be considered together with capital and operating costs when choosing the best technology for a given situation; but nevertheless, this table immediately raises the question of how to compare the energy efficiency of the various technologies. The appropriate means of comparison

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[10] This is equivalent to specifying the temperature of saturated steam, i.e., the high temperature driving the distillation process.

[11] C. Sommariva, *Desalination and Advanced Water Treatment: Economics and Financing.* Balaban Desalination Publications, 2010. (ISBN: 0-86689-069-6)

is to consider the exergy consumption[12] of the various systems in relationship to the least exergy (least work) required to desalinate the type of water in question. This comparison can be made directly using the second-law efficiency, η_{II}, which is the ratio of least work (or exergy) of separation, W_{least}(Fig. 1.2), to the actual exergy input to the desalination system:

$$\eta_{II} = \frac{\text{least exergy}}{\text{actual exergy}} = \frac{W_{\text{least}}}{W_{\text{actual}} + Q_{\text{actual}}(1 - T_{\text{cold}}/T_{\text{hot}})}$$

where W_{actual} is the actual work (electricity) input to the system, Q_{actual} is the actual heat input to the system, T_{cold} is the low temperature of the system, and T_{hot} is the high temperature at which heat enters the system (e.g., the temperature of steam entering an MSF plant).

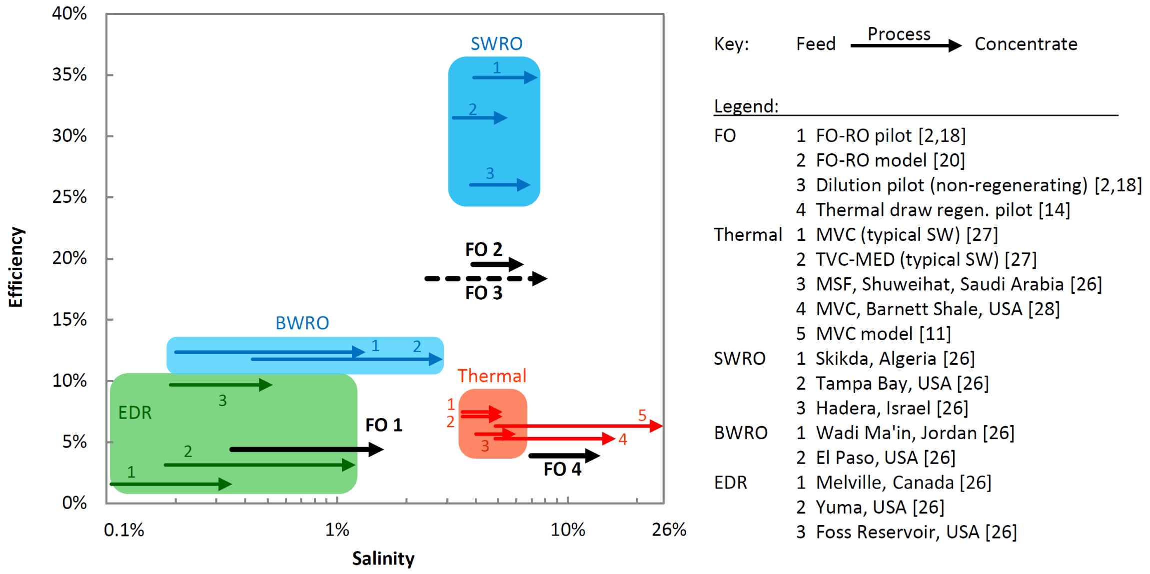

Figure 1.3: Efficiency-salinity map of desalination processes, with salinity in percent by weight. Processes are represented with arrows that begin and end at the feed and concentrate salinities, respectively. Citations in chart are in Tow et al., 2015.

Figure 1.3 shows the second law efficiency of various existing desalination systems for waters of various salinities[13]. Note in particular that these data refer mainly to commercialized designs, in other words, to designs optimized around cost factors rather than simply optimized for energy consumption. More energy efficient

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[12] Exergy is a thermodynamic measure of the work that can be done by a given transfer of thermal, chemical, or mechanical energy. For details of exergy and second-law efficiency, see Lienhard (2017), previously cited.

[13] E.W. Tow, R.K. McGovern, and J.H. Lienhard V, "Raising forward osmosis brine concentration efficiency through flow rate optimization," *Desalination*, **366**:71-79, 15 June 2015.

designs are possible[14], but they may require large areas of heat exchanger or of membranes than are not cost-effective.

The second law efficiency described previously refers to the performance of a desalination in terms of the energy input to that system as either heat or work. In many configurations, both of these energy sources derive from a common source of primary energy. For example, MSF desalination plants are usually coupled with electrical power generation. the MSF system receives both electricity and heat (as backpressure steam) from the power generation system, which in turn is driven by primary energy from combustion of fossil fuel. The cost of energy is the cost of the fossil input, and the carbon output per unit water depends not only on the efficiency of the MSF system but also on the efficiency of the associated power plant.

Mistry and Lienhard[15] analyzed such systems, and found that the second law efficiency with respect primary energy could be given by:

$$\eta_{II,\mathrm{primary}} = \frac{W_{\mathrm{least}}^{\mathrm{min}}}{W_{\mathrm{actual}}/\eta_{pp} + Q_{\mathrm{actual}}(1 - T_{\mathrm{cold}}/T_{\mathrm{hot}})}$$

where $W_{\mathrm{least}}^{\mathrm{min}}$ is the minimum value of least work for a given salinity (i.e., from Fig. 1.2 for 0% recovery[16]) and η_{pp} is the second-law efficiency of the power plant. For high power plant efficiencies (representative of combined cycle plants) and ordinary thermal desalination processes, Mistry and Lienhard found that the second law efficiency with respect to primary energy of SWRO plants substantially exceeds that of either MSF or MED systems in a coproduction configuration. For modest power plant efficiencies of 30% or so, and very high thermal plant efficiencies, the performance can be similar. Examples of thermal systems that outperform SWRO have been reported (see Sect. 2.2.2); but for this occur, the thermal plant must itself have very high energy efficiency and also an electricity consumption well below a comparable SWRO plant. Further, when electricity is produced with high second law efficiency, the advantage of SWRO over typical thermal desalination is greater.

Combining average energy consumption figures (Table 1.1[17]) with worldwide capacity and technology mix (Fig. 1.1), we estimate the global energy footprint of

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[14] This paper describes an FO-RO system that achieves higher system level energy efficiency through a relatively low RO membrane flux (large membrane area): C.D. Lundin and O. Bakajin, "Challenge testing osmotic pre-treatment for desalination," AWWA Conference Proceedings, 2013.

[15] K. Mistry and J.H. Lienhard V, "Generalized least energy of separation for desalination and other chemical separation processes," *Entropy*, **15**(6):2046, 2013. http://dx.doi.org/10.3390/e15062046

[16] For seawater at 35 g/kg salinity and 25 °C, $W_{\mathrm{least}}^{\mathrm{min}}$=0.72 kWh$_e$/m^3 when computing using the most recent correlations for seawater thermophysical properties: http:/web.mit.edu/seawater/ .

[17] For brackish water RO and ED systems, we use 1.25 kWh/m^3 and 0.9 kWh/m^3, respectively, which are representative values for a 3 g/kg feed at 90% recovery (see: K.G. Nayar et al., "Energy requirements of alternative technologies for desalinating groundwater for irrigation", IDA World Congress on Desalination and Water Reuse, San Diego, Aug. 2015.). The overall footprint value is

desalination to be about 200 TWh$_e$/yr, or an average power of 23 GW *on an equivalent electricity basis*. Values of thermal energy consumption were derated to electricity-equivalents (exergetic equivalents) by multiplication with a Carnot efficiency, $(1 - T_{\mathrm{cold}}/T_{\mathrm{hot}})$, as done in the equation above[18]. This efficiency is the maximum fraction of heat recoverable as work (electricity), so this conversion is a lower bound on equivalent-electric footprint of the thermal desalination technologies. Consequently, the energy footprint is likely a lower bound estimate.

Greenhouse gas emissions of various desalination systems

The vast majority of these commercialized desalination systems consume energy produced using fossil fuels, which emits greenhouse gases. The work required for RO may be produced from a co-located power plant or purchased from the grid. Most large-scale MSF and MED installations are driven by low-pressure steam bled from turbines in a co-located power plant. Although these thermally-driven processes are still operated in parts of the Middle East and elsewhere, RO is the dominant choice for new capacity based on its often lower cost and other situational advantages. Table 1.2 shows the GHG emissions (g CO$_{2e}$) per cubic meter of fresh water produced associated with powering a representative large-scale 3.5 kWh$_e$/m^3 reverse osmosis plant, based on the average lifecycle GHG emissions associated with each fuel source[19].

Table 1.2: Calculating GHG emissions (grams CO$_2$-equivalents per cubic meter of fresh water) associated with producing the energy (by fuel source[19]) to drive a modern large-scale 3.5 kWh/m^3 seawater reverse osmosis desalination plant.

Coal	**Oil**	**Natural Gas**	**Biomass**	**Solar-PV**	**Geothermal**	**Wind**	**Hydro-electric**	**Nuclear**
Average lifecycle GHG emissions for electricity production[19] (g CO$_{2e}$/kWh$_e$)								
1023 **g/kWh$_e$**	780	606	86	71	67	31	25	14
× 3.5 kWh$_e$/m^3								
Carbon footprint associated with powering a modern RO plant (g CO$_{2e}$/m^3)								
3580 **g/m^3**	2729	2121	300	248	233	109	89	49

Thermally based multistage flash (MSF) and multi-effect distillation (MED) desalination plants are often tied to power plant condensers or hot gas exhaust lines for the coproduction of power and water. Thermal plants are most energy efficient when operated in these configurations, rather than a stand-alone setting. Even when

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more sensitive to the value chosen for BWRO than for ED, as BWRO makes up a much greater portion of overall capacity.

[18] For T_{hot}, we use technology-representative top brine temperatures (90°C for MSF and 70°C for MED). For T_{cold} we choose 30°C.

[19] Shrestha et al., "Carbon footprint of water conveyance versus desalination as alternatives to expand water supply", *Desalination* 280:33–43, 2011.

operated in this manner, however, typical thermal plants use more energy per cubic meter of permeate than reverse osmosis and therefore have a higher associated carbon footprint[20]: 10,000–20,000 g CO_{2e}/m^3 for MSF and 8,000–16,000 g CO_{2e}/m^3 for MED when using fossil fuels as a source of primary energy. While thermal plants can be operated using renewable energy, such as concentrated solar power, to achieve negligible operating emissions, the economic viability of such plants is yet to be proven.

A top-down estimate of the desalination industry's total carbon footprint can be computed from three ingredients: (1) worldwide electricity production and carbon footprint by fuel source; (2) global desalination capacity, technology, and feed water mix; and (3) average desalination energy consumption by technology. Based on IEA data on the global power production mix[21] and the lifecycle-average GHG emitted per kWh_e produced (Table 1.2), we estimate[22] a worldwide average of 591 g CO_{2e}/kWh_e. Using average electric-equivalent energy (exergy) consumption values from Table 1.1 and global desalination capacity by feed water[23] and technology, we estimate that energy earmarked for desalination has a carbon footprint of about 120 million metric tons per year. Other top-down estimates have placed this number at 76 million metric tons per year[24]. A bottom-up analysis is required to improve estimate accuracy.

In addition to the energy consumption of a desalination system, the plant may also generate GHG emissions on a life-cycle basis, as through the production of necessary concrete or steel. To fully appreciate the global warming potential of any particular desalination system, a life cycle analysis is required. Further work in this area is needed.

1.3 Renewable electricity generation today and in the future

David Warsinger, Adam Warren

The past decade has seen a global transformation in the costs and market share of renewable power, led by wind and solar[25], as well as significant shifts in other sources. Operating on these changing electric grids[26] poses significant opportunities and tough challenges for low-carbon desalination.

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[20] Paddy Padmanathan, ACWA Power Presentation, IDA/GCWDA Nice Conference, 25 September 2016.

[21] "Key world energy statistics", International Energy Agency, 2016.

[22] This value is slightly lower than the 703 g CO_2/kWh_e used by the U.S. EPA's GHG Equivalencies Calculator, which is based on emissions from *non-baseload* power. Since desalination may consume baseload or non-baseload power, we average over the entire power generation mix.

[23] IDA Desalination Yearbook, 2013–2014

[24] Global Clean Water Desalination Alliance: H_2O minus CO_2 Concept Paper, http://www.circleofblue.org/wp-content/uploads/2015/12/Global-Water-Desalination-Alliance_6dec2015.pdf, 2015.

[25] The Future of Solar Energy, MIT Energy Initiative, 2015.

[26] The Future of the Electric Grid, MIT Energy Initiative, 2011.

These changes in renewables would shock many in the field whose numbers are even a few years out of date. As of 2016, the majority of added electricity capacity worldwide comes from renewables. The costs for wind[27] and solar[28] have decreased by roughly a factor of 1.5 and 4 respectively in just the last 10 years. In many regions of the world, utility-scale PV and wind power both have lower prices per kWh_e than local fossil fuels. A breakdown of renewable electricity share is shown in Fig. 1.4.

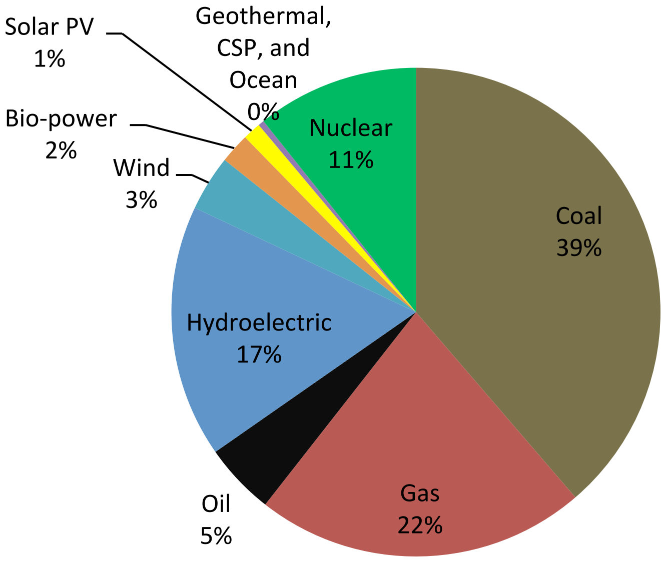

Figure 1.4: Estimated Renewable Energy Share of Global Electricity Production, End–2015, calculated with data from REN21[29]

Figure 1.5 shows global growth in renewables. The exponential growth rate in solar power is particularly extraordinary, though it has slowed slightly. The rapid growth of solar can largely be explained by changes in costs, though subsidies and incentives have helped enable the technology. As seen in Fig. 1.6, costs have dropped significantly due to decreases in the PV module price, with drops in hardware and labor decreasing significantly as well. Economies of scale and a maturing manufacturing base (and fully amortized plant costs) have helped decrease the module price. Meanwhile, innovations in assembly (largely related to pre-assembly of parts like clips, clamps, wires, and horizontal tubing) have reduced installation labor and impacted other costs as well. Efficiency gains have played a minor role, with US average commercial PV module efficiency increasing from 13.8% in 2010 to 16.7% in 2015[5].

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[27] 2014 Cost of Wind Energy Review, Christopher Moné et al., National Renewable Energy Laboratory, Technical Report NREL/TP-6A20-64281, October 2015

[28] Fu, Ran, et al. *US Solar Photovoltaic System Cost Benchmark Q1 2016*. NREL/PR-6A20-66532. Golden, CO: National Renewable Energy Laboratory (NREL), 2016

[29] Ren21, Renewables. "Global status report." *Renewable Energy Policy Network for the 21st Century, Paris, France* (2016). ISBN 978-3-9818107-0-7

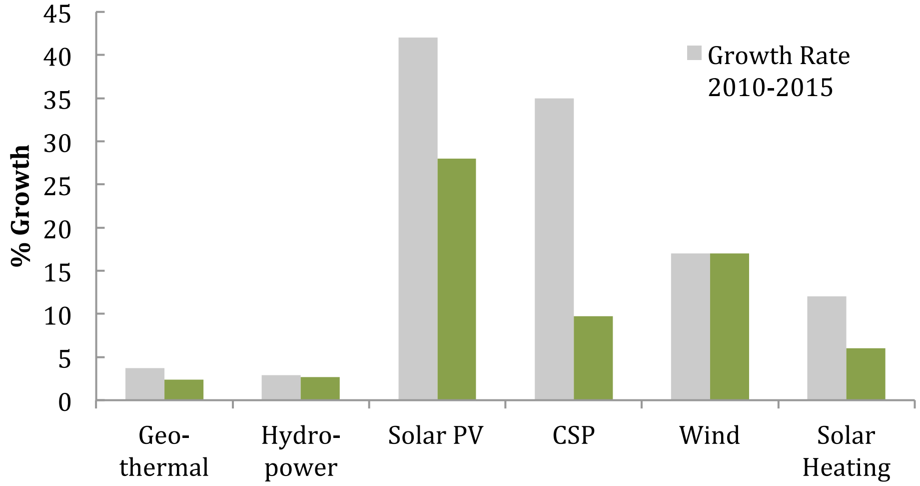

Figure 1.5: Average Annual Global Growth Rates of Renewable Energy Capacity, End-2010 to End-2015[30]

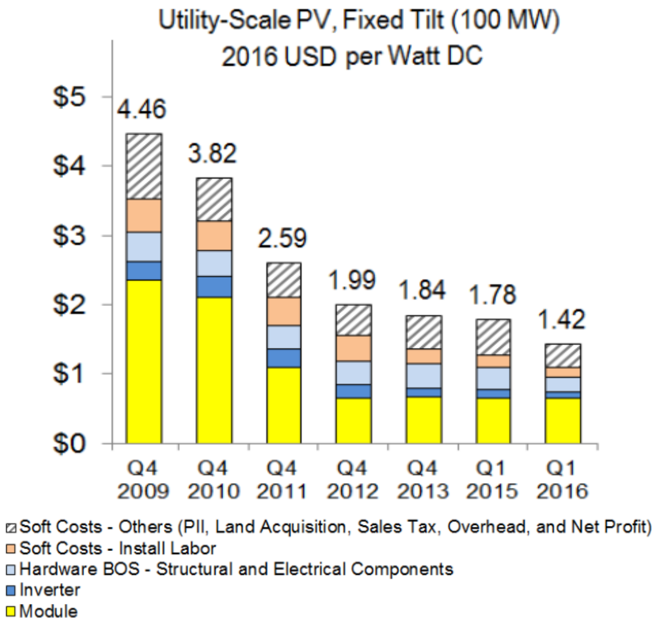

Figure 1.6: NREL PV system cost benchmark summary (inflation adjusted), Q4 2009–Q1 2016[31]

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[30] Made from data given in Ren21, Renewables. "Global status report." *Renewable Energy Policy Network for the 21st Century, Paris, France* (2016). ISBN 978-3-9818107-0-7

[31] Fu, Ran, et al. *US Solar Photovoltaic System Cost Benchmark Q1 2016*. NREL/PR-6A20-66532. Golden, CO: National Renewable Energy Laboratory (NREL), 2016

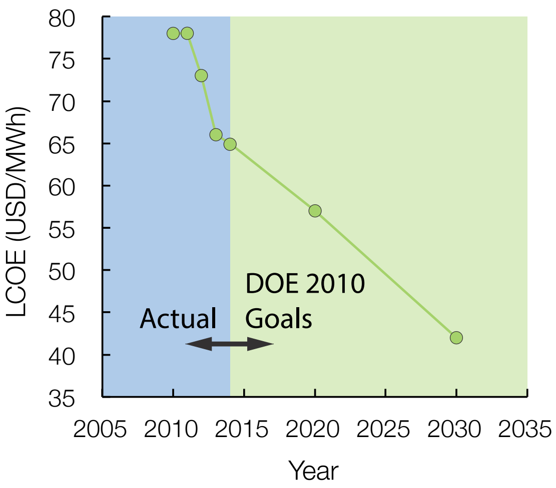

Figure 1.7: Historical land-based wind plant LCOE as calculated by NREL, including the U.S. Department of Energy's (DOE's) LCOE goals[32]

Wind power, the second largest renewable energy source after hydropower, has seen a steady decrease in costs, with initial market competiveness arising in late 1990's, well before the recent gains of solar PV. That has allowed wind to grow significantly, with more anticipated gains to be made (Fig. 1.7). These gains in wind power have been largely due to favorably scaling with increased turbine size, with additional gains from increases in capacity factor, increases in project life and reliability, reducing financing costs, economies of scale, and improvements in rotor design[33].

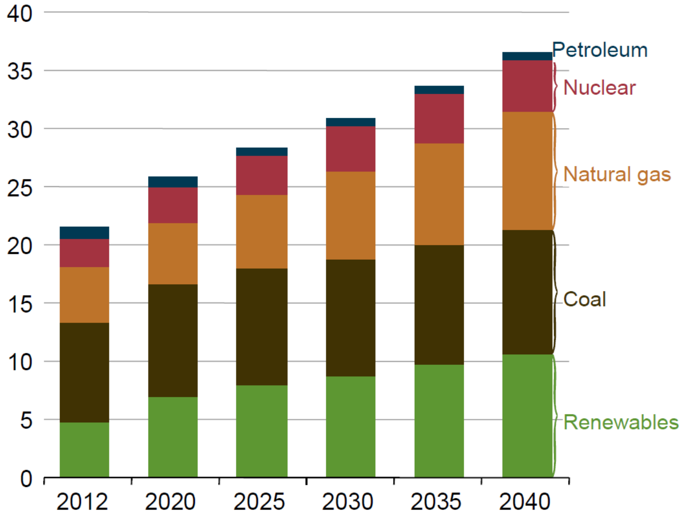

Figure 1.8: World net electricity generation by energy source, 2012–40 (trillion kWh)[34]

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[32] 2014 Cost of Wind Energy Review, Christopher Moné et al., National Renewable Energy Laboratory, Technical Report NREL/TP-6A20-64281, October, 2015.

[33] Wiser, Ryan, et al. "Expert elicitation survey on future wind energy costs."*Nature Energy* 1 (2016): 16135.

[34] International energy outlook 2016, US Energy Information Administration, Report Number: DOE/EIA-0484(2016), May 11, 2016

1.4 Status of nuclear power

Jacopo Buongiorno

With over 60 reactors under construction worldwide, the nuclear industry is currently experiencing moderate growth. Faced with intensifying concern over climate change, some analysts have concluded that without a significant expansion in the role of nuclear energy the United States, and the world as a whole, may be unable to meet the necessary targets for energy system decarbonization called for by political leaders, climate scientists and others. Construction of 300 GW_e of new nuclear capacity would completely replace coal baseload capacity in the U.S.[35]. The Electric Power Research Institute (EPRI) has estimated that 150-200 nuclear plants, each generating 1 GW_e, would generate enough electricity to enable conversion of the whole fleet of passenger cars and light trucks in the U.S. to plug-in hybrids, thus effectively ridding the U.S. of its dependence on oil, and drastically reducing the emissions of greenhouse gases into the atmosphere. Nuclear heat can also be used to convert biomass to biofuel: if all liquid fuel used for transportation in the U.S. came from biomass (e.g., corn, potato waste), the energy required from nuclear plants (in the form of low temperature steam) would be about 260 GW_t[36].

The above figures are ambitious but they are not unrealistic because the current U.S. nuclear fleet comprises 99 reactors (about 100 GW_e or 300 GW_t) that were built in a period of only 20 years. However, several challenges exist, the most important of which are discussed next.

- The production cost of nuclear electricity (fuel + OPEX) can be quite low, e.g., the average production cost of electricity from the (fully-amortized) U.S. nuclear fleet is currently ~\$0.024/kWh_e[37]. However, the capital cost of nuclear plants is high, due to the high cost of engineering, equipment, and installation. Current Gen3+ plants require an upfront capital investment of \$3-4 billion per 1 GW_e of installed capacity and take 5-7 years to build. Such long lead times also result in high interest payments during construction, which adds 30-40% to the cost and increases the financial risk of new nuclear plant projects. Therefore, the levelized cost of electricity for a new nuclear power plant in the U.S. is estimated to be in the range of \$0.09-0.10/kWh_e[38]. The low prices of natural gas and the expansion of intermittent, non-dispatchable solar and wind resources are also impacting economic considerations for nuclear and other baseload energy technologies.

- In spite of the excellent safety record of the nuclear industry, especially the U.S. nuclear industry, the public and governments of some countries have a negative

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[35] http://www.eia.gov/electricity/annual/html/epa_04_03.html

[36] C. Forsberg, "Nuclear energy for a low–carbon-dioxide–emission transportation system with liquid fuels", Nucl. Tech., 164, 348-367, Dec. 2008

[37] Nuclear Energy Institute, June 2015. http://www.nei.org/

[38] US Energy Information Administration, 2015 Energy Outlook of the EIA

perception of safety of nuclear plants. Prominent recent examples include Japan and Germany after the accident at Fukushima, Japan. Social acceptability of nuclear power today effectively means it must achieve a very high level of plant safety/robustness. In particular, risk of accidents from extreme natural events, such as massive earthquakes, tsunamis, tornadoes, wildfires and flooding, should be reduced, and land contamination following severe accidents should be made very unlikely.

- The current licensing process for new nuclear plants can be lengthy. For example, in the U.S. typically there are three steps before construction can begin: Early Site Permit, Design Certification, Combined Construction and Operating License. At least a decade is required to complete a new nuclear project. Moreover, the regulations tend to be very prescriptive, which limits the opportunity for innovation and which has made licensing anything other than light water reactors difficult. Innovators in the U.S. and elsewhere have been developing a range of advanced nuclear reactor and fuel cycle technologies that some believe will offer significant economic, safety and other advantages over the current generation of technologies.

- Concerns about disposal of nuclear spent fuel and proliferation are also important challenges for nuclear energy; however, their political dimension vastly outweighs their technical aspects. Very robust solutions are available for spent fuel disposal, e.g., mined or deep-borehole geological repositories. Spent fuel disposal has proven intractable in the U.S. so far, whereas successful examples of political management of this issue exist in Finland and Sweden, which in principle could be duplicated elsewhere. Obviously, an important technical, and policy, challenge is the very long time frame within which spent nuclear fuel remains hazardous[39] (~10^5 years); additional RD&D would clearly be helpful in this area.

1.5 Content of this report

Both desalination and renewable energy technologies have individually been the subject of extensive research and development. This workshop specifically focused on the research, development, and demonstration needed to cost-effectively combine these technologies for reduced carbon footprint in water production.

Improvements to either energy production or water production technologies can help to reduce the overall global warming potential of desalination processes. This report first highlights key opportunities in each area. Desalination systems themselves have seen steady improvements in energy efficiency over the past decades, and recent research and development have continued progressive reductions in the energy demand at a system level. For energy generation systems, we specifically explored needs in RD&D that would have implications for desalination systems. In particular, rapidly falling costs of renewable energy

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[39] http://www.nrc.gov/waste/high-level-waste.html

systems have radically transformed the potential for cost-effective, large scale, low carbon desalination.

The combination of low-carbon energy source and desalination systems raises several questions in relation to intermittent operation, dispatchability, grid-integration, and both energy and water storage as elements of an overall energy-water system. These questions are taken up next. Life cycle analysis is considered briefly.

The report concludes with roadmaps for each of the three areas, indicating the workshop's reading of impact and technology readiness for the various possible systems.

1.6 Methodology

This report was developed by an international group of technical leaders, who provided content, discussed and debated ideas, and who reviewed the final report. The participants in this invitation-only workshop each provided written content in advance of the workshop, which was then compiled into a draft report before the workshop. This draft was circulated among the attendees for revision ahead of the workshop. The workshop itself involved several stages, including presentation of the key ideas from the draft report and breakout groups that modified and prioritized these key RD&D needs. At the conclusion of the workshop, the participants ranked technologies relative to impact on decarbonizing desalination and technology readiness. After the workshop, the Workshop Committee compiled this feedback to develop the final form of the report, which was again reviewed and edited by the participants.

2. Lowering the Carbon Footprint of Desalination Systems

Contributors: Leon Awerbuch, Tzahi Cath, Karim Chehayeb, Chiara Fabbri, In Kim, Boris Liberman, Kishor Nayar, Kim Choon Ng, Michael Papapetrou, Mark Rigali, Rick Stover, Gregory Thiel, Natalie Tiggelman, David Warsinger, Roberto Segovia Yuste, Yuan Zhang

In this section, we discuss RD&D efforts and needs that drive down the carbon footprint of desalination systems. We include efforts to increase energy efficiency through new processes and process improvements; the development of next generation membranes; operational optimizations to mitigate fouling and/or lengthen membrane life; and novel hybrids, including those that recover chemical energy stored in brine. A large portion of the section focuses on reducing energy consumption, which currently drives a large portion of a desalination system's carbon footprint due to the prevalence of fossil-fueled steam and electricity generation. But even for renewables-driven systems, this is important, as the carbon footprint is shifted from the combustion of fuel to the manufacturing of solar panels, wind turbines, or solar-thermal steam generation. Finally, beyond the energy use, the section tackles the important ancillaries, from reducing the need for cleaning chemicals to site-optimal design.

2.1 Reverse osmosis

Early large-scale desalination plants, mostly in the arid Gulf countries, were based on thermal desalination techniques such as multi-stage flash (MSF) and multi-effect distillation (MED), which consume substantial amounts of thermal and electrical energy, resulting in a large emission of greenhouse gases when coupled to fossil drives. Since the early 2000's, reverse osmosis has dominated recently installed capacity, in part due to its lower energy consumption. However, seawater reverse osmosis (SWRO) still requires roughly two to three times the minimum energy specified by thermodynamics, and has an associated carbon footprint from component manufacturing, cleaning agents, brine disposal, and so forth.

In this section, we discuss state-of-the-art SWRO technology and pathways for reducing the carbon footprint of future SWRO designs, including:

- **process improvements**, which reduce direct electricity consumption;
- **next-generation membranes**, which will reduce the physical system size and improve solute rejection;
- **improved fouling control strategies** to reduce the need for over-sized systems and cleaning chemicals;
- **optimized control and operation**, which seeks to understand and improve performance when coupled with low-carbon drives.

Seawater reverse osmosis has improved considerably over the past three decades – in cost and carbon terms, but both are still significant barriers to sustainable deployment. These R&D challenges represent workshop consensus on the most significant pathways to drive down the carbon footprint of SWRO.

2.1.1 Process improvements for energy efficiency

In Kim, Rick Stover, and David Warsinger

The amount of energy required to desalinate seawater has declined dramatically in the past 40 years (Fig. 2.1). This decrease has been achieved with technological advances including the implementation and improvement of energy recovery devices (ERDs), the use of high-permeability reverse osmosis membranes and pump efficiency increases[40]. Specific energy consumption (SEC) values as low as 1.6 kWh_e/m^3 have been demonstrated with pilot-scale systems[41] using isobaric energy recovery devices, high-permeability SWRO membranes and positive-displacement pumps. These values can be compared to the thermodynamic minimum requirement of 1.06 kWh_e/m^3 for desalinating seawater at 35 g/L at a water recovery rate of 50%, indicating that up to 50% additional energy consumption reduction is theoretically feasible. Additional energy of about 1 kWh_e/m^3 is required for seawater intake, pretreatment, post-treatment, and brine discharge for large-scale desalination plants[42]. RO process technology improvements, discussed in this section, combined with membrane and equipment improvements described elsewhere in this document, have the potential to reduce the gap between actual energy consumption and the theoretical limit while still generating a reasonable water flux with efficient solute removal. RO process technology can also be developed to provide greater flexibility, thereby increasing compatibility with renewable energy sources.

High pressure pump size and process flexibility

Up to 72% of the total energy required for seawater desalination with reverse osmosis membranes is consumed by the high pressure pumps[43]. Increasing high pressure pump efficiency is, therefore, a direct means to increase energy efficiency. Positive displacement (PD) pumps provide wire-to-water efficiencies 90% or more and can operate flexibility if equipped with variable frequency drives. Compared to centrifugal pumps, PD pumps are expensive and limited in maximum capacity, however their high efficiency has led to their implementation in small- and medium-size desalination plants, especially in regions where power costs are high. Centrifugal pump efficiencies approaching 90% can be achieved in mega-size desalination operations with very large centrifugal pumps, however, the use of such pumps generally limit process flexibility.

One means to incorporate large high-efficiency high-pressure pumps in a flexible process design is the so-called pressure-center design. While conventional SWRO plants are comprised of trains with dedicated high-pressure pump, membrane arrays and energy recovery devices, pressure center designs decouple these main

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[40] M. Elimelech and W.A. Philip, "The Future of Seawater Desalination: Energy, Technology, and the Environment", Science vol. 333, pp. 712-717, 2011

[41] Seacord, T., Coker, S., MacHarg, J., "Affordable Desalination Collaboration 2005 results," Desalination and Water Reuse, Vol 16/2, 2006.

[42] C. Fritzmann, J. Löwenberg, T. Wintgens, T. Melin, "State-of-the-art reverse osmosis desalination", Desalination vol. 216, pp. 1–76, 2007

[43] N. Voutchkov, World Class Desalination Energy & the Environment, 2011

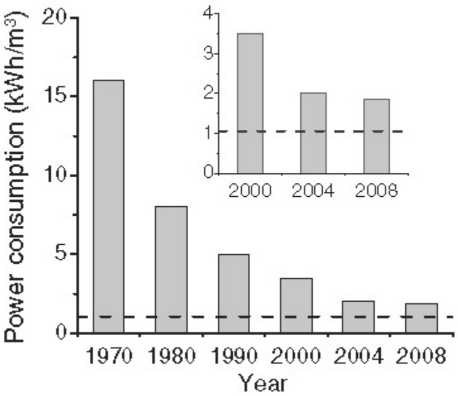

Figure 2.1: The change in energy consumption of SWRO plants from the 1970s to 2008 (Adapted from: M. Elimelech, W. A Phillip, Science 333, 712, 2011.)

process elements. Components feed and are fed from manifolds through valves that allow each component to be isolated. Three of fewer high pressure pumps can feed 16 or more RO membrane trains, for example, reducing energy consumption by up to 5% compared to the energy requirement to feed 16 trains with separate pumps. Pressure-center systems can start or stop quickly without overloading the power grid. Alternatively, a pressure-center desalination plant can produce 75% of the daily production during the night hours and 25% during the day, for example, providing load leveling for a country or region or maximizing use of renewable energy sources.

Batch and semi-batch RO systems

Most SWRO plants desalinate seawater using a single membrane stage fed by a high-pressure pump. A means to bring the feed pressure requirement close to the theoretical minimum pressure requirement is multi-staged membrane operation in which multiple high-pressure pumps and membrane modules are arranged in series[44]. The first stage accomplishes only some of the overall recovery and hence operates at a lower applied pressure. The concentrate from this stage is then brought to a higher pressure before being fed to a second stage, where additional recovery is achieved. This mode of operation allows smaller volumes of water to be brought to higher pressures, thereby consuming less overall energy. However, because the pressure of the concentrate from the final stage is much higher than the feed pressure of the first stage, it is not possible to use isobaric energy recovery devices in multi-stage configurations, undermining some of the energy savings potential of these designs for SWRO desalination. Also, the additional pumps required add capital costs, and the duty pressure requirements of the pumps make them non-standard.

Batch and semi-batch desalination have demonstrated the pressure-reducing benefit of multi-staging without the need for energy recovery devices or additional pumps[45,46]. Concentrate is recirculated until the desired percent recovery is

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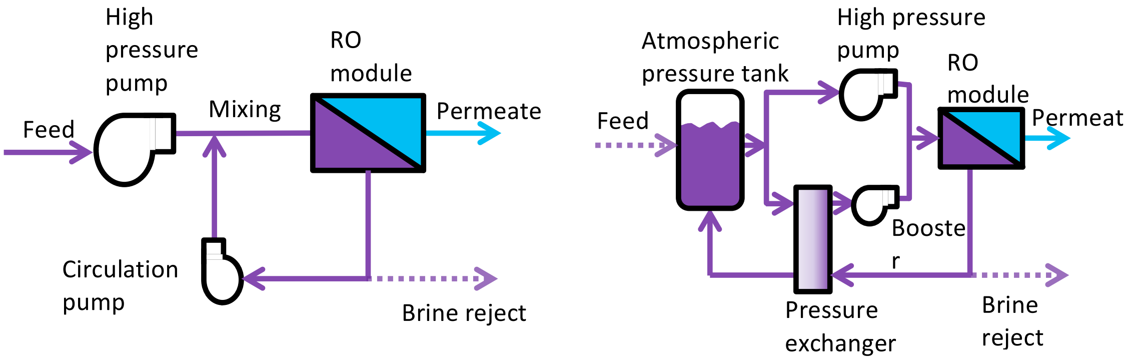
[44] L. Shihong, M. Elimelech, Desalination 366, 2015.

[45] A. Efraty, U.S. Patent 7,695,614 B2, 2010.

achieved. Desalination of 35 g/liter or 3.5% salinity seawater at 50% recovery and 9 gallons per square foot (14 liters per square meter) flux in pilot systems have shown that desalination is possible with just over 1.6 kWh_e/m^3 of RO energy, representing nearly a 20% reduction in SWRO energy requirements compared to traditional SWRO processes[47]. With their inherently discontinuous operation, these processes provide greater flexibility than conventional SWRO processes, thereby increasing compatibility with renewable energy sources. The development and optimization of suitable low-cost high-pressure components and tanks will enable implementation of batch and semi-batch processes designs in large-scale installations. However, while semi-batch has been established, batch systems are lacking in industry: new designs and implementation is a key area for RD&D



Schematic diagram of a closed-circuit reverse osmosis system. Feed continuously enters the system, but brine is rejected only at the end of the cycle. Pressure gradually increases over time. Dotted lines represent flows present

Batch RO design with a variable volume tank. In this variant, a pressure exchanger is used to reduce the pressure of the recirculating stream so that a standard, low-pressure tank can be used[48].

Figure 2.2: Schematic diagram comparing various process arrangements for batch and semi-batch RO

Low energy membranes

Recent reverse osmosis membrane developments have documented the potential for significantly increased permeability and corresponding increases in flux and decreases in energy requirements[49]. However, the utility of high permeability membranes in most SWRO plants is limited because they increase flux imbalance in standard membrane arrays of six to eight membrane elements in series. Excessively high through the first element in the array, where the osmotic pressure is lowest, can result in premature organic, biological or colloidal fouling. Shorter membrane arrays of three or four elements in partially mitigate flux imbalance, enabling the use of high permeability membranes. Short arrays could be arranged in multi-stage configurations with inter-stage boost pumps, however, multi-staged membrane

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[46] R. Stover, N. Efraty, IDA Journal V4 No. 3, 12, 2012.

[47] J. Jacangelo, A. Subramani, N. Voutchkov, Water Environment & Research Foundation, Desal-11-04, 2016.

[48] D. M. Warsinger, E. W. Tow, K. Nayar, and J. H. Lienhard V, Water Research, vol. 106, pp. 272-282, 2016

[49] M. Elimelech, W. A Phillip, Science 333, 712, 2011.

systems are costly and difficult to implement. Batch and semi-batch RO systems, describe above, accommodate short membrane arrays of three or four elements in series and are thereby more suitable for high-permeability, low energy membranes than traditional RO systems with longer arrays.

A means to enable use of high-permeability membranes in existing RO plants or in future plants with long membrane element arrays is with Hybrid membrane Inter-stage Designs (HIDs). Membranes of different nominal flux and salt rejection are combined in the same pressure vessel in a way that balances water flux along the vessel (Fig. 2.3). In HID, a low flux (low permeability) membrane elements are positioned at the head of the vessel, followed by increasingly higher flux elements towards the tail. The high flux elements in the tail decrease the required net driving pressure, which reduces energy consumption. Compared to the standard SWRO designs with a single membrane type throughout the array, HID offers higher average permeate flux with good permeate quality, and could save energy consumption by 8.3%[50].

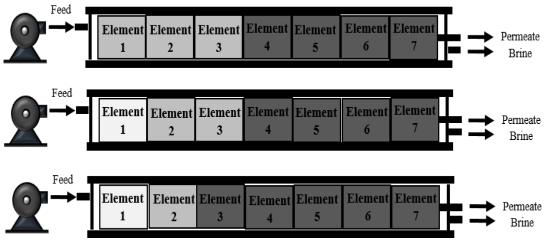

Figure 2.3: HID in SWRO plant (darker color indicates higher flux membrane)[51]

2.1.2 Next generation membranes

In Kim, Mark Rigali, David Warsinger, Yuan Zhang

Traditional SWRO depends on a semipermeable membrane capable of selectively separating pure water from seawater. The modern RO membranes are based on a non-porous thin-film composite (TFC) design in which a dense polymer skin provides the active-site architecture responsible for ion rejection[52].

The development of new membranes with high water permeability and salt rejection has the potential to reduce energy consumption and save capital and operational costs – all of which contribute to a lower carbon footprint. Nanostructured high flux membranes have the potential to significantly improve desalination performance. The associated high permeabilities can result in a decrease in the pressure needed to drive permeation, thereby reducing the energy

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[50] B. Peñate, L.G. Rodríguez, “Reverse osmosis hybrid membrane inter-stage design: A comparative performance assessment", Desalination vol. 281, pp. 354–363, 2011

[51] "Effect of boron rejection and recovery rate on a single-pass design of SWRO using hybrid membrane inter-stage design (HID) concept," Desalination, In Press

[52] Rempe, S.B., et al., 2011, Biomimetic Membranes for Water Purification. 2011 R&D 100 Submission. SAND2011-2061P.

consumption of single pass SWRO, potentially to as low as 1.5 kWh_e/m^3. Higher permeability could alternatively mean that fewer membranes are required to produce the same amount of fresh water. Simply stated, next generation membranes based on nanostructured materials hold the promise of significant improvements relative to the current generation, dominant membrane technologies[53].

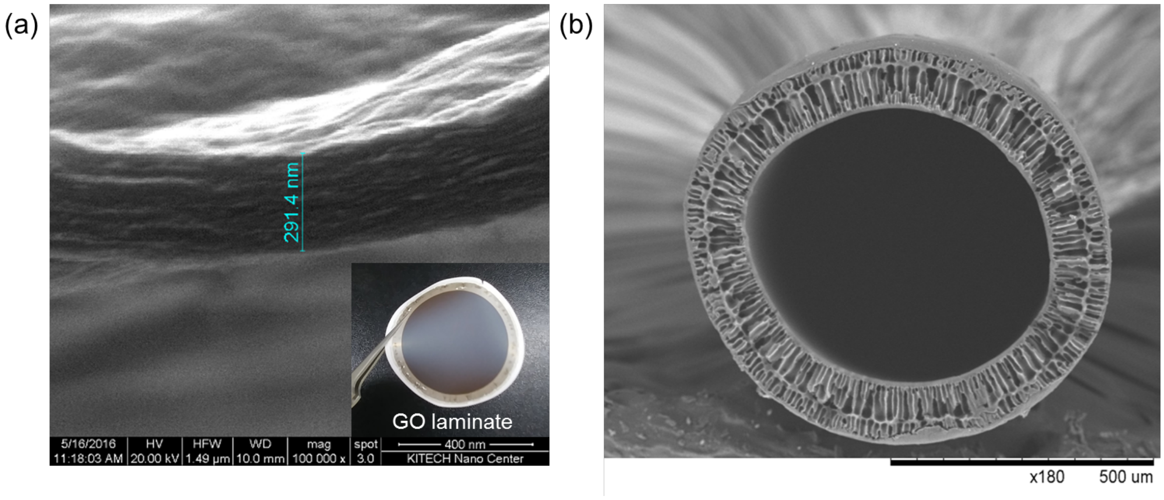

Figure 2.4: Graphene-based hollow fiber desalination membrane, (a) graphene oxide laminates and (b) hollow fiber membrane (In Kim et al.).

One way to improve the limitations of polymer desalination membranes is to develop mixed matrix membranes (MMMs), in which a filler material is embedded within a polymeric matrix. Such membranes are being explored to tailor the separation performance and add new functionality to membranes for water purification applications[54]. MMMs which use nanomaterials as a filler material, known as thin film nanocomposite (TFN) membranes are currently being developed. Theses membranes incorporate metal nanoparticles (e.g., gold, silver, iron oxide), zeolite, carbon nanotubes, TiO_2, graphene and polymerizable surfactants, etc. In addition, new classes of inorganic TFN membranes that use nanomaterials, but not mixed with polymers, have been recently proposed that aim to drastically increase water permeability. For example, graphene could act as a high-permeability desalination membrane, which might improve upon commercial polymer RO membranes by enabling higher permeability with good salt rejection (Fig. 2.4).

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[53] US Bureau of Reclamation (US BoR) and Sandia National Laboratories (SNL), 2003, Desalination and Water Purification Roadmap -A Report to the Executive Committee. Bureau of Reclamation, Denver Federal Center, Denver CO., 58 p. SAND2003-0337P.

[54] Lind, M.L. et al., "Tailoring the Structure of Thin Film Nanocomposite Membranes to Achieve Seawater RO Membrane Performance", Environ. Sci. Technol., vol. 44, pp.8230-8235, 2010.

Yet another avenue of exploration is nanostructured biomimetic membranes based on aquaporins. These proteins serve to transfer water across cell walls and RO membranes based on their structure have the potential to enable high salt rejection and faster water flow at lower driving pressures thus reducing the energy demand and carbon footprint of desalination.

The estimated water permeability of biomimetic membrane is at least an order of magnitude greater than that of conventional RO membrane, while salt rejection capability can still be maintained high[55]. In an ideal situation, desalination based biomimetic membranes can approach the minimum energy for desalination, as it can be operated at a hydraulic pressure that is just above the osmotic pressure of the saline water. The biomimetic technique also provides a potential method to control channel selectivity by genetic manipulation of the proteins, which would thus allow the desired desalination functions to be optimized.

As the biomimetic techniques are still at the infant state of the technology development, a number of research challenges remain to be addressed. Membrane stability is one of the critical issues because the biomimetic membranes with embedded aquaporin must be able to withstand high pressures to overcome osmotic pressure. Interaction of the proteins with the environment is another key area that needs fundamental understanding and study. High water flux could induce concentration polarization, and membrane fouling would also be exacerbated at higher water fluxes. The above are important issues that need to be further investigated for practical applications of biomimetic membranes. It can be expected that redesign of membrane modules will be needed.

Other avenues of investigation to improve permeability and rejection include but are not limited to:

- Nano-engineered membrane surfaces and coatings to mitigate biofouling
- Improvement of membrane manufacturing techniques, including electrospun porous nanofibers, hollow fiber RO membranes, and others
- Improvement of the chlorine resistance of membrane materials via coatings or new selective materials
- Development of novel membrane materials with improvements in permeability, selectivity, and robustness, potentially including: biomimetic pores, aquaporin membranes, ceramic membranes, nano-composite membranes, and carbon nanomaterials including carbon nanotubes and graphene oxide
- Improved membrane rejection, especially of emerging contaminants and boron
- Improved understanding of the physics in rejecting more complex particles such as endocrine disruptors.

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[55] Nielsen, C. (2009). Biomimetic membranes for sensor and separation applications. Analytical and Bioanalytical Chemistry 395 (3): 697-718.

- Improved manufacturing, design, and significant cost reduction for non-RO membranes, including membrane distillation and electrodialysis

Humplik et al.[56] observed that considerable effort is still required before these membranes become commercially viable, including the development of a fundamental understanding of transport processes, cost reduction, pore size optimization, and system level integration, but the promise of reduced capital and operating costs should encourage the development of these new materials. In addition, improvements in advanced fabrication techniques are required. The effort must begin with the end in mind: a fully functional and commercializable desalination membrane. The research and development approaches envisioned will utilize a closely coupled computational and experimental effort moving from laboratory and bench scale technologies to pilot scale and full scale demonstration. Further, this effort will require a close collaboration between the fundamental research institutes, membrane manufacturers and end users (water utilities).

2.1.3 Fouling, cleaning, and scaling

Chiara Fabbri, Boris Liberman, George Papadakis, Rodrigo Segovia Yuste

Understanding fouling to enhance RO performance and facilitate coupling with renewable sources

Membrane biofouling in a 100,000 m^3/day RO seawater desalination plant can result in more than 10,000 tons of CO_2 in 25 years, as a consequence the higher pressure to overcome biofouling, membrane replacements, and chemical cleanings. In the past, several approaches have been implemented to reduce the energy consumption of RO, such as optimized design configuration coupled with highly efficient equipment (motors, pumps and energy recovery devices etc.). A different approach to minimize the carbon impact of the desalination plant is to design it to operate at variable production rates so that it can be coupled with an intermittent, renewable energy source, such as wind and solar.

Research is needed to study and further understand the phenomena taking place on the RO membranes operating under variable pressure and intermittent conditions. Furthermore, the development and experimental validation of models of RO membranes operating under non-constant pressure and/or intermittently is necessary so that to describe and predict the membrane behavior operating under such conditions.

One important challenge associated with this transient operation is the potential for increased membrane scaling, bio, organic and mineral fouling, collectively known as fouling. Increased fouling also necessitates greater cleaning, and/or membrane replacement activities, both of which have an associated carbon footprint.

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[56] Humplik, T. et al., 2011**,** Nanostructured materials for water desalination. Nanotechnology **22,** 19pp. doi:10.1088/0957-4484/22/29/292001.

Fouling is the accumulation of marine organisms and their metabolic products on the membrane surface[57,58,59]. Fouling is also the sedimentation of Natural Organic Material (NOM) and mineral particles on the membrane surface. Scaling is a form of fouling caused by the crystallization of sparingly soluble compounds, which increase the energy demand for the separation of product water from the brine, and that involves the deterioration of product water quality[60,61,62] having therefore a significantly detrimental effect on the efficiency of the RO desalination process. The presence of fouling increases energy use, chemical demand, and cleaning frequency creating also a larger amount of waste sludge that needs to be disposed. Frequent cleanings and high chemical injection reduce RO membrane life, and diminish productivity due to the need to stop the RO systems for Cleaning In Place (CIP) activity. Fouling implies a more frequent membrane replacement. Advancements in plant design, membrane materials and optimization of operational conditions have contributed to fouling prevention[63,64] but no one of these is able to completely eliminate fouling.

Biofouling is particularly complex and little is known about the marine bacterial community that causes biofouling. There are assumptions that the bacterial community regulates its behavior through quorum sensing. Impeding the quorum sensing might prevent the sharing of metabolic activities between different biological societies and, thus, prevent biofilm formation.

From operational experience, we know that early detection of biofouling plays an essential role in an adequate anti-biofouling strategy. Presently, there is no specific technique able to detect the biofouling of the RO membrane. Today the tendency to have the membrane fouled is mainly determined by measuring changes in pressure drop over the RO membranes, which however is not exclusively linked to the biofouling and therefore cannot be considered accurate.

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[57] Costerton J. W. 1995. Overview of microbial biofilms. J. Ind. Microbiol. 15:137–140

[58] Flemming H. C., Schaule G. 1988. Biofouling on membranes–a microbiological approach. Desalination 70:95–119

[59] Flemming H. C., Schaule G., Griebe T., Schmitt J., Tamachkiarowa A. 1997. Biofouling–the Achilles heel of membrane processes. Desalination 113:215–225

[60] Abd El Aleem F. A., Al-Sugair K. A., Alahmad M. I. 1998. Biofouling problems in membrane processes for water desalination and reuse in Saudi Arabia. Int. Biodeterior. Biodegrad. 41:19–23

[61] Azis P. K. A., Al-Tisan I., Sasikumar N. 2001. Biofouling potential and environmental factors of seawater at a desalination plant intake. Desalination 135:69–82

[62] Flemming H. C., Tamachkiarowa A., Klahre J., Schmitt J. 1998. Monitoring of fouling and biofouling in technical systems. Water Sci. Technol. 38:291–298

[63] Zhang M., Jiang S., Tanuwidjaja D., Voutchkov N., Hoek E., Cai B. Composition and Variability of Biofouling Organisms in Seawater Reverse Osmosis Desalination Plants. Appl Environ Microbiol. 2011 Jul; 77(13): 4390–4398

[64] Bereschenko L. A., et al. 2008. Molecular characterization of the bacterial communities in the different compartments of a full-scale reverse-osmosis water purification plant. Appl. Environ. Microbiol. 74:5297–5304

Systematic and effective strategies for biofouling control need to be established and microbial communities at different stages of treatment processes (intake, cartridge filtration, and SWRO) of a desalination pilot plant need to be examined. Investigations of the microbial community that causes RO membrane fouling have not progressed much beyond studies focused on freshwater or wastewater RO treatment systems[65].

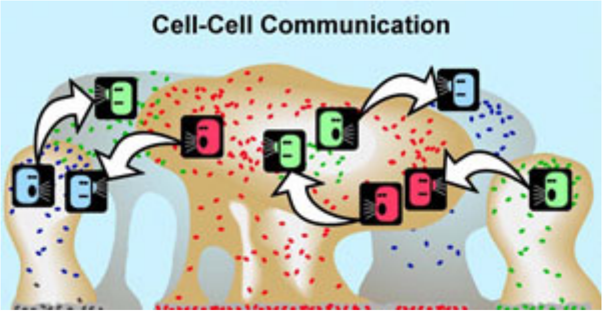

Figure 2.5: Sessile cells in a biofilm "talk" to each other via quorum sensing to build microcolonies and to keep water channels open. (http://bacteriality.com/2008/05/biofilm/)

A detailed R&D program to carry out systematic investigation of biofouling bacterial communities at both a temporal and spatial scale should be carried out. The investigation should lead to the investment of significant economic resources in the development of effective strategies for understanding, controlling and addressing biofouling. Understanding the nature of membrane biofouling, with the possibility of early detection, will allow the development of techniques to control the biofouling and, eventually, to improve membrane resistance to fouling. Understanding the biofouling tendency will also allow the adequate design of the system, with the implementation of various features to take advantage of the lower electricity rates for high production and vice versa, and will facilitate the coupling of the desalination plant with the renewable power source.

In parallel to the systematic investigation of biofouling bacteria communities, a dedicated effort for the development of in situ reverse osmosis sensors capable of detecting the biofouling early is important. It is important to develop and implement physical, rather than chemical methods of biofouling prevention, with the preference being for non-chemical online treatments that do not interrupt the ongoing RO desalination process.

Additionally, investigation of membranes increased spacer design and fluid dynamics to reduce the biofouling impacts could lead to reduced specific energy consumption and chemical cleaning. Carbon footprint may trade-off with capex.

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[65] Bereschenko L. A., Stams A. J. M., Euverink G. J. W., van Loosdrecht M. C. M. 2010. Biofilm formation on reverse osmosis membranes is initiated and dominated by Sphingomonas spp. Appl. Environ. Microbiol. 76:2623–2632

Keeping the RO Membranes of the future continuously clean

The main boost in desalination technology will come from new membranes currently in development, including carbon nanotubes, graphene, aquaporin, and others. The common feature of all these membranes is high flux operation, dozens of times higher than the present membranes flux. This dramatic increase in flux promises a list of technological and commercial benefits. The drawback of the new RO membrane is related to a misbalance between ultrafiltration (UF) pretreatment, which will be similar to that currently in use, and the high flux operation of the new RO membranes. The UF pretreatment membrane allows the passage of small organic molecules that will plug the high flux membranes in a short time. This, in turn, will increase the required feed pressure and negatively affect the expected low carbon footprint of future desalination technology.

The standard clean-in-place (CIP) method is not applicable in this new, high flux RO technology. Currently the period between CIPs is 60-90 days. This period will be reduced about 50 times, proportionally to a 50 times increase in flux. Each CIP procedure requires stoppage of an RO train, connection to the CIP system, a few circulations of reagent solutions, soaking, flushing between solutions, reconnecting to the HP pumping system, and startup. Normally the CIP process requires 6-8 hours of RO train stoppage, i.e. every two days of high flux operation will require, 6-8 hours stoppage for membrane cleaning. This operation regime makes the new high flux membranes not effective. In addition, CIP cleaning solutions cause ecological problems during delivery, storage, preparation and disposal.

Specific aims for membrane cleaning development include:

- Avoid RO train stoppage for CIP, and provide fast and frequent on-line membrane cleaning.
- Replace harsh chemical membrane cleaning with physical methods to keep the membranes continuously clean.

Possible methods and avenues for this effort include[66]:

- Periodically changing the process on the membranes from RO to forward osmosis (FO), which provides fast and frequent online backwash. It is important to maintain the gauge pressure on the semipermeable membrane constant during the process changes from RO to FO. Some components of large commercial desalination system such as pumps,

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[66] Bar-Zeev, E. and Elimelech, M., 2014. Reverse osmosis biofilm dispersal by osmotic back-flushing: Cleaning via substratum perforation. Environmental Science & Technology Letters, 1(2), pp.162-166; Qin, J.J., Oo, M.H., Kekre, K.A. and Liberman, B., 2010. Development of novel backwash cleaning technique for reverse osmosis in reclamation of secondary effluent. Journal of Membrane Science, 346(1), pp.8-14; Ramon, G.Z., Nguyen, T.V. and Hoek, E.M., 2013. Osmosis-assisted cleaning of organic-fouled seawater RO membranes. Chemical engineering journal, 218, pp.173-182; Lee, S. and Elimelech, M., 2007. Salt cleaning of organic-fouled reverse osmosis membranes. Water research, 41(5), pp.1134-1142; Qin, J.J., Wai, M.N., Oo, M.H., Kekre, K.A. and Seah, H., 2009. Impact of anti-scalant on fouling of reverse osmosis membranes in reclamation of secondary effluent. Water Science and Technology, 60(11), pp.2767-2774.

interconnectors etc., are very sensitive to large changes in gauge pressure, while are tolerant to small gauge pressure changes.

- Dissolution of scaling proto-crystals by FO permeate backflow and high ionic strength of the draw solution.
- Frequent removal of particles before strong van-der Waals forces interact with the membrane surface.
- Periodic dehydration of bacteria by sharply changing the osmotic pressure around them from below to above the cytoplasm osmotic pressure.
- Changing the feed-brine flow regime from a smooth regime to pulse-wise flow production regime: periodically, the velocity is changed from zero to high velocity. In other words, the Dead End RO process changes frequently to a Cross Flow and back to a Dead End process.
- Continuous or periodic micro pressure strokes of the semipermeable membrane, combined with foulant evacuation by flush through, causes:
    - Loss of Quorum Sensing among bacteria
    - Delay in formation of scale
    - Prevention of particle attachment to the membrane
    - Particles movement in the feed-brine spacer from low velocity areas

Existing technology (the IDE PROGREEN™ design, which has been in operation for a few years in a few plants[67]) that allows operation of the desalination plant without any chemicals (no chlorination, no bisulfite, no coagulation, no flocculator, no antiscalant), has shown that such operation reduces the carbon footprint by an additional 5-6%. New technology is needed to maintain the next generation of membranes clean continuously using physical (not chemical) online treatments, while allowing uninterrupted high flux operation.

2.1.4 Special considerations for small-scale/stand-alone RO

Chiara Fabbri

The reliable and safe provision of fresh water is turning out to be one of the major constraints in small islands and remote areas. Remote small islands have unique features that affect the water supply due to limited surface area for water collection or retention possibilities, their sensitiveness to natural disasters (cyclone, erosion and climate change), the supply demand mismatches and the isolation from larger inhabited areas. Remote communities are often located in areas with access to seawater or brackish groundwater. For such communities, small-scale reverse osmosis desalination plant can provide fresh water even if some of them are still relying on water transported by tankers or boat.

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[67] Liberman, B. "Direct Osmosis Cleaning", U.S. Patent No. 7,563,375 (July 21, 2009); Liberman, I. "RO Membrane Cleaning Method", U.S. Patent No. 7,658,852 (Feb. 9, 2010); Liberman, B. and Liberman, I., 2005. Replacing membrane CIP by Direct Osmosis cleaning. INTERNATIONAL DESALINATION AND WATER REUSE QUARTERLY, 15(2), p.28; Liberman B. UK Patent 2519880, 12. 08.2014

Desalination is an energy intensive process and in the remote and isolated communities the electric grid and the proper infrastructure are normally lacking and therefore a typical remote desalination plant would be powered by a diesel generator which is a source of pollution for the environment and it is cost extensive due to the fuel. A renewable energy powered desalination plant can be the optimal solution to address the water constrain and in particular reverse osmosis desalination plant coupled with photovoltaics is the most promising solution for small-scale desalination in remote area.

One of the major challenges associated with reverse osmosis desalination plant coupled with photovoltaics is the capability of the plant to accommodate variations in the solar radiation that is directly linked with the variation in the water production. The intermittent power input received by the plant requires the system to adjust its settings; the adjustment shall be done through plant autonomous control since it is not practical for an operator to monitor the system continuously.
Early systems simply combined a photovoltaic array and batteries to store energy to power the reverse osmosis desalination system. However, battery-based systems were found to be expensive and have limited lives. In recent years photovoltaic-powered reverse osmosis systems without batteries have been the subject of significant research.

Photovoltaic-powered reverse osmosis systems can help to address the supply/demand mismatch and have several benefits bringing to the reduction of the fuel consumption reducing the cost burden of a clean and reliable water supply, reducing the need for water imports and increasing the security of supply and the independence. Generally, the major common components of photovoltaic-powered reverse osmosis are:

- Photovoltaic modules
- Pre-treatment units
- Reverse Osmosis Membranes
- Post treatment units

Photovoltaic-powered reverse osmosis system is regarded as the most promising approach to produce fresh water however there are challenges that still need to be overcome:

A. Design challenges
    - discontinuous operation and therefore customized design is needed
    - quite large space required for the energy supply system (solar PV modules)
    - limited availability of energy recovery devices for small scale plants
    - limited operational experience

B. Logistic challenges
    - Local availability of chemicals (pre-treatment, antiscalant, post-treatment)

  - water quality monitoring (off-site laboratory)

C. O&M challenges
  - limited availability of experienced and trained O&M personnel

The challenge is to develop a suitable and sustainable desalination system to provide drinking water with a strong focus on reliability having high availability and minimal maintenance, even in extreme conditions.

The possibility to carry out a direct coupling of the PV and the reverse osmosis desalination plant removing the batteries decreases the maintenance level however due to the intermittent PV power supply it is required to design a desalination plant able to cope with variable pressure and variable feed flow conditions. The membrane manufacturers have been reluctant to guarantee the performances of their products that are used in intermittent conditions especially because:

- A high start/stop frequency may lower the performance and the lifetime of the membranes;
- Biofouling may incur if proper design solution to minimize it is not implemented or operation of the plant is not carried out properly
- Water quality increases with steady-state conditions and therefore intermittent operation may lower the obtained water quality.

Masdar in partnership with Mascara NT is piloting a 30 m^3/d reverse osmosis desalination plant fully powered by PV panels in Abu Dhabi, UAE to demonstrate the technical feasibility and economic viability of a stand-alone small scale photovoltaic powered reverse osmosis plant.

2.2 Novel thermal systems

2.2.1 Membrane distillation

In Kim

There is a clear and growing consensus in the international academia, industry and government that desalination technology development needs to be more environmental-conscious, especially in the direction of reducing carbon footprint. In this respect, membrane distillation (MD) has started to regain a high level of expectation in connection with renewable energies and hybrid desalination systems.

MD research had been stagnant for several decades since its origination in 1960s due to technological limitations and dominant research attention to RO, however, recent research attempts using nanotechnology and computational modelling tools like CFD have mitigated existing problems of MD, such as membrane wetting, low flux, and temperature polarization, to a good extent[68,69,70].

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[68] Enrico Drioli, Aamer Ali, Francesca Macedonio, Membrane distillation: Recent developments and perspectives, Desalination, Volume 356, 15 January 2015, Pages 56-84, ISSN 0011-9164, http://dx.doi.org/10.1016/j.desal.2014.10.028.

One of the unique advantages of MD over other desalination systems is its high utilization efficiency of low grade heat, including solar energy, geothermal energy, and industrial waste heat, which allows for a reduction in electrical energy requirements and more extensive applications[69]. Moreover, the capability of MD to be integrated with other membrane processes like FO is highly favoured as the key element of next generation desalination system[69,71].

MD is a promising option for future desalination system since it is expected to provide competitive energy consumption rate with heat recovery, along with unique benefits for sustainable development like low fouling propensity, theoretical 100% recovery rate, and compact plant structure[72]. However, it is the case that most MD applications still remain in the laboratory or the small-scale pilot stage. For practical implementation, more RD&D activities, particularly large-scale plant demonstration, are required to validate recent substantial advances in MD membrane fabrication and module designs[73].

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[69] B.B. Ashoor, S. Mansour, A. Giwa, V. Dufour, S.W. Hasan, Principles and applications of direct contact membrane distillation (DCMD): A comprehensive review, Desalination, Volume 398, 15 November 2016, Pages 222-246, ISSN 0011-9164, http://dx.doi.org/10.1016/j.desal.2016.07.043.

[70] Heru Susanto, Towards practical implementations of membrane distillation, Chemical Engineering and Processing: Process Intensification, Volume 50, Issue 2, February 2011, Pages 139-150, ISSN 0255-2701, http://dx.doi.org/10.1016/j.cep.2010.12.008.

[71] Sui Zhang, Peng Wang, Xiuzhu Fu, Tai-Shung Chung, Sustainable water recovery from oily wastewater via forward osmosis-membrane distillation (FO-MD), Water Research, Volume 52, 1 April 2014, Pages 112-121, ISSN 0043-1354, http://dx.doi.org/10.1016/j.watres.2013.12.044.

[72] Mohammed Rasool Qtaishat, Fawzi Banat, Desalination by solar powered membrane distillation systems, Desalination, Volume 308, 2 January 2013, Pages 186-197, ISSN 0011-9164, http://dx.doi.org/10.1016/j.desal.2012.01.021.

[73] Heru Susanto, Towards practical implementations of membrane distillation, Chemical Engineering and Processing: Process Intensification, Volume 50, Issue 2, February 2011, Pages 139-150, ISSN 0255-2701, http://dx.doi.org/10.1016/j.cep.2010.12.008.

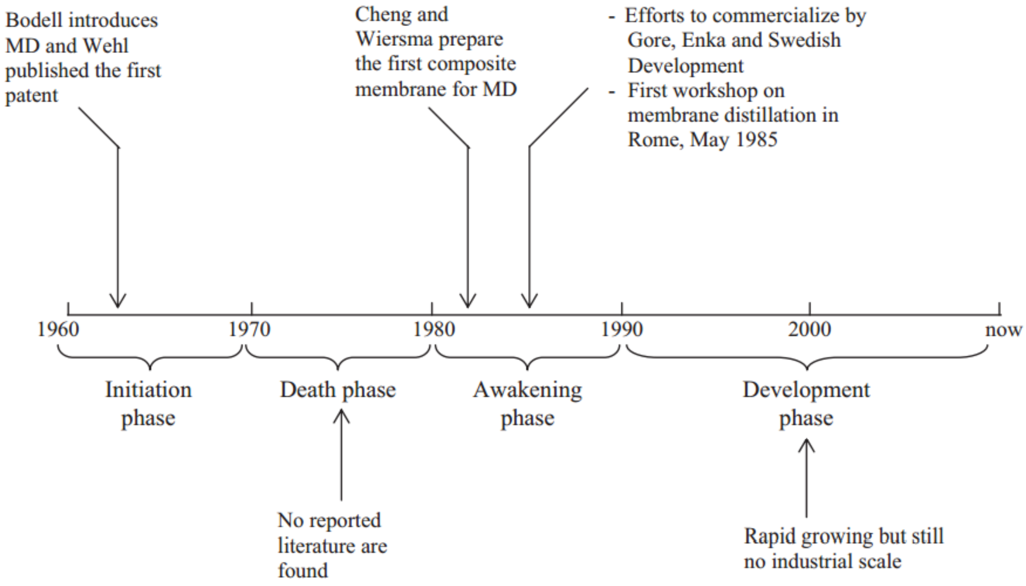

Figure 2.6: Milestones in the development of membrane distillation (Adapted from Heru Susanto, Towards practical implementations of membrane distillation, Chemical Engineering and Processing: Process Intensification, Volume 50, Issue 2, February 2011, Pages 139-150, ISSN 0255-2701, http://dx.doi.org/10.1016/j.cep.2010.12.008.)

2.2.2 Solar-powered MEDAD hybrid for future sustainable desalination

Kim Choon Ng

The need for an accurate and impartial method of comparing the performance of all desalination methods cannot be overemphasized. The performance ratio (PR) for evaluating the efficacy of desalination processes, hitherto, has been plagued by the uncertainty of conversion efficiency of derived energies available in respective countries. It should be justly defined only by the consumption of *primary energy*: defined simply by the form of energy available naturally[74,75,76,77]. The PR at the thermodynamic limit (TL) is about 828, corresponding to a minimum least work of about 0.78 kWh_{pe}/m^3 needed for desalting standard seawater.

When fossil fuels are burned to produce the derived energies (electricity, steam, etc.) via conversion plants (gas and steam turbines, heat recovery boilers, etc.), CO_2 is obstinately emitted, contributing to major global warming of the atmosphere. As cogeneration plants, e.g., the combined cycle gas turbines (CCGT), are widely implemented in generating the needed useful effects, the differentiation of exergy

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[74] K.C. Ng and M.W. Shahzad, Sustainable Desalination Using Seawater Thermocline Energy, *Renewable & Sustainable Energy Review* (in review).

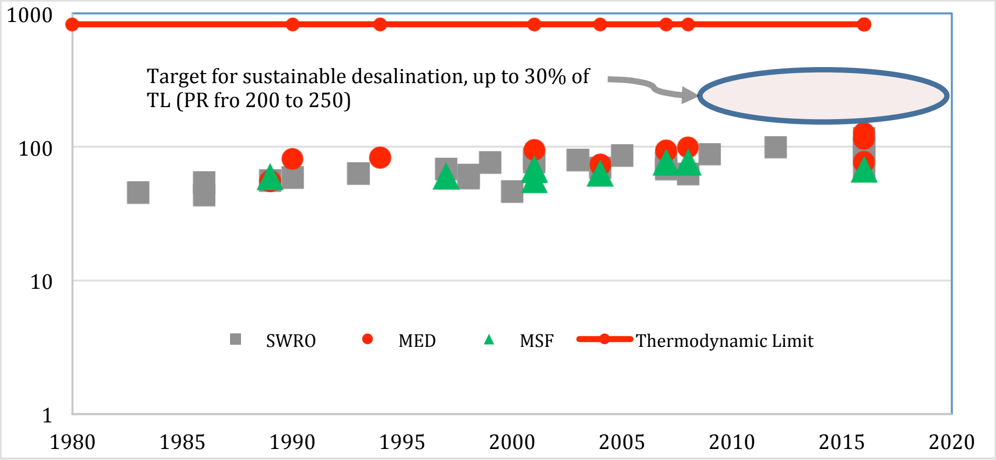
[75] M.W. Shahzad and K.C. Ng, Demystifying Primary Fuel Cost Apportionment in Cogeneration Plants, *Applied Energy* (in review).

[76] M.W. Shahzad and K.C. Ng, On the road to water sustainability in the Gulf, *Nature Middle East*, (2016), doi: 10.1038/nmiddleeast.2016.50.

[77] M.W. Shahzad, K.C. Ng, and K. Thu, Future sustainable desalination using waste heat: kudos to thermodynamic synergy, *Environmental Science: Water Research & Technology* 2 (1), (2016) 206-212, doi: 10.1039/C5EW00217F

destruction of input fuel consumed in individual processes is the key to having a level playing field for efficiency comparisons of desalination plants. The hybridization of thermally-driven desalting processes, e.g., solar-powered multi-effect distillation (MED) and the adsorption desalination (AD) is highlighted in this section as an example. The integration of both thermally-driven cycles leads to excellent thermodynamic synergy in utilizing the low exergy steam, achieving a quantum jump in water production and yet it is at the same energy input. This synergetic maximization of low exergy energy input has the potential of achieving the sustainable goals of future desalination. Based on thermodynamic processes[78,79], a target for desalination PR is plausible to attain 20-30% of TL, where the current desalination methods unfortunately fall short, achieving merely 10-15% of TL[80]. Obviously, a higher efficiency for desalting process leads to lower emission of carbon.

The viability of a solar-powered Multi-Effect Distillation Adsorption (MEDAD) hybrid cycles, consuming renewable solar thermal energy for desalting processes, was examined, and showed that the cycles reduce carbon emission significantly. Emphasizing the environmental consideration, the improved PR exempts those primary energy sources that have zero carbon emission, and only the primary energy consumption that pollutes with CO_2 emission is considered. The solar-powered MEDAD hybrids have achieved a high PR of 15% of the TL, which is among the highest efficiencies reported for a desalting method. Figure 2.7 shows the chronological trends of PRs between all desalination methods based on the *primary energy* consumption: the current methods are far remote from the thermodynamic limit. With PR defined in terms of primary energy, the excellent performance of this thermally-driven hybrid challenges the usual perception that membrane-based methods outperform thermally-driven desalination methods.



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[78] The thermodynamic limits are discussed in Section 1.2 of this report.

[79] M.W. Shahzad, K. Thu and Kim, K.C. Ng, A Waste Heat Driven hybrid ME+AD Cycle for Desalination, Water Technology, Royal Society of Chemistry, Environmental Sciences, Water Research & Technology, (2016) doi: 10.1039/C5EW00217F.

[80] The percentage of TL has the same meaning as the Second Law efficiency discussed in Section 1.2.

Figure 2.7: Improvements in performance ratio (PR) of desalination methods over the years and the thermodynamic limit has a PR of 828 at minimum work needed to desalt the standard seawater[81].

As today's supply of the derived energies are generated by efficient combined cycle gas turbines (CCGT) plants, the differentiation of exergy destruction incurred by such power plants is the key to having a level playing field for efficiency comparison amongst all methods of desalination. An exergy destruction analysis indicates that gas turbines of CCGTs consumed 3 times more exergy destruction of input exergy(fuels) than the exhaust heat recovery steam generators (HRSGs), where the latter powered the steam turbines via high enthalpy steam expansion[82,83,84]. Only less than 3% of the total exergy of fuel is consumed by the thermally-driven desalting processes, due primarily to their use of steam at low pressures and temperatures, where the remaining ability to do work on turbines are greatly diminished.

At KAUST, a solar-powered MED+AD pilot plant with a nominal capacity of 2–5 m^3/day and powered solely by non-polluting solar thermal input has been designed and tested. It demonstrates the practicability for seawater desalination driven mainly by solar thermal input under the meteorological conditions of Jeddah (SA). The test results recorded a PR of 118, which is 15% of TL[85]. The extent a MEDAD (solar-powered) could be designed to accommodate increase in the stages, by lowering the BBT of the hybrid cycle, is depicted in Figure 2.8. From literature, other alternative desalination approaches have been proposed that include the raising of the top-brine temperature (TBT) of seawater feed, and thereby more distillation stages could be operated. To avoid the formation of scales on tube surfaces, a nano-filtered (NF) pre-treatment of seawater feed system will be incorporated. Recent studies by Osman et. al.,[86,87] using the Gulf seawater and the percentages of dissolved salts removed, responsible for major scaling such as Ca^{++}, Mg^{++} and SO_4^{--}, were 30±3%, 60±2% and 90±1.5%, respectively.

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[81] K.C. Ng and M.W. Shahzad, Sustainable Desalination Using Seawater Thermocline Energy, *Renewable & Sustainable Energy Review* (in review).

[82] Renewable Energy Technologies for Water Desalination, H. Mahmoudi, N. Ghaffour, M.F.A. Goosen, J. Bundschuh, by CRC Press, Chapter 11, ISBN 9781138029170 - CAT# K27597.

[83] N. Lior, "The Second Law of Thermodynamics and Entropy", chapter 44, Handbook of Engineering, E. Dorf, Ed., CRC Press, (1996), pp. 462-478.

[84] N. Lior, "Thoughts about future power generation systems and the role of exergy analysis in their development", Energy Conversion and Management J., vol. 43, 2002, pp. 1187-1198

[85] N. Ghaffour et al., Renewable energy-driven innovative energy-efficient desalination technologies Applied Energy 136 (2014) 1155–1165.

[86] Osman A. Hamed, Technical and economic evaluation of power/water cogeneration plants, SWCC 7th Acquired Experience Symposium, 2–5 Mar. (2014), Al-Khobar, Saudi Arabia.

[87] O.A. Hamed, et al., Thermodynamic analysis of Al-Jubail power/water co-generation cycles, SWCC Technical Report, No. TR3808/APP98002, (2000).

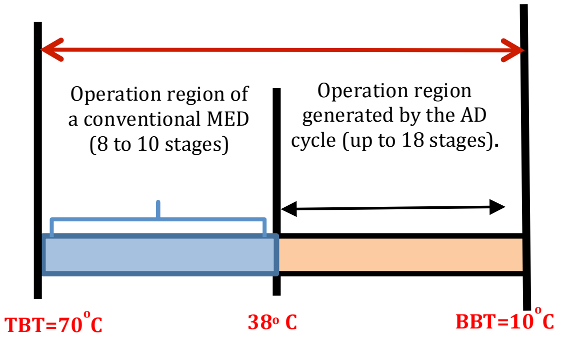

Figure 2.8: Operating regime of a hybrid MEDAD cycle[88,]

Their results tallied with the earlier findings from Hasson and Semiat[89]. Similar tests will be conducted by many scientists and engineers covering a full temperature range of TBT to low BBT of 125°C to 10°C, respectively. The scaling formation potential limits are the key issues for practical viability which will be followed with great interest, along with the maximization of the PRs, by many research groups around the world[90,91,92,93,94].

In conclusion, the current state of all desalination methods, membrane-based RO or thermally-driven MED/MSF, fall quite short of the thermodynamic limit, about 10–15% of TL. Based on thermodynamic experiences and the advent of thermally-driven processes that exploit the thermodynamic synergy of low exergy steam, it is highly tenable that such readily available technologies can pave the way for sustainable desalination, achieving a PR up to 250 by incorporating innovation that push back the limits of TBT and BBT of seawater feed.

2.2.3 Low temperature thermal desalination

Kim Choon Ng

Is there truly a low-temperature powered desalination and if there is, at what temperature level is needed to have a practical rate for seawater desalination process? Fortunately, most tropics regions of the world are endowed with warm

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[88] M.W. Shahzad and K.C. Ng, Demystifying Primary Fuel Cost Apportionment in Cogeneration Plants, *Applied Energy* (in review).

[89] Hasson, D. and R. Semiat, *Scale control in saline and wastewater desalination.* Israel journal of chemistry, 2006. **46**(1): p. 97-104.

[90] M.W. Shahzad and K.C. Ng, On the road to water sustainability in the Gulf, Nature Middle East, (2016), doi: 10.1038/nmiddleeast.2016.50.

[91] M.W. Shahzad, et al., An Experimental Investigation on MEDAD Hybrid Desalination Cycle, Applied Energy 148 (2015) 273–281.

[92] K.C. Ng, et al., Recent developments in thermally-driven seawater desalination: Energy efficiency improvement by hybridization of the MED and AD cycles, Desalination 356 (2015) 255–270.

[93] M.W. Shahzad, et al., Multi Effect Desalination and Adsorption Desalination (MEDAD): A Hybrid Desalination Method, Applied Thermal Engineering 72 (2014) 289-297.

[94] K.C. Ng et al., Progress of adsorption cycle and its hybrid with conventional MSF/MED processes in the field of desalination, International Desalination Association (IDA) Journal of Water Desalination and Reuse, 6-1 (2014) 44-56.

surface seawater temperatures (about 28° – 30° C) from the sun and cold seawater (about 5°– 10° C) at depths up to 1000 m. This may seem as a re-visit to the "ocean thermal energy conversion or OTEC" which were studied extensively in the 60s and 70s but now, the topic is renewed for practical desalination when operated as multi-effect distillation (MED), as shown in Figure 2.9.

This concept exploits what daily solar irradiance of the sun, providing an annual average of more than 1800±50 kWh/m^2-year. Despite much seawater evaporation, the temperatures of sea surface, within the tropics, hover around 28 to 30°C, whilst the deep seawater temperatures are dependent of the bathymetry of the sea beds, varying from 10°C at 600 m up to 5°C at a 1000 m or more. Hence, mother nature has provided us with all year round constant supply of thermocline energy at a temperature differential of 20 to 25 K.

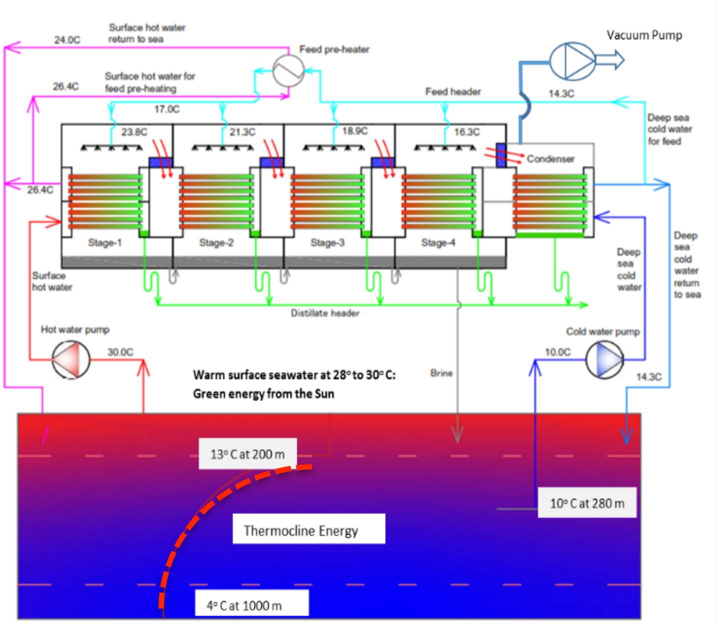

Figure 2.9: An example of the thermocline-driven seawater desalination with a 5 - 6 stage MED plant (Wakil Muhammad and Kim Choon, KAUST)[95].

Yet, there is no need of any capital investment of either the solar thermal collectors for warm energy or the energy-intensive chillers providing chilled water for cooling at condensers. Perhaps the most efficient technology that can operate with the small temperature difference is the robust multi-effect distillation (MED), where the temperature drop across each stage is less than 4 K. Hence, an optimum number of stages of MED here is 5 to 6 stages, making the low-temperature thermal desalination (LTTD) to be a truly "green desalination" method: The only parasitic pumping needed are the warm and the cold seawater pumps, delivering the seawater feed to the top-brine stage and the cold energy to the condenser. Based on

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[95] M.W. Shahzad and K.C. Ng, Demystifying Primary Fuel Cost Apportionment in Cogeneration Plants, *Applied Energy* (in review).

the estimated pipe lengths and diameters, the parasitic electricity consumption for LTTD is conservatively at 1.8 kWh_e/m^3 and all other energy of MED is supplied by the renewable thermocline energy.

When converted to primary energy, the PR of thermocline-based seawater desalination is > 180, which is nearly 21% of the thermodynamic limit (PR=828), as shown within the sustainable region of Figure 2.10. The proposed thermocline-based seawater desalination would have the highest efficiency thus far, and almost no chemicals are needed in the desalting process as the evaporating temperatures of MED stages commenced from the ambient to the 10°C of condenser.

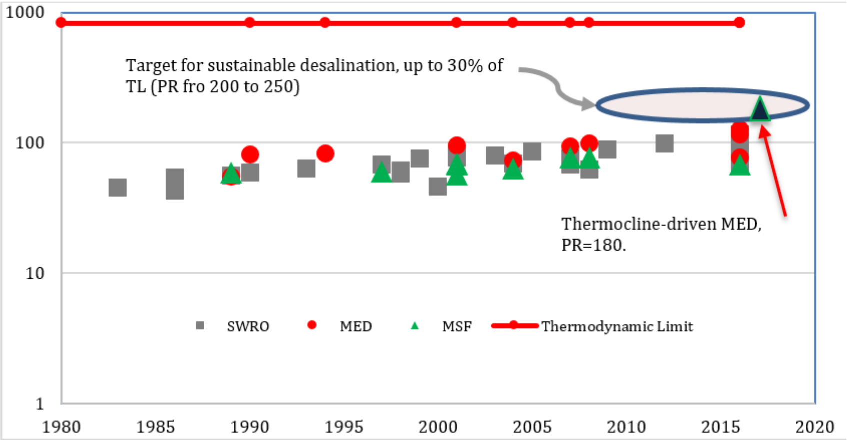

Figure 2.10: The PR of LTTD falls with the region needed for sustainable desalination and theoretically could be the most efficient desalination process available to date[96],.

The only caveat of thermocline-based LTTD is that the processes require a unique sea bed bathymetry, namely, the sea bed drops steeply in just a few kilometers from the shores for economical installation. There are many suitable locations in the world having such deep bathymetry sea beds; For example, the shores off Salaha (Yamen), Muscat (Oman), Hawaii (big island, USA), Karavatti island (Indian ocean), Sulawesi island (Indonesia), etc. Figure 2.11 depicts the typical bathymetry of two coastal shores where LTTD plants can be a viable choice for sustainable desalination and yet these plants emit very low amount of carbon.

In conclusion, thermocline-driven desalination is a viable green technology with a nearly infinite supply of thermal energy. It utilizes only a small amount of electricity for pumping of surface seawater feed and cooling water from sea bed up to 1000 m, giving an unprecedented PR of > 180, or about 21% of the thermodynamic limit. Being at a thermal equilibrium with the ambient, the seawater feed can be used directly without the need of chemicals for scale and foaming controls (pre-treatment) as the seawater feed is supplied at ambient temperatures.

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[96] M.W. Shahzad and K.C. Ng, Demystifying Primary Fuel Cost Apportionment in Cogeneration Plants, *Applied Energy* (in review).

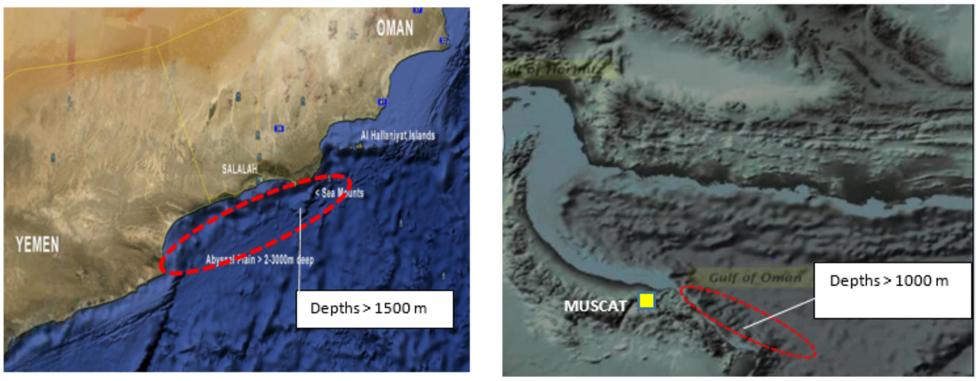

Figure 2.11. Two examples of thermocline-based desalination where the sea bed bathymetry of over 1000m deep water just a few kilometers from the shores[97,].

2.3 Electrodialysis

Karim Chehayeb, Kishor Nayar, Michael Papapetrou, Natalie Tiggelman

Electrodialysis (ED) has been used over the past 50 years for several desalination applications: treating brackish water for producing freshwater, concentrating seawater for salt production, and more recently for efficiently desalinating seawater. While ED represents only 3% of total installed desalination capacity today, the technology has a huge potential for being scaled up for low carbon desalination. Recently, at a pilot level installation, Evoqua Water Technologies (formerly part of Siemens) achieved seawater desalination at a record low energy consumption of 1.85 kW/m^3.[98] R&D interest in ED has increased in recent years, with other ongoing work in the EU through the REvivED water project[99] and, other work at MIT[100,101.] To fully scale up the deployment of the technology and realize the full low carbon desalination potential of ED, significant additional research and development efforts are needed. Two approaches can be taken here: reduce the energy consumption of ED processes or design ED for better integration with renewable energy technology. In this section we present the research needs for the former. To reduce energy consumption of ED for full scale deployment broadly the following need to be done:

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[97] M.W. Shahzad and K.C. Ng, Demystifying Primary Fuel Cost Apportionment in Cogeneration Plants, *Applied Energy* (in review).

[98] Siemens Low Energy Desalination Demonstration Unit Results, http://www.industry.siemens.com/topics/global/en/fairs/siww/water-convention/Documents/Low-Energy%20Desalination%20Demonstration%20Unit%20Results.pdf

[99] REvivED water project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 685579, http://revivedwater.eu/

[100] https://energy.mit.edu/news/mit-and-kuwait-university-researchers-awarded-5-5-million-for-work-on-next-generation-desalination-systems/

[101] http:// news.mit.edu/2016/solar-powered-desalination-clean-water-india-0718

- Improve ED stack design and customize the ED process to waters being treated
- Increase deployable ED membrane area and ED membrane performance
- Market and technology adoption research along with research on ED operations under different conditions
- Collaborative research and development with integration of new innovations

ED stack design and multi-staging ED

ED process design is sensitive to the salinities of the water being treated, with the optimal seawater ED designs being different from brackish water ED designs. The key research question to answer is: "Which is the best design for the electrodialysis stack and system for each application?"

There is a clear R&D need in identifying which designs lead to the lowest carbon footprint. There is also a need to better understand the key design variables, such as system dimensions (channel height, length/width of the stack, number of cell pairs), and system operating conditions (flow velocity, voltage/current). In addition, there are opportunities to improve overall performance by splitting an ED system into separate stages, and optimizing each stage. Further research on when and how to stage ED systems might decrease the energy consumption of these systems.

ED membrane research and increasing membrane area

Increasing deployable ED membrane area and membrane performance directly reduces the carbon footprint of the ED technology. One of the main challenges preventing the scale up of ED has been the high capital costs of ED. Research and development needs include:

- membrane research to design low resistance ED membranes for seawater ED
- policy for encouraging the manufacturing of ED technology to create economies of scale around ED membranes leading to cheaper membranes

Market and technology adoption research

ED for desalination of seawater is not widely applied yet and therefore its adoption can also be slowed down by the lack of awareness, operational experience, tools and expertise. While ED has been used for brackish desalination, further innovation on ED designs have the potential to increase adoption. To improve the adoption of the ED technology, there is a research need to better understand current market and technology operator needs, and re-design ED systems to match their needs. There is also a clear need for more public research data on the performance of ED in different operating conditions.

Collaborative research and development with integration of new innovations

Collaborative research, development, and innovation activities between academia and industry are also needed to develop new ED configurations, peripheral systems, advanced applications and suitable tools and training activities. Some activities that would help maximize the impact are listed below indicatively:

- Need to better integrate innovations in individual ED components and identify the best configurations and component combinations (e.g.:- newer membrane are being made by companies such as FUJIFILM and Saltworks, with improved carbon electrodes being made by GE)

- Develop best practice guidelines with regards to operation and maintenance
- Study the use of industrial scale electrodialysis desalination as a flexible load that can deliver benefits to a power system with high share of variable renewable energy systems like solar and wind energy
- Develop peripheral systems and consumables, for example, pre-treatment and post-treatment technologies
- Study other innovative applications of the developed technologies and new configurations
- Build tools for decision makers to give them an idea of the performance and costs they can expect
- Training of engineers, consultants and technicians in the new technology

The proposed activities can contribute in establishing electrodialysis as a valuable new process in the desalination industry, providing a source of safe, affordable, and cost-competitive drinking water, using significantly less energy than today's state-of-the-art systems. By reducing the energy requirements of water production and by driving down the water desalination costs, the proposed activities can have a positive contribution to the "water-energy-food nexus" issue as well. Finally, these reduced energy requirements are very suitable to be covered by variable low carbon energy technologies like solar and wind energy, as electrodialysis is less sensitive to variations in the electricity input than other state-of-the-art desalination technologies.

2.4 Hybrid desalination systems: a solution to reducing carbon footprint, cost reduction and environmental challenges

Leon Awerbuch

Like many new technological ideas, it took over 20 years to see hybrid system implemented on large scale and adopted by desalination industry, today primarily in the Middle East Gulf States.

The hybrid desalting concept is the combination of two or more processes in order to provide better environmental solutions and a lower water cost product than either alone can provide. For purpose of this short review, hybrids in desalination will deal with combination of distillation and membrane processes with power generation. It also applied to renewable energy side when we can hybridize solar photovoltaic with wind energy in order to better balance the intermediate operation of each of the resources running separate, or thermal solar with photovoltaic in order to optimize cost of energy and minimize thermal storage requirements.

In desalination, hybrid systems received significant attention recently with implementation of desalination and power plants at Fujairah I and Fujairah II in UAE, Ras Al -Khair in Kingdom of Saudi Arabia, SWRO expansion plants in Fujairah I and Az-Zour South in Kuwait and current ongoing competition for hybrid of power and MSF-RO or MED-RO desalination Station in Az-Zour North phase II in Kuwait allowing 25% RO.

Early suggestions for hybrid desalination were based upon elimination of the requirement for a second pass to the RO process so that the higher-salinity RO product could be combined with the better quality product from an MSF or MED plant. This is the simplest application of hybrid desalination. Since then, other concepts have been proposed for hybrid desalination. Today, although RO can produce potable TDS in one pass, blending allows a simple solution where national standards require low levels of boron.

Dual purpose power-desalination plants make use of thermal energy extracted or exhausted from power plants in the form of low pressure steam to provide heat input to thermal desalination plants for multistage flash (MSF) or multi-effect (MED) distillation processes. The electrical energy can be also effectively used in electrically-driven desalination processes like Reverse Osmosis (RO) and Vapor Compression Distillation (VCD).

2.4.1 Energy conservation using hybrid systems

In view of the dramatic concern with global climate conditions and a dramatic reduction in renewable generated power cost, hybrid (RO + distillation), hybrid (NF+distillation) or tri hybrid (NF+RO+distillation) systems offers significant savings in energy costs in comparison with the distillation-only option.

In many countries, particularly in the Middle East, peak power demand occurs in summer and then drops dramatically to 30-40%. In contrast, the demand for desalinated water is almost constant throughout the year. This creates a situation where over 50% of power generation is idled. This inequality of demand between electricity and water can be corrected by diverting the excess of available electricity to water production. The daily peak of power demand coincides with higher temperature which significantly reduces power output therefore hybridization of solar energy with fossil fuel power production reduces significantly carbon footprint and provides great solution to shave off peaks.

Water can be stored, while large scale electricity storage is not practical at this time.

In this case, excess electricity can be diverted to water production incorporating electrically-driven Seawater Reverse Osmosis (SWRO) and/or Vapor Compression with the low-pressure steam-driven technology of MSF or MED, making its advantages to design an integrated Hybrid Plants.

One method of making use of idle power capacity is the use of electrically driven RO or VCD plants in combination with Desalination Aquifer Storage Recovery (DASR) both for averaging the desalination capacity, for strategic and economic fresh ground water storage or improving quality of the basin.

2.4.2 Hybrid – the new alternative

In the simple hybrid MSF/RO or MED/RO desalination power process, a seawater RO plant is combined with either a new or existing dual purpose thermal desalination/power plant, resulting in the following advantages:

- A common, considerably smaller seawater intake can be used.
- Product waters from the RO and MSF or MED plants are blended to obtain suitable product water quality.
- Product waters from the RO and MSF or MED plants are blended, therefore allowing higher temperature of distillate.
- A single pass RO process can be used.
- Blending distillation with membrane products reduces strict requirements on Boron removal by RO.
- The useful RO membrane life can be extended.
- Excess power production from the desalting complex can be reduced significantly, or the power-to-water ratio can be significantly reduced.

The fully integrated hybrid MSF/RO or MED/RO desalination provides additional advantages of integration features, such as:

- The feed water temperature to the RO plant is optimized and controlled by using cooling water from the heat-reject section of the MSF/MED or power plant condenser.
- The low-pressure steam from the MSF/MED plant is used to de-aerate or use de-aerated brine as a feed water to the RO plant to minimize corrosion and reduce residual chlorine.
- Some components of seawater pretreatment process can be integrated.
- One post-treatment system is used for the product water from both plants.
- The brine discharged-reject from the RO plant is combined with the brine recycle in the MSF, or is used as a feed to MED.
- The hybridization of Nanofiltration as softening membrane process for feed of distillation plants MSF and MED could lead to significant improvement in efficiency, recovery or productivity of desalination plants.

In general, the hybrid idea allows part of the distillation plant’s heated coolant reject to be de-aerated, using low-pressure steam from the distillation plant (to reduce corrosion and residual chlorine), and used as the feed to the SWRO plant. The higher temperature of the feed improves membrane performance (flux, at constant pressure, increases by 1.5–3% for each degree C). This is particularly important during the winter, when seawater temperatures can drop to as low as 15°C. The MSF or MED plant’s distillate, at less than 20 ppm TDS, is blended with the SWRO plant’s product, making it possible to meet potable water standards for maximum TDS and chloride concentrations with higher SWRO plant product salinity. This, in turn, means that the SWRO plants can be operated at higher conversion ratios, warmer seawater is reducing consumption of energy and chemicals and extending membrane useful life.

In one variant of the “classic scheme,” the SWRO plant’s reject brine becomes the feed to the MSF or MED plant particularly if the seawater is softened by Nanofiltration (NF) membrane, utilizing its high pressure, with a turbocharger, to boost the MSF plant’s recirculation pump. The conversion ratio of the hybrid NF/SWRO+ MSF/MED plant is significantly increased. The ongoing work on Nanofiltration membrane softening technology, combined with distillation and hybrid options of NF-MSF-RO or NF-MED-RO, offers new potential for improving hybrid systems.

The use of distillation plant coolant reject as feed to a SWRO plant within selected hybrid plant schemes reduces both seawater supply and brine and coolant rejection requirements vis-à-vis non-hybrid, separate and independent (“stand-alone”) thermal and SWRO plants.

Where seawater supply and pretreatment and brine rejection costs are high (long intake and reject lines, large pumping power requirements, high seawater turbidity, etc.), they add an important cost element to the energy vs. capital cost trade-off equation for deriving the optimal distillation Performance Ratio (PR) the plant efficiency.

For all membranes, water permeability (i.e., permeate production) declines with operating time, while product salinity and chloride concentration increase. The drop in production can, with time, be compensated by installing extra membrane rack space and installing additional membranes as required. The increase in product salinity cannot be compensated for except with large scale membrane replacement.
In the case of hybrid systems (RO + distillation), a single pass RO system can be specified while maintaining a long membrane life. This is made possible by blending the RO product water with the high purity distilled water produced by the thermal desalination unit.

2.4.3 Membrane performance as a function of seawater temperature

The operating temperature of SWRO can be controlled and increased by taking as input the warm discharged cooling seawater from thermal desalination plants. As important eliminates need for built new intake and outfall structure as demonstrated by 30 MIGD Seawater RO expansions in Fujairah I and Kuwait Az-Zour South plants.

Feed water temperature affects the two main performance characteristics of a membrane: flux and salt rejection. Higher feed water temperatures increase not only flux but also salt passage. For all membranes, water production is a function of temperature, at constant feed pressure. Production will go up with temperature increasing by 1.5% to 3% per degree Celsius for nearly all membranes, thereby enabling reduction of the number of RO membrane modules required for a given permeate capacity. This is, of course, contingent on feed water of sufficient quality so that membrane fouling rate will not increase during operation at higher flux.

The results imply that the energy consumption of RO can be reduced using a simple integration of MSF/RO hybrid arrangement in which the RO plant is fed the preheated seawater rejected from the MSF heat rejection section.

It is quite obvious that higher recovery can be obtained with lower salinity feed, which has clear process implications when we consider Nanofiltration in front of RO system or the use of blending seawater feed with lower salinity water (concentrate of brackish RO, for example) to lower the feed salinity to RO system.

Higher membrane permeability at elevated temperature may also result in a higher recovery rate. However, higher feed water temperature and recovery rate are associated with an increase of osmotic pressure. The permeate TDS systematically increases as the feed temperature and recovery rate are increased. Fortunately, this salinity increase can be easily compensated in hybrid systems (RO + thermal desalination unit) where the ratio of distilled water to membrane permeate can be controlled to achieved required product TDS.

The increase of recovery rate at constant feed pressure at increased temperature in a RO hybrid system leads to reduction of specific power consumption.

Some critics of higher temperature of operation of RO and NF membranes suggest higher rate of fouling due to increased biological activities. The increase of seawater temperature, which is happening inside the condenser or rejects section of the distillation plant, is being achieved in a matter of seconds. The assumption is that this rapid rate of temperature increases results in a thermal shock, possibly reducing biological activity in seawater feed to the membrane unit.

Another issue of concern is the compaction of membrane material (permeability decline) during long term operation at high feed pressure and elevated temperature, today maximum temperature for continuous operation for most of the membrane is 40°C, but clearly we need membranes capable for continuous operation above 50º C. I am convinced that such membrane for seawater will be developed in view that in summer in some places of the Gulf like in Dubai DEWA plants the intake seawater exceeds 42 °C.

In Nanofiltration systems, the increase in temperature of seawater feed results in higher rate of water permeability increase more than is expected in RO unit. In Nanofiltration membranes, the concentration polarization increase with temperature is lower than in RO membranes due to significantly higher salt transport through NF membranes and operating pressures of NF are significantly lower from 10-20 bars.

In hybrid systems, the use of Nanofiltration membranes operating at higher temperatures in combination with RO and MSF/MED provides additional opportunities to reduce desalination costs due to available heat from the power plant condenser or reject section of distillation plants. Specifically, by using feed comprising variable proportions of softened seawater and water containing a higher concentration of hardness ions than the softened stream, concentration of hardness is sufficiently reduced, thereby allowing a beneficial increase in the Top Brine Temperature (TBT) of the distillation desalination process. Higher operating temperatures provide an increase in productivity, recovery and performance at lower energy and chemical consumption. As a result, the cost of desalinated water production, including operation and maintenance, could be significantly reduced.

Hybrid plants have the potential to increase the average annual membrane permeate flow through increased flux rate and reduce the required membrane surface in the SWRO plants.

The blending of SWRO and thermal plants' products makes it possible to use the low-salinity (less than 20 ppm TDS) distillation plant product to compensate for higher salinity SWRO plant product. However, if the plants are designed to operate at the high conversion ratios used today in most modern SWRO plants (45–50%), it is projected that product salinity will exceed 500 ppm TDS after about four years of operation, as a result of membrane performance degradation.

Recovery ratio (conversion) is one of the key RO design parameters. It determines the size of the feed water handling system (e.g., intake, pretreatment, high pressure pumping) for a given plant size. Higher recoveries decrease the cost of the feed water handling system and the required electrical and chemical consumption, while increasing the initial and replacement costs of the membrane system.

Some of the reasons why higher recovery ratios have not been used in the past are related to the performance characteristics of the membranes and the product water quality specifications. Higher recovery ratio increases required feed pressure due to increase of the average osmotic pressure in the RO system. Also, due to the salt rejection property of available membranes, product water specifications (typically 500 ppm TDS and/or 250 ppm chloride) could not be easily met at higher recovery ratios. In a hybrid system, higher recovery ratios of RO unit can be incorporated into the plant design.

Most aromatic composite membranes require dechlorination of the feed water as they are very sensitive to even very small concentrations of residual chlorine and/or bromine. If feed water to an RO system is being chlorinated, then the addition of large quantities of sodium bisulphite is required to reduce free chlorine in the feed water. As an alternative, free chlorine removal can also be accomplished by use of a de-aerator, followed by significantly reduced quantities of sodium bisulphite.

De-aeration of the feed water also reduces corrosion significantly. In the case of hybrid systems, low pressure steam suitable to operate the de-aerator is readily available from the MSF plant at low cost. De-aeration can reduce the specification for high pressure piping from SMO - 254, SS - 317L to lower grades and more economical SS 316L.

2.4.4 Examples of existing hybrids

Jeddah Hybrid

The first straightforward hybrid plant scheme has been adopted in Jeddah I and II to blend higher TDS RO permeate with distillate from existing MSF plants, and is described in detail by Awerbuch and by many other papers.

The results of conceptual and design work led to construction of the simple hybrid project at Jeddah 1, phase I and II plants. The Jeddah 1 RO plant is 30 mgd (113,600 m^3/day) combining Phase I, which has been operated since 1989, and Phase II, which has been operated since March 1994. The plant is owned by Saline Water Conversion Corporation (SWCC), design by Bechtel, and constructed by Mitsubishi Heavy Industries, Ltd. The operation and analysis of the plant, which utilized Toyobo Hollosep double element type hollow fiber RO modules, indicate that the life of the membrane was extended to over 10 years. In addition to 30 mgd RO permeate, the Jeddah complex produces 80 mgd distillate from Jeddah II, III and IV and 924 MW electricity. Jeddah I RO plant successfully adopted an Intermittent Chlorine Injection method (ICI) in order to prevent membrane degradation by oxidation reaction and biofouling.

Yanbu – Medina Hybrid

The objective of minimizing the power-to-water ratio led to the construction of Medina and Yanbu Phase II in the Kingdom of Saudi Arabia, with 130,000 m^3/day (33.8 mgd) in Medina and Yanbu. The plant is able to produce power at 164 MW electricity and 288,000 m^3/day (76 mgd) of desalinated water.

Two 82 MW back pressure steam turbines (BTG) provide steam to four 36,000 m^3/day (9.5 mgd) MSF distillation units and the electricity to 15 RO units of 8,500 m^3/day (2.25 mgd), each. Although the plant was not designed as an integrated Hybrid, it provided a very good example of significant reduction of the power to water ratio (PWR).

Fujairah I Hybrid

The Fujairah I project, owned by Emirates Sembcorp Water and Power Company and commissioned in 2004, comprises a hybrid MSF-RO system again combined with power production with a capacity of 893 MW and a seawater desalination capacity of 455,000 m^3/d.

The Fujairah I plant, due to hybridization, initially generated only 500 MW net electricity for export to the grid, and 662 MW gross for water production capacity amounting to 455,000 m^3/day (100 MIGD). One of the great points of hybridization is that allows the control of power to water ratio meeting both water and power demand, otherwise, a similar MSF-only plant in Shuiwaihat required 1,500 MW for the same 455,000 m^3/day (100 MIGD) capacity.

The Fujairah desalination plant is split into 284,000 m^3/day (62.5 MIGD) from the thermal part and 170,000 m^3/day (37.5 MIGD) from the membrane process.

Doosan Heavy Industry and Construction Company was the Engineering-Procurement and Construction (EPC) contractor. The main contract was awarded in June 2001. Doosan selected Degrémont as a subcontractor to receive the basic design and major equipment supply of the SWRO Plant. The 100 MIGD (455,000 m^3/day) water production started on June 31, 2003 with a total construction, commissioning and startup time of less than two years.

For this plant, the design decision was made to separate intake for the RO plant, through which the specific intermittent chlorination requirements for SWRO can be maintained. It was chosen over the use of a common seawater extraction system. Feeding of preheated cooling water from the MSF reject section to the RO plant was now utilized in 30 MIGD expansion awarded to Acciona. Initially the idea was rejected because perception that that MSF seawater that had been chlorinated continuously, and in part shock dosed, was not acceptable to RO membrane, however detail study demonstrated that the residual chlorine on outlet of MSF reject section is low and easily eliminated in the pretreatment stage composed of DAF and if necessary by chemical scavenger.

Fujairah II

The largest hybrid MED-RO plant is the Fujairah II desalination project was constructed by SIDEM and Veolia and provides 591,000 m^3/d of water.

The Greenfield development is producing 2000 MW of power and 130 MIGD of water. It will use five high-efficiency Alstom GT26 gas turbines in combined cycle mode and 12 SIDEM 8.3 MIGD Multi Effect Distillation desalination units with a 30 MIGD Reverse Osmosis desalination plant.

Ras Al- Khair

The largest operational desalination plant in the world had previously been the 880,000 m^3/d Shoaiba 3 thermal desalination plant in Saudi Arabia. This was displaced in April 2014 when the Ras Al-Khair hybrid plant went on stream.

As the world's largest seawater desalination plant, for which Doosan won the construction order in September 2010 from the Saline Water Conversion Corporation, the Ras Al-Khair plant produces 1,036,000 m^3/d, sufficient to meet the daily water requirements of around 3.5 million people. The plant produced its first freshwater earlier this year, although the project was actually scheduled for completion in December 2015. As the world's largest hybrid plant, the project uses both membrane technology (reverse osmosis, RO at 309,360 m^3/d) and thermal technology (multi-stage flash evaporation, MSF with a capacity of 727,130 m^3/d).

This plant also features the largest single MSF trains composed of 8 units with capacity of over 91,000 m^3/d each. The RO plant has 17 trains.

The Ras Al-Khair plant is dual purpose with an export production capacity of 1.025 million m^3/d desalinated water and an electricity production capacity of 2,400 MW, providing 1350 MW for the Maaden Aluminum Complex, 1050 MW to the Saudi Electricity Company, and about 200MW for internal consumption on site.

The Ras Al-Khair hybrid was the only solutions possible based on limited availability of natural gas for this project to produce all the capacity required. Therefore, the hybrid 70% thermal and 30% RO was the adopted solution.

2.4.5 Hybrid variations

As the concepts and applications of hybridization are accepted between distillation processes and RO, we believe that membrane manufacturers will develop a new generation of membranes. This new generation of membranes is characterized by a very high specific flux – about double the flux of the current generation – with a small reduction in salt rejection. Developed for brackish water desalting high flux membranes have demonstrated the ability to significantly reduce the cost of desalting and will be ideal for hybrid plants that include distillation units.

Hybrid systems using multi-effect distillation

Multi-effect distillation (MED) is, in our opinion, the most important large-scale evaporative process offering significant potential for water cost reduction. Particularly MED and MED-NF has great potential with thermal renewable energy like thermal solar both concentrated or low temperature, geothermal, solar ponds or alternative nuclear energy. The major potential advantage of the MED process is the ability to operate at relatively low temperatures and produce a significantly higher Performance Ratio (PR) in excess of 15 pounds of the product per pound of steam, where MSF limits PR to 11.

The energy consumption in thermal plants has two parameters of efficiency. Furthermore, we need heat and electricity. The first parameter is the amount of produced water per unit of steam, called gain-output ratio. That historically was about 8 pounds of water per pound of steam coming from the power plant. Today, we already have plants exceeding a ratio of 11. The second parameter in thermal desalination plants is electric power consumption, which for MED is about 0.9 to 1.5 kWhr/m^3 per ton of water processed.

As a matter of fact, in January 2014 Veolia/Sidem won Az Zour North Phase 1 IWPP - 1550 MW +107 MIGD an EPC contract to build a desalination plant in Kuwait with a daily production capacity of 486,400 cubic meters of water. The plant is MED-TVC with 10 x 10.84 MIGD units in total 107 MIGD. But most important is the ability to lower the process power consumption to 0.9 kWh/m^3 with GOR 11, meaning that 1 ton of steam generates 11 tons of desalinated water. Hyundai will be responsible for building the 1,500-MW power station. The key here is that the energy for the desalination plant is provided by backpressure steam from combine cycle power plant typically at 2.7 bars.

The lower the pressure of the steam we can use for the desalination and the higher GOR the less power loss is experienced in the power cycle. This loss is assigned to energy consumption of desalination.

The future calls for increasing the top operating temperature, finding new ways to improve heat transfer performance to reduce the heat exchange area, searching for an increase in heat transfer performance by tube enhancement, and using a very thin wall in tubular materials. The critical challenge is to adopt Nanofiltration as means to dramatically increase output and increase the efficiency of MED plants.

Hybrid using nanofiltration - membrane softening

Novel Thermal Hybrid systems can be combined with clean renewable and nuclear energy. Nanofiltration Softening Membranes may reduce fouling to enable a variety of low temperature and higher temperature thermal technologies. Low temperature technologies include Multi–Effect Distillation solutions, high efficiency solar water heating panels, and solar ponds both with pure water or salinity gradient. High temperature technologies with NF membranes include concentrated solar parabolic trough collectors or low-cost, and high-efficiency non-tracking trough CSP receivers (already in the development). The ideas also apply to solar dual purpose power or alternative nuclear energy.

Membrane softening technology adapted to hybrid with distillation processes could lead to a significant increase in the productivity of existing and future distillation plants, as well as resulting in better process economics. As a result, the selectivity of NF membranes for monovalent and bivalent anions is significantly different as compared to regular RO membranes. Specially designed NF membranes have the capability of high rejection for divalent ions (Ca, Mg and SO_4), while allowing relatively high passage of monovalent ions (Cl, Na and K). The nanofiltration membrane performed significantly better than the design specifications. Sulfates rejection exceeded at all times 95% rejection, calcium hardness was reduced by over 55%, magnesium hardness by over 80%. These results were achieved at feed temperature controlled at 35 °C.

Membrane softening technology adapted to hybrid with distillation processes could lead to a significant increase in the productivity of existing and future distillation plants as well as resulting in better process economics. Pioneering work on Nanofiltration membrane NF softening technology as applied to desalination processes and specifically to seawater desalination was develop by two groups: Leading Edge Technologies Ltd (LET) and the Saline Water Conversion Corporation (SWCC) of Saudi Arabia.

The great potential of nanofiltration membrane softening technology was brought to focus by an award by Sharjah Electricity and Water Authority (SEWA) to LET and

Besix Consortium for the first commercial LET Nanofiltration System to increase the capacity of an existing MSF plant from nominal 22,7000 m^3/day to 32,800 m^3/day (5 MIGD to 7.2 MIGD). This 40%+ increase in capacity of MSF unit was a result of a two-year demonstration and simulation program developed jointly with SEWA.

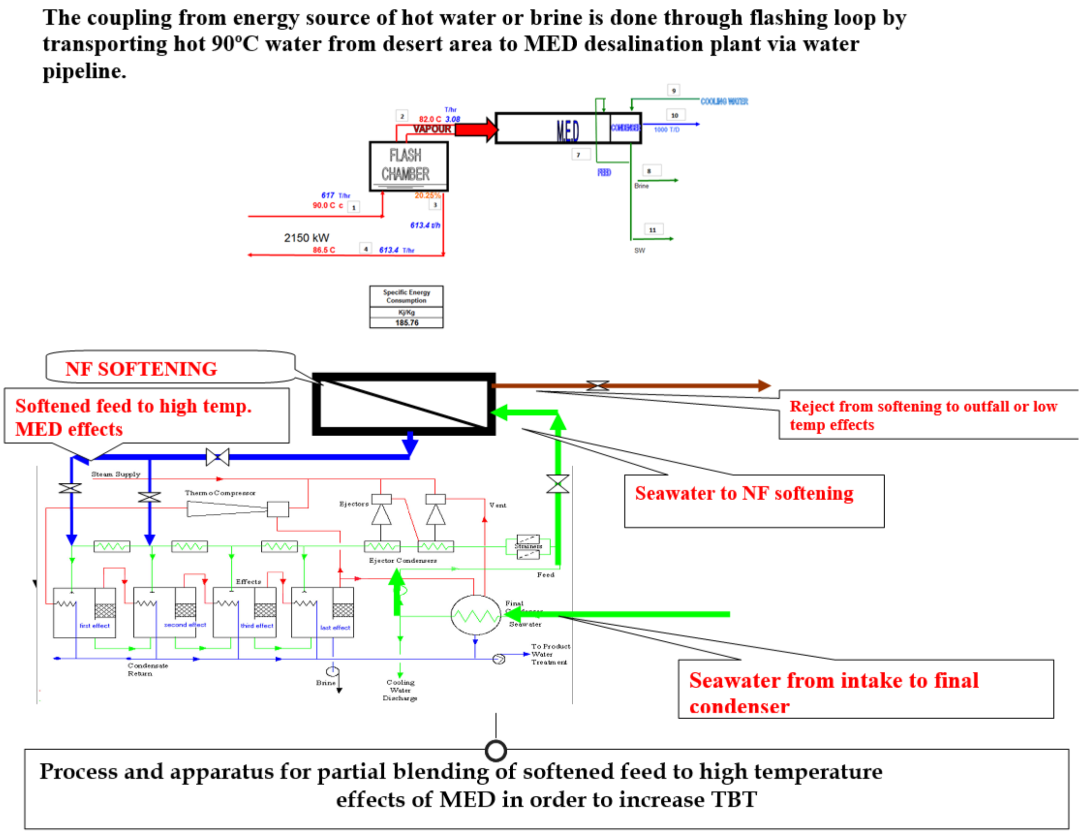
While certain features of the plant need to be adjusted to further increase and maximize the plant output, in response to higher operating temperatures and increased product volumes, no major technical issues were encountered that could prevent the application of the LET technology.

The additional capacity is achieved without building a new intake structure or new power plant in a very limited space that would not allow construction of a new desalination plant. The system involves construction of a NF plant to provide partial membrane softening of feed to MSF as well as modifications to existing MSF plant to be capable to achieve the increased capacity.

NF membrane softening technology could significantly improve operation and reduce the cost of the MED process, by eliminating the risk of scaling and fouling. NF technology will permit an increase in the top temperature, resulting in a significant increase in output and the performance ratio. This brings us to a discussion of the use of renewable energy, and in particular, solar energy in combination with advanced desalination plants.

Advanced MED can be combined with solar energy, geothermal energy, or solar ponds. The MED process operates with top brine temperature of only 64 °C to 75 °C, depending on salinity of the seawater, in order to avoid scale deposition on heat transfer surfaces. Therefore the energy supply can be at low temperature, in the form of hot water or hot brine at less than 90 °C or steam at a low 0.35 bar pressure. Therefore, the only electrical energy required is for running the process pumps, which will be less than 1.4 kWh/m^3. To minimize cost and energy required for desalination, LET developed in partnership with AquaSwiss an advanced very high efficiency hybrid MED-NF with nanofiltration membranes which are softening feed to enable high temperature effects. The novel design proposed is to combine solar pond with advanced MED-NF.

A solution combining low temperature thermal energy with low temperature hybrid MED -NF may be competitive in comparison with PV-RO. The heat for the MED unit can be supplied from gradient hot concentrated solar pond brine or geothermal brine. The hot brine will be sent to a flash chamber and will generate the required steam to the MED unit. From the flash chamber the colder brine will be pumped back to the solar pond to recover heat from solar radiation. Make up brine will be added from MED brine discharge in order to keep solar pond brine salinity constant. In order to improve the overall specific energy consumption a nanofiltration unit has been added to treat the feed water to the hot group of effects. The NF unit will remove all the sulfates dissolved in the feed, allowing to operate the MED at a top brine temperature of almost 80 °C without scaling problems.



The coupling from energy source of hot water or brine is done through flashing loop by transporting hot 90ºC water from desert area to MED desalination plant via water pipeline.

Process and apparatus for partial blending of softened feed to high temperature effects of MED in order to increase TBT

Figure 2.12: The coupling from energy source of hot water or brine is done through flashing loop by transporting hot 90°C water from desert area to MED desalination plant via water pipeline[102].

We have designed a full size commercial desalination plant of 25,000 m^3/day with 20 effects with thermal energy consumption of 137.6 kJ/kg, or PR=16.25. Even without NF, we could achieve PR of 13.8 never before achieved without thermocompression TVC with heat input at 90 °C. The exciting possibility for desalination is the fact that with such high efficiency and low temperature, the energy easily can be provided by solar pond, geothermal energy or concentrated solar collectors and provide easy storage of hot water assure 24 hours' continuous operation.

Of course, the LET Integrated Modification approach of using NF could be also effectively introduced to MED technology. NF softened feed being introduced to high temperature effects of MED, by blending with normal seawater feed. At the same time, the additional NF-softened feed could be introduced to the brine recycle stream at high temperature stages. If it is required, the NF membrane softened feed could be preheated to feed water Heat Exchangers.

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[102] UK Patent Application (19) GB (11) 2 443 802 of Leading Edge Technology, Ltd. Title: Thermal desalination plant integrated upgrading process and apparatus.

There are many potential variants for NF hybridization with NF-MED-RO. One option is for seawater to be preheated in MSF or MED reject section, and then softened by Nanofiltration membrane, followed by SWRO. The reject brine of SWRO has significantly reduced level of scaling ions sulfate, calcium and magnesium and therefore, the reject brine can be the feed for the distillation plant.

The needed research should be both analytical as well as in pilot plants to establish the ratio of NF feed blend with seawater to high temperature effects, to avoid scaling of carbonates and sulfate and maximize recovery. This should be follow by demonstration plant of 10,000–25,000 m^3/day.

2.4.6 Results and outcomes

When research is completed, this competitive solution could be applied rapidly to small and large size plants both new and as a retrofit to existing plants to increase capacity, efficiency and recovery. Using geothermal, solar or nuclear energy.
The ability of nanofiltration to softening seawater would allow MED process to operate up to TBT of 85 °C instead of current TBT of 64 °C. The increase in TBT allows one to introduce up to 10 additional effects. This is a result of removing scaling ions by using LET NF softening process, specifically ions of sulfate, calcium, magnesium and alkalinity from seawater feed. It would allow the increase of MED top operating temperature, which in return with more effects, allows for the increase in the Gained Output Ratio (GOR) to 16–18 (kg of distillate per 1 kg of steam) provided by renewable or alternative energy. This dramatically improves efficiency of MED desalination plants which today maximum GOR in the Gulf does not exceed 11.5. At the same time the increase in TBT and GOR reduces over 50, percent the amount of cooling seawater required. The softening also allows for much better recovery of seawater, reaching overall concentration factor CF 2.5 rather than today CF of 1.4. Finally, the optimized design will lead too significant over 50% reduction in capital cost of producing energy and water in comparison with today MED plants.

Rehabilitation and upgrading of existing plants

Many of the existing distillation plants are approaching their design life of 25 years, and the owners have to consider life extension with additional upgrading in the capacity and efficiency of the desalination plants. There are new technologies using Nanofiltration softening membranes of seawater and integrated upgrading of distillation plants, which as result of hybridization, permit distillation plants to raise top operating temperature and increase the design production from existing plants by over 40 %. Such rehabilitation and upgrading minimizes the environmental impact and produces more critically needed water without building new intake – outfall structures and new power plants.

Resource conservation and environmental impacts of various hybrid configurations

Resource conservation and environmental impacts are aspects that have to be considered when designing hybrid systems. The use of renewable energy for

desalination is critical in reducing carbon footprint: CO_2 emissions. Increasing the efficiency of thermal desalination processes is reducing costs of solar field or renewable energy sources, and also reduces environmental impact of thermal discharges. Combining thermal and membrane desalination processes and technologies within a single plant or in hybrid plant schemes can reduce desalinated water costs, in dual-purpose stations; add flexibility and better match the demand to the combined water and power production; and, most importantly, minimize the environmental impact of power desalination plants.
In near future, the consideration of carbon dioxide footprint will have a significant impact in justifying hybrid plants.

2.5 Salinity gradient and waste heat energy recovery

Tzahi Cath, Michael Papapetrou, Yuan Zhang

Desalination of seawater and brackish groundwater has become very energy efficient, allowing desalination of impaired water at an energy cost close to the thermodynamic limit of separation. This has been accomplished through development and implementation of energy recovery devices and new system designs that convert the hydraulic pressure energy of the brine into a useful energy in the incoming feed stream. However, when considering the chemical energy embedded in the brine, there is still work to do and more energy to recover and reuse in engineered and natural systems. There are different possible configurations for including salinity gradient technologies in hybrid desalination systems[103].

There has been increased interest and research on Salinity Gradient Power over the past 10 years, primarily for energy generation from natural water streams rather than for desalination energy recovery. The two Salinity Gradient Power technologies that have been studied extensively in recent years are pressure retarded osmosis (PRO) and reverse electrodialysis (RED). Furthermore, low grade heat (LGH) from industrial processes can be utilized to more efficiently treat and desalinate water.

2.5.1 Reverse electrodialysis (RED)

Reverse Electrodialysis has achieved great progress moving from TRL 2 to TRL 4-5 over the last few years. The most relevant development is the project REAPower[104] where the use of brine for power generation was studied resulting in a 1kW prototype that operated in a real environment demonstrating the potential for using RED as a desalination energy recovery system[105].

Within this project FUJIFILM has developed Ion Exchange Membranes optimized for this application, which performed very well and have the potential to be produced

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[103] For more information, see "Salinity gradient power and desalination", Chpt. 9 in *Sustainable Energy from Salinity Gradients*, A. Cipollina, G. Micale (Eds.), Elsevier 2016: pp. 219–256.

[104] www.reapower.eu

[105] M. Tedesco, C. Scalici, D. Vaccari, A. Cipollina, A. Tamburini, G. Micale, "Performance of the first Reverse Electrodialysis pilot plant for power production from saline waters and concentrated brines", J. Membrane Science 500 (2016) 33–45.

in high quantities at competitive prices. Also the company REDstack developed custom-made stacks which have operated well. With these stacks and membranes over 10 W/m^2 cell pair[106] have been reached in the lab. When operating in a real environment though the performance, while still good was about 40% lower than expected based on the lab experiments.

This result points to the necessity for further R&D on the impact that multi-valent ions (mainly magnesium and calcium)[107] have on the power generation process. Pre-treatment methods or improved membranes are required for dealing with this issue.

On the stack side, improvements with regards to the flow distribution and the pressure drop across the channels will be always required in a process of continuous improvement of the process performance. With regards to the electrode rinse solutions and the redox reactions, alternative solutions should be explored especially with regards to environment, safety and stability. Finally, as the technology moves to higher TRL issues such as system integration, Scaling-up and Manufacturing have to be explored.

2.5.2 Pressure retarded osmosis (PRO)

The attractiveness of the PRO process is that power can be generated to offset energy requirement of a desalination plant. A PRO process could theoretically generate power between 0.35 kWh$_e$/m^3 and 0.7 kWh$_e$/m^3, depending on whether seawater or SWRO brine used as the draw solution[108]. When SWRO brine solution can be used in a PRO process, a concomitant advantage is that the SWRO brine would be diluted to a lower salinity level that would allow for its disposal with lower environmental impact compared to its original saline concentration.

However, one of the limitations of the PRO technology is the availability of the low salinity feed water. There is an inevitable trade-off between water production and power generation. Typical feed water sources for a PRO process could be river water or secondary effluent. In Singapore, for instance, low salinity brine stream from NEWater factories may be an appropriate source.

The main barrier for innovation and commercialization of the PRO processes is the lack of suitable membranes for PRO. Current membranes have limited water permeability, poor selectivity, and they are not robust enough to withstand the hydraulic pressure needed to recover significant portion of the chemical energy

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[106] M. Tedesco, E. Brauns, A. Cipollina, G. Micale, P. Modica, G. Russo, J. Helsen , Reverse Electrodialysis with saline waters and concentrated brines: a laboratory investi gation towards technology scale -up, J. Memb. Sci. 492 (2015) 9 –20.

[107] M. Tedesco, A. Cipollina, A. Tamburini, G. Micale, Towards 1 kW power production in a reverse electrodialysis pilot plant with saline waters and concentrated brine , Journal of Membrane Science, 522 (2017) 226-236

[108] Achilli, A., T.Y. Cath and A.E. Childress (2009). Power generation with pressure retarded osmosis: An experimental and theoretical investigation. Journal of Membrane Science 343 (1-2): 42-52

embedded in the brine. To facilitate successful adoption of PRO, robust and sustainable semipermeable membranes are needed that have high water permeability, high salt selectivity, and that can withstand hydraulic pressures higher than 5.5 MPa (800 psi). While many studies modeled the process using hypothetical conditions and membrane characterization, minimal efforts have been made to identify materials and processes to make suitable membranes for PRO. And while many studies identify the draw solution as a major parameter that needs to be studied, it is a pure destruction of the main problems that need a solution: the membranes.

To overcome the barriers to adoption and commercialization of the PRO processes, substantial material science research is needed to address the robustness of membranes while ensuring high permeability and selectivity. One approach that has not been investigated and requires more attention is composite membranes that combine inorganic porous support layer underneath an active polymeric or inorganic thin selective layer. This might resolve the limited robustness of current generation membranes that deform and lose integrity at pressures above 2 MPa (300 psi). If better membranes for PRO are available, it will be possible to enable enhanced energy recovery during seawater desalination.

2.5.3 Salinity gradient and osmotic heat engines

Thermally driven membrane desalination processes that can utilize low-grade heat (LGH) can be used to regenerate artificial salinity gradients in salinity gradient heat engines. Membrane distillation (MD) is an example of such a technology.

While alternative and renewable energy technologies that focus on reducing the dependence on fossil fuels often attract a lot of attention, increasing the energy efficiency of existing industrial processes also has the potential to significantly reduce fossil fuel consumption. Industrial processes consume nearly 30% of the U.S. energy supply, and 20 to 50% of the energy consumed is lost in the form of low-grade heat [109]. For example, conventional coal-fired power plants have an average efficiency of 32%, leaving a large percentage of unused heat to be potentially recovered[110]. Existing commercial technologies that can generate energy from LGH operate at temperatures higher than 90 °C, including the Organic Rankine Cycle (ORC), which operates commercially with a temperature input of between 90 °C and 300 °C[111,112,113,114]. Therefore, waste heat lower than 90 °C represents a significant

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[109] Department of Energy, Waste heat recovery: Technology and opportunities in U.S. industry, 2008, Department of Energy, Washington, D.C.
http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf

[110] Analysis of heat rate improvement potential at coal fired power plants, U.S. Energy Information Administration May, 2015

[111] Department of Energy, Waste heat recovery: Technology and opportunities in U.S. industry, 2008, Department of Energy, Washington, D.C.
http://www1.eere.energy.gov/manufacturing/intensiveprocesses/pdfs/waste_heat_recovery.pdf

[112] N. Naik-Dhungel, Waste heat to power systems, U.S. Environmental Protection Agency May 30, 2012

opportunity for technologies that can economically utilize lower temperature resources.

Salinity gradient engines are closed-loop, membrane-based energy cycles that convert thermal energy to produce electrical energy. As an example, in the MD+PRO configuration (sometimes called an osmotic heat engine, or OHE), MD utilizes LGH to separate diluted brine into two streams: deionized water and high concentration brine. The two streams are then transferred into the PRO process, where the osmotic pressure difference between the streams, separated by the PRO membrane, is converted into mechanical energy that can be further converted into electrical energy via a turbine-generator set. The diluted brine from the PRO process is then regenerated in the MD process. Operating within a closed-loop configuration such as the OHE (Fig. 2.13) offers several benefits over open-loop PRO configurations, including the use of high purity working fluids, which can eliminate membrane fouling and scaling, control of solution chemistry and temperature, and reduced environmental emissions.

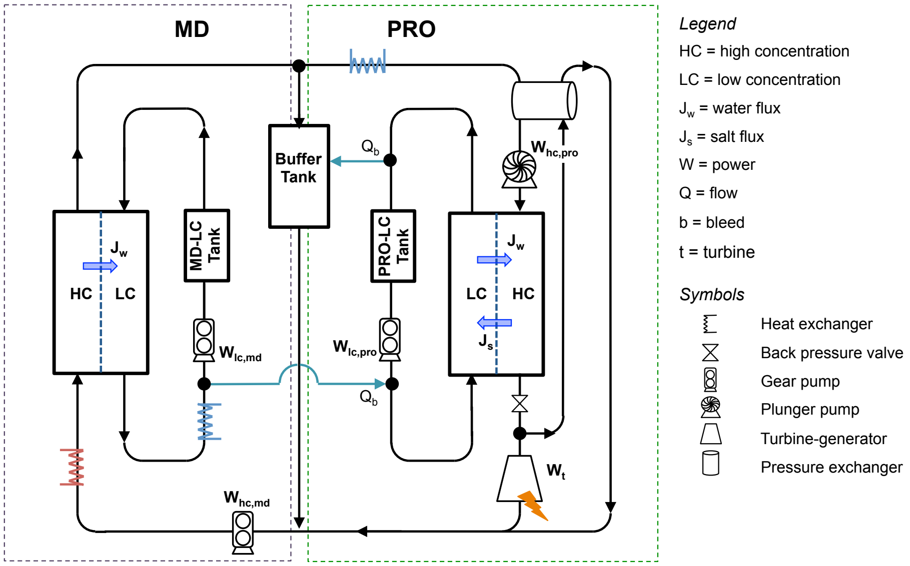

Figure 2.13: Schematic of the closed-loop OHE. The blue arrows represent the portion of the PRO feed stream bled to the MD feed stream for recovery of solutes and control of PRO feed chemistry[115]*.*

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[113] S. Quoilin, M.V.D. Broek, S. Declaye, P. Dewallef, V. Lemort, Techno-economic survey of Organic Rankine Cycle (ORC) systems, Renewable and Sustainable Energy Reviews 22 (2013) 168-186.

[114] B.F. Tchanche, G. Lambrinos, A. Frangoudakis, G. Papadakis, Low-grade heat conversion into power using organic Rankine cycles - A review of various applications, Renewable and Sustainable Energy Reviews 15 (2011) 3963-3979.

[115] K.L. Hickenbottom, J. Vanneste, L. Miller-Robbie, M. Elimelech, M.B. Heeley, T.Y. Cath, Techno-economic assessment of a closed-loop osmotic heat engine, 2016, submitted for publication

If better membranes for PRO and OHE are available, it will be possible to recover energy from LGH resources at the cost of less than $0.10 per kWh and enable enhanced energy recovery during seawater desalination.

Configurations that involve RED as the energy generation technology are studied in a European funded project, which tests regeneration options from heat at temperatures between 50 and 100 °C. Small pilot systems are under development[116].

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[116] RED Heat-to-Power project funded the EU Horizon 2020 research and innovation programme under agreement No. 640667, http://www.red-heat-to-power.eu/

3. Integrating Desalination Systems with Low-Carbon Grids and Power Sources

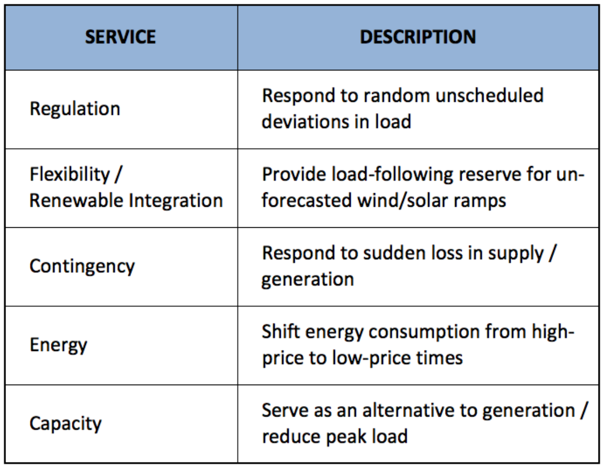
Contributors: Thomas Altmann, Jennifer Daw, Chiara Fabbri, Vasilis Fthenakis, Angelina Galiteva, Malcolm Jacques, George Papadakis, P.K. Tewari, and Adam Warren

3.1 Grid integration at municipal, national, and international scales

Jennifer Daw and Adam Warren

Properly designed desalination systems can provide value to the grid or associated microgrid by flexibly varying load in order to shift demand to times of lower generation costs, reduce peak load, and flatten aggregate demand, and to mitigate the integration challenges associated with intermittent renewables. Potential work will develop a greater understanding of the design and operation of integrated energy-water systems and will develop a suite of design and decision-support tools to reduce the levelized cost of energy and water in integrated systems. These design tools and the performance of flexible desalination equipment will be evaluated with grid simulations and hardware-in-the-loop (HIL) testing.

Table 3.1: Potential Grid Services from Flexible Desalination[118]



SERVICE	DESCRIPTION
Regulation	Respond to random unscheduled deviations in load
Flexibility / Renewable Integration	Provide load-following reserve for un-forecasted wind/solar ramps
Contingency	Respond to sudden loss in supply / generation
Energy	Shift energy consumption from high-price to low-price times
Capacity	Serve as an alternative to generation / reduce peak load

In the context of climate change and population growth, the interrelationship of water and energy is becoming more critical. Drinking water and wastewater plants are one of the larger energy consumers for local governments, accounting for 30-40% of total energy consumed and approximately 3–4% of energy use in the U.S.[117, 118] Climate change creates uncertainty in the long-term availability of water supplies impacting the design and operation of water and energy systems. Resilient, integrated energy and water systems that provide reliable water and energy

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[117] U.S. Department of Energy, Water Energy Tech Team. Accessed 9/10/16.

[118] M. Hummon, D. Palchak, P. Denholm, J. Jorgenson, D. J. Olsen, S. Kiliccote, N. Matson, M. Sohn, C. Rose, J. Dudley, S. Goli, and O. Ma. "Grid Integration of Aggregated Demand Response, Part 2: Modeling Demand Response in a Production Cost Model," NREL/TP-6A20-58492, 72 pp., 2013 http://www.nrel.gov/docs/fy14osti/58492.pdf

supplies are a great need for communities at both a large and small scale.[119,120] Desalination systems have largely been disconnected from electric utilities' efforts to improve overall energy efficiency and improve grid stability, although there are some exceptions.[121]

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 (see Table 3.1). The benefit to industry from offering these services depends on the electricity market rules in the different countries[122]. 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.

Further RD&D in this area should develop and demonstrate design and decision-support tools to create resilient, integrated energy-water systems that reduce energy and water costs while supporting higher-penetrations of renewable energy. The proposed tools will extend existing generation and grid/microgrid design tools to incorporate the services provided by a flexible desalination load.[123,124] The proposed optimization-based tools can then be used to design and operate integrated energy-water systems and to identify where and if new desalination research on flexibility is warranted.

In particular, the following is proposed:

- Stage 1 – Define the Opportunity Space: The Global Clean Water Desalination Alliance teams will research currently available energy-water design and optimization tools and approaches being used in the desalination sector to identify the tools' capabilities and limitations. This stage will assess the broader opportunities for grid services and renewable energy integration with desalination's systems by quantifying the potential impact. The team will select two case studies: a grid-connected system and an isolated, microgrid system, to estimate typical loads, energy use, and potential

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[119] A. Santhosh, A.M. Farid, and K. Youcef-Toumi. "Real-time economic dispatch for the supply side of the energy-water nexus." Applied Energy, pp. 122, 42–52, 2014

[120] Dyson, Mark, James Mandel, et al. "The Economics of Demand Flexibility: How "flexiwatts" create quantifiable value for customers and the grid." Rocky Mountain Institute, 9 pp, August 2015. http://www.rmi.org/Knowledge-Center/Library/RMI-TheEconomicsofDemandFlexibilityFullReport

[121] B. Sparn and R. Hunsberger. "Opportunities and Challenges for Water and Wastewater Industries to Provide Exchangeable Services," NREL/TP-5500-63931, 19 pp, November 2015.

[122] The EU IndustRE project has explored related business models: http://www.industre.eu/.

[123] T. Simpkins, D. Cutler, K. Anderson, D. Olis, E. Elgqvist, M. Callahan, and A. Walker. "REopt: International Conference on Energy and Sustainability, June 30-July 2, 2014, Boston, Massachusetts, ES2014-6570, pp. V002T03A006; 8 pp., 2014

[124] Energy Exemplar, "PLEXOS® Integrated Energy Model." Accessed May 16, 2016. http://energyexemplar.com/software/plexos-desktop-edition/

benefits from ancillary services (e.g. power quality, reduced water and energy costs, improved resiliency, reduced congestion, etc.).

- Stage 2 – Optimal Design and Operation: Using insights from Stage 1, the team will develop an integrated energy-water design and decision-support tool based on existing optimization-based design tools that facilitate (i) optimal design and (ii) optimal operation of an integrated energy-water system. The tools will be developed in modular, adaptable formats with flexibility to accommodate different generation and desalination technologies. The tools will facilitate integrated decision-making for the design and planning of new infrastructure and as well as the operation of integrated systems. The tools will be designed to minimize the levelized costs of power and water for a variety of system types and to incorporate grid services and improve energy system resiliency. The functionality of the new tools will be validated with data provided by industry partners and though model validation to be conducted in the final stage.
- Stage 3 – Model Validation & Hardware-in-the-Loop (HIL) Testing: Leveraging the work performed in Stage 2, a distributed HIL testing system will be developed to link generation equipment, power system simulations, and desalination equipment. This linkage will provide an opportunity to test grid service opportunities identified in previous stages for their impact on water and energy system operations. Findings from this stage will help guide future research in the development of flexible, integrated energy-water equipment and controls.

3.2 Autonomous grids and integration at small scales

George Papadakis, C. S. Karavas, E. Dimitriou, E. Sh. Mohamed, Vasilis Fthenakis, and A. Atia

The intermittent and variable energy production by renewable energy (RE) technologies and the integration of new desalination plants will require a cost effective planning strategy in order to design the optimum energy supply system; autonomous hybrid system or autonomous microgrid or grid-connected microgrid. The proper operation of the system requires advanced energy management and control systems. In the case of reverse osmosis (RO) desalination plants powered by RE, the energy management system (EMS) controls all system components in order to satisfy the demand and secure its economical operation. The EMS makes an adaptive and intelligent system able to operate the RO plant effectively under various conditions of RE power production by keeping the interchange between production and consumption stable. Finally, with desalination plants connected to the main grid, it must be investigated how to minimize the needed energy and water cost without sacrificing the quality of the produced water under intermittent operation and how to address grid operation problems by allowing RO desalination to act as a means of alternative storage, for load shifting or for frequency stabilization and thus increase RE penetration into the grid.

Desalination is a sustainable and economically viable solution in order to address the water scarcity when the energy requirements are satisfied by RE. In recent years, distributed energy sources (DES) show a significant penetration in grid networks and in autonomous hybrid systems. In the age of distributed energy, many consumers are producers as well. As a result, the worldwide energy system is undergoing significant changes and a gradual conversion of the grid infrastructure is inevitable. The complexity of the energy supply systems and the intermittent operation conditions of Renewable Energy Technologies (RET) require energy management and control systems which become part of power-consuming apparatuses as well as of the desalination systems [125,126].

The smart hybrid energy systems facilitate efficient supply of renewable energy from RET to desalination plants. Multi-agent decentralized energy management and control systems (MAS-DEMS) based on computational intelligence, where all the components of the system will be controlled and will be able to act as an independent agent, can optimize electricity supply to desalination plants and can operate the desalination plant under variable and intermittent conditions.

The present idea proposes to research three different energy supply systems for RO desalination. Each system includes a MAS-DEMS. This system's approach offers the possibility to incorporate distributed computational intelligence and advanced control techniques. The various topologies and operation modes are shown below:

a) Operation in stand-alone power system

Stand-alone hybrid desalination systems (Fig. 3.1) can cover the water needs in areas lacking of central electricity grid. The EMS will ensure the production of the highest quality and quantity of freshwater with the lower amount of energy, utilizing renewable energy.

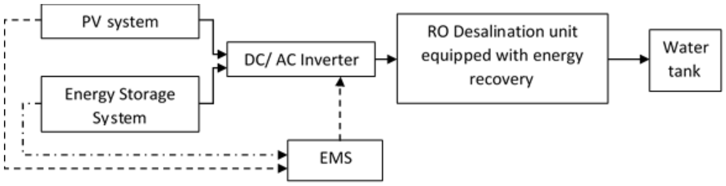

Figure 3.1: Standalone operation

b) Autonomous Microgrid

Microgrids are usually small-scale integrated energy systems which comprise low voltage distribution systems with distributed energy resources and energy storage devices. Microgrids are mostly employed in remote or isolated communities. Microgrids can operate autonomously (Fig. 3.2), covering the electrical, thermal and water needs of the residents. The EMS increases the energy use efficiency of

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[125] C. S. Karavas, G. Kyriakarakos, K. G. Arvanitis, and G. Papadakis, "A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids," Energy Conversion and Management, vol. 103, pp. 166-179, 2015.

[126] G. Kyriakarakos, A. I. Dounis, K. G. Arvanitis, and G. Papadakis, "A fuzzy logic energy management system for polygeneration microgrids," Renewable Energy, vol. 41, pp. 315-327, 2012.

distributed resources and optimizes RO desalination plant water production throughout the year.

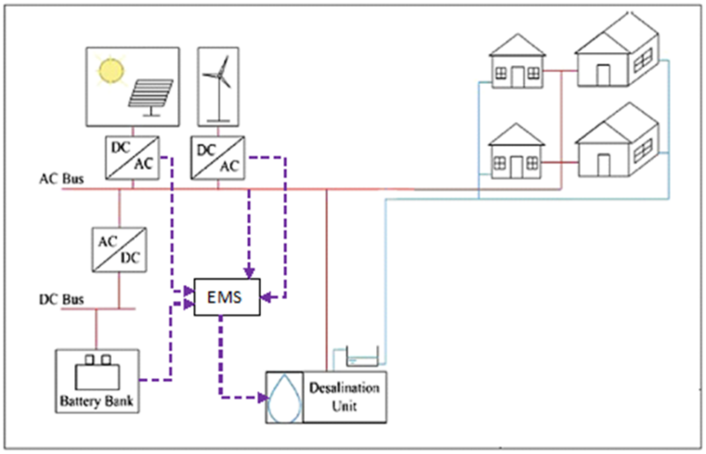

Figure 3.2: Microgrid operation (C.S. Karavas, ongoing work)

c) Grid Integration – island grids (Fig. 3.3)

The grid powered RO desalination may be seen as a type of alternative storage i.e. electricity to water. The objective is to use RO overcapacity to store water when electricity is available at lower prices or when there is surplus of electricity on the grid from RET. An RO plant could then function as a deferrable load to the electricity grid. In addition, in order not to burden the grid, RO offers a load shifting option. The generated electricity by RET is consumed by the desalination plant and the surplus of energy is supplied to the grid. The EMS will associate with the control of the desalination plant and will decide when the desalination plant will operate (depending on electricity price). Furthermore, desalination plants can operate during grid disturbances thus maintaining frequency stability.

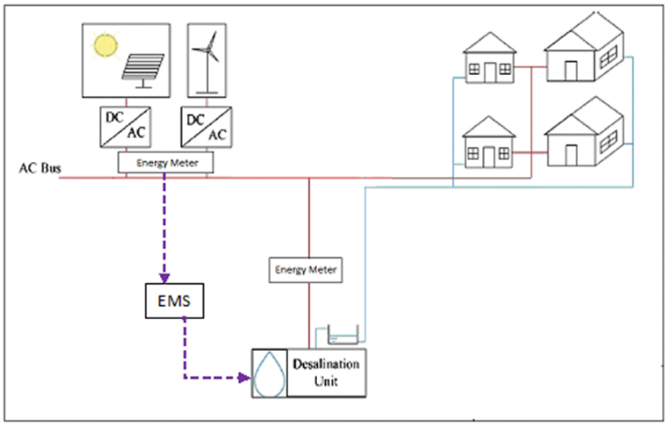

Figure 3.3: Grid-connected operation (C.S. Karavas, ongoing work)

The current research results will allow the optimization of energy supply systems configuration for RO desalination plants. The energy production is based on RE thus decreasing the CO_2 emissions. Advanced energy management and control systems will enable automated real time decision making on both the supply and the demand side, both of electricity and water networks thus leading to optimizing costs of energy and water.

3.3 Energy storage for desalination

Malcolm Jacques

3.3.1 Grid-level electricity storage

Increasing integration of intermittent renewables into electric grids are increasing the need for energy storage for technologies such as desalination, without which electricity users must reduce in power use or be shut down completely down.

Grid-level electricity storage systems, capable of providing MW's of power and MWh's of energy at very short notice (seconds to days) for varying periods of time (seconds, minutes, hours), are essential for providing a range of services that assist and enhance grid operations. Operators of electricity grids need to maintain a balance at all times between generation and demand. Any imbalance between the amount of electricity being generated and used can result in voltage and/or frequency variations and other power quality measures that are unacceptable to grid operators and end-users. Serious imbalances between generation and demand can result in brown-outs, black-outs and shut-down of power generation systems.

Traditionally, grid operators have relied on the fact that large central power generation assets are under the control of systems operators and can be dispatched or curtailed in response to changes in demand. All major power plants are equipped with standardized Automatic Generation Control (AGC) systems that react automatically to signals received from grid operators to increase or decrease power generation. Sudden increases in demand have historically been managed by maintaining "spinning reserves", fossil-fueled power plants that can be dispatched within seconds. Fast-start, gas-fired power plants, usually open-cycle gas turbines, known as "peakers", are used by grid operators to balance supply and demand.

The value of being able to store electricity during periods of excess generation, low demand and low cost for use at peak demand, high cost times has been widely recognized by grid operators around the world.

The rapid adoption of renewable energy systems, particularly wind turbines and solar PV, results in grid operators being faced with increasing amounts of intermittent power being injected into the grid over which they have very little or no control. For example, large wind farms installed in southern California can generate as much as 4200 MW. Sudden, uncontrolled changes in power generation from wind and/or solar systems requires grid operator to have dispatchable resources available that can be ramped up or down at very short notice to match these significant changes in renewable generation. Again, fast-start, gas-fired peakers are the most commonly used resource to meet the ramping requirements of grid operators. However, fast-start gas-turbines are quite expensive and produce significant amounts of GHG, thereby counteracting the GHG benefits of power generation from renewable resources. Grid-scale energy storage represents a low-carbon alternative to fast-start peakers.

The greenhouse gas emission targets being set around the world, requires increasing amounts of electricity generation from intermittent renewable resources. Grid-scale energy storage id needed to mitigate the impact of intermittency and will become an essential component to achieve a cost effective, low-carbon electricity supply system. Grid-scale energy storage offers the potential to improve the utilization of renewable generation assets, avoiding additional investment in transmission and distribution networks and reducing investment in the back-up generation needed to accommodate increasing amounts of intermittent renewable generation.

The various types of grid-level electricity storage systems available can be broadly classified by the form in which the electrical energy is stored, as follows. Paired with each are some primary research needs for the topic.

- Mechanical: includes Pumped Hydroelectric Storage(PHS), Compressed Air Energy Storage(CAES) Flywheels
    - Integration of pumped hydro with desalination
- Electrochemical: Batteries, (Including Nickel-Cadmium, Lithium-Ion, Lead-Acid, Metal-Air, Sodium –Sulphur; Flow Batteries or Rechargeable Fuel Cells
    - Reducing cost of raw materials (especially electrodes), the manufacturing, cell fabrication
    - Improved anodes with better conductivity
    - Cathodes with reduced toxicity, lower cost materials
    - Improved electrolytes with better conductivity, improved safety

- Electrical: Superconducting magnetic Energy Storage (SMES), Electrical Double Layer Capacitors (Supercapacitors)
- Thermal: Cryogenic Energy Storage (CES)

(Details of the technologies employed and examples of applications of grid-scale electricity storage systems can be found at www.energystorage.org the web-site of the Energy Storage Association (ESA)

Grid-level storage can be deployed at two locations on the grid, either on the high voltage transmission lines or on the lower voltage distribution grid.

The transmission grid, generally characterized by high voltages in the 115–765 kV range, includes large central generation stations, transmission lines, transmission substations, or transmission-connected customers. The services that energy storage can provide to transmission grids include:

- Transmission deferral
- Transmission congestion relief
- Voltage support

- Frequency regulation
- Spinning reserves
- Black start capability.
- Energy arbitrage/load shedding.
- Resource adequacy (meeting peak demand on a daily basis)

At the distribution level, (voltages ranging typically from 4 to 69 kV) which includes medium voltage distribution lines, distribution substations, and commercial / industrial customers tied directly to the distribution system, and customer substations, energy storage can also provide:

- Distribution congestion relief
- Distribution line upgrade deferral
- Energy arbitrage/load shedding

To be of value to the transmission and distribution grid operator, energy storage systems need to be capable of providing MW of power for periods varying from a few seconds to a few hours and be available at very short notice at anytime. Location of the grid-scale energy storage on the grid can also be important for addressing transmission and/or congestion issues and/or transmission/distribution line deferrals.

Incorporating grid-scale energy storage systems raises regulatory issues largely due to the fact that storage can be considered as both a generators and a consumer of electricity. Different regulatory bodies deal with the generation assets and the transmission/distribution assets. Assigning values to the various services that energy storage systems can provide has therefore been difficult and slow. "Bundling" of the various services that can be provided by different energy storage systems is a complex issue for regulators, grid operators and developers of energy storage systems.

3.3.2 On-site electricity storage

Electricity storage systems may also be of value to individual consumers and producers of electricity. Grid-connected, on-site electricity storage assets located on the customer-side of the electricity meter can provide a range of benefits to individual customers. Potential benefits range from emergency back-up power, power quality, electricity arbitrage (time-of-use bill management), demand charge reduction, and increased self-generation with conventional and/or renewable energy systems.

The use of electricity storage systems for desalination has been largely restricted to small desalination plants that are not connected to a reliable grid, e.g. remote locations, islands and mining/minerals operations. In many of these remote locations there are abundant supplies of renewable energy, particularly wind and solar. Consequently electricity storage systems, mostly batteries, have been deployed to enable the desalination plants to continue operations during periods of little or no wind or sun. Fully autonomous, small, desalination systems have been developed that make use of solar PV to provide the power needed for reverse osmosis desalination.

Cost and reliability of the water supply are the main concerns for designers and operators of desalination plants. If grid power is available, and there is a significant difference in the cost of power between peak and off-peak periods, is it more cost effective to design the desalination plant to operate only during off-peak periods? What are the capital cost and operating implications of running a desalination plant for less than 24 hrs/day? This situation is exacerbated when considering the use of renewables to power a desalination plant. For example, a desalination plant powered 100% by PV (available only 8 hrs/day) must be at least 3× the size of a plant operated 24/7 with a steady source of power. Are the additional capital and operating costs of a larger desalination plant plus the costs of PV less than the costs of providing a steady source of power for a smaller desalination plant 24/7?

Electricity storage systems can be used to store PV power during periods of peak production, thereby reducing the size of the desalination plant required to meet a specified daily production rate of desalinated water, but at the additional expense of the storage. These are complex issues that must be evaluated on a site specific basis. However, it is worth noting that as the cost of PV and wind power come down, the case for desalination plants powered by renewables becomes much stronger.

In situations where the cost of renewable power is very low (or conventional power is very high) there may be a strong economic case for storing desalinated water rather than storing electricity. Again, this will depend on the relative costs of electricity storage versus the increased capital cost for a larger desalination plant plus water storage.

Desalination plants may also be considered as a form of energy storage if surplus, cheap electricity can be used to produce desalinated water, which is then stored for use at times of higher power and/or water costs.

3.4 Low-carbon power-water hybridization

3.4.1 Solar-thermal desalination

Thomas Altmann, Diego-César Alarcón-Padilla, Lidia Roca, and Guillermo Zaragoza

Overview

Large-scale desalination requires large amounts of energy. In the case of solar energy, for large-scale solar electricity production, the technology options are photovoltaic (PV) and concentrated solar power (CSP) technologies. PV requires the use of expensive batteries in order to achieve large capacity factors, while thermal storage can help quadruple the capacity factor in CSP with respect to PV. This means that CSP is more suitable for coupling to desalination, since intermittent operation has a negative impact on the overall performance of the process. Moreover, the availability of waste heat in the CSP plant allows for the integration of thermal desalination plants, exploiting interesting synergies in the combination of desalination and solar power production.

The combination of CSP with desalination (CSP+D) has been analyzed using models but never demonstrated at pilot plant scale. It is necessary to characterize the process in real operation, to calibrate the models and fully assess the techno-economic feasibility of the technologies. Further challenges that require additional research are: (i) hybridization with other renewable energy, including PV, or with fossil sources in order to achieve full continuous operation; (ii) adaptation to variable demand curves of electricity and fresh water; (iii) optimal operation in and out of standard conditions.

Solar desalination is generally presented as the most optimal solution for sustainable desalination, since water needs are usually larger in places with high solar radiation. In order to guarantee a steady power supply, storage of the solar energy is required. Solar thermal energy technologies have easier, more economic and flexible means of energy storage than PV, which is a considerable advantage especially at large capacity [127].

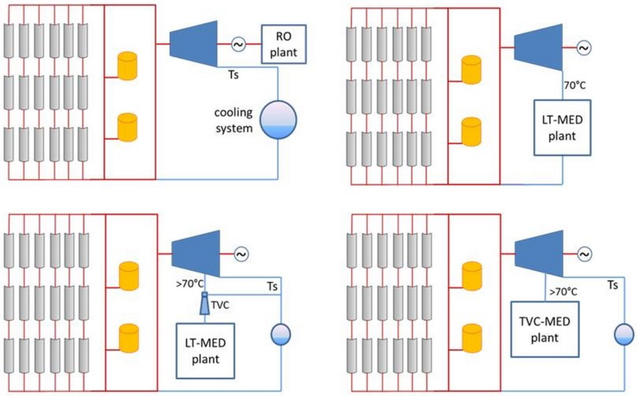

Figure 3.4: Different configurations for CSP+D using RO, LT-MED and TVC-MED plants[128].

Concentrated solar power (CSP) plants are able to deliver thermal energy at medium and high temperatures (150–1000 °C) with relative high solar collection efficiencies. This thermal energy can be used in a power generation process. A desalination system can be coupled using directly the generated electricity, as in the case of Reverse Osmosis (RO), or using part of the steam coming from the power cycle, as in the case of Low-Temperature Multi-Effect Distillation (LT-MED) or Thermal Vapor Compression Multi-Effect Distillation (TVC-MED) plants in a

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[127] "Solar Thermal Electricity. Global Outlook 2016". European Solar Thermal Electricity Association (ESTELA). 2016. http://www.estelasolar.org/wp-content/uploads/2016/02/GP-ESTELA-SolarPACES_Solar-Thermal-Electricity-Global-Outlook-2016_Full-report.pdf

[128] "Solar Desalination: Constraints And Opportunities Of Different Technologies Based On Energy Efficiency And Cost, G. Zaragoza, P. Horta, P. Palenzuela, D.C. Alarcón-Padilla. IDA World Congress on Desalination and Water Reuse, San Diego, Aug. 2015.

cogeneration scheme (CSP+D), as illustrated in Fig. 3.4. These thermal cogeneration schemes have the additional environmental advantage of eliminating or reducing the cooling requirements of the power plant, but at the cost of introducing a penalty in the thermal-to-power efficiency of the plant by removing steam from the power cycle [129].

CSP plants compete with photovoltaic (PV) power plants that have experienced a huge cost reduction during the last decade. However, CSP technology presents a series of advantages like the availability of an affordable thermal storage capacity that drives CSP plants to achieve values of about 75% in the capacity factor (ratio of the yearly actual output to its potential output if it were possible for the plant to operate at full nameplate capacity over such period of time). This allows for dispatchable generation, which means the ability of supply electricity and fresh water at the request of the power and water grid operators. Large scale PV plants do not have at present that possibility since their capacity factor barely goes above 20%, so power is dispatched matching the curves of the solar radiation available at any instant of time, which is a barrier for the integration of renewable energy on energy grids due to the subsequent complication of management.[130] (This might be solved with integration in a CSP plant, e.g. CSP + PV + RO + MED.)

Despite the large capacity factors that CSP plant can offer, 100% autonomy is an unrealistic objective for standalone solar power plants due to economic factors. Thus CSP+D plants have to deal with intermittent and transient operation out of nominal values due to the variable nature of solar irradiance. Hybridization with other renewable energy sources or with fossil fuels can help reaching 24-h continuous operation in similar conditions as conventional cogeneration plants.

The specific objectives of the research in the field of large capacity desalination driven by CSP technologies are:

- To select the most viable configuration: either an electricity-driven desalination process powered by a CSP plant, or a thermal cogeneration scheme where a thermal desalination system is coupled to the power cycle using the exhaust steam from the turbine or live steam from any intermediate extraction.
- To explore the possibilities of hybridization of the CSP plant with other renewable/fossil energy sources for more efficient desalination. (One scenario may be to sell electricity to the grid when the desalination plant is operating at nominal conditions and CSP + renewable source is supplying more than nominal requirements of desalination plant.)

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[129] P.Palenzuela, D.C. Alarcón-Padilla, and G. Zaragoza. "Concentrating Solar Power and Desalination Plants. Engineering and Economics of Coupling Multi-Effect Distillation and Solar Plants". Springer International Publishing, 172 pp. ISBN: 978-3-319-20535-9, 2015.

[130] M. Mehos, C. Turchi, J. Jorgenson, P. Denholm, C. Ho, and K. Armijo. "On the Path to SunShot. Advancing Concentrating Solar Power Technology, Performance, and Dispatchability". U.S. Department of Energy (DOE) NREL/TP-5500-65688, SAND2016-2237 R. United States. doi:10.2172/1256863. 2016. http://www.osti.gov/scitech/servlets/purl/1256863.

- To assess the impact of the thermal storage size (related to the plant capacity factor) in the final cost of the electricity and the fresh water produced.
- To assess and optimize the location (distance from the coast) of the CSP+D plant in order to maximize the availability of direct normal irradiance.
- To assess the impact of intermittent operation in the case of standalone CSP+D plants.
- To develop innovative thermal desalination technologies and components (i.e. variable-area thermo-compressors) that are optimized to work out of nominal conditions following the solar radiation variability.

The following methodology is suggested in order to achieve the above mentioned aims:

- Development of mathematical models for CSP+D plants and validation in pilot plants.
- Implementation of experimental facilities for testing the new concepts proposed or elements designed.
- Development of integrated simulation tools for the assessment of electricity and water cost obtained with CSP+D plants at different geographical locations.
- Development of computer tools for the assessment of the environmental benefits (CO_2 emissions, effluents impact, etc.) associated with the implementation of CSP+D plants.

The main outcome of this research project will be to provide a series of tools to facilitate the implementation of CSP+D technologies. Due to the usual coincidence of water scarcity problems and high insolation levels, the impact will be very significant, since this large-scale technology has the potential to fulfill the increasing electricity and desalinated water demands in many areas of the world without increasing carbon emissions.

Specific concept: automatic control for the adaptation of thermal desalination to transient energy sources

Thermal desalination has traditionally been operated with constant sources of heat based on fossil fuels. The temperature level required for this heat (usually not higher than 80-90 °C) is adequate for using a field of static solar thermal collectors as a source of renewable energy. The main barrier for solar thermal desalination is its high investment costs, however. The nature of solar radiation is transient and therefore the heat supply from the solar field is unsteady. This decreases the performance of the system, since operation in non-stationary conditions is less thermodynamically efficient. The nominal efficiency of the desalination systems is usually characterized in steady-state conditions, but in real operation coupled to a field of solar thermal collectors the performance of thermal desalination has shown to decrease significantly and this has serious impacts, which ultimately are barriers for the penetration of the technology[131]. On one hand there is an economic penalty associated to large investment costs for the energy collection. The energy efficiency of thermal desalination systems is evaluated in terms of the specific energy consumption (per unit volume of distillate produced). The lower the energy efficiency, the greater the amount of heat used by the system to produce distillate, therefore the higher the required investment in the solar field for a greater collection of energy. On the other hand there is an environmental impact in the case of a hybrid system. This is a frequent case when solar energy is coupled with a steady source of energy (using fossil fuels) for guaranteeing stationary operation of thermal desalination. The lower efficiency when operating with an unsteady solar energy source means that more fossil fuel is used and therefore the desalination process has a larger carbon footprint.

The role of automatic control on the efficient management of energy has been widely recognized from different points of view, mainly in the context of smart grids and buildings efficiency[132,133,134]. Its application in the context of solar desalination is yet in its very early stages and so far has mostly focused on the solar field[135,136]. However, efforts considering as well the desalination system indicate a potential for improvements that could lead to significant cost reduction[137,138,139]. Through optimal management and by adapting generation to demand, it should be demonstrated how automatic control allows to achieve cost savings and to reduce the environmental impact on the operation of solar desalination. The barriers for implementation can be overcome with operational strategies that adapt the desalination process to the source of energy and vice versa. Storage devices play an important role in energy systems to balance the system following disturbances

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[131] M. Papapetrou, M. Wieghaus and C. Biercamp. "Roadmap for development of desalination powered by renewable energy, promotion of renewable energy for water production through desalination, PRODES Project", ISBN 978-3-8396-0147-1, 2010.

[132] M. Castilla, J.D. Álvarez, F. Rodríguez, and M. Berenguel. "Comfort control in buildings". Advances in Industrial Control Series, Springer, 2014.

[133] A. Del Real, A. Arce, and C. Bordons. "An integrated framework for distributed model predictive control of large-scale power networks". IEEE Transactions on Industrial Informatics, Vol. 10(1), pp. 197-209, 2014.

[134] E. Planas, A. Gil-de Muro, J. Andreu, I. Kortabarria, and I. Martínez de Alegría. "General aspects, hierarchical controls and droop methods in microgrids: A review". Renew Sust Energ Rev, Vol. 17, pp. 147–159, 2013.

[135] Qi, W. J. Liu, and P.D. Christofides. "Supervisory predictive control for long-term scheduling of an integrated wind/solar energy generation and water desalination system". IEEE Transactions on Control Systems Technology, Vol. 20(2), pp. 504–512, 2012.

[136] Wu, L., Y. Hu, and C. Gao, "Optimum design of cogeneration for power and desalination to satisfy the demand of water and power", Desalination, Vol. 324, pp. 111–117, 2013.

[137] R. Porrazzo, A. Cipollina, M. Galluzzo, and G. Micale. "A neural network-based optimizing control system for a seawater-desalination solar-powered membrane distillation unit". Computers and Chemical Engineering, Vol. 54, pp. 79-96, 2013.

[138] R. González, L. Roca, and F. Rodríguez. "Economic optimal control applied to a solar seawater desalination plant". Computers and Chemical Engineering, Vol. 71, pp. 554–562, 2014.

[139] H. Chang, G-B. Wang, Y-H. Chen, C-C. Li, and C-L. Chang. "Modeling and optimization of a solar driven membrane distillation desalination system". Renewable Energy, Vol. 35, pp. 2714-2722, 2010.

and/or significant load changes. A heat buffer allows for short-term storage of heat to facilitate a more continuous supply to the desalination system. With model predictive control, variations in the energy supply can be anticipated and the operation point conveniently adapted to minimize a defined cost function. Analysis, design and application of modeling, forecasting, control and optimization techniques are proposed here in the framework of model-based predictive control or in a hierarchical control structure where an upper layer is devoted to determine optimal set-points.

The proposed research activities are: (i) development of dynamic models of thermal desalination processes, prediction models of energy sources and demand curves, and prediction models for environmental variables and disturbances; (ii) modelling of storage systems and auxiliary equipment for energy cost reduction; (iii) adaptation of the developed models for control purposes and validation in test-bed plants; (iv) development of hierarchical, hybrid and, in general, model-predictive based control and management strategies to optimize production from the economic and energy use points of view; (v) implementation and validation of the strategies in pilot plants over realistic conditions; and (vi) scaling of the developed models and control strategies to large-scale/commercial cases.

Model-based predictive control systems can help achieving a more efficient performance in solar thermal desalination systems. With significant savings in the investment on the energy collection system, solar thermal desalination can be more competitive. This can facilitate the implementation of autonomous solar thermal desalination systems for decentralized desalination. In addition, model-based predictive control strategies can reduce the carbon footprint of larger solar thermal desalination systems designed in a hybrid mode with fossil fuel support.

3.4.2 PV-RO and grid-scale PV

*G. Papadakis, C. S. Karavas, E. Dimitriou and E. Sh. Mohamed***,** *V. Fthenakis, A. Atia, C. Garcia Ortega, J. Barragan and J.L. Carvajal, Thomas Altmann, and Angelina Galiteva*

The main goal of the current research topic is the development of autonomous or grid-integrated renewable energy powered hybrid desalination systems that can drastically reduce CO_2 emissions, costs and energy consumption[140, 141, 142. 143]. Referring to actual renewable energy market, it experienced a quick levelized cost of

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[140] Fthenakis V., Atia A., Bkayrat R., Ng Kim C., Alghasham T., Khalid A., Sgouridis S., Prospects in Solar Water Desalination: Towards Affordable H_2O without CO_2, Proceedings 31st European Photovoltaic Solar Energy Conference, Munich, June 2016.

[141] S. Karavas, G. Kyriakarakos, K. G. Arvanitis, and G. Papadakis, "A multi-agent decentralized energy management system based on distributed intelligence for the design and control of autonomous polygeneration microgrids," Energy Conversion and Management, vol. 103, pp. 166-179, 2015.

[142] G. Kyriakarakos, A. I. Dounis, K. G. Arvanitis, and G. Papadakis, "A fuzzy logic energy management system for polygeneration microgrids," Renewable Energy, vol. 41, pp. 315-327, 2012.

[143] G. Kyriakarakos, A. I. Dounis, K. G. Arvanitis, and G. Papadakis, "A fuzzy cognitive maps–petri nets energy management system for autonomous polygeneration microgrids," Applied Soft Computing, vol. 12, pp. 3785-3797, 2012.

electricity adjustment within the past years. Such trend was particularly intense in the photovoltaic energy sector and especially with regard to grid-connected utility scale IPP bids and auctions all around the world (Figure 3.5).

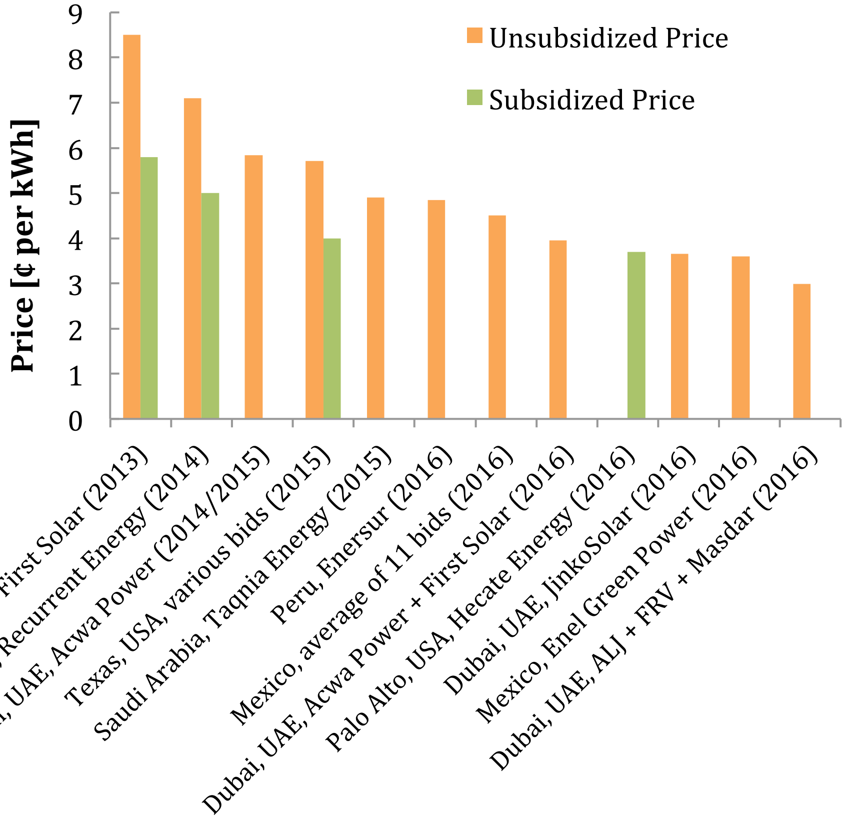

Figure 3.5: Low photovoltaic solar bids (2013–2016)[144]

Based on both the needs previously described for desalination systems and the actual photovoltaic energy cost trend, the target of this research topic is to investigate further that hybridization of PV+RO[145,146]. Both technologies could be considered today as mature technologies, so the main target is to investigate the optimum integrated solution taking into consideration the actual constrains that the referred hybridization has. Photovoltaic technology is an intermittent energy source

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[144] Saurabh Mahapatra , Dubai Gets Record-Low Bid Of 2.99¢/kWh For 800 MW Solar PV Project, May 2nd, 2016, https://cleantechnica.com

[145] Atia A., Fthenakis V., and Bkayrat R., Techno-economic Evaluation of Stand-Alone PV-Powered Seawater desalination Plants in Saudi Arabia, pp. 4075-4080, Proceedings 29th European Photovoltaic Solar Energy Conference, Amsterdam, Sept. 2014

[146] Fthenakis V., Atia A., Morin O., Bkayrat R., and Sinha P., New Prospects for PV Powered Water Desalination Plants: A case study in Saudi Arabia, Progress in Photovoltaics: Research and Applications, 4, 543–550, 2016.

with low capacity factor. So, it implies that the RO system[147] should not work in a continuous basis. The results of this would be a hybrid system with low-carbon emission but not economically better than the traditional RO systems. In addition to that, RO system would work at partial loads and RO system reliability should be properly analyzed in order to ensure the lifetime of the plant[148].

However, alternative solutions could be analyzed in order to increase the capacity factor and make it similar to actual operation mode for a RO plants and ensure the reliability of the PV-RO hybridization achieving the targets defined above: autonomous/grid-connected, low CO_2 emission, low cost and low energy consumptions. Such proposed alternatives are:

- PV + RO + CSP + Grid (as backup).
- PV + RO + EES (Electrical Energy Storage) + Grid (as backup).
- PV+ RO + CSP + EES (Electrical Energy Storage). Autonomous.

Our group will initially focus on the hybridization of PV with RO seeking to take advantage of two unique attributes of PV (low emissions and low cost). Because CSP has the intrinsic capability of dispatchability, it can be employed together with PV and EES with RO plants to achieve low CO_2 emissions and low cost.

The research issues that need investigation include but are not limited to the following:

1. The intermittent nature of solar energy and its effect on the PV + RO design optimization.
2. CSP and EES optimization for hybrid solution with and without Grid backup.
3. Quantifying fouling potential due to the intermittent operation.
4. The overall energy management and control of the system.
5. The overall design and optimization of the system components.
6. Quantifying the sustainability of the integrated system (technical, economic environmental and social sustainability) through holisitic Life Cycle Assessment (LCA). LCA will be useful in comparing the previously listed potential hybridizations.

Seawater desalination is an energy intensive process; therefore, clean energy solutions are of upmost importance for this technology. However, current desalination systems are heavily depending on fossil fuels as an energy source, resulting in higher CO_2 emissions. Current hybrid desalination systems are mostly combined with power plants to form dual-propose power-water systems that lower the cost of water and produced electricity. However, fossil fuels are still the main source of energy for electricity generation. The electricity and heat generation for

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[147] Dimitriou, E.Sh. Mohamed, C. Karavas, and G. Papadakis, Experimental comparison of the performance of two reverse osmosis desalination units equipped with different energy recovery devices. Desalination and Water Treatment, 2015. 55(11): p. 3019-3026.

[148] Dimitriou, E.Sh. Mohamed, G. Kyriakarakos, and G. Papadakis, Experimental investigation of the performance of a reverse osmosis desalination unit under full- and part-load operation. Desalination and Water Treatment, 2014. 53(12): p. 3170-3178.

hybrid water desalination units can be produced by renewable energy, such as solar energy. This will require optimization of the design and simulation of process operation, especially when the hybrid desalination units are operated under intermittent and variable conditions.

Due to the intermittent nature of solar energy, solar-powered desalination membranes could operate outside of their optimum operation window. Therefore, research is needed to investigate the effect of the variable and intermittent operation (non-stable pressure and flow rate) on the salt passage at the ion level, fouling (colloidal, biological and organic) and scaling (minerals and salts precipitates) of membranes. More specifically, simulation models of seawater RO membrane elements in part load operation are needed focusing on membrane aging. Furthermore, development of pilot systems in order to test the membranes' performance is required (i.e. destructive and non-destructive tests).

Considering the hybrid system with multiple solar technologies, electrical energy storage and with or without grid support, the complexity of the system and the intermittent operation conditions will need an advanced energy management (EMS) and control system. Therefore, a multi-agent decentralized energy management system will be implemented. This EMS is based on computational intelligence, where all the components of the system will be controlled and will be able to act as independent agents. The advanced control system gives the hybrid desalination units the possibility of operating at the optimum operation point according to the available RE power and according to the incoming feed water and the required quantity and quality of the produced fresh water. [149,150]

3.4.3 Nuclear-powered desalination

Leon Awerbuch, Ibrahim Khamis, and P.K. Tewari

Overview

Interest in using nuclear energy for producing desalinated water is growing[151]. The use of nuclear reactors for seawater desalination has already been demonstrated in several countries with operational experience of over 200 reactor-years. However, there has so far been only one large-scale nuclear cogeneration plant for seawater desalination — the desalination unit at the Aktau NPP in Kazakhstan, which was commissioned in 1973 and operated until 1990. The deployment of large-scale nuclear cogeneration for desalination may face several challenges which can be

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[149] Mohamed ES, Papadakis G, Mathioulakis E, Belessiotis V. The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system; experimental and economical evaluation. Desalination. 2005;184:241-6.

[150] Kyriakarakos G, Dounis AI, Rozakis S, Arvanitis KG, Papadakis G. Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. Applied Energy, Vol. 88, Issue 12, December 2011: 4517 - 4526.

[151] Report and Conclusions of Technical Meeting on the User-Vendor Interface in Nuclear Cogeneration for Electricity Production and Seawater Desalination, organized by International Atomic Energy Agency (IAEA) Vienna, Austria from 14 to 16 March 2016.

mitigated by appropriate technical or institutional measures. The challenges involved in nuclear desalination generally include: optimization of the plant design for cogeneration purposes; enhancing safety of coupling; establishing joint infrastructure; training of human resources for both disciplines (nuclear power industry and desalination); and assessing the financial capital and public acceptance.

The cogeneration of electricity and useful heat for desalination is advantageous in that the necessary infrastructural facilities can be shared, as in the case of hybrid plants, and it also provides inherent design strategies for better thermodynamic efficiency besides economic optimization. New improved designs with reduced lower specific energy consumption and low temperature evaporation processes that make use of waste heat or low grade heat as energy sources are an attractive option for newly deployed seawater desalination systems.

Both nuclear power and desalination technologies are highly mature, yet the coupling between the two is still an issue due to the variety of nuclear reactor types and desalination systems. Each reactor type and available design presents a number of distinctive features, with advantages and disadvantages for the specific case under study. These features should be evaluated and used to form the basis upon which the final decision to develop a cogeneration plant is made. However, it should be noted that the designs of modern commercial NPPs, which have been developed and standardized for the conditions prevailing in industrialized countries, might not be applicable for cogeneration purposes in less developed countries without modifications to take into account the local conditions there. Among other factors that should be taken into account in the choice of reactor type and desalination plant are the possibilities for local participation in the project, financing prospects, and transfer of technology. In order to ensure the effective localization and integration of nuclear desalination technologies as part of a cogeneration system, it is essential that potential users in less developed countries receive as much information as possible from the vendors of reactor designs and desalination technologies.

The analysis of the nuclear power reactor and desalination plant supply market also includes the evaluation of the potential supplier industry for both the nuclear reactor and the desalination technology. The international trade in nuclear equipment and materials is conducted under the control and supervision of the governments involved and is under strong political influence. Depending on the political and commercial relations between the importing country and the potential exporters, the effective availability of suppliers might be limited to a few (or even just one) potential suppliers. This would imply also a possible limitation on the choice of the available nuclear cogeneration types.

A greater understanding of the considerations, constraints and requirements involved is required among the users and vendors of both nuclear power and desalination technologies.

With dramatic interest in finding solutions to combat climate change in view of the impacts of global warming on water resources, nuclear desalination can offer significant potential to substitute fossil fuel as a source of energy for desalination. The preservation and creation of freshwater resources by desalination is not only an essential challenge for sustainable human development; without water, there will be no agriculture and thus no food security, no industry and thus no economic development. To champion environmental responsibility, making new water affordable to all people by desalination and water reuse it requires use of alternative nuclear and renewable energy to power desalination and should be a mandate throughout the world.

Broad RD&D needs

In nuclear desalination, the RD&D work needs to be oriented in the direction of cost reduction strategies through technological innovations starting from basic research to demonstration and deployment with out-of-box approach. Future RD&D efforts in nuclear desalination may be directed in the following directions:

- Energy efficiency
- Need to understand coupling aspects
- Design & development of high performance coupling systems
- R&D on nuclear fuel cycle and reactor type as energy source
- Small size nuclear reactors (especially small modular and "micro" reactors with power ratings <300 MWe and <10 MWe, respectively)
- Low grade and nuclear waste heat utilization
- Environmental aspects
- Cogeneration aspects

The outcome of the R&D efforts will help in (i) bringing down the carbon footprint; (ii) making the water technologies more affordable to the bottom of the pyramid in society; (iii) addressing the environmental concerns; (iv) cogeneration of water and electricity. Nuclear desalination has potential to play an important role in ensuring energy, water and environment security which are basic life support systems. There is need for establishing a 'Centre of Excellence' addressing broad spectrum of research, development, demonstration and deployment.

Specific concept: MED-RO-Nuclear Hybrid

Leon Awerbuch and Ibrahim Khamis

Expert consensus[152,153] indicates straight MED technology hybridized with RO as best suited for nuclear desalination. The optimal technology solution for nuclear desalination was considered a hybrid of Multi-Effect Distillation (MED) with Reverse Osmosis (RO). The MED unit size and efficiency in recent year's demonstrated full ability to reach unit size of 50,000 m^3/day and in the near future

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[152] Report and Conclusions of Technical Meeting on the User-Vendor Interface in Nuclear Cogeneration for Electricity Production and Seawater Desalination, organized by International Atomic Energy Agency (IAEA) Vienna, Austria from 14 to 16 March 2016.

[153] https://www.iaea.org/NuclearPower/News/2016/2016-03-24-NPTDS.html

up 91,000 m^3/day. Today, the Gained Output Ratio (GOR) is exceeding GOR = 11 and in the future will exceed GOR = 15. The electrical energy consumption is between 0.9 kWh_e/m^3 to 1.3 kWh_e/m^3. Seawater Reverse Osmosis (RO) has fully demonstrated its ability to reliably produce desalinated water with low electrical energy consumption of 3.5 kWh_e/m^3 (for the entire plant), and could run during construction of the nuclear plant, as well as, more importantly, during nuclear refueling, during maintenance and non-availability of nuclear steam. RO has been also proven for its use during nuclear emergency.

The integrated hybrid MED-RO design can make use of warmer seawater discharged from NPP or reject sections final condenser of MED to reduce energy consumption, reduce size of seawater intake and outfall. To minimize energy consumption and reduce power losses of NPP it is recommended to use straight MED with the lowest extractions steam pressure available using straight MED, rather than MED-TVC. To use steam from extraction section of NPP turbine 0.15 MPa cannot be sent directly to MED, because of high volume of steam at lower pressure the piping would be too big with very large diameter, making it economically not practical. We proposed an indirect energy transfer trough water transformer system. The power plant low pressure extraction steam is initially exchanged in a separate smaller condenser to a closed cooling water circuit. The heat absorbed by the water is transferred by pipeline to MED flashing chamber to provide steam for the first effect of MED at about 68.5 °C. The flashed water cooled to 68 °C together with portion of the vapor condensed in the first effect is pumped by return water pipeline to condenser at the steam turbine proximity. The significant benefits of such a design are listed below:

- Elimination of the large steam piping from power plant to the evaporators, including heat and steam loss.
- Elimination of the MED steam transformer as there is no need for a thermocompressor. The condensate is re-flashed deaerated and totally returns from first effect. No hydrazine contamination of the product.
- The heat can be transferred in water pipeline a long distance allowing NPP power and water islands to be at optimum location.
- We recognized that there is significant difference in construction time of NPP of at least 6 years versus desalination plant of 30 months, therefore it was recommended that the Feasibility Study and Minimum Functional Specification (MFS) be prepared at the beginning of the NPP project and the Final Specification for Desalination Plant with optimum Ratio of MED to RO portion will issue closer to beginning of constructions of desalination plant.
- The consideration has to be given to different life time design for NPP sixty years and desalination of 20-30 years with rapid changing and improving desalination technology.
- In specifying NPP and desalination islands it is recommended that the standards for desalination island both design and operations does not use nuclear design criteria but more conventional established desalination practice, however the monitoring of safety, radioactivity of air and water, quality of desalination products and brine needs to be responsibility of nuclear developer.

- It is recommended that the isolation loops, steam and water transformers as well as first effect of MED make use of titanium for heat exchange surfaces. The Ti tubes although more expensive can use smaller wall thickness compensating with lower wait and for lower heat transfer in comparison with Al-Brass or Cu-Ni 90:10.
- Close cooperation is required between suppliers of NPP-Desal and the countries purchasing the projects, independent if this is based on privatized approach 0tv IWPP or EPC contacts. There was a consensus on the need for better working relationship and cooperation between owners/ developers, users and suppliers and engineers to address some of the issues that are unique to the nuclear power stations
- An important understanding is required of local standards and regulations.
- Carefully assessment of the technical, financial and political risk needs to be provided.
- There is very important need to educate both parties the NPP and desalination islands about technology implication, operational and maintenance requirements of both. It really needs to provide extensive courses and training for the future operators of NPP-Desal plants. Managerial and skills required for safety, operation and maintenance,

It was recognized that continuous public relations campaign is needed to assure the public of safety, explain benefits and reliability of Nuclear Desalination.

4. Broader Environmental Issues:

Contributors: Noam Lior, Tom Pankratz

4.1 Sustainable desalination

Noam Lior

Reducing CO_2 emissions from desalination processes can be accomplished by increasing energy efficiency, fuel switching (primarily by using low embodied CO_2 emissions renewable energy), using/building low-embodied emissions plants, reducing the CO_2 releases to the atmosphere from the feedwater, brine, and distilled water, and by water and energy pricing that includes all the expenditures as well as the cost of the externalities, especially of the CO_2 emissions. CO_2 emissions reductions must be considered within a complete holistic analysis of desalination sustainability in general.

Although CO_2 emissions from water desalination amount to only 0.8% of the World's total (in 2011), their reduction to meet global warming arrest objectives is nevertheless an important goal. At the same time, it must be considered within a more holistic analysis of desalination sustainability in general[154], in which it plays only a very partial role. A problem in focusing the desalination sustainability challenge on CO_2 emission reduction may create other problems that worsen the sustainability of desalination, and if accomplished, may create an illusion of achievement of sustainable desalination.

Formally, the sustainability paradigm integrates the evaluation of **environmental**, **economic** and **social** impacts (the *sustainability pillars*) that are also strongly interconnected, in multi-generational time scales and affected space boundaries, as a quantitative measure for its evaluation; this requires cradle-to-cradle lifecycle and regional assessment. Consequently, any success in improving some sustainability indicator, such as specific CO_2 (more properly of all greenhouse gases) emissions, must be also examined and judged against its effect on all other environmental indicators, as well as on all the economic and social ones.

Refocusing now on greenhouse gas emissions generated by desalination, their primary sources are:

A. The used energy sources for the process (including water treatment), plant construction and operation and decommissioning, and water distribution and use,
B. Embodied emissions of the desalination and power plant,
C. The significant emissions from the feedwater, and perhaps discharge reservoir, due to the desalination process.

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[154] N. Lior, "Sustainability as the quantitative norm for water desalination impacts", Desalination (published on line), 15 August 2016. http://dx.doi.org/10.1016/j.desal.2016.08.008

The main technical ways to mitigate the consequences of item A above are increase of energy efficiencies of all processes, including the use of cogeneration and polygeneration, as well as "fuel" switching, including the use of renewable energies when it is not accompanied by significant greenhouse gas emissions. The latter may result from emissions embodied in the construction materials and ground surface modifications associated with large amounts of materials and surface that renewable energies use requires.

Item B consequences can be mitigated by appropriately innovative design and by choice of construction materials that have low embodied emissions, as well as convenient low energy and emissions recyclability.

Item C consequences are the most difficult to mitigate. In thermal desalination they result to large extent from raising the liquids temperature and thus releasing the dissolved CO_2. In that sense the ambient temperature processes like RO are in principle less emitting but the depressurization of liquids does cause some dissolved gas emissions. It may be possible to invent and implement devices to control and capture such emissions, but he latter still leave the captured gas without yet any available reliable way to properly dispose of it.

From the standpoint of the Social and Economic sustainability pillars, the most effective way to reduce greenhouse gas emissions is by internalizing this externality, i.e. including its cost in the price of energy and water and applying government subsidies only for users who cannot afford the real cost. This would not only reduce emissions but would also strongly increase water conservation and improve its management.

Research should be focused on:

1. Items A, B, and C described above.
2. Gradual transition to renewable energy use, perhaps focused on electricity generation so that RO can be used
3. System design and controls that maximize energy efficiency when using time-variable energy inputs and having variable water demands, i.e. with minimal energy storage and principally relying on desalted water storage.
4. Water pricing policy that is based on real costs, including the externalities, and emphasizing water conservation and management.
5. Significant expansion of the focus from just CO_2 reduction to full sustainability of desalination.

The broader issues include:

1. As already mentioned above, reducing CO_2 emissions from water desalination is indeed an important goal but must be considered within a more holistic analysis of desalination sustainability in general, in which it plays only a very partial role. A problem in narrowing the problem to just

CO_2 emission reduction may create other problems that worsen the sustainability of desalination, and if achieved, create an illusion of accomplishment of water desalination sustainability.

2. Obviously, the first effort in reducing emissions due to water desalination is to minimize its use by proper water management, including conservation, pricing, recycling, conveyance, and, more drastically, by not attempting to "make the deserts bloom" if not vitally necessary.
3. Encouragement of much higher and stable long-term R&D and education investment in this field, so that more sustainable methods can be developed.

4.2 The ins and outs of desalination

Tom Pankratz

Recent advances in membrane technology and energy efficiency have increased desalination's performance and reliability while reducing its capital and operating costs. These improvements are taking place at the same time that the cost of producing water from traditional sources has risen, and in an increasing number of locations, desalination can be employed on a cost-effective basis to treat brackish groundwater, seawater and even oilfield produced waters.

However, even as the cost and performance of the desalination process itself has improved, there are two aspects of a desalination system that may prove to be an insurmountable obstacle in the development of a project. These highly site-specific challenges are the plant's water intake arrangement and/or its concentrate disposal system.

Background

More than 19,000 brackish, seawater and industrial desalination systems, with a total production capacity of over 88 million cubic meters per day, have been installed since 1965[155]. In each of these systems, a saline water source is separated into two streams: a product water stream that is 'fit for purpose' and a concentrate stream that contains the dissolved solids that have been separated from the product water stream.

Despite the large number of plants installed, and the growing level of process standardization that exists, there are two elements of a desalination project that are unique to each project and represent its largest cost variables: the method by which a plant obtains its feed water and the method by which it disposes of its concentrate. Together, the identification of the technical, environmental and commercial issues of these two related issues must be considered as the first step of any project 'fatal flaw' analysis, including the energy intensity

Intake: Desalination facilities require an intake system capable of providing a reliable quantity of feed water. For seawater and other surface water plants, it is

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[155] GWI DesalData's *29th Worldwide Desalting Plant Inventory*, June 2016.

also desirable and cost effective to have a consistent water quality, while achieving *de minimis* environmental impacts.

These intake-related environmental impacts that are normally of most concern are *impingement*, which refers to trapping fish and other larger aquatic organisms against the intake screen, and *entrainment*, which occurs when smaller organisms pass through the screen and into the process equipment.

Historically, many desalination plants have been co-located with electric power generation plants where they were able to share the use of power plant cooling water intakes. However, the US power industry's use of once-through seawater cooling systems is largely being abandoned for impingement/entrainment related reasons and some states require that surface water desalination plants be standalone facilities with purpose-built intakes.

Because intake designs are highly site specific—perhaps more so than any other aspect of the desalination plant—the design, modeling, monitoring and permitting activities that surround them may represent a significant portion of a project's capital costs. Whereas, seawater intakes formerly represented 4 to 12 percent of an entire facility's capital cost, some intake arrangements may now cost 25 to 50 percent of a project's capital cost[156].

Although brackish groundwater sources do not have impingement or entrainment issues, a wellfield that supplies brackish a water plant must consider subsidence issues or that the source water quality may degrade or the supply may diminish over time.

It is possible that intake-related issues may ultimately determine the feasibility of the desalination plant itself. Therefore, improving the intake option particularly for seawater desalination projects would likely provide the single biggest cost and environmental benefit to many prospective desalination projects, particularly seawater projects.

<u>*Concentrate Management*</u>: Depending on the desalination process employed, the concentrate (or "brine") resulting from a desalination process usually represents 20 to 60 percent of the total feed water flow rate (excluding the cooling water flow requirements of some thermal processes). Its potential environmental impact is a function of its total dissolved solids (TDS) concentration, which may range from 1.5 to 5 times the TDS of the source water.

Historically, the lowest cost alternative has been to discharge concentrate to a surface water; however, it is therefore necessary to mitigate the possibility of impacts related to chloride toxicity or other concentrate constituents.

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[156] T.M. Missimer, *Water Supply Development, Aquifer Storage, Concentrate Disposal for Membrane Water Treatment Facilities*, 2009.

A typical surface water concentrate discharge system for a desalination plant may represent 5 to 10 percent of a desalination plant's costs, whereas the deepwell injection of concentrate into a confined aquifer may be a significant, even prohibitive cost of a brackish water desalination plant, depending on the well(s) depth and distance from the plant.

Concentrate disposal alternatives for small plants also include discharge to a publicly owned treatment plant (POTW) or an evaporation pond.

Research needs

The aim of conducting research into these areas is to make desalination more environmentally and economically attractive in areas where it may currently be considered infeasible.

Intakes: Research related to intakes might consider new methods of mitigating the environmental impacts of surface intakes could consider:

- Determine new methods of siting intakes to minimize impingement and entrainment,
- Develop new intake screens/devices that exclude organisms larger than 0.5 mm,
- Addressing macrofouling challenges and better cleaning/mitigation measures in marine environments and
- Develop better statistical models/methods to quantify the impact on marine populations and,
- Develop/improve subsurface, i.e. sub-seabed, intake arrangements such as slant wells, radial wells and infiltration galleries.

Concentrate: Several concentrate-related research opportunities may be considered:

- Volume reduction – By improving desalination process recovery rates, or by employing additional hybrid desalination processes (e.g. high recovery RO, membrane distillation, forward osmosis, etc.), there will be a two-fold benefit; the first being reduced concentrate volumes requiring disposal, and the second being the increased water production with its associated benefit of eliminating the cost of additional pretreatment infrastructure,
- Zero liquid discharge (ZLD) – ZLD or near-ZLD means the elimination of discharge permits and (presumably) the recovery of virtually all water for beneficial reuse and,
- Resource recovery – There are likely to be some opportunities, albeit limited, to recover minerals or other constituents from concentrate.

Outcomes

One report has estimated the amortized capital cost component of the total water cost at 38 percent of the total water cost[157]. In a typical seawater RO plant, the capital cost of an intake and outfall can represent 20 percent or more of the capital cost. Therefore, it is clear that any improvement in the cost of an intake/outfall can have a material impact on the cost of water.

Desalination is proving to be a reliable alternative water supply and an important component of a weather-independent water supply portfolio. It has also shown that it can have the following *quantity-related* benefits:

- Increased reliability of the water supply,
- The avoidance of curtailing economic activities due to water shortages,
- The reduction of withdrawals from the overdrawn natural water storage bodies to avoid further seawater intrusion and,
- The addition of "new" municipal wastewater, which is available for treatment and reuse.
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Desalination also often provides the following *quality-related* benefits as a result of blending the high-grade desalted water with lower grade natural water:

- Reduced hardness lowers scaling rates of water heaters, appliances and piping,
- Lowers consumption of detergents and scale-cleaning chemicals; and, improves laundering and dishwashing quality,
- Lower chloride and sodium concentration in reused wastewater reduces irrigation rates, and
- Improves crop productivity and reduces soil damage[158,159].

The impact of this research should result in a more predictable permitting process, lower development costs and a reduced total water cost that would enable desalination technology to be employed where it might not have been previously considered.

4.3 Brine treatment, mitigation, and avoidance for desalination operations

Mohammad A. El Ramahi

Desalinating saline water sources using current best practices generates a stream of brine, which is regarded as a waste or by-product stream. In seawater desalination applications the brine is typically disposed of in the sea, while in-land desalination applications have to rely on other means such as evaporation ponds or injection in disposal wells. Advanced environmental modeling and outfall technologies seek to minimize the environmental impact of disposing the brine to the environment. However, certain regional and local conditions call for the mitigation or avoidance of

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[157] GWI *Desal Market Report*, 2010.

[158] *Water Desalination Report*, Volume 52, number 26, 27 June 2016.

[159] A. Tenne, D. Hoffman, E. Levi, *Quantifying the actual benefits of large-scale seawater desalination in Israel*, April 2012.

brine disposal to the environment. These conditions include concerns over rising local salinity levels of the sea, an aquifer, or on land, and the limited availability of saline water sources inland.

Technologies to increase the recovery of fresh water from saline sources—brine concentration and zero-liquid-discharge (ZLD) technologies—exist, but are associated with high cost and high energy consumption. Moreover, most of the currently available technologies show difficulties in extracting potentially valuable components that are present in the brine at low concentrations. Extracting such components can potentially enable economically viable brine concentration or ZLD solutions, mitigating or offsetting the brine treatment costs. Economically viable brine treatment can avoid or mitigate the potentially negative impacts resulting from desalination and increase the recovery of limited inland water resources. Research and demonstration of new brine treatment technologies capable of recovering valuable components, and mitigating or avoiding brine discharge at a low cost and high energy efficiency is therefore required.

Specific Aims

- Solutions should be—or have the potential to become in the near future—economically viable to such an extent that environmental regulations are not the single driver for the implementation of these new solutions;
- The recovery of valuable components, even if present in low concentrations, from brine should be regarded as a potential means to achieve economic viability of the solution;
- The solutions should take into account the utilization or disposal of the potentially high quantities of non-valuable components such as common salts;
- Examples of local and regional conditions calling for new solutions:
    - An increasing salinity of seawater, either due to limited mixing at local intakes and outfalls or due to the limited natural mixing of the body of seawater with lower salinity water sources such as other seas or oceans, rivers, rainfall, etc.;
    - Limited saline groundwater sources with limited to no natural recharge;
    - The avoidance or mitigation of contaminating (salinity, chemicals, other) saline water reservoirs with discharged brine at inland locations.

Outcomes

- Improved resource utilization of limited natural resources by an increased recovery of fresh water and other components from limited saline water resources;
- Mitigated or avoided negative environmental impacts resulting from the generation and discharge of brine from desalination operations;

Intermediate results:

- Prioritized list of physical, chemical, biological, mechanical, etc. processes that show the most promise to achieve low cost, high energy efficiency, resilience and economically viable brine treatment enabling mitigation or avoidance of brine disposal.
- Bench scale demonstration of solutions capable of the economically viable mitigation or avoidance of brine disposal from seawater desalination and/or saline groundwater desalination from multiple sources (i.e. complex brines with multiple salts, other recoverable components and possible contaminants);
- Demonstration, by pilot under real-world conditions, of at least one solution.

5. Selected Regional Perspectives and Case Studies

Contributors: Mark Johnson, Boris Liberman, Alexander Ritschel, Adel Sharif, Yuan Zhang

5.1 USA: R&D opportunities for cost- and energy-competitive clean water production

Mark Johnson

In June 2013, the Obama Administration's Climate Action Plan[160] based on three key thrusts—cutting carbon emissions in the United States, preparing the United States for the impacts of climate change, and leading international efforts to address global climate change. Additionally, the Administration announced a U.S. target of a 26-28% reduction (from 2005 levels) in GHG emissions by 2025 as part of the U.S.-China announcement on climate change and clean energy cooperation.

For policymakers, meeting these targets intersect with the increasingly severe instances of water stress across the United States. Indeed, water stress in the US is no longer limited to California. Population growth in coastal areas in Texas and Florida have grown 20% during the last decade and share similar levels of water stress. The arid heart lands (south west and mid-west) depend on fresh water aquifers and rivers whose resources are dwindling and are projected to be insufficient to meet future needs. The mid-Atlantic, which is generally not considered draught sensitive faces stress emanating from needs of rising population and their need for power (which uses water) which is stressed further by salt water intrusion into aquifers from the Atlantic Ocean[161]. To counter the pending water stress, we need to develop a strategy to utilize the vastly available non-fresh water sources, which includes (in order of low to high salinity) treated wastewater, brackish water (aquifers cover nearly the entire heartland), agricultural waste water, sea-water and extracted water from CO_2 injection, and produced water from oil gas, and also to address potential bio-contaminants.

To achieve a goal of "pipe parity"—meaning clean water produced from a range of sources for various uses such as municipal drinking water, the opportunities for energy minimization and use of clean energy in water production need to be identified. The key enablers for achieving pipe parity will be materials innovation, innovative devices, cost-effective manufacturing, process control and system/plant level control and optimization.

The consumption of energy for producing clean water can, depending on the salinity level, be substantial; e.g. the energy cost for desalination alone for sea water is 2–5 kWh per m^3 of supplied municipal water. When adding the energy cost for the other steps, the combined energy consumption and associated CO_2 output (considering electric power derived from fossil sources) would soon outweigh that of the steel industry if desalination of sea water was expanded to offset fresh water intake for

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[160] https://www.whitehouse.gov/sites/whitehouse.gov/files/achievements/atf_climate_booklet.pdf

[161] UN Water, Policy Brief (2011)

potable use. Production of clean water in a manner that reduces energy consumption and GHG emissions while remaining cost-competitive is a systems-level challenge that depends on a number of variables associated with the intake, pre-treatment, desalination, post-treatment, waste stream management of the water and transport of the purified water to the target. Further, the importance of these relative variables depends both on source (e.g. brackish, seawater, produced waters, extracted waters) and use (municipal, industrial, agricultural).

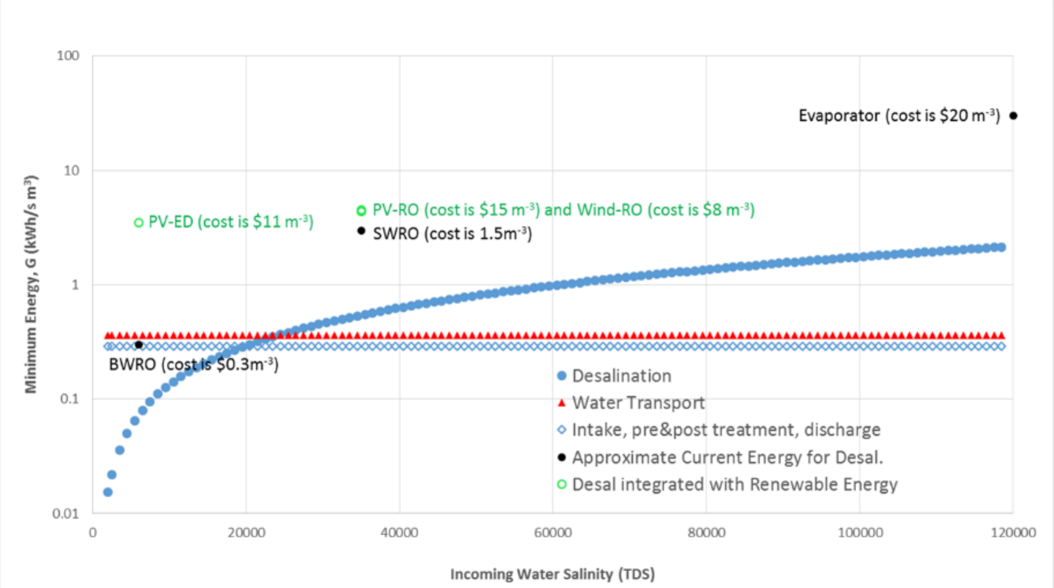

Figure 5.1: Minimum energy consumption for desalination in comparison to other costs and actual industrial consumption

While energy efficient desalination forms a core element of low-GHG clean water production, from a systems-level perspective its relative importance may differ. Figure 5.1 shows the theoretical limit for desalination (when assuming 50% recovery, to a salinity of 500 TDS, based on minimum thermodynamic work[162]) in comparison to an approximate estimate for transporting the water through a horizontal tube for 1 km (as a 1st approximation through estimation of friction loss according to the Darcy-Weisbach equation) along with approximate values for pre-treatment and post treatment. The figure illustrates the relative importance of lowering energy for desalination when considering different water sources. For example, the energy (and hence emissions) opportunities for water recovery from brackish waters—which could potentially supply usable water for a majority of the inland United States—may be less than energy savings association with energy efficient pumping and implementation of smart manufacturing technologies, depending on the distance water must pumped. Thus, focusing on energy-efficient desalination technologies alone is insufficient to make low-GHG clean water

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[162] Yunus Cerci, Yunus Cengel, Byard Wood, Nafiz Kahraman, and E. Sinan Karakas, Improving the Thermodynamic and Economic Efficiencies of Desalination Plants: Minimum Work Required for desalination and Case Studies of Four Working Plants, Program Final Report for US Department of the Interior, Bureau of Reclamation, 2003.

production techno-economically feasible in many regions where water scarcity is an increasing concern.

The figure also includes typical values for Reverse Osmosis (RO) plants when applied to sea and brackish water and for a thermal evaporator operated plant for high TDS. The latter shows that reducing the energy consumption (and associated C footprint for desalination is paramount for the case of highly saline water sources, such as those originating from deep underground injection of CO_2 where energy efficient RO technology cannot be used. While this currently remain a niche area, it could become substantial if deep well CO_2 injection becomes part of the CCS strategy[163]. Sea-water is an intermediate case where there is room for more energy efficient desalination but equally so for improving efficiency in the other areas.

Figure 5.1 also has data points for reported energy consumption for desalination powered through renewable sources (PV) and suggests that current barriers are related to the significantly higher cost. There are other challenges associated with renewables due to variable power and ability to scale up to provide adequate power to large plants.

When considering the identified challenges and opportunities, there exist a range of R&D opportunity spaces with the potential to achieve "pipe parity"—meaning clean water produced from a range of sources for various uses at or below current cost, energy use, and emissions:

- Materials (anti-corrosion piping, anti-fouling, high salt rejection membranes/filters etc.)
- Novel design of devices (e.g. alternative desalination techniques required for very high TDS, Desalination methods that may be directly integrated to renewable power sources like solar-thermal, membrane-less desalination, Efficient pump designs, energy recovery systems)
- Manufacturing (cost effective materials and parts, e.g. solutions to some materials challenges may exist but are too expensive to commercially adopt)
- Process understanding and control (separations, heating, pressurization, energy recovery, bio- treatments)
- Systems-level integration (to account for power and contaminant variability; e.g. salinity or bio-organism variations due to GHG or other causes and for integrating solar/wind/wave energies where variable power supply needs to be compensated)

Given the diversity of water needs and respective requirements, there are multiple shared technical challenges that need to be addressed to demonstrate pipe-parity approaches to clean water processing and production (e.g. non-fouling membranes or efficient pumps). Likewise, some challenges such as integration with renewables may be specific to certain cases. What is certain however, is the need for research

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[163] US DOE, Office of Fossil Energy, http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-storage-rd

spanning across TRL (Technology Readiness Levels) from basic foundation research (e.g. materials discovery) to enabling technologies (e.g. manufacturing) to system test beds to industrial adaptation.

5.2 Sorek and Carlsbad: pressure center design and variable tariff pricing

Boris Liberman

The SWRO Pressure Center Design is implemented in the world's desalination plants - Ashkelon, Commissioned 2005; Hadera 2010; Sorek 2013; Carlsbad 2015. All the above desalination plants incorporates IDE's developed pressure center design. The pressure center provides a cost effective solution for large plants, where low power consumption, flexibility of operation, online maintenance, and high availability and reliability are of critical importance to ensure continuous and economical water production.

The Pressure Center design includes three main components:

- **Pumping Center**: Large, 6MW each, high efficiency high pressure pumps (usually three in operation and one standby) to feed all RO trains.
- 14 to 16 **SWRO Membrane Trains**, with 140 pressure vessels each containing eight RO elements.
- **Energy Recovery System** (ERS): One common block of energy recovery devices serves all RO trains.

The pressure center design offers the following benefits:

- Lower energy consumption due to high efficiency of the large high pressure pumps and motors.
- Variable production – flexible regimes (peak and non-peak hours), without stopping the trains, providing extremely low specific power consumption when lower than design production rate is required.
- Flexible operation of RO trains at fluctuating salinity and temperature conditions.
- High standby reserve ensures uninterrupted water production and high availability and reliability.
- Significantly reduced carbon footprint.

The flexibility of the Pressure Center design is based on the fact that a large membrane area – 2000 pressure vessels – is connected to large number of energy recovery devices, and large high pressure pumping capacity. The flexibility is a result of the system's ability to connect these three components in different configurations. At the time of a low production request, it must be taken into account that all membranes and all energy recovery systems are connected to a small high pressure capacity, which provides extremely low specific power consumption. This low specific power consumption occurs due to low flux per membrane area, and the consequent low losses of said low flux. The large energy recovery capacity allows operation with low recovery and low average osmotic pressure (feed-brine).

A Pressure Center based RO plant can operate effectively with significant fluctuations in power supply until almost zero, as it has a "Hot Shut Down" regime when high pressure pumps are not in operation. Nevertheless, all membranes and ERS systems will be maintained at pressure of approximately 25 bar for about one hour. The Direct Osmotic forces maintain this pressure.

On return of the power supply, the high pressure pump starts within seconds, and the RO process for the production of water begins. Starting the RO system from the 25 bar "Hot Shut Down" regime is very different from starting it from zero pressure, which can take long time.

This ability to make rapid changes in the production rate is implemented in the Hadera desalination plant, where there is a significant difference in the night and day power tariffs.

The Hadera plant has been in operation for 10 years, with daily changes in the production capacity from about 18,000 m^3/h to 7,000 m^3/hr within a few seconds, with all product water quality parameters complying strictly with the specifications.

This flexibility can be used for operation with solar and wind power stations, where the power supply is flexible, providing the additional benefit of low carbon footprint. The design of RO desalination plants using the pressure center design allows use of these plants as large and cost effective energy accumulators.

The Carlsbad desalination plant

The San Diego County is a semi-arid region that suffers serious droughts and has very limited local water resources. As part of its long-term strategy, the County Water Authority has adopted desalination as a vital solution to enhance the region's water supply. The Carlsbad Desalination Project is a crucial element of this plan, and will provide sufficient high-quality drinking water to meet 7% of the city's potable water needs.

The Carlsbad project includes a seawater reverse osmosis desalination plant and conveyance pipeline for the production and delivery of 54 million US gallons of drinking water a day (204,412 m^3/day) to the San Diego Water Authority. IDE Technologies was contracted for the Engineering, Procurement and Support Services, as well as Operation and Maintenance (O&M) for a period of 30 years. The desalination plant design is based on well proven technologies that have been successfully implemented in long operating SWRO plants Ashkelon and Hadera in Israel, among them IDE's proprietary Pressure Center design.

The Carlsbad plant is the largest, most technologically advanced and energy-efficient desalination plant in the western hemisphere, in which the carbon footprint has been almost entirely eliminated.

The project is adjacent to, and north of, the Encina Power Station. The intake pump station is connected to the east side of the outflow structure. One hundred and ten million gallons (mgd) of seawater are delivered daily to the desalination facility, for the production of 54 million gallons per day (mgd) of potable water.

Figure 5.2: The Carlsbad desalination plant

The raw seawater, which contains 34,500 ppm Total Dissolved Solids (TDS) and up to 30 ppm suspended solids, is pretreated in a robust system, which has been designed to allow flexible operation parameters, as well as accommodate expected red tide, rain and algae bloom events. The pretreatment is based on flocculation and coagulation of raw seawater, followed by deep bed gravity Multi media filtration.

Sorek SWRO plant

The Sorek desalination plant, located in the south of Israel, is the world's largest and most sophisticated plant. The Sorek SWRO desalination facility is capable of producing 165 million gallons per day (mgd) (624,000 m^3/day) of potable water from the Mediterranean Sea, which is delivered to the national water distribution system. The plant sets significant new benchmarks in both desalination capacity and water cost. IDE deploys its proprietary advanced Pressure Center desalination technology. The plant also includes, for the first time in a large-scale facility, 16 inch membranes in a vertical arrangement of the pressure vessels.

Figure 5.3: The Sorek desalination plant

5.3 United Arab Emirates

Alexander Ritschel

The UAE is considered a “water scarce” country. The UAE has just 83 cubic meters of renewable water per person per year – well below the UN scarcity threshold of 1,000 cubic meters. This has led the UAE to become reliant on seawater desalination to fulfill a large share of its water requirements.

Based on future projections on the water needs for the UAE, the country will require additional water desalination capacity as early as 2021. This inspires the UAE to find new and sustainable solutions capable of addressing water demand in a water scarce country. As stated by His Highness Sheikh Mohammed bin Zayed Al Nahyan, Crown Prince of Abu Dhabi, in 2011: “Water is more important than oil for the UAE.” Even with the UAE’s robust economy and modern infrastructure, the need for water continues to be a critical priority for our nation’s agenda.

The UAE is investing heavily in cutting-edge technologies to improve energy efficiency and overall performance of desalination technologies. In this respect, in

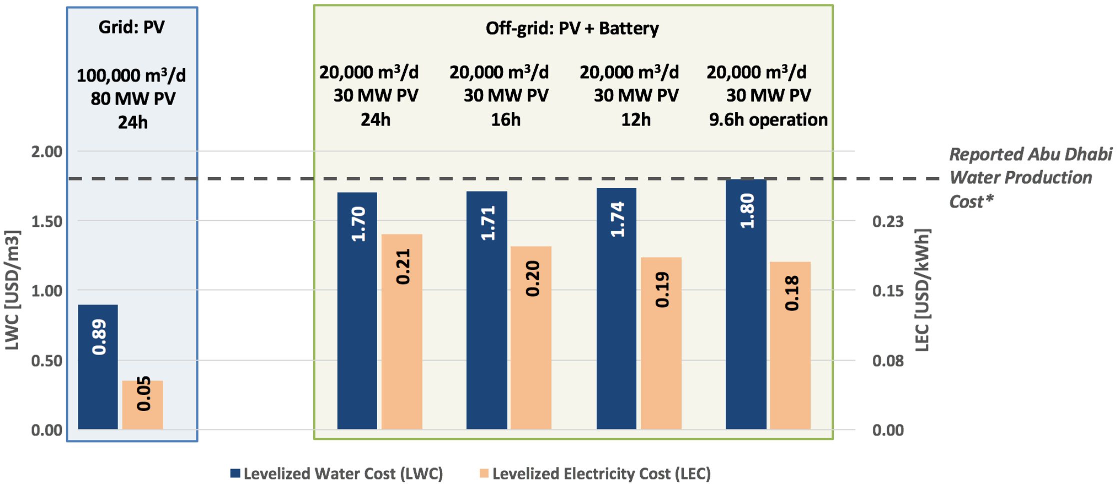
2013, Abu Dhabi Future Energy Company – Masdar; launched the Renewable Energy Seawater Desalination Pilot Program. The program develops and demonstrates highly energy-efficient, cost-competitive advanced and innovative seawater desalination technologies that are suitable to be powered by renewable energy. Moreover, these technologies will be easily scalable to utility size, improving the access to water within the UAE, Middle East and the World. The Abu Dhabi Government is sponsoring this Masdar led initiative, with significant co-funding provided by participating industry partners.

After a competitive tender for which 24 companies applied, four commercial partners were chosen: Abengoa, Suez, Veolia, and Trevi Systems. A fifth company, Mascara NT, joined the program in 2016. Each partner constructed and is operating a pilot plant deploying advanced or innovative desalination technologies. Operations will span about 16 months to demonstrate reliability, robustness and perform further optimizations on site. The five pilot plants are located in Ghantoot, within the Emirate of Abu Dhabi and benefit from accessibility to deep seawater.

Two categories of seawater desalination technologies are included in the program: advanced seawater desalination technologies; and innovative seawater desalination technologies. The target energy intensity of the demonstrated reverse osmosis technologies is 3.6 kWh/m^3. This value refers to an annual average and is based on feed water with a concentration of total dissolved solids of 42,000 mg/l and a temperature of 30°C. During the first stage (about 10 months), the plants will operate on a continuous basis in order to demonstrate continuous high efficiency and reliable performance of the new technologies. The second stage of the program (about 6 months) has a more experimental character, and the partners can adapt and improve the plants to further innovate on their technology. The large-scale deployment and implementation of one or more of the developed energy-efficient desalination technologies in the UAE or elsewhere is envisaged after the end of the program.

As a rule of thumb, seawater desalination requires 10 times more energy than the treatment of fresh surface water. This puts pressure on the energy and carbon footprint of countries such as the UAE. The current natural gas fueled power and desalination plants contribute about one-third of the UAE's total greenhouse gas emissions. Deploying more energy efficient desalination technologies such as those piloted by Masdar and its partners have the potential to save the Emirate of Abu Dhabi about $90 million annually in energy costs alone if 15% of Abu Dhabi's future desalination capacity incorporates these energy-efficient technologies.

An important effort within the UAE to reduce the emission of global greenhouse gases of desalination is the push for renewable energy. The vast majority of current desalination capacity is co-located and directly coupled with natural gas fired power plants, providing the required electricity and thermal energy to desalination water. Techno-economic modeling of numerous scenarios has resulted in a preliminary insight into the viability of solar powered desalination for the UAE. Figure 5.4 below provides an overview of the estimated cost of water for grid-connected and off-grid solar powered seawater reverse osmosis desalination systems in the UAE. The off-grid scenarios incorporate different operational modes: ranging from 24h operation of the desalination system (high reliance on energy storage) to 9.6h operation (high reliance on water storage).



* As reported by the Abu Dhabi Regulation and Supervision Bureau and adjusted to exclude transmissions and distribution cost.

Figure 5.4: Estimated cost of water for multiple solar powered seawater desalination scenarios in the UAE[164].

Further research on the technical limitations and opportunities for desalination to provide demand response services to the electricity grid are of high relevance to the UAE and the wider region. The region is characterized by a very high potential for solar technologies, and the UAE is rapidly expanding the share of solar (especially photovoltaic) power in its electricity mix. Desalination plants may be able to fulfill an important role in balancing electricity supply and demand, mitigating the lack of dispatchability that characterizes most solar energy technologies. However, concerns on plant reliability, energy efficiency and lifetime under a more flexible operation of desalination plants have to be addressed. Advancing this field of research by developing and demonstrating solutions is expected to support the adoption of solar technologies in the UAE and the Middle-East even at high solar penetration ratios for local electricity grids, further reducing greenhouse gas emissions.

Through public and private sector cooperation and innovation, Masdar anticipates real opportunities for the UAE to bring to the global market a next generation of desalination technologies. The UAE's approach to looking at water in the context of a broader water-energy nexus enables the country to address multiple sustainability challenges in a more holistic manner. This program, by bridging the gap between

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[164] Florian Hemmer, Alexander Ritschel, Sophie Bertrand, Camila de Matos Passos, Hassan Arafat, Arttu Tuomiranta, Savvina Loutatidou: "Techno-economic modelling of solar-powered seawater reverse osmosis desalination in the UAE," 2016.

Research and Development (R&D) and commercial implementation, provides tangible opportunities for local and international innovators to scale up, pilot and demonstrate technologies addressing water access and carbon dioxide emissions from desalination.

The partners active in the pilot program have also teamed up with the Masdar Institute of Science and Technology (MI) to jointly conduct R&D on desalination. The resulting five industry-funded research projects operate alongside the pilot program. The projects address different topics in desalination aligned with the needs of the pilot plants, these R&D projects include theoretical and experimental assessments, lab scale prototypes and recommendations for further improvements on the topic. Table 5.1 below identifies the above mentioned R&D projects:

Table 5.1 R&D projects associated with each partner company

Partner	R&D Project with MI
Abengoa	Strategies to reduce scaling and fouling in membrane distillation based on extensive evaluation of scaling and fouling chemicals and processes in the lab and pilot plant.
Suez	Develop an optimized design of a full-scale solar energy powered seawater reverse osmosis plant.
Trevi Systems	Development and manufacturing of advanced membranes for Forward Osmosis
Veolia	Evaluation and demonstration of different capacitive deionization systems to replace the second pass reverse osmosis treatment step.
Mascara	Evaluate and recommend cooling methods of photovoltaic (PV) panels for off grid solar desalination to increase PV efficiency and lifetime.

Traditionally, the Middle East desalination market is largely driven by a demand for robustness rather than energy efficiency. This has led to a situation where seawater desalination has typically been realized through rather energy-intensive thermal driven processes. The pilot program and R&D projects aim to offer viable solutions for a next generation of desalination, characterized by high energy efficiency and reliance on renewable energy. Given that the installed desalination capacity within the GCC region accounts for about 50% of the world's capacity, the research, development, piloting and demonstration in the region is of high importance.

5.4 India

P.K. Tewari

India has a highly seasonal pattern of rainfall, with 50% of precipitation falling in just 15 days. As per Central water Commission, total annual rainfall in the country is estimated as 4000 billion cubic meters (BCM). The utilizable or internally renewable water resources are estimated to be 1200 BCM. The annual water demand is increasing. It was about 800 BCM in 2010 and estimated to touch 1500 BCM in 2050 which is more than the utilizable or internally renewable water resources. There are areas which face perennial water shortage. Several regions are suffering from excess contaminants like salinity, fluoride, iron, arsenic, heavy metals and microbial contaminations of ground water. Growing population in cities and industrial growth are putting great stress on the aquatic environment. The adverse impact of climate change may lead to variation in rainfall patterns and evaporation rates. Any such changes would have major implication on water and environment. Nuclear desalination and low carbon water purification has potential to offer solutions to the challenging water issues. BARC has an active R&D program on desalination and water purification.

Seawater desalination provides an additional source of fresh water, thus enhancing fresh water availability in the coastal areas. Interest in using nuclear energy for producing potable water from seawater has been growing worldwide. Nuclear energy has capability to reduce the carbon foot print providing low carbon desalination. It can be used in the form of heat/ electricity for producing fresh water from seawater. Nuclear desalination involves three technologies: nuclear, desalination and their coupling system. A Nuclear Desalination Demonstration Plant (NDDP) based on hybrid technology was developed in BARC and is operational at Kalpakkam in India (see Fig. 5.5). The hybrid 4500 m^3 per day high performance Multi-Stage Flash (MSF) and 1800 m^3 per day advanced Reverse Osmosis (RO) desalination system, together constitute the largest capacity 6300 m^3 per day operating nuclear desalination plant based on hybrid technology attached to Madras Atomic Power Station (MAPS). It produces two qualities of desalinated water from seawater: distilled water for high end applications from MSF and potable water for drinking and other uses from RO. Co-location of desalination and power plants has benefit of sharing the resources and infrastructural facilities.

MAPS MSF RO

Figure 5.5: Nuclear Desalination Demonstration Plant (NDDP) at Kalpakkam (India)[165]

There is scope to utilize low grade heat/waste heat of nuclear reactors as energy source. A 30,000 litres per day low temperature evaporation (LTE) seawater desalination plant utilizing waste heat of nuclear research reactor was also set up in BARC, Trombay (Fig. 5.6). It uses waste heat of the cooling water being used for cooling the reactor. The technology has been transferred for deployment in a commercially viable manner.

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[165] S.T. Panicker and P.K. Tewari, "Nuclear Energy for Water Desalination", Nuclear Energy Encyclopaedia, John Wiley & Sons, pp 65-70, 2011

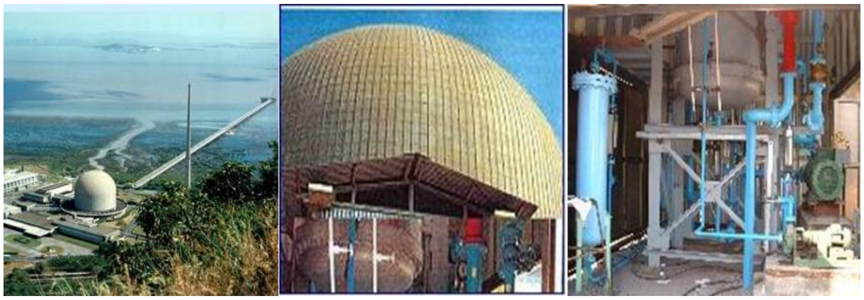

Figure 5.6: LTE Seawater Desalination Plant utilizing Waste Heat of Nuclear Research Reactor[166]

There is need for future R&D efforts, which may include the following directions:

- High performance energy efficient systems
- Need to understand coupling aspects
- Design & development of advanced coupling systems
- R&D on nuclear fuel cycle and reactor type as energy source
- Small size nuclear reactors
- Low grade and nuclear waste heat utilization
- Hybrid desalination technologies
- Recovery of uranium from brine and sea water

BARC has developed several types of low carbon water purification technologies (Indian Patent nos. 19596, 186210, 186375, 194101, 194106, 195317) for rural and remote areas (Fig 5.7). Field demonstration of the technologies for purification of raw water contaminated with bacteria, virus, fluoride, arsenic, iron and other contaminants has been carried out in different parts of the country. The water purifier does not require electricity. It causes no wastage of water and can be maintained easily. It costs about US $15 a piece. With a capacity of 350 litres per hour, the community project costs around US $1500 to set up. There is need for research and development in enhancing the membrane performance and life to make them more affordable.

(a) (b)

Figure 5.7: (a) nanocomposite membrane-based water purification and (b) community-level water purification unit in remote area[167]

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[166] S.T. Panicker and P.K. Tewari, "Nuclear Energy for Water Desalination", Nuclear Energy Encyclopaedia, John Wiley & Sons, pp 65-70, 2011

Renewable energy based low carbon desalination and water purification systems have also been developed. Small and community size solar energy driven Reverse Osmosis (RO) and Ultra-Filtration (UF) units have been demonstrated for producing clean water. Bicycle mounted solar based RO and UF units of 10 and 80 litres per hour capacity respectively, have been demonstrated and technology transferred. Thermal and membrane based technologies for waste water treatment and water recycle have high potential in industrial sectors leading to effective water management, product recovery from effluent and minimal waste disposal. There is need for development of membrane capable of removing particular species from the effluent/ waste water stream.

The R&D efforts will help in (i) bringing down the carbon foot print; (ii) making the water technologies more affordable to the bottom of the pyramid in society; (iii) addressing the environmental concerns; (iv) cogeneration of water and electricity. There is need to step up research in the development of nanocomposite membrane. Besides tuning the physicochemical properties of membranes (hydrophilicity, porosity, charge density, thermal, and mechanical stability), the incorporation of nanomaterials may provide membranes with unique properties of nanomaterials and also induce new characteristics and functions based on their synergetic effects. It may provide a new dimension to design the next generation of polymeric membranes with high performance properties. The potential applications of nanocomposite membranes could cover the whole filtration spectrum including micro-filtration, ultra-filtration, nanofiltration, reverse osmosis and forward osmosis.

Several challenges may have to be addressed to optimize the design of the nanocomposite membranes[168] such as (i) fundamental understanding with respect to the effect of nanomaterials on membrane structures and correlating them to the membrane performance; (ii) approach for better dispersion of nanomaterials; (iii) compatibility of nano-fillers with polymers to avoid leaching of nanomaterials into to the environment; and (iv) large scale production and industrial application with cost effectiveness.

5.5 Qatar water security: R&D needs and challenges

Adel Sharif

The Qatar Water Security Grand Challenge program is aiming to develop scientific solutions to address Qatar's requirements for achieving water security by having access to high quality, affordable, available and sustainable water that meets and supports Qatar's social and development programs. To achieve this, R&D activities with the strategy to take ideas from the lab to the market in the three targeted areas

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[167] S.T. Panicker and P.K. Tewari, "Nuclear Energy for Water Desalination", Nuclear Energy Encyclopaedia, John Wiley & Sons, pp 65-70, 2011

[168] P.K. Tewari,"Nano-composite Membrane Technology: Fundamentals & Applications," CRC Press, Taylor & Francis Group, pp 146, 2015

of *desalination, water reuse and aquifer recharge* have been carried out. The research drivers are increasing energy efficiency, reducing cost, minimizing health risks and reducing environmental impacts. The areas of research are hybrid desalination systems, novel membrane processes and renewable energy driven technologies.

Fast-expanding urban communities and industrial developments in Qatar continue to present significant economic and socio-political challenges. The areas of strategic research and development set out to address the Water Security Challenge which is focused to provide significantly cheaper industrial plants and greater water delivery at a lower price per liter, to meet the growing demands, without compromising environmental sustainability. Current desalination technologies, thermal and membrane methods have many limitations, including high energy and capital cost, especially for thermal methods, coupled with negative environmental impacts for both membrane and thermal methods, due to the discharge of brines and chemicals. R&D have the potential to address these issues. However, taking ideas from the lab to the market is challenging and takes a long time.

It is clear that an *urgent* need exists for the development and transfer, for application of new and step-change purification technologies that can combine significantly lower energy requirements with greater volumetric throughput at increased separation efficiencies. The combination of these design criteria will in turn lead to lower capital investment at start up and lower operating costs with improved capacity and an increase in the lifetime of the plant operation. It is also of strategic importance to detach desalination technologies from non-renewable energy supplies by using alternative energy sources.

Further RD&D should aim to achieve water security by ensuring that Qatar has access to high quality, affordable, available and sustainable water that meets and supports its social and development programs. To achieve that, the following R&D activities have been investigated with the strategy to take ideas from the lab to the market in the three targeted areas of: desalination, water reuse and aquifer recharge. The research drivers are: increasing energy efficiency, reducing cost, health risks, environmental impacts and achieving social sustainability. A number of processes and technologies for application in desalination, renewable power generation and water reuse as well as industrial water treatment have been invented. Specific inventions include:

- Novel desalination processes and equipment design based on the principles of FO combining significantly reduced mechanical energy input with maximum environmental sustainability[169] [170]

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[169] A. O. Sharif and A.K. Al-Mayahi, Solvent Removal Method, US Patent No. US 7,879,243; (2011); European Patent No. EP 1,651,570 (2011)

[170] A. Al-Zuhairi, A. A. Merdaw, A. O. Sharif, Forward Osmosis from Lab to Market, Water Science and Technology: Water Supply Journal, doi:10.2166/ws.2015.038 (2015)

- Direct use of solar and geothermal thermal energy for clean water production using low grade heat Forward Osmosis (FO) desalination process[171] [172].
- A novel power production method using solutes gradient principles that allows the harnessing of low grade ambient temperature for clean water and power production[173] [174] [175].
- Novel irrigation techniques which allow the direct use of seawater or waste water for crops and trees irrigations without the use of high capital and operating cost desalination technologies[176] [177].
- Novel industrial water treatment for cooling towers and enhanced oil recovery, as well as water reuse and dewatering techniques[178].

These inventions and associated technologies has the potential to offer significant advances in achieving water security, cost and sustainability objectives of new investment in desalination, and associated technologies in Qatar and elsewhere.

In the research phase of the program the following systems and schemes will be investigated:

- *Hybrid desalination and water treatment systems.* This includes the combination of conventional thermal desalination techniques such as multi-stage-flash (MSF), Multi Effect Distillation (MED) with membrane processes; namely Reverse Osmosis (RO) and Forward Osmosis (FO).
- *New membranes and processes*. This involves the investigation and development of new membranes for application in Forward Osmosis[179] [180], including designer membranes as well as the investigation of new regeneration methods for FO systems including a novel low grade heat

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[171] A. O. Sharif, Separation Method, European Patent No. EP2089142

[172] A. O. Sharif and H. B. Mahood, Alcohol Striping Method with Forward Osmosis, Filed (2014), UK patent application number GB 1403883.0

[173] A. O. Sharif and Maryam Arayfar, A Thermal Regeneration Forward Osmosis Process, Filed (2013), UK patent application number GB1321711.2.

[174] A.K. Al-Mayahi and A. O. Sharif, Osmotic Energy, European Patent No. EP 1,660,772B1, (2007); Japan Patent No. JP 4,546,473, (2010)

[175] A. Altaee, A. O. Sharif, Pressure Retarded Osmosis: Advancement in the Process Applications of Power Generation and Desalination, Desalination; 356, 31-46, (2015)

[176] A. O. Sharif and Maryam Arayfar, A Thermal Regeneration Forward Osmosis Process, Filed (2013), UK patent application number GB1321711.2.

[177] A. Altaee, G. J. Millar, A. O. Sharif, G. Zaragoza, Forward Osmosis process for fertilized solutions from seawater using a mixture of draw solutions, *Desalination and Water Treatment,* 34, 1-17, (2016) DOI: 10.1080/19443994.2016.1180642

[178] A.K. Al-Mayahi and A. O. Sharif, Cooling Apparatus, US Patent No. US 7,823,396 B2; (2010); Process for Introducing a Solution Into an Evaporative Cooling System, European Patent No. EP 1,781,401, (2011).

[179] A. O. Sharif and A.K. Al-Mayahi, Solvent Removal Method, US Patent No. US 7,879,243; (2011); European Patent No. EP 1,651,570 (2011)

[180] A. Al-Zuhairi, A. A. Merdaw, A. O. Sharif, Forward Osmosis from Lab to Market, Water Science and Technology: Water Supply Journal, doi:10.2166/ws.2015.038 (2015)

regeneration method using low boiling point draw solutions[181] [182]. New processes such Zero Liquid Discharge and salt harvesting techniques will be investigated and their suitability to Qatar will be assessed. The research program will also involve the investigation of integrating solar thermal techniques with distillation methods and the development of site specific technologies that relevant to Qatar and its climate, including low carbon desalination technologies combining solar thermal with osmotic power using the solute gradient method[183] [184] [185].

- *Advanced pre-treatment methods* for membrane processes; namely for RO systems to assess their applicability in Qatar as an alternative to thermal desalination for additional new plants to meet increased water demand[186].

On the development and technology transfer front, the following activities have been carried out:

- Pilot plant studies of the most promising technologies and schemes that involve scaling up and produce near market products;
- Partnership with stakeholders. The strategy of taking ideas from the labs to the market requires partnership with the state's stakeholders in the water and power sectors; as well with industries in the oil and gas sector that use large amount of water.

The activities of the technology transfer which, will depend on successful outcomes of the pilot plant studies, require a commercial partner for scaling up, business development and deployment.

The successful development and application of technology in a cost-effective, competitive and sustainable manner demands a high quality and innovative research base. This has been obtained by pursuing a significant program of research at Qatar Environment and Energy Research Institute in parallel with the application and demonstration activities in Qatar with commercial partners. This science and engineering program has quality and size with a high research rating and impact since this has attracted excellent researchers worldwide and has the most enduring support, both politically and financially.

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[181] A. O. Sharif and H. B. Mahood, Alcohol Striping Method with Forward Osmosis, Filed (2014), UK patent application number GB 1403883.0

[182] A. O. Sharif and Maryam Arayfar, A Thermal Regeneration Forward Osmosis Process, Filed (2013), UK patent application number GB1321711.2.

[183] A. O. Sharif and Maryam Arayfar, A Thermal Regeneration Forward Osmosis Process, Filed (2013), UK patent application number GB1321711.2.

[184] A.K. Al-Mayahi and A. O. Sharif, Osmotic Energy, European Patent No. EP 1,660,772B1, (2007); Japan Patent No. JP 4,546,473, (2010)

[185] A. Altaee, A. O. Sharif, Pressure Retarded Osmosis: Advancement in the Process Applications of Power Generation and Desalination, Desalination; 356, 31-46, (2015)

[186] A. Altaee, G. J. Millar, A. O. Sharif, G. Zaragoza, Forward Osmosis process for fertilized solutions from seawater using a mixture of draw solutions, *Desalination and Water Treatment,* 34, 1-17, (2016) DOI: 10.1080/19443994.2016.1180642

5.6 Singapore: low-energy desalination

Yuan Zhang, Mien Ling Chong

Currently, desalination is one of the key sources of water supply in Singapore (including both desalinated seawater and NEWater[187]), and it has an important role to play in meeting our long-term water demand. The energy needed for driving desalination processes has steadily declined over the past few decades, mainly attributed to the development of high-permeability membranes, the use of more efficient pumps, and adoption of energy recovery devices (mostly for seawater desalination)[188]. The theoretical minimum energy required for desalination of 35,000 ppm seawater at 50% recovery is about 1 kWh_e/m^3, realized when separation occurs at the reversible thermodynamic equilibrium. However, the actual energy consumption is much higher than the minimum energy required due to the finite size of reverse osmosis (RO) process, low pump efficiency, energy loss, and operating as a non-reversible thermodynamic process[189]. As such, potential desalination technologies that can drive down the carbon footprint of desalination need to be identified, and strategies for development of desalination technologies to achieve water sustainability in Singapore are needed.

As an island surrounded by the sea, seawater desalination is a natural option for Singapore. The successful development of desalinated seawater and NEWater, together with local catchment sources and imported water, form the Singapore's "Four National Taps" strategy. Singapore has established 5 NEWater plants and 2 desalination plants including Tuaspring, the largest desalination plant (70 mgd) in Southeast Asia under a 25-year design-build-own-operate (DBOO) agreement. By 2020, there will be two more 30 mgd desalination plants to boost our drought resilience. A fifth desalination plant will also be built on Jurong Island. We plan to double our seawater desalination capacity by 2030, and triple it by 2060 to meet up to 30% of our future water needs.

Singapore currently uses reverse osmosis for its seawater desalination. This process produces pure drinking water by pushing saline water through membranes to remove dissolved salts and minerals. However, by 2060, this method of desalination will use four times as much energy as compared to 2016 with additional plants running.

Seawater desalination is an energy-intensive process, as high pressure is required to overcome the osmotic pressure and drive water modules through membranes. Energy is the most important cost component for desalination, and plays a critical role in determining the viability of a desalination process. Because of high total

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[187] NEWater is high-grade reclaimed water produced from treated used water that is further purified using advanced membrane technologies and ultra-violet disinfection, making it ultra-clean and safe to drink. (https://www.pub.gov.sg/watersupply/waterquality/newater).

[188] Elimelech, M. and Phillip, W.A. (2011) 'The Future of Seawater Desalination: Energy, Technology, and the Environment', Science, 333(6043), pp. 712–717.

[189] C. Fritzmann, J. Löwenberg, T. Wintgens and T. Melin (2007) 'State-of-the-art of reverse osmosis desalination', Desalination, 216(1-3), pp. 1–76.

dissolved solids (TDS) concentration of seawater, desalination is more energy intensive and more costly than conventional water treatment and NEWater. With rising energy cost, this can be further accentuated.

From the above considerations, it is clear that the energy requirement for seawater desalination will need to be significantly reduced. Moving ahead, we are looking at exploring low-energy desalination to achieve water sustainability for Singapore. PUB's goal is to halve the desalination energy used in the future.

While membrane technology has served Singapore well in enhancing resilience in its water supply, it is well noted that membrane-based technologies are more energy-intensive than conventional water treatment processes. Projecting into 2060, desalinated seawater and NEWater are expected to meet 80% of the nation's water demand as compared to the current 40%. The overall energy consumption will be expected to increase significantly.

Singapore has hence been continuously striving for technological breakthroughs to reduce energy consumption in seawater and brackish water desalination. The goal is to achieve greater energy efficiency for desalination technologies and enhance product water quality for cost effective water reuse and desalination. Some key R&D research areas that PUB has been looking at and will look at are as follows:

- Ultrapermeable Membranes (which use aquaporin, carbon nanotubes, graphene, etc., to improve membrane permeability)
- Biomimicry
- Electrochemical desalting
- Process improvements
- Pre/post-treatment (additional energy of > 1kwh/m^3 consumed in general)
- Engineered osmosis (Pressure Retarded Osmosis)

Novel electrochemical (EC) desalination technologies have attracted a lot of attention in the field of seawater and brackish desalination, as they are a voltage driven processes and do not require high pressures for desalination, unlike the pressure-driven RO process. Over the past few years, ED-based processes have made significant development in Singapore. One of the key projects is the development of electro-deionisation; using an electric field to pull dissolved salts from water. Plans are put in place to scale up the technology and demonstrate it at a 3,800 m^3/day (feed capacity) facility in PUB's R&D Facility at Tuas. With continued R&D, it can be expected that a target value of half of the current energy consumption can be attained.

Biomimetic technology, inspired by nature, is considered one of the new promising membrane technologies, alongside mixed matrix membranes embedding carbon nanotubes or graphene[190]. Such ultrapermeable membranes have potential to reduce desalination energy consumption, although with some limitations related to concentration polarization, mass transfer coefficients, and other factors[191]. Aquaporin water channels were found to be responsible for the high flux of water across cell membranes. The technology has the potential to lead to breakthroughs in desalination by transcending the limitation of conventional membrane technology to approach the minimum energy for treatment.

Singapore has been providing support for R&D of biomimetic membranes, focusing on developing highly permeable and selective aquaporin biomimetic membranes. The current research in this area has delivered promising results at the fundamental level. However, it is worth noting that with higher water flux, concentration polarization would be more severe and this could hinder performance. Fouling would also be exacerbated at high water fluxes. In addition, economic issue such as the cost for protein production and incorporation into the membrane as well as membrane lifespan & maintenance will need to be assessed to ascertain the viability of the biomimetic techniques. In addition to biomimetic techniques, PUB is also actively looking at the mimicking of biological processes by which mangrove plants and euryhaline fish extract freshwater from seawater using small amount of energy.

The application of engineered osmosis for power generation in the form of pressure retarded osmosis (PRO) offers promise. A key concept to apply PRO in Singapore is to co-locate facilities for desalination and NEWater production, which would allow osmotic energy to be harnessed for power generation out of brine streams that are traditionally intended for disposal. This concept also has environmental significance with regard to brine management[192].

Other potential areas for energy reduction are associated with intake, pre-treatment, post-treatment, brine discharge, and integration of desalination processes with clean energy (e.g. solar energy). Eliminating the pretreatment stage or reducing the pretreatment demands would dramatically reduce the amount of power required, capital cost, as well as environmental impact of desalination plants, but this requires the development of high-performance, fouling-resistant desalination membranes with well-tailored surface properties, as well as membrane modules with improved hydrodynamic mixing[193].

The energy consumption for desalination can be reduced through continued R&D, which would be crucial to achieve water sustainability for Singapore. Singapore is in

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[190] A.G. Fane, R. Wang, M.X. Hu, "Synthetic Membranes for Water Purification: Status and Future," Angew. Chem. Int. Ed. 2015, 54, 3368 – 3386.

[191] R.K. McGovern and J.H. Lienhard V, "On the asymptotic flux of ultrapermeable seawater reverse osmosis membranes due to concentration polarisation," *J. Membrane Sci.*, **520**:560-565, 15 Dec. 2016.

[192] Tan, Y.S., Lee, T.J. and Tan, K. (2009) Clean, Green and Blue: Singapore's Journey towards Environmental and Water Sustainability. ISEAS Publishing.

[193] Elimelech, M. and Phillip, W.A. (2011) 'The Future of Seawater Desalination: Energy, Technology, and the Environment', Science, 333(6043), pp. 712–717.

a strong position to develop the technologies by leveraging on competitive advantages in this field. In particular on the application level, where leading technology providers are currently in collaboration with PUB to further develop their respective technologies.

6. Technology Roadmaps

To prioritize future research efforts, we have assessed many of the technologies and developments outlined in the report using two metrics: (1) technology readiness level, and (2) impact. First introduced by NASA in the 1970s[194] and now widely-used internationally, technology readiness levels describe nine (or ten) levels of technology maturity, ranging from idea through basic and applied research to pilot and full commercial scale implementation. Table 6.1 summarizes the TRL scale as defined by the European Commission's Eighth Framework Programme for Research and Technological Development, Horizon 2020[195]. Impact describes the degree to which successful implementation of a technology would reduce the global warming potential of desalination, defined here on a scale from 1 (no GHG reduction) to 5 (all GHG emissions eliminated). Global warming potential (GWP) includes carbon and other greenhouse gases (GHG) which contribute to climate change such as methane, nitrous oxide, tetrafluoromethane, and hydrofluorocarbons. *High impact* technologies and developments have the potential to apply to broad geographies and large populations and/or reduce to near-zero the desalination carbon footprint. *Low impact* technologies and developments may apply to narrow geographies and populations and/or only minimally reduce the carbon footprint of desalination.

Table 6.1: European Commission's Horizon 2020 definition of technology readiness levels (TRL)[196]

TRL Level	Description
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technological validity in a lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment
7	System prototype demonstration in an operational environment (industrially relevant environment in the case of key enabling technologies)
8	System completed and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

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[194] J.C. Mankins, "Technology readiness assessments: A retrospective", *Acta Astronautica* 65(9–10):1216–1223, 2009.

[195] "20.G. Technology readiness levels (TRL)", General Annexes to the Horizon 2020 Work Programme 2016–2017, European Commission.

[196] European Association of Research and Technology Organizations, The TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations, 2014

Scores for each technology or research focus, collected at the workshop, represent the numerically averaged aggregate opinion of the report authors. A map of these scores, plotted as impact versus technology readiness (Fig. 6.1), illustrates the four key sectors that define the RD&D prioritization hierarchy:

1. **Red: road-ready solutions.** Highest priority efforts have high and broad impact (>3) and high TRL (>5)
2. **Orange: high-risk, high-reward.** Second highest priority efforts have high and broad impact (>3), but low TRL (< 5).
3. **Green: evolutionary developments.** These efforts have TRL > 5, but relatively low or narrow impact (<3).
4. **Blue: currently low priority**. These efforts have relatively narrow or low impact (<3) and low TRL (< 5).

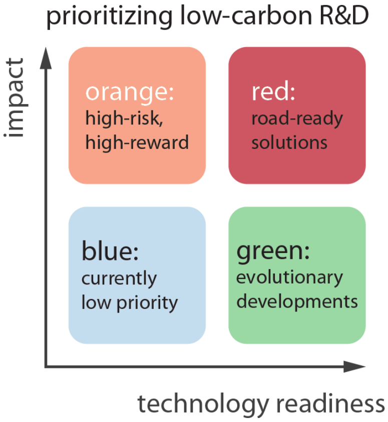

Figure 6.1: The workshop framework for prioritizing RD&D in low-carbon desalination classifies projects according to their 'impact' and 'technology readiness level', which leads to four broad buckets: red (highest priority), orange (second highest priority), green (third highest priority), and blue (low priority).

The sections that follow illustrate the aggregate scores given by workshop participants under the two broad subheadings of the report: lowering the carbon footprint of desalination systems and integrating desalination systems with low-carbon grids and power sources. As work to better quantify desalination's lifecycle GHG footprint continues, we aim to refine these scores.

6.1 Towards lower-carbon desalination systems

A map of average aggregate impact and TRL scores for technologies in the 'low-carbon desalination systems' segment is shown in Fig. 6.2. Each point on the chart represents an average over 18–21 responses, depending on the technology. The results indicate that, on average, the expert workshop participants rank hybrid desalination technologies, process improvements for energy efficiency, and advanced pretreatment systems as the areas of greatest RD&D need. Next generation membranes appear in the high-risk, high-reward category and advanced membrane cleaning is viewed as evolutionary. Salinity gradient energy, forward osmosis, and membrane distillation, on average, ranked in the relatively 'low priority' bucket. Nevertheless, there was significant variation in opinion. As illustrated by the bars in Fig. 6.2, there was no uniform consensus on any technology falling in a single bucket.

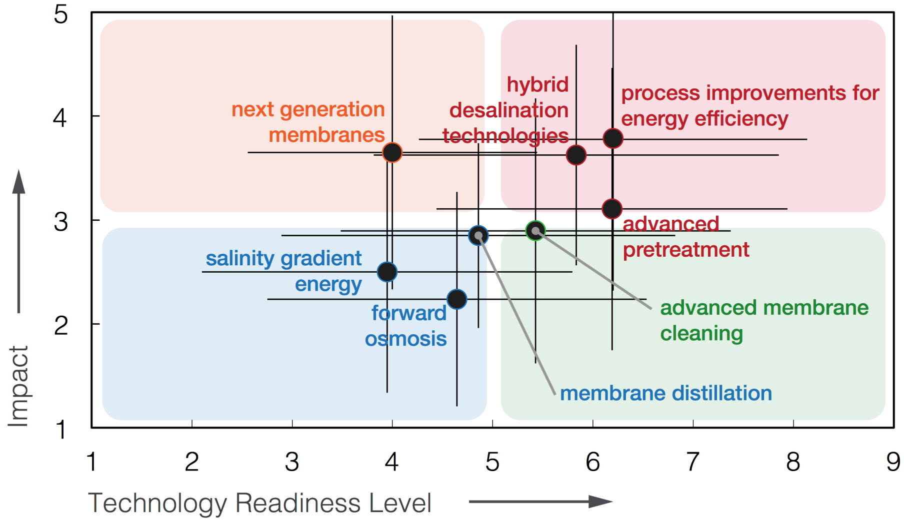

Figure 6.2: Aggregate opinion from workshop participants reveals three areas of high-impact, high-TRL RD&D needs: hybrid desalination technologies, process improvements for energy efficiency, and advanced pretreatment. Dots indicate mean score from about 20 responses; bars indicate standard deviation.

6.2 Towards integrating desalination systems with low-carbon grids and power sources

A map of average aggregate impact and TRL scores for technologies in the 'integrating desalination systems with low-carbon grids and power sources' segment is shown in Fig. 6.3. Each point on the chart represents an average over 16–17 responses, depending on the technology. The results indicate that, on average, the expert workshop participants rank optimizing power and water cogeneration, and developing and demonstrating PV-RO, wind-RO, and CSP-thermal hybrids as the areas of greatest RD&D need. The wide distribution in PV-RO and wind-RO scores may partially reflect a range of TRL for different variants of these technologies. Group discussion indicated that small-scale, directly-coupled PV-RO and wind-RO have lower TRL than large scale, indirectly-coupled variants. Optimizing intermittent desalination system operation and autonomous grids appear in the high-risk, high-reward category. Salinity gradient power ranked in the relatively 'low priority' bucket. Nevertheless, there was significant variation in opinion. As illustrated by the bars in Fig. 6.3, there was no uniform consensus on any technology falling in a single bucket.

Finally, there was significant discussion on the results for the two nuclear-powered desalination hybrids. After discussion, the workshop group generally agreed that their impact scores (around 3) were too low, given the low-GHG emissions associated with nuclear power. However, there was disagreement among participants regarding the overall environmental impact of nuclear power, with several expressing concerns with spent fuel disposal.

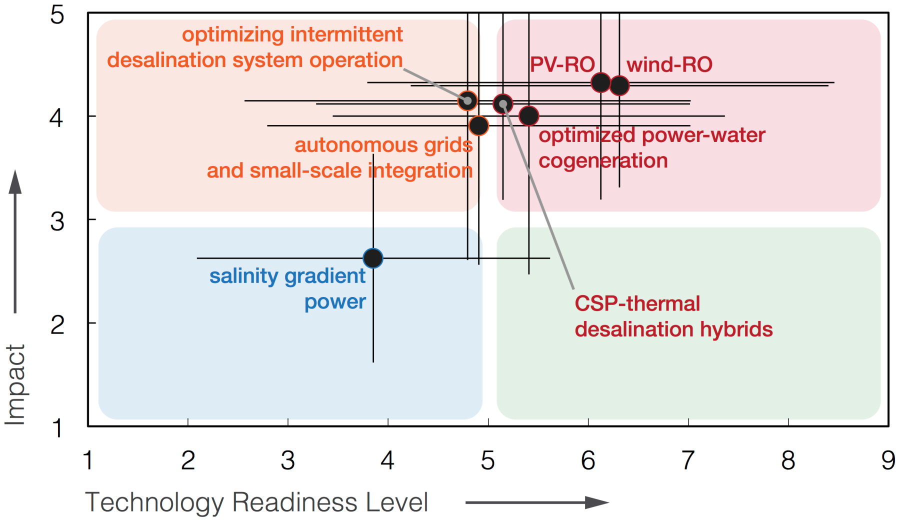

Figure 6.3: Aggregate opinion from workshop participants reveals four areas of high-impact, high-TRL RD&D needs: optimizing power-water cogeneration, and further development and demonstration of PV-RO, wind-RO, and CSP-thermal desalination hybrids. Dots indicate mean score from about 17 responses; bars indicate standard deviation.

7. Summary and Recommendations

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 perhaps desalination energy can come within a factor of 1.5 to 2. In addition to the desalination energy, further energy will always 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 \$0.02/kWh_e for land-based wind with access to the best wind resources.

Summary of research, development, and demonstration needs

- 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.

Photos

Front cover: Wind-powered desalination plant in Corralejo, Canary Islands, Spain
6: Desalination plant, Arrecife, Canary Islands, Spain
7: Rows of solar collectors near the sea
Back cover: Interior of reverse osmosis desalination plant

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