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Technology and Engineering of the Water-Energy Nexus

Prakash Rao,¹ Robert Kostecki,¹ Larry Dale,¹ and Ashok Gadgil¹,²

¹Energy Technologies Area, Lawrence Berkeley National Laboratory, Berkeley, California 94720; email: PRao@lbl.gov, R_Kostecki@lbl.gov, LL_Dale@lbl.gov, AJGadgil@lbl.gov
²Department of Civil and Environmental Engineering, University of California, Berkeley, Berkeley, California 94720

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Abstract
The global demand for water and energy is projected to grow, but there likely will be significant constraints in our ability to keep meeting it. These constraints will be imposed partly by the interdependence between water, energy, and climate change. If left unchecked, these connections can exacerbate water and energy shortages and aggravate climate change impacts. Energy is used to supply and treat water; moreover, emissions from energy generation contribute to climate change, which affects water supplies and increases the demand for energy to sustain Earth’s growing population and economy. The linkage between water and energy can offer opportunities for better meeting expected demand while minimizing damage from shortages of either. This article focuses on the technological and engineering aspects of various connections in the water-energy nexus where advancements can enable greater supply of one or both. It also outlines the benefits and challenges associated with each connection.
INTRODUCTION

In 2016, the World Economic Forum (WEF) ranked water crisis¹ as one of the most likely and impactful risks facing the world within the next 10 years. It is ranked above better-known risks such as weapons of mass destruction, food crisis, infectious diseases, terrorist attacks, and cyberattacks. The same WEF ranking placed failure to mitigate/adapt to climate change as the most impactful risk in their survey (1). Climate change and global freshwater supply have been identified as two of the nine planetary boundaries that define the limits of stability for Earth’s environmental systems, with climate change connected to and impacting freshwater use. A recent study concluded that climate change has already exceeded its suggested safe boundary (2). Furthermore, Carpenter et al. (3) report that we will approach the upper safe limit for planetary environmental impacts from human freshwater consumption by mid-century. An urgent challenge facing governments, policymakers, and other stakeholders is to meet the growing resource demands, particularly for energy and water, to ensure adequate supply and distribution while simultaneously limiting greenhouse gas emissions. Because water and energy are linked in their extraction, conversion/treatment, and use, efforts to limit planetary impacts and mitigate associated risks from increasing use of one need to be undertaken without increasing the impacts and/or risks associated with the other. Understanding and effectively managing these linkages will greatly aid in addressing this challenge.

As global populations and standards of living increase, demands on our water resources are expected to increase sharply. Global water demand is expected to increase by 55% in 2050 compared to 2000 levels. This will have a significant impact on populations living in water-stressed areas, which are expected to increase from 1.6 billion in 2000 to 3.9 billion in 2050 (4).

Climate change can impact global and regional water cycles, runoff, and water scarcity (5–7). Some models project that the number of people living under absolute water scarcity would increase by 40% if the Earth experienced a 2°C increase in global temperatures (8). This presents a risk to global security, health, and economic development (9).

While plentiful energy services are not essential for human life (as is the case with water), they are essential to the function and development of modern human societies. Although there has been

¹The WEF defines this as a significant decline in freshwater availability affecting human health.
some decoupling between growth in gross domestic product and energy demand in industrialized countries, population growth and increased living standards elsewhere are expected to continue to increase global energy demand. In its most recent projections, the International Energy Agency estimates an approximate 40% increase in global energy demand and a comparable increase in CO₂ emissions between 2015 and 2050 (10). This supports the importance of coordinating two key long-run global policy aims: (a) ensuring a suitable supply of water and energy services to meet the growing demands and (b) limiting greenhouse gas emissions to mitigate the impacts of climate change.

Although this review focuses on technology and engineering, we must keep one caveat in mind: Given the magnitude and speed of actions needed for the above dual objectives, there is general agreement that laissez-faire markets and technology innovation will be inadequate by themselves to achieve these objectives and government regulation at some level will likely be needed. For instance, Bakker (11) identifies water market failures and the need for regulation to ensure equitable access to water. Large future costs attributed with energy use have been invoked to justify regulation of CO₂ emissions through regulated market mechanisms (12, 13). However, within any given policy framework, technology has great potential to improve energy and water generation/supply and use efficiency and can contribute a great deal to achieving the goal of reducing CO₂ emissions via optimization of the linkages between water and energy.

The water-energy nexus refers to the multiple points of mutual reliance of water and energy for societal use, from extraction, to processing, through point of use (and continuing through to disposal in the case of water). The components of the water network include water supply (extraction, treatment, and distribution), point of use (power generation, industrial, commercial, agriculture, residential), and wastewater treatment (conveyance, treatment, and disposal). Each component requires an energy input thereby hardwiring energy into water acquisition, use, and disposal. In sum, energy consumed by the water/wastewater network is significant; estimates of the share of US electricity consumption responsible for water supply and wastewater treatment alone range between 3% and 4% (14, 15).

Similarly, the majority of energy generation is reliant on water. Eighty-seven percent of US electricity supply is generated using water-cooled technologies, and 45% of all water withdrawals in the United States were used for thermoelectric cooling (16, 17). Water is also frequently used as an energy carrier in multiple end-use systems. For example, water use in steam systems in the US manufacturing sector accounts for 11% of all US manufacturing water use (18).

Optimization of the water-energy nexus to meet growing demands requires a balanced multidisciplinary approach. Economics, social sciences and decision making, and local and national policy, on one hand, and science and technology, on the other, are among the disciplines with important roles to play in understanding and optimizing the coupling between water and energy to provide greater access of each. This review focuses on the role of technology and engineering. Technology is defined here as the development of physical mechanisms and/or processes intended to produce a desired result [e.g., reverse osmosis (RO) membranes and devices for producing potable water from saline water]. Engineering is defined as the integration of technologies into broader systems (e.g., incorporation of RO desalination into stable long-term operation of municipal drinking water supply).

The word nexus conjures an image of a central connecting point; however, in the context of the water-energy nexus, there are many points where these fields connect. As we see, although the overlap is not large, it is often critical. Some large power generation processes can get shut down for lack of adequate cooling water, and some water can remain inaccessible for societal use without deploying energy.
This review is structured as follows. We begin the review with a global summary of energy for water, and water for energy at a high level. Then we review five specific water-energy topics in more detail: (a) water use for cooling thermoelectric power plants, (b) energy costs of desalination for municipal water and (c) its potential role in facilitating grid integration of renewable electricity, (d) water and energy efficiency at the point of use, and (e) advanced resource recovery from municipal wastewater streams. We consider each of these five topics central for a good understanding of the water-energy connections throughout the various stages of societal use of water and energy. However, these five do not exhaust all water-energy connections.

In an effort to balance depth and breadth of coverage while staying within the parameters of this review, we had to make some hard choices. We refer the reader to relevant articles in the literature for three additional key technology topics that could not be addressed here. These topics are (a) water for oil and gas extraction, (b) the water-energy-food nexus, and (c) water-energy policy. The following three paragraphs briefly explain the importance of each of these, and point the reader to references for further reading.

Water use, groundwater contamination, and wastewater treatment are issues in oil and gas extraction (known as fracking), particularly in the context of recent massive exploitation of vast shale gas deposits in North America. We suggest References 19–23, and the papers cited therein, for readings on water for fracking.

The connections between food, water, and energy—and implications for land use, resource availability, and climate change adaptation—are emerging topics. We suggest References 24–28, and the papers cited therein, for readings on these topics.

New technology or engineering solutions that provide greater water and/or energy access will generally require regional and local policies to facilitate adoption. Specifically, the integration of water policy and energy policy is needed. We suggest Reference 29, and the papers cited therein, for readings on water-energy policy.

GLOBAL WATER-ENERGY Nexus

This section provides a high-level overview of the global water-energy nexus. It begins with a discussion of patterns in the energy-for-water supply nexus, followed by a similar discussion of the water for energy supply nexus. The section concludes with observations about future trends in the water-energy nexus. Region-specific details of the nexus, although important, are necessarily excluded from this high-level overview.

Energy for Water Supply

Energy is an important input in the conveyance, distribution, purification, and treatment of water. Food and Agricultural Organization of the United Nations AQUASTAT data indicate that global water consumption increased from 2,876 billion m$^3$ to 4,169 billion m$^3$ between 1975 and 2010 (30). Water consumption is a subset of water use and is the amount that is not returned to the original source (i.e., via evaporation). Energy inputs associated with the use of water increased more rapidly over this time—from 1,639 to 2,834 TWh. This led to a 20% increase in the energy intensity of water over this period, rising from 0.57 kWh/m$^3$ in 1975 to 0.68 kWh/m$^3$ in 2010 (see Table 1). This increase represents a change in the average energy intensity across all water supplies—at the margin the increase has been more rapid. For example, in Southern California the energy intensity of new water supplies has been increasing more than 2% annually for more than a century (see Figure 1).

Despite the rapid growth in energy used for water, globally the energy used to supply water in 2010 represented only a portion of global energy sales—between 1.7% and 2.7%.
Table 1  Global energy for water patterns in 2010 (30, 31)

| Water consumption                          |        |
|--------------------------------------------|--------|
| Global total (billion m$^3$)               | 4,170  |
| Increase over 1975 (%)                     | 45%    |
| Agricultural (billion m$^3$)               | 2,920  |
| Groundwater (billion m$^3$)                | 1,020  |
| Water consumption for energy (billion m$^3$)| 2      |

| Water source breakdown                     |        |
|--------------------------------------------|--------|
| Surface withdrawals (billion m$^3$)        | 3,170  |
| Groundwater and nonfreshwater withdrawals (billion m$^3$) | 1,000  |

| Energy use                                 |        |
|--------------------------------------------|--------|
| Global energy use (TWh, inferred)          | 129,000|
| Energy use for water (TWh)                 | 2,830  |
| Increase over 1975 (%)                     | 75%    |

| Energy use by water source                 |        |
|--------------------------------------------|--------|
| Surface water (TWh)                        | 1,640  |
| Groundwater (TWh)                         | 856    |
| Nonfreshwater (TWh)                       | 333    |

| Energy intensity                           |        |
|--------------------------------------------|--------|
| Global Average (kWh/m$^3$)                 | 0.68   |
| Increase over 1975 (%)                     | 20%    |

| Value, energy for water, water for energy$^a$|        |
|----------------------------------------------|--------|
| Energy for water ($ million)                 | $643   |
| Water for energy ($ million)                 | $89.7  |

$^a$Values use global average electricity and water retail prices for selected cities.

Figure 1

Rising energy intensity of Southern California water supplies as new water supply capacity has been added in Southern California. Total capacity is 5.3 billion m$^3$/year. Selected water supplies ordered by date of acquisition. The trend has been for the incremental energy intensity to increase. Note that the Los Angeles Aqueduct, which was built more than 100 years ago, actually generates power. Data points connected only to guide the reader’s eye and are from References 32–34.
Nevertheless, this energy represents an important fraction of total water costs [30, 35; see also data from statista.com, accessed on August 10, 2017 (https://www.statista.com/statistics/183700/us-average-retail-electricity-price-since-1990/)]. Several factors explain the increase in the global energy intensity of water. Most of the increase is due to increasing reliance on more energy-intensive water sources, including groundwater and desalinated water. The energy intensity of water sources differs—groundwater usually requires more energy to access than surface water. For example, on average, surface conveyance to agriculture uses 0.08 kWh/m³ and groundwater almost twice that amount (0.16 kWh/m³) (30).

Desalination uses more energy than accessing either groundwater or surface water. Modern RO seawater plants consume an average of 4.75 KWh/m³ for the entire desalination system—25 times more energy on average than pumped groundwater. Today, desalination supplies less than 1% of withdrawals, but consumes more than 9% of the world’s energy for water—up from 1% of energy in 1980 (30).

The United States was the largest user of energy for water prior to 2000. However, since that time, the Middle East, India, and China have all surpassed the United States as large users of energy for water. The energy intensity of water rose in the Middle East, due to a rapid increase in desalination. India’s energy-for-water use grew in large part because of the increased reliance on groundwater for irrigated agriculture. China is now the largest user of energy for water because of the rapid growth of industrial and municipal water use in that country (30).

### Water for Energy Supply

Water is used in most stages of energy production. All electricity production via thermal sources needs cooling for heat rejection, and water is commonly used for this purpose. One must differentiate between two types of water uses in this process: (a) water used in energy production that is “consumed” (i.e., is lost via evaporation and/or not returned to the original source), and (b) the total water withdrawn from the source (withdrawals), much of which is returned to the source at a higher temperature. The electricity sector is responsible for a large fraction of global freshwater withdrawals. The sector’s share of water consumption is much smaller. In 2008, the global energy sector consumed 52 billion cubic meters of water (Table 2) (31). This quantity represents a small fraction (roughly 1.2%) of total global water consumption. In value terms, it represents an even smaller fraction of energy production value. For example, the cost paid for water consumed to generate electricity from most thermal power plants is typically 1% or less than the value of electricity production from the plant (35). Table 2 provides further details on global water consumption-for-energy.

Most water in the energy sector is consumed to extract fuels including petroleum, coal, natural gas, and uranium. Petroleum extraction alone accounts for approximately 40% of all water consumed to produce energy. Much of this water is likely of low quality and does not directly compete with other freshwater uses (31). In the United States, for example, onshore oil production and refining is estimated to use between 150 and 300 billion m³ of water annually, but most of this water (70%) is recycled from earlier extraction and is of poor quality (36).

The second largest category of water consumed in the production of energy is for thermal power plants. Water used for this purpose is often drawn from freshwater streams or groundwater, thus competing with other uses of freshwater (16, 31).

Electricity generation is characterized by a wide range of available fuel choices, generating methods, and cooling technologies. This makes it possible to generate electricity in regions with little or no water. The wide range of available fuel choices (natural gas, coal, nuclear, biomass,
Table 2  Global water for energy patterns in 2008 (31)

| Water consumption for energy production (2008)                      |       |
|---------------------------------------------------------------|-------|
| Global water consumption (billion m³)                         | 4,169 |
| Water consumption in the energy sector (billion m³)            | 52    |
| Energy sector water consumption (% of global water consumption)| 1.2%  |

| Water consumption for primary fuel extraction (billion m³)       |       |
|---------------------------------------------------------------|-------|
| Coal, oil, and gas                                             | 26.7  |
| Nuclear fuel                                                   | 2.1   |
| Biodiesel and ethanol                                          | 10.1  |
| Total                                                         | 39.0  |

| Water consumption for electricity generation (billion m³)       |       |
|---------------------------------------------------------------|-------|
| Coal steam turbine (ST)                                        | 8.1   |
| Nuclear ST                                                     | 2.2   |
| Other nonrenewables (oil ST, gas ST, combined cycle and gas turbine) | 1.9   |
| Renewables (biomass)                                          | 0.8   |
| Total                                                         | 13.0  |

| Value of water and energy                                      |       |
|---------------------------------------------------------------|-------|
| Electricity water consumption value ($ billion)                | 16,000|
| Global electricity production (TWh)                           | 22,613,000|
| Global electricity production value ($ billion)                | 5,133 |
| Embedded water cost (% of electricity value)                  | 0.3%  |

waste heat, geothermal, solar, and wind), generating technologies (steam turbine, combined cycle, gas turbine, photovoltaic), and cooling methods (once-through cooling with freshwater, cooling ponds, and dry cooling) for thermal power provide electricity producers with flexibility to adapt to existing water conditions.

Coal and nuclear steam turbine plants are common fuel technology choices for generating electricity in most of the world. Using cooling towers, cooling ponds, or once-through freshwater cooling technologies, these plants all tend to consume between 100 gallons and 1,100 gallons per MWh (37). Using the same cooling technologies, combined cycle natural gas plants consume roughly half the water consumed by coal and nuclear steam turbine plants (31). Water consumption for these plants range from less than 1% of withdrawals (for once-through cooling plants) to more than 70% of withdrawals used by plants with cooling towers (16). Across all fuel and plant types, dry cooling lowers water requirements and decreases plant efficiency. The water withdrawals and consumption for several thermoelectric power plants based on power generation and cooling system technology are provided in Figure 2 (37). In the next section we discuss in more detail water withdrawals and consumption in thermoelectric power plants.

Electricity from renewable energy sources (RESs), including solar photovoltaics and wind, consumes little or no water but these sources provide intermittent generation. Hydroelectric power from reservoirs, a special category of renewable energy, is jointly produced with water supply and is under better control of the operators than electricity from wind and photovoltaic sources. Reservoir management, however—the coordination of reservoir storage and releases to better match the timing of electricity and water demand cycles—includes important energy water trade-offs. One form of reservoir management, pumped storage, is widely practiced and is discussed briefly in the later section on renewable energy integration (16).
Future Trends in the Global Water-Energy Nexus

Some ongoing technological and environmental trends suggest that the water intensity of energy will decline in the future. The electricity generation mix in much of the world has been moving toward water-conserving technologies. Natural gas is replacing coal as the most common fuel choice in many regions, and natural gas-fired plants tend to require less water for cooling than coal-fired plants (38). Similarly, rapidly expanding wind and solar generation in the industrial countries, and wind, solar, and hydropower generation in China, suggest a future with declining water consumption per unit energy generation. Rising prices of water in some regions may also contribute to this trend of declining water use (39).

In contrast, other trends, particularly in the extraction of energy fuels, suggest that water-for-energy requirements may be increasing in some areas. For example, fracking to extract natural gas in the United States is consuming an increasing amount of water in many parts of the country. Ambitious plans to extract and process fossil fuels in North China are likely to increase water consumption in that country as well (40).

Global Overview of Water Energy Linkages: Concluding Thoughts

The two sides of the water-energy nexus—water for energy and energy for water—show interesting similarities. A common feature is that, quantitatively, only a small fraction of each resource (1% to 2%) is tied up in the production of the other. This helps to keep internal water energy multipliers small—so that a jump in the demand for one resource is unlikely to cause a large, cyclical jump in the demand for the other. The dependencies that do exist can be quite critical. For example, without adequate water for cooling (i.e., resulting from prolonged droughts and/or warming of surface water with climate change), thermal power plants have to curtail their power output or shut down. And without necessary energy inputs, new water resources (e.g., desalinated seawater) may be inaccessible. Therefore, the small fractions of one resource devoted to the other should not lead one to mistakenly conclude that the dependencies are marginal.

One difference between the two sectors is that the value of energy to the water sector tends to be larger than the value of water to the energy sector. For example, conservatively valued at
retail water and energy prices, global energy for water is seven times more valuable than global water consumed by energy (Table 1). This disparity would likely be larger if wholesale prices were available to value water and energy inputs. This generalization ignores environmental costs associated with water and energy use, including potentially large environmental damage from higher stream temperatures. Siddiqi et al. (41) reach a similar conclusion about the energy-water nexus in the Middle East. This implies that, as a general rule, water managers are likely to care more about energy use than energy managers care about water use.

Finally, there is a stark difference in the availability of options to find low-water-intensive energy and low-energy-intensive water. Low-energy-intensive water supply options are limited. In most areas, the better low-cost, high-quality, and accessible water supply options have already been tapped; remaining options are either impaired or remote. This suggests that the energy intensity and cost of water is likely to continue rising in the future unless new technologies are found to help lower the amount of energy needed to access remote and saline water supplies.

However, low-water-intensive energy supply options appear abundant. The options for producing low-water-intensive energy include the use of natural gas, solar photovoltaics, wind sources, and the choice of dry-cooling technologies linked to traditional thermal power plants. This abundance of options does not guarantee that future energy will not use (or will use less) water, but it makes that outcome much more likely.

This article reviews in more depth five connections in the water-energy nexus: (a) thermoelectric cooling, (b) desalination and (c) its role in facilitating renewable energy integration, (d) point-of-use efficiency, and (e) advanced wastewater treatment.

**THERMOELECTRIC COOLING**

Reducing water use for thermoelectric cooling can substantially reduce the water-for-energy component of the water-energy nexus. A brief pedagogical description of basic power generation technologies is provided to facilitate the reader’s understanding of water use in a power plant. Thermoelectric power plants convert thermal energy (heat), usually generated through combustion of fossil fuels or a nuclear reaction, to mechanical work, which in turn creates electrical power. In practice, the efficiency of converting heat to work depends on the energy source. In the United States in 2015, coal power plants operated at 33% efficiency, whereas natural gas power plants operated at 43% efficiency [see data from eia.gov, accessed on August 10, 2017 (https://www.eia.gov/electricity/annual/html/epa_08_01.html)]. All the heat not converted to mechanical work must be rejected to the environment, and this commonly requires cooling. This explains the majority of water use for thermoelectric power plants, which constitutes the overwhelming majority of freshwater withdrawals for the production of any kind of energy. Water withdrawal and water consumption of a thermoelectric power plant will be dictated by the type of power plant (e.g., steam, simple, or combined cycle) and the cooling technology (e.g., wet, dry, or hybrid) employed (see Figure 2).

Steam cycle power plants generate high pressure steam through the combustion of fossil fuels or a nuclear reaction. The high pressure steam is expanded over a turbine that generates electrical power. Lower pressure steam exits the turbine and needs to be cooled before re-entering the steam generation system. Steam cycle power plants can operate using a diversity of fuels including coal, natural gas, and nuclear energy. Of the power plant options discussed here, steam cycle plants require the most cooling. They also require water to make-up for water lost as part of the steam generation cycle (e.g., through blowdown, leaks, deaeration). Simple (i.e., combustion) cycle power plants typically operate on natural gas. Their operating principal is similar to jet engines for commercial airliners. Air is compressed, mixed with natural gas, and ignited. The expansion
of the air powers a turbine that generates electrical power. The air is then exhausted. Of all the power plant technologies discussed here, simple cycle plants require the least amount of cooling. A combined cycle power plant improves on the overall efficiency of a simple cycle power plant by using the hot exhaust gases to generate steam, which in turn generates additional electrical power via the same mechanism as a steam cycle power plant. The overall plant power efficiency increases, but so do the water requirements compared to those for a simple cycle plant. In the United States in 2016, thermoelectric power plants made up 84% of electricity generation. 67% used steam cycle, 11% natural gas-fired simple cycle, and 21% natural gas-fired combined cycle (42, 43).

Three general cooling methods are used in thermoelectric power plants: wet, dry, and hybrid. Wet cooling uses evaporation to remove heat from the cooling water, whereas dry cooling rejects waste heat into ambient air via water-to-air heat exchangers, thereby lowering the temperature of the cooling water. The former is a more effective method of heat rejection but leads to water consumption, whereas the latter is a less effective method of heat rejection but uses (and consumes) no water. Hybrid systems use a combination of both and can switch based on ambient conditions. Wet cooling tower technologies include once-through cooling, recirculating cooling towers, and cooling ponds. Dry-cooling technologies include direct (i.e., air-cooled condensers) and indirect (i.e., where the condenser and the mechanism to reject heat to the atmosphere are physically separated) options (44). In the United States in 2012, 53% of thermoelectric power plants used recirculating cooling towers, 43% used once-through cooling, 3% used direct dry cooling (none used indirect), and less than 0.5% used hybrid systems (45). However, the trend for new plants is moving toward recirculating systems. In fact, the use of once-through cooling systems is banned in California, and all systems must be replaced with recirculating cooling towers or dry-cooling systems.

Figure 3 shows the change in water withdrawals (blue bars) and consumption (light-blue bars) associated with switching a power plant from a coal-fired steam cycle plant with once-through cooling (baseline) to natural gas combined cycle with once-through cooling (case 1), and coal-fired steam cycle plant with a recirculating cooling tower (case 2) (46). Once-through cooling systems require the greatest amount of water withdrawals. Water withdrawals can be reduced by employing a recirculating cooling tower. However, given cooling towers rely on evaporation as the
dominant form of heat rejection and once-through cooling systems rely on sensible heat transfer, the consumptive water use increases sharply.

The reduction in water use associated with switching to either dry-cooling or recirculating systems comes at the expense of reduced power plant efficiency. Water is a much better cooling agent than air and can therefore reject heat faster per unit volume/mass from the power plant. The result is that power plants with wet-cooling technologies are more energy efficient compared to ones with dry-cooling technologies. Furthermore, power plant efficiency increases with lower condenser temperature. The condenser temperature is directly related to the temperature of the cooling water or air. Recirculating systems will have higher cooling water temperatures than once-through cooling systems, resulting in lower overall plant efficiency. Models of coal-fired steam cycle power plants employing once-through cooling in Texas predicted a 3–4% decrease in net plant efficiency when switching to dry cooling and a 0.3–1% decrease when switching to a recirculating system. For natural gas combined cycle plants using once-through cooling, the models predicted a 2–3% decrease in plant efficiency when switching to dry cooling and less than 1% decrease when switching to recirculating systems.

Thermoelectric cooling also introduces thermal pollution into the discharge stream. To preserve aquatic biotope, river temperatures should be kept below 32°C. Once-through cooling systems can raise the temperature of the inlet water by as much as 15°C. One analysis showed that 57% of once-through cooling systems in the United States had a peak discharge temperature during summer months greater than 32°C for every year between 2001 and 2005 (48). In the United States, there are several examples of power plants needing to be shut down due to high river temperatures; in some cases the ambient river temperature was above the permitted discharge temperatures even without the influence of the power plant. Thermal pollution is exacerbated during drought conditions—long hot and dry periods increase electricity demand (attributable to increased air conditioning) that requires greater amounts of cooling water, which is already at elevated temperatures. Such was the case in Texas in 2011 during an exceptional drought and heat wave. Analysis shows that electricity demand increased 6% and water demand for electricity generation increased 9%. Through implementation of less water-intensive technologies, such as replacing coal-fired steam cycle plants with natural gas combined cycle plants, and employing recirculating cooling systems in place of once-through cooling, power plants were prepared to meet the increased loads and water constraints without any disruption (49).

The switch from coal-fired steam power plants to natural gas combined cycle plants is already occurring due to low-cost natural gas. Similarly, new power plants in the United States are being constructed with recirculating cooling towers rather than once-through cooling systems (45). This trend is primarily driven by environmental regulations, such as the Clean Water Act Section 316(b) (16). However, retrofitting once-through cooling systems with recirculating systems in the absence of regulations is not cost effective, partly because power plants typically do not pay for the cooling water (46). Furthermore, retrofitting once-through cooling systems with recirculating systems instead of dry-cooling systems results in similar amounts of water savings but at lower costs (47).

Emerging technologies and practices offer opportunities to reduce the water usage of thermoelectric power plants. One technology reduces the evaporative losses from the cooling tower by precooling the hot water from the power plant condenser using dry cooling. By using sensors and controls, the amount of cooling performed by the dry-cooling component can be varied based on ambient conditions, water temperature, and water and energy costs. Pilot tests on a 1 MW system yielded a 55% reduction in water withdrawals compared to a recirculating cooling tower (50, 51). Additional technologies and research under development but without known pilot-scale tests include use of desiccants in dry-cooling systems to lower capital costs and improve performance.
during periods of warm outdoor air temperatures (52), methods to lower the dew point of cooling
tower supply air to increase cooling effect (53), and use of treated municipal wastewater to offset
freshwater withdrawals (54).

DESALINATION

In several parts of the world, existing freshwater supplies cannot sustain the regional population
(owing to increasing population size or increasing prosperity). Importing water/interbasin transfers,
increased recycling/reuse, and desalination of saline water are three available options. Each
option must be weighed based on its ability to meet water demands and the associated financial
and environmental costs. For many parts of the world—Middle East, Australia, Spain, Singapore,
Southern California—desalination plants have been selected to help meet water demands. In some
cases, as in the United States’ San Diego County, desalination was selected as a part of an effort
to diversify the water supply portfolio (55).

The term desalination is used for describing activities that go beyond removing salt from wa-
ter. The term also describes processes applied to remove dissolved contaminants (salts or other)
from a diversity of water sources. These include converting brackish or seawater to potable wa-
ter (defined as <500 ppm) and purifying potable water to ultrapure water (i.e., for semicon-
ductor manufacturing). Although data on the uptake, energy, and CO2 emissions from desali-
nation were not found for a single year within the literature, estimates of each are provided
for various years. In 2015, global desalination capacity was 86.5 million m³/day. Of the ca-
pacity in 2015, 81% used saline water (>1,000 ppm) as its source (56). In 2013, desalination
provided 1.5% of global water supply (57). In 2012, energy consumption for desalination was
0.4% of global electricity consumption (75.2 TWh), producing 65.2 million m³/day of water
(58). For the year 2015, it is estimated that desalination plants worldwide emitted approximately
76 million tonnes of CO2 (59).

Although desalination is a critical component of many regions’ water supply, several barriers
to its uptake still exist: (a) high capital and water costs; (b) difficulty in acquiring the coastal land
for development; (c) high energy intensity; and (d) environmental impacts including those from
energy source-dependent CO2 emissions, saline water intake, and concentrate discharge. As an
example of the high water costs, Cooley & Phurisamban (60) estimated the cost of alternate water
supplies in California and found seawater desalination to be the most expensive option at more
than $2,000/acre-foot. Figure 4 (60) shows the authors’ results.

However, desalination offers several benefits, including (a) abundant (and usually no-cost) feed
water (e.g., ocean water), (b) resiliency against droughts and water scarcity, (c) more predictable
water cost in regions where rights to freshwater sources are contentious, and (d) potential to serve
as energy storage for integrating RESs into the electric grid (60, 61). This review focuses on the
energy intensity of saline water (sea and brackish water) desalination for municipal potable water,
its implications on cost, and strategies for reducing the energy intensity.

Several well-known water desalination technologies are currently commercially available. The
most prominent ones are RO, multi-effect distillation (MED), multi-stage flash (MSF), and
electrodialysis (ED). An estimated 65% of global desalination in 2015 was through RO, with
21%, 7%, and 3% using MSF, MED, and ED, respectively. The remaining water supplied by
desalination used other processes (e.g., nanofiltration, ion exchange, etc.) (56). Emerging tech-
nologies that have not been implemented widely at commercial scale include forward osmosis

2 An acre-foot is a common unit in the US agriculture sector and equates to 1,233 m³.
Stormwater capture

Brackish desalination

Nonpotable reuse

Indirect potable reuse

Seawater desalination

Figure 4

Total project costs (in 2015 USD/acre-foot) for various water supply options in California. “Large” stormwater capture corresponds to projects with annual yields of 6,500 to 8,000 acre-feet (AF), and “small” to those with annual yields of 280 to 1,500 AF. For all other alternate water supplies shown in the figure, “large” corresponds to annual yields greater than 10,000 AF and “small” to less than and including 10,000 AF. Seawater desalination is the most expensive option. Brackish desalination, however, is estimated to be cost competitive with other alternate options. Adapted with permission from Reference 60.

(FO), which must be coupled with a draw solution dilution technology (e.g., RO) and capacitive deionization (CDI). Aside from being categorized by commercial availability, these technologies can be categorized by their major energy source. Membrane technologies (RO and ED) primarily use electricity. CDI uses an electrochemical process and is also electrically driven. FO, if coupled with RO, is considered a membrane technology; otherwise, it can be thermally driven. Thermal technologies include MED and MSF. In their current state, certain technologies are better suited for certain salinities. ED and CDI are better suited for low salinity brackish water, whereas MSF and MED are better suited for seawater. RO is suitable across all salinities. Given the dominant uptake of RO compared to other technologies, this review will concentrate on RO processes.

Several parameters dictate the energy intensity of a desalination process, including the feed and product water salinities, their flow rates, and the recovery rate (amount of product water produced per unit of intake water). Additionally, the availability and temperature of any heat sources and the temperatures of the feed water will impact the energy intensity for thermal processes. This contextual information is often not found in the literature when reporting the energy intensity of desalination. Furthermore, the energy consumption from thermal sources is often not converted to an electrical equivalent when comparing to electric technologies. Table 3 provides a summary of the energy intensity of the desalination operation for RO (seawater and brackish), MSF, MED, and ED as reported in the available literature. Although complete contextual information is often missing from the literature, as much as is available is provided in Table 3. Thermal energy has been converted to the electrical equivalent by assuming a 33% efficient process for converting heat to electricity (matching the assumed efficiency of the US electric grid). More information on the energy intensities in Table 3 are provided in References 57, 61–70.

Desalination is a separation process that is accompanied by supporting operations: intake of feed water, pretreatment to remove coarse and suspended contaminants and adjust water chemistry, post-treatment of product water for integration with the potable water system, and the management of the concentrate. Although the desalination process is likely to be the most dominant energy use, each of these supporting steps will also require energy. If the desalination plant is located far away from the source or concentrate disposal sites, pumping for conveying feed
Table 3  Summary of globally reported seawater and brackish water desalination energy intensity for the desalination operation and associated water costs (57, 62–71)

| System                        | Reported low-energy intensity | Reported high-energy intensity | Reported Total Water Cost  
|-------------------------------|-------------------------------|-------------------------------|-----------------------------|
|                               | Electrical (kWh/e/m³)         | Thermal (kWh,equiv/m³)        | Total (kWhT,equiv/m³)       | Electrical (kWh/e/m³)         | Thermal (kWh,equiv/m³)        | Total (kWhT,equiv/m³)       | ($) /m³                      |
| RO (seawater)                 | 1.483                         | NA                            | 1.58                        | 7.5                          | NA                            | 7.5                          | 0.45–1.72                   |
| RO (brackish water)           | 0.3                           | NA                            | 0.3                         | 3                            | NA                            | 3                            | 0.2–1.33                    |
| MSF                           | 7.5                           | 2.5                           | 10                          | 30.3                         | 5                             | 35.3                         | 0.56–1.75                   |
| MED                           | 4                             | 1.5                           | 5.5                         | 20.2                         | 2.5                           | 22.7                         | 0.52–1.5                    |
| ED (brackish water)           | 0.5                           | NA                            | 0.5                         | 1.8                          | NA                            | 1.8                          | 0.6–1.05                    |

Abbreviations: ED, electrodialysis; kWh, kilowatt-hours; kWh,e, kilowatt-hours electrical; kWh,equiv, kilowatt-hours electrical equivalent; kWhT,equiv, kilowatt-hours total equivalent; MED, multi-effect distillation; MSF, multi-stage flash; NA, not applicable; ppm, parts per million; RO, reverse osmosis; TDS, total dissolved solids.

*A challenge identified in the literature is the lack of consistent reporting of reference conditions, such as salinity, flow rates, recovery, and input thermal energy temperature. Reference conditions as available in the literature are provided in these notes.

*Cost is for energy (electricity, thermal, or both sources), capital expenses, and operations and maintenance.

*RO (seawater): Low-intensity value is for closed-circuit operation at 42% recovery of 379 ppm product water from 36,357 ppm feedwater; high-intensity value is for single-pass RO.

*RO (brackish): 50–70% recovery.

*MSF: Low-intensity value is for a typical unit size of 90,000 m³/day that includes integration of waste heat, and has a top brine temperature of 120°C; high-intensity value is for 30,000–100,000 ppm TDS feedwater salinity with <10 ppm TDS product water quality.

*MED: Low-intensity value is for a typical unit size of 22,700 m³/day that includes integration of waste heat with the top brine temperature maintained at 70°C; high-intensity value is for <20 ppm TDS product water quality.

*ED: Low-intensity value is for 1,000 ppm feed water and 75% recovery; high-intensity value is for 5,000 ppm and 75% recovery.
Figure 5
Breakdown of energy consumption by operation for a typical currently installed seawater RO (reverse osmosis) plant with an energy recovery device and capacity of 1,000 m³/day–5,400 m³/day. Energy for the RO process is the dominant energy use, but not the only one. Adapted with permission from Reference 72.

Figure 5 (72) shows the breakout of energy consumption by process for a typical currently installed seawater RO plant producing 1,000 m³/day–5,400 m³/day equipped with an energy recovery device (common equipment in RO plants to recover pressure energy from concentrate streams and transfer to the incoming feed water). Although the RO process consumes 84% of the energy consumption for a typical seawater RO desalination facility, state-of-the-art facilities reduce this share to ∼50%–67% (73).

In addition to contributing to CO₂ emissions, the energy intensity of a desalination operation also impacts the cost of the produced water. Energy costs constitute 44% of the product water cost for a typical RO-based seawater desalination system. Other costs include fixed costs (37%), maintenance and parts (7%), membrane replacement (5%), labor (4%), and consumables (3%) (74). For a typical RO facility, the major fixed costs components are desalination system (31%), power system (26%), pretreatment system (12%), and intake/outfall (11%) (75).

The energy intensity of RO processes has dramatically decreased over the past 30 years, from slightly more than 15 kWh/m³ in the 1970s to approximately 2 kWh/m³ today. Several physical constraints limit the ability to reduce the energy intensity of RO much further. One such constraint is the thermodynamic minimum energy intensity for desalination. For seawater at 35,000 ppm and 50% recovery of 0 ppm product water, the thermodynamic minimum is 1.06 kWh/m³ (73). Each desalination technology will have additional unavoidable losses attributable to the second law of thermodynamics. For seawater and brackish waters above 2,000 ppm, these additional losses are lowest for RO compared to MSF, MED, and other technologies (76, 77). In operation, a limiting factor on the energy intensity of conventional single-stage RO systems is the pressure requirement to overcome the osmotic pressure at the end of the RO module. At this point, the water to be desalinated is nearing the salinity of the reject stream concentrate and will require a higher pressure (and therefore energy consumption) for further desalination compared to the pressure requirement at the entrance of the RO module (78).

Within the literature, several opportunities are being explored for reducing the energy intensity of RO processes. Studies have shown that semibatch and staged RO processes can reduce energy consumption by 13% and 15%, respectively, over single-stage RO systems for 50% recovery from seawater (79). High-permeability membranes are also being studied as a potential opportunity to reduce the energy requirements of desalination; with higher water permeability,
process efficiency would increase. However, with increasing flow rates, fouling of membranes is a concern. Furthermore, high permeability membranes are more expensive to produce, resulting in higher capital costs. Shrivastava et al. (80) and Werber et al. (81) have shown that further increases in membrane permeability above today’s designs would have a minimal impact on overall desalination system energy intensity. However, increasing membrane selectivity may be able to reduce overall system energy intensity by reducing/eliminating pre- and post-treatment energy requirements, particularly for processes requiring very pure product water (80, 81).

FO is another desalination technology that is gaining increasing interest. FO has been commercialized in applications where concentrating wastewater to high salinity streams and/or desalinating high salinity feed waters is desirable, such as in oil and gas production. However, for seawater desalination, FO has not been commercialized. Studies have shown that FO cannot outperform RO for seawater desalination from an energy intensity perspective (77, 82, 83). However, FO offers a unique opportunity to offset the electricity cost with the use of low-grade heat, but such a technology is still in its infancy. Additional opportunities are likely to exist in improving pumping efficiency, advanced pretreatment techniques to prolong membrane life and reduce fouling, and integration of renewable energy. The next section discusses the role desalination could play in integrating electricity from renewable sources into the electric grid.

RENEWABLE ENERGY WATER INTEGRATION

Recent studies found that renewable energy could supply 80% of electricity demand in the contiguous United States in 2050 (84). The major constraint for increasing penetration of RESs is their availability and intermittency, which can be addressed using energy storage or load shifting when available to rectify the imbalance between renewable energy generation and energy demand (85). Aggressive deployment of energy-efficient technologies and power generation from RESs in the United States can reduce annual water withdrawals from 2010 levels by 38.7 trillion gallons by 2050, i.e., approximately 30% below 2010 levels (86). Significant penetration of the electricity generation sector with RESs will also significantly impact the management of local, national, and global water resources. Understanding some of the implications of such trends for energy and water use are critically important (87).

The relatively high energy intensity of desalination compared to other freshwater sources creates a wide price disparity presenting a barrier to desalination adoption in many regions of the world. Furthermore, the high energy intensity makes it difficult to integrate desalination in regions attempting to reduce CO₂ emissions. Although saline water is readily available throughout the world, inexpensive and clean energy that is readily accessible to power desalination plants is not.

As RES technologies continue to improve, and as freshwater becomes scarce and fossil fuel energy prices rise (e.g., due to a carbon tax or trade caps on CO₂), renewable energy for desalination becomes more viable economically (62). Integration of renewable energy resources with desalination systems can be accomplished by (a) establishing appropriate electrical energy storage systems (e.g., pumped hydro storage/generation plants) to smooth out renewable energy resource intermittency, (b) incorporating renewable sources into the electric grid for utilization by desalination facilities, and (c) technological matching of the energy demand of the desalination process with the intermittent renewable energy power output. Power supply management and demand-side management are considered as the two options available to address the mismatch of base-load type operation of RO and intermittent pattern of power generation by RES (88). In the first two cases, an appropriately controlled hybrid renewable energy resource system that is capable of providing a steady energy output greater than the nominal power demand of the desalination
Figure 6
Combined technologies of RESs (renewable energy sources) and desalination methods (90). Abbreviations: ED, electrodialysis; MED, multi-effect distillation; MSF, multistage flash distillation; MVC, mechanical vapor compression; PV, photovoltaic; RO, reverse osmosis; TVC, thermal vapor compression. Adapted with permission from Reference 90.

process can be envisioned. In the demand-side management option, the desalination process only operates when the energy output of the renewable energy resource unit is able to cover the energy demand.

Renewable energy may provide water desalination cost reductions due to lower greenhouse gas emissions. For example, an RO seawater desalination system operating on traditional fossil fuel-based energy sources produces 1.78 kg and 4.05 g of CO₂ and NOₓ per 1 m³ of desalted water, which can be reduced to 0.6 kg/m³–0.1 kg/m³ and 1.8 g/m³–0.4 g/m³, respectively, with electricity generated from wind or solar energy (89). In all cases, a successful design and implementation of a renewable energy–desalination combination depends on a financial analysis of the investment associated with the selected combination.

Renewable energy resources provide various advantages over conventional energy sources, but their application for desalination has been limited mainly because of technology issues (e.g., supply intermittency, cost, and availability) (90, 91). Integration of RESs is needed to reduce greenhouse gas emissions and eliminate desalination’s dependency on fossil fuels (92). Numerous experiments and pilot operations have been carried out throughout the world in an attempt to couple effective desalination processes and RESs (Figure 6). The selection of a renewable energy resource depends on several factors, including magnitude of water/energy demand, feedwater salinity, and the quality of water required after treatment, geographic location and related socio-economic-political-environmental conditions, the availability of grid electricity, and other technical infrastructures (e.g., water and energy storage). Intermittency of renewable energy and inadequate water-energy storage strategies can impede the development of desalination plants due to demand-supply mismatch. When considering resource availability, solar thermal energy and photovoltaics are considered to be more adaptable than wind and geothermal energy, which are location dependent. However, geothermal energy offers better continuity and predictability of power output than the intermittent and less predictable solar thermal, photovoltaic, and wind energy.

Renewable energy resources have been successfully deployed in stand-alone desalination systems in remote regions where the electricity grid is not readily accessible (69, 93). Desalination
using solar energy includes solar thermal desalination processes that are integrated with or used as desalination systems such as solar stills (94) and solar ponds (95), which allow harnessing low-temperature solar heat to supply the energy required for desalination. These simple and inexpensive technologies are suitable for small production systems and regions where the freshwater demand is less than 200 m³ per day (96).

The feasibility of using photovoltaics (with the produced energy being stored in batteries) to power RO desalination units at remote sites was demonstrated for small applications (less than 50 m³/day) in sunny areas that are off the grid (97). The investment cost is relatively high in photovoltaics/battery-powered desalination units, resulting in high water production costs. Battery-less photovoltaics-powered RO systems have been tested before (98) but technical problems associated with the need for a prolonged operation in standby mode still need to be overcome. Similar problems are encountered in stand-alone desalination systems directly coupled to wind turbines at remote locations (99), which can be mitigated by back-up energy systems such as batteries or diesel generators (97). Small-scale, stand-alone systems for seawater desalination powered with wind photovoltaics operating to deliver 35 m³/day of water at 2.33 kWh/m³ have been designed and deployed (e.g., in Eritrea) (100). Although several studies have been performed using hybrid renewable energy desalination systems, none of them represent large-scale applications.

Geothermal energy power generation is a mature technology, which can be used to provide energy for desalination systems (101). The primary advantage of geothermal energy, compared to solar and land-based wind, is that it is both continuous and reliable and does not require storage (102). It can generate electricity to power on-site RO plants. The first desalination plant powered by geothermal energy was constructed in 1972 in the United States. The concept was further analyzed by the Bureau of Reclamation of the US Department of the Interior (103). In 2010, the Queensland Geothermal Energy Center of Excellence, Australia, estimated that a 1,000-m³/day–100,000-m³/day geothermal plant can produce potable water at $0.73/m³–1.46/m³ (between 1.5 and 3 times the cost of recycled water from traditional sources).

Pumped hydro energy storage (PHES) is a technology commercially available for grid-tied electricity storage. PHES is widely adopted for utility-scale electricity storage (104). A PHES facility is typically equipped with reversible pumps/generators connecting an upper and a lower reservoir. The pumps utilize relatively inexpensive electricity from the grid during off-peak hours to move water from the lower reservoir to the upper one to store and create energy. During periods of high electricity demand (peak hours), water is released from the upper reservoir to generate power. The ability of PHES bulk electricity storage to even out peaks and valleys of renewable production are potentially useful to many sectors of society, including power generators, system operators, distribution companies, and new end users. So far, experience of pumped storage using seawater is limited to a single project in Japan, the 30 MW Okinawa project with a head of 136 m (105).

The most comprehensive assessment of PHES opportunities conducted in the United States was by the Army Corps of Engineers (106). According to that assessment, the United States is endowed with potential PHES sites capable of handling >1,000 GW, roughly equal to the US total electricity generation capacity in 2014 (1,068.4 GW) [see data from eia.gov, accessed on August 10, 2017 (https://www.eia.gov/electricity/annual/html/epa_04_03.html)]. The currently available 86 GW from PHES facilities (107), which is a fraction of global available capacity of 480 GW, falls short of the projected increase of RESs share in the power generation sector. As intermittent renewable power gains market share, the need for bulk electricity storage will increase, potentially increasing the development of PHES.
The main limiting factors for PHES are environmental and financial concerns and uncertainties rather than the availability of technically feasible sites. PHES developers are proposing innovative ways of addressing the environmental impacts, including the potential use of waste or saline water in PHES applications. Such new opportunities and the increasing need for greater energy storage may provide adequate technology for large-scale penetration and integration with intermittent RESs such as wind and solar power (108).

The most challenging issue associated with the large-scale implementation of renewable energy desalination technology is the optimum matching of the intermittent renewable energy power output with the steady energy demand of the desalination process. Properly designed demand-response management can be used to address these problems (88). Through innovative system design, RES integration, and management, desalination at practical scales offers opportunities beyond supplying potable water and can serve as a flexible and multipurpose asset to balance and support the electricity infrastructure, integrate RESs, and provide energy and water storage capabilities.

Considering that water reservoirs can be located far away from the end user, RES units can provide the energy required for extraction and conveyance of water. A scenario hypothesized by the current authors could include saline water extraction, desalination, and conveyance to storage locations carried out during periods of availability of inexpensive electricity from RESs. RESs, in conjunction with local water storage at high elevations and pumped-hydro energy generation, can create electric grid-balancing opportunities. The produced freshwater could either be integrated directly into the water system or stored at higher elevations and used for hydroelectric power generation during periods of high electric demand (109). The extracted electricity would offset electricity requirements of the desalination process or it could be delivered directly to the grid. Such systems can serve as a spinning reserve by allowing for operational flexibility to produce or store produced fresh or brackish water in response to electric demand in small autonomous island grids as well as massive energy demand-response schemes, with the latter providing an alternate source of revenue for the desalination facility. Additionally, through selection of appropriate saline water sources and use of emerging and existing technologies, environmental impacts might be lessened and water costs dramatically reduced.

WATER-ENERGY END USE EFFICIENCY

When water arrives at its end use, additional energy is often required for pumping and heating. In some regions (e.g., United States, Netherlands, and Taiwan), this is the dominant energy use for water, with 80% of the energy consumption at the point of end use and 20% for water supply (extraction, treatment, and transport) and wastewater treatment (110). In general, a reduction in water use will yield a reduction in energy use and associated CO₂ emissions. As an example, state-mandated water reductions in California in 2015 resulted in significant energy savings. Data from July to September of 2015 showed a 28.3% reduction in water use resulting in savings of 460 GWh and nearly 110,000 MT CO₂eq in water infrastructure energy consumption and emissions. These savings equaled all first year savings from California’s investor-owned utility energy efficiency programs implemented over the same time period (see Figure 7) (111). With 19% of all of California’s energy use related to water (e.g., end uses, supply, and treatment), small but significant reductions in energy usage from water conservation, as observed in 2015, had been predicted almost a decade ago (112).

The example of California’s energy savings from its water mandate illustrates water efficiency directly enabling energy savings. Considerable energy is used for domestic hot water heating, and
it is one of the most energy-intensive water processes. Reductions in the volume of hot water used will result in reduction in both energy and water use. Examples of measures reducing hot water usage include low-flow shower heads, efficient clothes washers and dishwashers, and behavioral changes (110, 113–115).

Less addressed in the literature is the water-energy nexus within manufacturing systems. Here, too, energy for water can be a nontrivial portion of total energy demand. For example, in the United States alone, industrial steam systems use 1.3 million m³ of water per day as boiler make-up water and 3,780 TBtu/year of energy for making steam from this water. Of the water use, 81% is for direct steam injection, 15% for blowdown, and 3% is leaked (18). Reductions in these uses will result in water and energy savings. Steam system measures, such as returning condensate, fixing broken steam traps and leaks, and eliminating continuous blowdown, will reduce both the energy required to produce steam, and water for generating steam. Additionally, unique energy-and water-saving opportunities exist within manufacturing systems given the variation in processes and water use characteristics. As one example, recovery of hot water released in the cooking of tomatoes had the potential to yield substantial water and energy savings at a tomato processing facility (116). In another example, a plastics manufacturer was able to offset 250,000 gallons of make-up cooling tower water per year and reduce the cooling system pump and fan load by 80% through rainwater harvesting (117).

Not all water efficiency measures will realize energy saving at the point of end use. However, they will realize energy savings within the water supply and treatment network. The magnitude of these savings will vary by region and water source. The national average of energy intensity for water supply and treatment is 0.42 kWh/m³–0.55 kWh/m³. In New York State alone, the range is 0.12 kWh/m³–0.36 kWh/m³. The range for the national average electricity intensity for wastewater treatment and disposal is 0.2 kWh/m³–0.8 kWh/m³ (15). As an example, water reuse within a facility may not always save energy at the end use, but it reduces energy consumption in the water and wastewater network. In a survey of California food processor’s water use, 95% of discharge water from canned fruit operations was used for irrigation. Similar percentages were shown for tomato paste (76.9%) and canned tomato products (99.3%) (118). These water savings will result in energy savings for providing irrigation water. As another example, low-flow toilet...
fixtures will yield water and wastewater system energy savings. A quantification of the energy savings in the water and wastewater distribution system associated with replacing 276 standard toilets (average of 3.84 gallons per flush or gpf) in low-income multi-family dwellings with low-flow toilets (duel flush 1.6/0.8 gpf with average 1.58 gpf) was 5,712 kWh/year. It should be noted that the energy intensity of wastewater treatment in the district in which this was conducted (Southern California) was 0.03 kWh/m³, much lower than the national average (119).

Water-saving measures at the end use will likely yield additional water savings at the source, which, in turn, yields greater energy savings. Water losses attributable to leaks within water distribution networks are estimated to be 14% in the United States and as high as 50% in developing countries. However, there is significant diversity in the losses even within the United States. Of 32 water authorities polled by the American Water Works Association, real water losses as a percent of water supplied in 2015 ranged from lows of 4% (Albuquerque, New Mexico; Avondale, Arizona; and Las Vegas, Nevada) to a high of 53% (Mifflinville, Pennsylvania), with cities such as Philadelphia (31%) and Birmingham, Alabama (34%), experiencing high losses (120–122). In addition to losing treated water, energy for pumping and treating the water is lost, too. A leak audit program at three water utilities in Southern California revealed potential for more than 313,000 m³/year of water savings with an accompanying electricity savings of 178,000 kWh/year (119). Furthermore, reducing leaks from current levels in Texas (13%) and California (10%) to 5% would result in a reduction of 1.4 Mt and 3.4 Mt of CO₂(eq) per year (quantified using life-cycle assessment methods). To minimize greenhouse gas emissions due in part to leaks, pipes should be replaced at least every 20 years. To provide context, the current average replacement schedule for municipal pipes in the United States is once every 200 years (123). Similarly, life-cycle assessments of pressure management, where the pressure of a water system is controlled based on current water demand and minimum pressure requirements, in the Philadelphia and Halifax water supply systems showed potential savings of 130,000 m³ of water per year each with accompanying greenhouse gas reductions of 50 Mg/year and 170 Mg/year in Philadelphia and Halifax, respectively (124).

Certain energy efficiency measures may not directly enable water savings, but can still reduce the amount of energy and CO₂ emissions associated with using water and reduce the amount of water required to generate the energy. For electricity-saving energy efficiency measures, the reduction in electricity will yield water savings (both withdrawals and consumption) at the power plant if it is a thermoelectric plant. Figure 2 shows typical water use and consumption rates for various thermoelectric power plants per megawatt-hour of electricity generation.

ADVANCED RESOURCE RECOVERY FROM MUNICIPAL WASTEWATER

Wastewater treatment is a critical component of meeting potable water demands and maintaining public health standards. Lack of wastewater treatment can lead to the spread of deadly viral, bacterial, and parasite-caused diseases as well as the contamination of freshwater supplies. The World Health Organization (WHO) estimates that 2.4 billion people in 2015 (32% of the global population) did not use a sanitation system where human waste is separated from human contact (referred to by WHO as improved sanitation). This estimate is only for simple separation of waste; the number of people living without a wastewater treatment system (transfer, treatment, and safe disposal) is likely much higher. The economic benefits of improving wastewater sanitation globally are immense. According to the WHO, every 1 USD invested in improving wastewater sanitation will result in saving 5.50 USD through increased productivity, reduction in premature deaths, and...
reduced healthcare costs. Additionally, as the global population increases, the number of people needing wastewater sanitation systems will increase. Although access to wastewater sanitation has kept pace with global population demands in some areas (e.g., southern, western, and eastern Asia), it has not in others (e.g., sub-Saharan Africa and Oceania) (125, 126).

Energy is essential to powering wastewater systems. Meeting wastewater sanitation requirements now and in the future will require significant amounts of energy. However, great opportunities exist to recover energy, nutrients (which would otherwise require energy to produce), and clean water from wastewater streams. Energy optimization and resource recovery of wastewater treatment can simultaneously improve global health and increase the supply of clean energy and water.

The average energy intensity of treating wastewater with aerobic sludge treatment and anaerobic sludge digestion is 0.6 kWh/m³ of wastewater (127). Average energy intensities for conventional wastewater treatment for several countries/regions are 0.41 kWh/m³ in Taiwan, 0.43 kWh/m³ in the United States, 0.46 kWh/m³ in Ontario, Canada, and 0.49 kWh/m³ in New Zealand (115). In the United States, municipal wastewater systems (excluding private systems) use more than 30 billion kWh of electricity per year, equaling 0.8% of total US electricity use. In a typical plant, 52% of this energy is used for aeration, 30% for biosolids processing, 15% for pumping, and the balance for miscellaneous uses (15). Energy efficiency opportunities related to operational and equipment upgrades exist in wastewater treatment plants (15, 128, 129). However, this review focuses on opportunities to recover energy and water from municipal wastewater streams. Agricultural and industrial wastewater flows are not addressed in this review.

In many instances, nutrient recovery is possible and desirable. A brief overview of its importance and connection to energy and water recovery from wastewater systems is provided here. Numerous contaminants exist in municipal wastewaters, including organics, nitrogen (N), phosphorous (P), heavy metals, toxins, and pathogens. The composition of municipal wastewater—and the available energy from its waste content—will vary based on the qualitative nature of the waste produced by the population being served. Traditionally, wastewater treatment has existed primarily for public and environmental health purposes. Although these will always be prime drivers, wastewater treatment is now being seen as an opportunity to recover clean energy, nutrients essential for agriculture that would otherwise require energy to produce, and water (130). N and P recovery will become increasingly important as global agricultural demands continue to grow. Furthermore, rates of consumption of both are outside of the safe planetary boundaries and are classified as “high risks” to the Earth’s systems (2). Ammonia, which is used in fertilizers, is produced using energy-intensive industrial processes and fossil fuels. However, in wastewater treatment systems, energy is used to remove N. If N can be recaptured, then energy to produce ammonia would be offset. P is a nonrenewable and irreplaceable resource in food production. Although 20% of P mined for fertilizer is excreted by humans, it is difficult to recover P from current wastewater treatment processes. With global P production expected to peak as early as 2025, the need to recover P from wastewater is a pressing issue (131–133).

Municipal wastewater contains a significant amount of energy, although not all is recoverable. By one estimate, the chemical energy content (e.g., methane production potential) per unit of municipal wastewater is 2.1 kWh/m³ for domestic to 4.7 kWh/m³ for mixed (commercial and residential) wastewater. Theoretically, if all of this chemical energy were captured (i.e., 100% of global population using a wastewater system, 100% capture of methane, 100% conversion efficiencies), the methane in municipal wastewater for a global population of 6.8 billion people would be greater than 82 GW (134). Although fuel capture and conversion efficiency and economic considerations will limit the extent to which this potential can be realized, significant opportunity
for energy recovery exists. In the United States (as of June 2011), only 104 of the nearly 16,000 wastewater treatment facilities captured methane as biogas and used it in a CHP (combined heat and power) system. These 104 facilities yield 190 MW of electricity generation capacity. The US Environmental Protection Agency estimates that because of economies of scale an additional 257 to 662 mostly large facilities could economically capture and use biogas, providing 178–260 MW of electricity generation capacity (135). These estimates are for conventional anaerobic digestion of activated sludge. Some limitations of anaerobic digestion include the need for high concentrations of organic matter (>3 kg per m³ of waste), warm wastewater temperatures (>20°C), and high minimum flow rates (typically >3,785 m³) to be economically viable. One study of wastewater treatment plants with biogas capture and use in Austria showed that both an energy-efficient single-stage and a two-stage activated sludge plant could operate as a net energy producer over long time frames (1 year or greater). However, the plants would still have periods where they would need to purchase electricity (136). Calculations have shown that complete anaerobic digestion (of both the sludge and low-concentration wastewater stream) can produce twice the amount of biogas compared to aerobic digestion, while consuming less energy for the process and producing less sludge to be handled and disposed (127, 137). In order to avail of this opportunity, the facility’s physical footprint would have to be significantly higher. Three advanced processes to enhance energy recovery from wastewater—microbial fuel cells (MFCs), microalgae, and anaerobic membrane bioreactors—are discussed here. For a review of other energy recovery options, including incineration, hydropower generation, onsite wind and solar power, and heat pumps, see Mo & Zhang (138).

The use of microbial electrochemical technologies, such as MFCs, to recover energy from wastewater streams is an emerging field of research. In MFCs, wastewater is streamed through a cathode/anode pair. Special bacteria (exoelectrogenic microorganisms) that can extract electrons from the biodegradable matter are added to the waste streams. The electrons collect at the anode, and oxygen is used to oxidize the cathode thus generating a voltage potential. The benefits of MFCs include direct electricity generation from wastewater, while consuming less energy for the process and producing less sludge to be handled and disposed (127, 137). In order to avail of this opportunity, the facility’s physical footprint would have to be significantly higher. Three advanced processes to enhance energy recovery from wastewater—microbial fuel cells (MFCs), microalgae, and anaerobic membrane bioreactors—are discussed here. For a review of other energy recovery options, including incineration, hydropower generation, onsite wind and solar power, and heat pumps, see Mo & Zhang (138).

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The use of microalgae is being studied as another potential energy capture mechanism for municipal wastewaters. Microalgae with lipid content can be grown within the wastewater streams substituting conventional treatment processes. When grown, the microalgae can be harvested and converted into biodiesel (140). In addition to providing a CO₂-neutral substitute for fossil fuel, microalgae have a higher lipid productivity rate per unit of cultivation area (measured in mass/surface area/day) than macroalgae. Furthermore, compared to growing biomass specifically for energy generation, wastewater microalgae do not impinge on land use for crop production and do not require additional freshwater. Another benefit of microalgae is its ability to effectively remove N and P from wastewater streams. However, a significant barrier to greater uptake is the technical and economical difficulty in harvesting microalgae (138, 141, 142).

Membrane bioreactors, such as anaerobic fluidized bed membrane bioreactors, have shown promise at the laboratory scale to produce methane gas from low-concentration waste streams (143). Anaerobic membrane bioreactors have also shown promise for recovering nutrients (such as N and P) in addition to energy, but so far only at laboratory scale (131, 144).
Municipal wastewater also offers opportunities to extract clean water. Once treated, the majority of municipal wastewater is discharged to the surface or ground. For communities seeking alternate water supplies, these waters can represent an attractive option. Reuse options for municipal wastewater include industrial (i.e., cooling, boilers, process), agricultural, countering seawater intrusion, municipal (i.e., urban landscape irrigation), recreational impoundment, habitat restoration, direct or indirect potable reuse, surface water augmentation, and groundwater recharge. The opportunity for municipal wastewater reuse is estimated to be significant: 38%–50% of California’s municipal wastewater discharge and 38% of US municipal wastewater discharge. Throughout the world, 21 million m$^3$/day of treated municipal wastewater is being reused in countries/regions such as the United States, Mexico, Australia, China, and the Middle East. Energy and cost ranges for municipal water reuse are highly site specific. In general, they are more attractive than seawater desalination but less attractive than water conservation. In Southern California, where the energy intensity for conveying freshwater is extremely high (2.31 kWh/m$^3$), the energy and cost savings from direct potable reuse have been estimated to be 0.8 kWh/m$^3$–1.3 kWh/m$^3$. The energy intensity may also be attractive when compared to conventional treatment. In Melbourne, Australia, a waste stabilization pond turns municipal wastewater into nonpotable reuse water and uses 0.5 kWh/m$^3$ less energy than conventional treatment. Barriers to municipal wastewater reuse include public perception and concentrated waste streams. Reuse may exacerbate existing contaminant removal deficiencies of wastewater treatment plants, such as inadequately removing pharmaceuticals. Nonpotable reuse may also require the construction of a dedicated distribution system to prevent cross-contamination of potable water, creating high capital cost requirements. When used to offset freshwater use for industrial cooling, additional barriers include biofouling of cooling towers and mineral scaling and corrosion on heat transfer surfaces and/or conveyance pipes (60, 121, 145–148).

CONCLUSION

The technologies and engineering of the water-energy nexus offer opportunities to meet expected resource demands (for water and energy) while limiting the impacts on Earth’s environmental systems. Quantitatively, only a small fraction of water and energy supplies are tied up in the water-energy nexus, but the dependencies are quite critical. On the one hand, low-energy-intensive water supply options are relatively limited. On the other hand, low-water-intensive energy supply options appear abundant. Technology and engineering have a key role in capturing opportunities to provide access to both while minimizing environmental impact. Discussed here were five couplings in the water-energy nexus: (a) thermoelectric cooling, (b) desalination and its potential (c) integration with renewable energy, (d) water-energy efficiency at the point of use, and (e) advanced wastewater recovery. A summary along with emerging topics/questions for each are provided below.

Of the five areas reviewed here, thermoelectric cooling is the only area where complete decoupling of water from energy is possible. Through use of simple cycle power plants with dry-cooling technologies, water can be entirely eliminated from the electricity generation process via thermoelectric power plants. However, this decoupling will come at increased capital cost and reduced plant efficiency. Wet-cooling technologies offer opportunities to more cost effectively reduce water withdrawals (but increase consumption). An emerging question is whether integrated water and energy system planning aided through sensor and control systems can help a power plant determine the optimal use of water resources and modulate its operations in real time based on environmental and economic factors.

The energy requirements for RO desalination, the most dominant desalination technology, have dropped precipitously over the past 40 years. Further reductions will be difficult to achieve.
However, hybridization of desalination technologies offers opportunities for reducing desalination costs and expanding the flexibility of operations with nontraditional waters of various degrees of salinity and ionic composition at various locations. Moreover, matching desalination operations with renewable energy generation offers a significant opportunity for reducing the cost of water and emissions associated with desalination. Overall product water recovery in a desalination process can be increased and cost reduced through the serial or simultaneous application of more than one desalination process and use of different forms of energy from multiple sources. The main challenge associated with the large-scale implementation of renewable energy-desalination technology is the optimum matching of the intermittent renewable energy power output with the steady energy demand of the desalination process. This can be achieved through development of novel desalination technologies suitable for coupling with RESs and/or cost-effective integration of the existing technologies across water-energy sectors.

All water efficiency and energy efficiency measures at the point of end use will result in savings of the other resource. However, some measures will only lead to saving via the embedded water or energy, and not the water/energy directly used at the point of use. A greater understanding of the water-energy linkages in more complex point-of-end-use systems may reveal unique and large opportunities for water and energy reductions.

Advanced resource recovery from municipal water supplies can offset the requirement for new water supplies, recycle critical elements, such as P and N, and provide enough energy to enable a self-sustaining process. Increased knowledge and sharing of best practices could increase the recovery of energy from wastewater streams. To capture greater amounts of energy than what is currently economically feasible, technologies are required that can capture methane from a greater percentage of the sludge. Water recovery from municipal wastewater streams can be particularly attractive to communities in water-stressed regions, but it must first overcome public perception, concentrated waste disposal, and infrastructure barriers.

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