Desalination Innovations Needed to Ensure Clean Water for the Next 50 Years

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In stark contrast to progress on almost all the UN Sustainable Development Goals, clean water supply and safety issues are worsening globally, threatened by groundwater depletion, shrinking glacial melt, major rivers running dry, increasing salinity of soils and groundwater, more dangerous and tenacious waterborne pathogens, worsening water pollution with new emerging contaminants, and more frequent conflicts around water (Boretti and Rosa 2019; Gunasekara et al. 2014; Mekonnen and Hoekstra 2016). And the challenges are widespread: today 3.6 billion people face water scarcity for at least part of the year (Mekonnen and Hoekstra 2016), and this number is expected to grow to ~5.6 billion by 2050 (Boretti and Rosa 2019).

To address this crisis, the global water supply must be substantially increased through the purification and reuse of water from large sources that have salts or small contaminants. This purification is called *desalination*, but the term applies to any water process that removes the smallest compounds.

Needed Technological Improvements

Although use of desalination has emerged rapidly in some parts of the world, there remain significant barriers. These vary by location, because water is typically a local resource (long-distance water transport is expensive and requires energy-intensive pumping), and by whether a system is inland or seaside and whether it is a large-scale grid-connected or remote off-grid system. Barriers to the widespread use of desalination must be overcome with new technological solutions.

High-Salinity Capabilities

Current desalination technologies are competitive for seawater and mild-salinity groundwater in many regions, but they are rarely economically viable for treating salinities beyond seawater brine (i.e., >7 percent salt by weight; Swaminathan et al. 2018). This challenge is particularly important for inland regions where there is no large body of water (such as the ocean) for disposal of the brine.

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Technologies for inland application require extremely high recovery of the pure water and, ideally, the ability to dispose of the solutes as solid waste (so-called *zero-liquid discharge*, ZLD) (Tong and Elimelech 2016). To achieve ZLD, technologies need to have much better prediction and control of salt crystallization to avoid forming blocking layers on membranes (Warsinger et al. 2015) or heat exchangers (Tong and Elimelech 2016), depending on the technology. Unfortunately, the energy requirements of these high-salinity technologies dominate costs and must decrease dramatically through efficiency improvements.

Resource Recovery

The byproduct streams of high-concentration desalination are not just another waste product: with proper approaches they can be used to recover valuable salts and resources from saline sources. Such resources would include not only specific salts such as easier-to-extract magnesium but also, potentially, highly sought elements like gold and lithium. Selective removal of these compounds will require new and improved versions of technologies such as crystallization, electrodialysis, and ion-selective membranes (Tong and Elimelech 2016).

While today resource recovery from desalination is minimally used, to be sustainable and widely cost competitive, large or inland desalination must capitalize on this option to extract resources while minimizing potential contaminants (Du et al. 2018).

Renewable Integration and Time-Varying Capabilities

A major challenge for desalination technologies is their integration in a changing and more renewable electric grid while minimizing their CO_2 production. Current large-scale desalination plants run as steady-state base-load power electricity users. However, as grids become more dependent on renewable energy sources, it may become uneconomical to run desalination plants during peak demand (in Israel some plants idle operation in those scenarios; Dreizin 2006).

Desalination must switch to adaptive, time-varying technology to improve efficiency and meet the needs of renewable power through, for example, demand response and salinity-gradient power using desalination system components for peak prices. Approaches will include process innovations, such as novel components for batch desalination (Warsinger et al. 2016), as well as modified and new control methods and other components (e.g., pumps and energy recovery devices) to run in varied operating conditions (Khiari et al. 2019).

The control and optimization of time-varying desalination will be a major target for innovations in artificial intelligence (Dudchenko and Mauter 2020).

Better Membrane Technology

Current membranes for some desalination technologies, such as reverse osmosis, as well as pretreatment steps are highly effective. However, membranes still need further research and development.

Reverse osmosis membranes don't block small uncharged solutes well, such as boron (in the form of boric acid) and disinfection byproducts like NDMA (N-nitrosodimethylamine; Al-Obaidi et al. 2018; Warsinger et al. 2018). Other membrane-based technologies, such as membrane distillation or forward osmosis, require significant improvement before full-scale deployment.

Most membrane technologies also need further chemical modification and surface design to minimize membrane fouling (She et al. 2016), more resistance to destructive cleaning chemicals, and they may benefit somewhat from increases in permeability. Resilience to high pressures remains a challenge for reverse osmosis membranes in particular (Davenport et al. 2018).

Other Innovations

Widespread adoption of desalination will depend on a variety of additional innovations in pre- and post-treatment and in the operation of these systems. For example,

- Better control of biological and other types of membrane fouling is needed; innovative areas include novel cleaning compounds, backwashing processes, phage-based technologies, and reactive nanoswimmers.
- Novel catalytic processes may destroy emerging contaminants and provide safe reject brine (Hodges et al. 2018; Warsinger et al. 2018).
- Substantial process intensification will improve performance by combining different driving forces (e.g., pressure, heat, electric fields) with reactive systems.
- New manufacturing techniques, including additive manufacturing, will be key in making membrane modules that minimize concentration gradients, pressure losses, and fouling.

The Future

As water supplies decline in quantity and quality, demand is increasing because of population growth, shifts to meat-based diets, population concentrations in cities, and economic growth. The need for safer water, water reuse (Warsinger et al. 2018), and expanded water supplies means that much of the world's water treatment will need to include desalination membranes. Although it is a scarce technology today, desalination will one day be a ubiquitous cornerstone of the world's clean water.

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