Sustaining Water Resources: Environmental and Economic Impact

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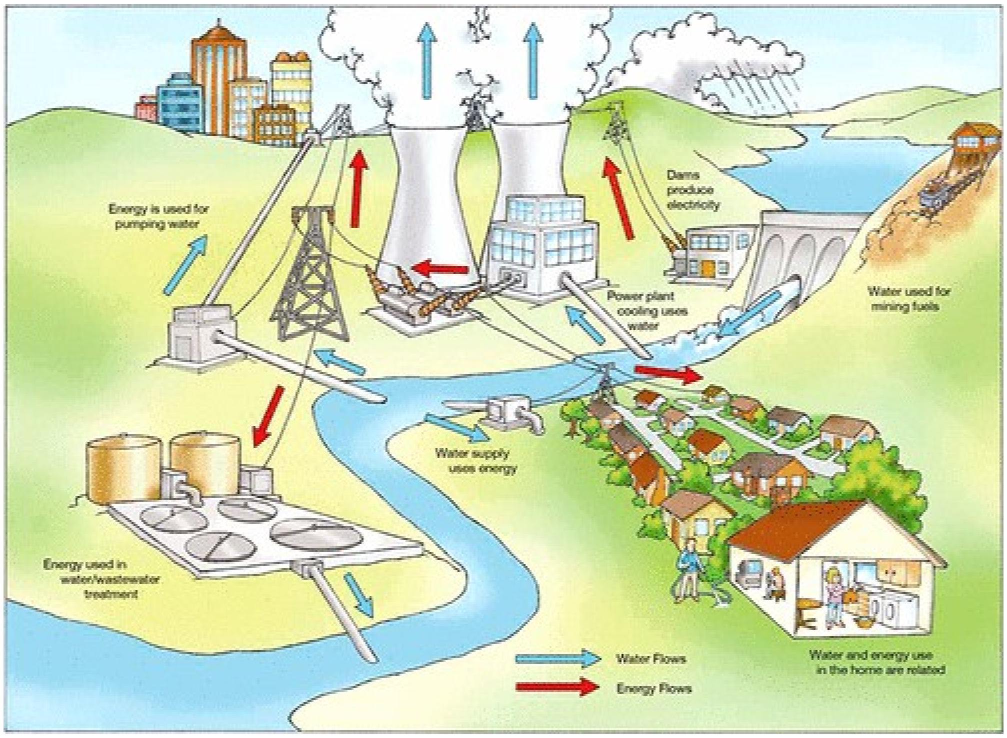
Abstract



Water is essential to human health and economic development due to its utilization in sanitation, agriculture, and energy. Supplying water to an expanding world population requires simultaneous consideration of multiple societal sectors competing for limited resources. Water conservation, supply augmentation, distribution, and treatment of contaminants must work in concert to ensure water sustainability. Water is linked to other sectors, and the quantity and quality of water resources are changing. The efficient use of water in agriculture, the largest user of water worldwide, via drip irrigation is described as is the use of energy-intensive reverse osmosis to supplement freshwater supplies. Efforts to manage watersheds and model their responses to severe weather events are discussed along with efforts to improve the predictability of their function. The regional competition for water resources impacts both energy and water supply reliability, which requires that nations balance both for sustainable economic development. The use of water and energy in the US is described which provides a lens through which to both rethink the interrelationship of water and energy as well as evaluate technological developments. Advances in nanotechnology are highlighted as one emerging technology. These results underscore the multifaceted nature of water sustainability, its interrelationship to energy and economic development, and the need to develop, manage and regulate water systems in a concerted manner.

KEYWORDS: Water sustainability, Water conservation, Watershed management, Water−energy nexus

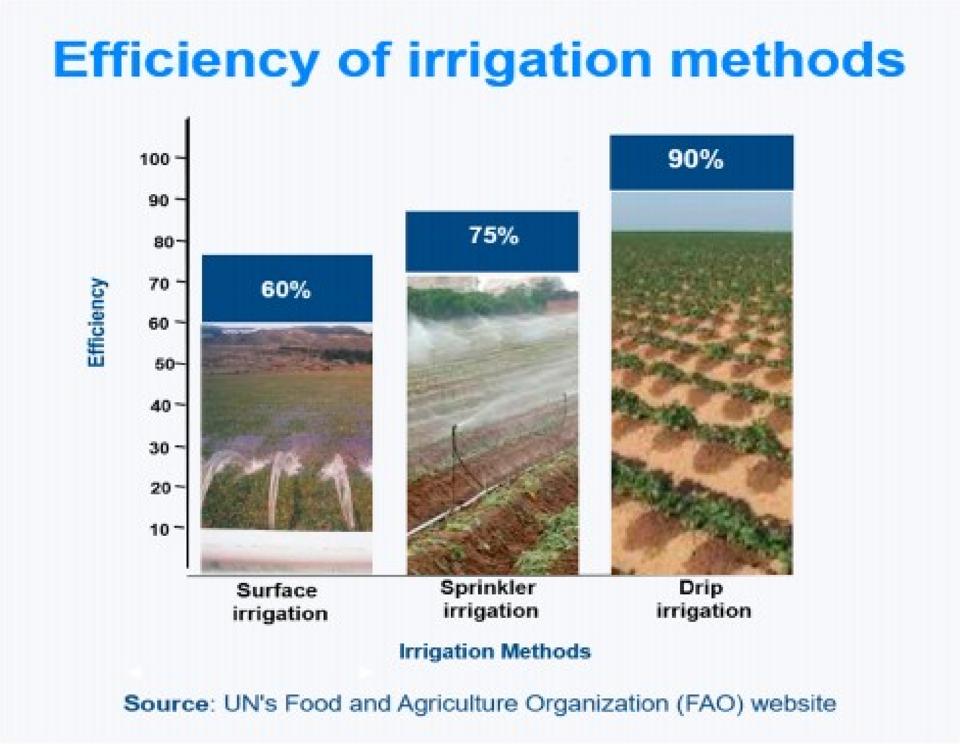
Introduction

Supplying water needs to an expanding world population requires simultaneous consideration of multiple societal sectors competing for limited resources.(1,2) There is tangible evidence of worldwide freshwater shortages created by destabilizing changes in climate coupled by increasing demands for food security, energy production and consumer use. Water is important for agriculture; hydroelectric power generation; energy-resource extraction, refining, and processing; consumer use; and human health.(2) For example, desalination, may relieve the dire need for freshwater but it also needs continued investment to reduce its high energy footprint and to take brine disposal steps that protect marine life. Dams, constructed to harness water to generate clean hydropower energy, need to ensure that fisheries providing a major protein food source are protected. Access to electricity enhances economic growth and can eliminate the practice of burning biomass for cooking which spews out CO_2 into the atmosphere. Efforts to improve water and sanitation security while protecting water resources and

water-related ecosystems are inexorably linked to energy sustainability in the modern global economy.(4) The United Nations has adopted sustainable development goals that recognize the need to build economic prosperity that addresses poverty, inequality and climate change on a global scale.
(5) Elements of a strategy to address water sustainability include water conservation, supply augmentation, distribution, and treatment of contaminants. In addition, the competition for water resources will impact both regional energy and water supply reliability and require that nations balance the demands and availability of water and energy for economic development. Current efforts that address needs to improve management development and regulation of water and energy systems in a concerted manner are described herein.

Water Conservation

Since more than 70% of the water we consume globally(6) goes to agriculture and there will be about 11 billion mouths to feed by the year 2100,(7) every drop needs to be carefully managed. Drip irrigation, pioneered in Israel’s Negev desert, involves the precise targeting of water and nutrients to the plant and root zone. This prevents water being wasted on the rest of the soil and optimizes moisture and aeration conditions, resulting in higher yields and significant savings in water, energy and fertilizers. The data in Figure 1 gives evidence of the water efficiency of various irrigation methods.(8)



Source: UN's Food and Agriculture Organization (FAO) website

Figure 1. Comparison of irrigation method efficiencies.

In Israel, more than 75% of irrigated agriculture uses drip irrigation. Almost 85% of Israel's wastewater is recycled by treating sewage with the technology of activated sludge, whereby microorganisms grow by decomposing organic matter in wastewater aerated in contact with oxygen. The treated wastewater is subsequently separated from the sludge in clarifiers and the resulting effluent is further purified and sent to storage reservoirs for farming needs independent of drought (*vide infra*).(8) Drip irrigation has converted the Israeli desert into farmland and is increasingly doing so worldwide which shows its impact at scale. For instance, drip irrigation has been adopted to protect against drought/flood in California, and to practice economically viable agriculture in India.

Integration of drip irrigation with digital farming technologies is further enhancing its sustainability advantages. Netafim's NetBeat platform(9) is one such example of "smart farming" technologies. Using in-field sensors and satellite imaging to collect real-time crop and weather data, it analyzes the data in the cloud using sophisticated crop models, and then provides farmers with automated recommendations that enable them to optimize irrigation, fertilization and crop protection decisions to optimize production while conserving water, and therefore, energy. The upshot is an improvement in the ability of farmers to grow even more produce using even less water, energy and other inputs.(10,11)

Installation costs for drip irrigation vary depending on crop, field size and cost of labor. For example, installing one acre of a family drip irrigation system in a developing country takes 1 day and can be performed by the grower. In comparison, installing one acre of subsurface drip irrigation for an alfalfa field by a professional team can cost approximately $500 USD (excluding the cost of peripheral equipment). Maintenance costs vary, too. For instance, maintaining a drip irrigation system in a sugar cane farm in Africa requires 9 days of unskilled labor per acre each year.

Augmenting Freshwater Supplies

By far, the preferred method worldwide of augmenting freshwater supply is desalination of ocean water via reverse osmosis (RO). Indeed, Israel gets 80% of its drinking water from desalination.(8) The energy-intensive desalinization process applies pressure pumps to push filtered seawater through delicate membranes, producing freshwater and thick brine. The polyamide membranes used are subject to rupture and biofouling. Ultrafiltration membrane filtration of incoming water feed is the preferred pretreatment technology in desalination. The compact design of bundled hollow fibers in UF membranes protects RO membranes from costly frequent replacements. With pore size of 0.01 µm, they provide high efficiency in removing suspended solids, microorganisms, most pathogens and colloidal matter. The UF process also addresses environmental concerns by limiting the usage and disposal of coagulants. Recent work with lightweight durable nanomaterials such as graphene for membranes look promising (*vide infra*) as a new technology to reducing membrane rupture. To avoid severe negative environmental impact on marine life, desalination plants are usually built adjoining power plants where the brine is added slowly to the cooling waters of the power plant, diluting the effluent before returning it to ocean water.(11) Desalination also has an economic impact: the energy consumption for desalinating seawater typically operates at 3–4 kWh/m.(3) The world’s largest RO desalination plant, in Sorek, Israel, produces 624,000 m^3/day at a cost of $0.52/m^3.(12)

Freshwater Distribution and Resiliency

Enhancing the resiliency of water resources is critical for continued prosperity, as well as for diverting economic and geopolitical instability. Indeed, the 2017 World Economic Forum Report(13) identified water crisis as a top global threat, compounded by droughts, floods and other extreme weather events. After all, water-related disasters account for 70% of all deaths related to natural disasters. In addition, an estimate(14) of the global economic loss from natural disasters (such as hurricanes and wildfires) in 2017 alone was $306 billion, almost double the loss from the previous year.

It is increasingly recognized that we can no longer rely on historical hydrological trends and simple measurement and modeling methods to optimally mange our water resources. Here, we briefly describe two research directions important for water resiliency, including advancing mechanistic prediction of watershed responses to hydrological extremes and approaches to store water for subsequent use.

While watersheds are recognized as the Earth’s key functional unit for assessing and managing water resources, developing a predictive understanding of how much precipitation is delivered to watersheds and how watersheds respond to extreme events (such as floods and droughts) is challenging due to the complex hydrological-biogeochemical nature of watersheds.(15−18) This is particularly true in mountainous watersheds regions, where atmospheric processes are complex and extreme lateral gradients in watershed topography, vegetation and hydrology exist. Mountainous watersheds, referred to as “water towers of the world”(19) provide 60 to 90% of the world’s fresh water resources and are being particularly threatened by global warming trends.(20,21) As snowpack stores water for subsequent downgradient delivery, warming-induced changes in snowpack and snowmelt timing can dramatically alter available water resources. Examples of vulnerable and important Western US mountainous systems in terms of water supply include the Colorado Rocky and the California Sierra Nevada Mountains. Among other societal benefits, the snow fed Colorado River, which originates in the Rocky Mountains, supplies more than 1 in 10 Americans water for municipal use, as well as irrigation water for more than 5.5 million acres of land. The basin also supports more than 4,200 megawatts of electrical generating capacity providing power to hundreds of local areas and millions of people.(22,23) Snowmelt from the California Sierra Nevada Mountains drain to rivers that supply water to roughly 25 million Californians via the State Water Project.(24)

Several developments over the past decade provide a springboard for improving our predictive understanding of complex watershed behavior. For example, remote sensing, UAV (Unmanned Aerial Vehicle) technologies, surface geophysical approaches and the Internet of Things are changing the way that we characterize and monitor watershed behavior.(25,26) The networked sensing approaches have the potential to greatly improve our ability to track water and its constituents: vertically from the atmosphere to the ground surface through deep groundwater, and across watersheds and basins. High-performance computing capabilities are allowing process-based simulation of interactions between different compartments of watersheds,(27−31) allowing a more mechanistic understanding of how watersheds respond to intense precipitation, prolonged droughts, artificial recharge, and other perturbations. Increasingly autonomous data sets are being assimilated into models for improved predictions. The technological advances are expected to lead to new insights about how fine-scale processes contribute to aggregated watershed behavior(18) and new abilities to predict watershed responses to extreme events over space and time scales important for water management.

In addition to improving prediction of watershed function it is critical to develop new approaches to store excess water for future use. For example, managed aquifer recharge (MAR) approaches, currently in practice in select locations, take advantage of immense aquifer pore volume to store or "bank" excess water which can be subsequently extracted when needed.(32) MAR holds potential to store water at a volume equivalent to all conventional dams currently in the US, but with far more flexibility and at lower cost. MAR offers additional benefits beyond water resiliency, including flood risk reduction, mitigation of land subsidence, and improvement in water quality. For example, over pumping of groundwater can lead to subsidence of the land surface (which can dramatically impair water and other infrastructure) as well as a decrease in water quality.(33) Opportunities exist to develop: (a) minimally invasive characterization methods that can *a priori* identify subsurface locations that have large storage capacities, (b) approaches to model and remotely monitor where injected water moves beneath the subsurface, enabling a predictive understanding of MAR efficacy "at scale", and (c) new techniques that enhance control of permeation for infiltration as well as adsorption and reactivity for water quality benefits.

Technologies Enabling Treatment of Polluted Waters

The pollution of our precious freshwater supplies has been steadily increasing by demands of an exponentially increasing world population and industrialization of our societies. The chemical and petrochemical industries release toxic, mostly organic and nonbiodegradable chemicals into pristine water systems. Likewise, fertilizer runoff and pesticides from agriculture, pharmaceuticals and hormones that persist after purification in drinking waters, plastics that choke the livelihood of marine life are but some major examples.

Still some technologies exist that have had considerable success in remediation of our water supplies The most common technology for recycling sewage waters is the activated sludge process which replenishes urgently needed water resources. In Israel, the Shafdan treatment plant (*vide supra*) of municipal wastewater is a well-established additional source for irrigation.(34) In Orange County, California, recycled water is purified to provide drinking water for 2.4 million residents.(35)

For remediation of water supplies polluted by heavy metal contaminants, adsorbents are playing a key role. Such pollution has been well documented in reports by Iran’s Tembi River, Nigeria’s Warri River and others.(36−40) One technology that has been effective for purifying water effluents contaminated with toxic metals is to pass effluents through a classic ion exchange column, divided into cation or anion resins, in which the resins absorb the toxic metal contaminant and pure water flows out of the column. The global market for ion-exchange resins was 1.45 billion dollars in 2015 and is projected to reach 2.26 billion dollars by 2.26, due to bulk water treatment needs.(41) More specialized water treatment needs can be addressed using ion-selective polymers. The common feature of all ion-selective polymers is the presence of a ligand selective for a targeted substrate or class of substrates. Cross-linked polystyrene beads can be the support onto which the ligand can be immobilized or the ligand can be incorporated using a functional monomer. Alexandratos and colleagues have developed resins of polystyrene beads which are bonded with specific ligands to produce more selective ion-exchange polymers, specifically targeted to select for arsenic, actinides, perchlorate, silica or uranium.(42) In order to be of practical significance, the process needs to enhance binding of contaminants at a rapid rate and high capacity. Cross-linking of the polymer to form beads is advantageous because of their adaptability to continuous processes but the polymer can also be linear and then separated from water by ultrafiltration after binding the pollutant. The perchlorate and actinide-selective polymers known respectively as Purolite 530E and Diphonix, are examples of products produced commercially. In the development of the actinide selective polymer, Diphonix, the Alexandratos team noted that the water-soluble diphosphonic acids had high affinity for actinides but attracted them slowly. The problem was solved by adding sulfonic acid which attracts everything but eventually only the actinide was kept on the column due to its high selectivity. In the laboratory, Diphonix developed in this manner removes over 99.9% of uranium from water. Multiple examples(43,44) exist showing ion-selective polymers to be versatile reagents for targeted separations and thus continue to have a significant environmental impact in an increasing water-stressed world.

Another pollutant found in drinking water, even bottled water, is microplastics,(45,46) tiny beads of polyethylene plastic often added to health and beauty products. Existing technologies for their removal are carbon block filters or reverse osmosis filters and ion exchange. The former reduces microplastics to 2 μm while the latter can filter down to 0.001 μm, essentially removing them all but at a significantly higher cost. Although known to be harmful to marine and aquatic life, there is no known human health effect from microplastics either in drinking water or from exposure to other sources such as food ingestion, nutrient supplements, personal care products or air inhalation. Microplastic occurrence, removal, and health effects are an emerging research area with significant public perception interest.(47)

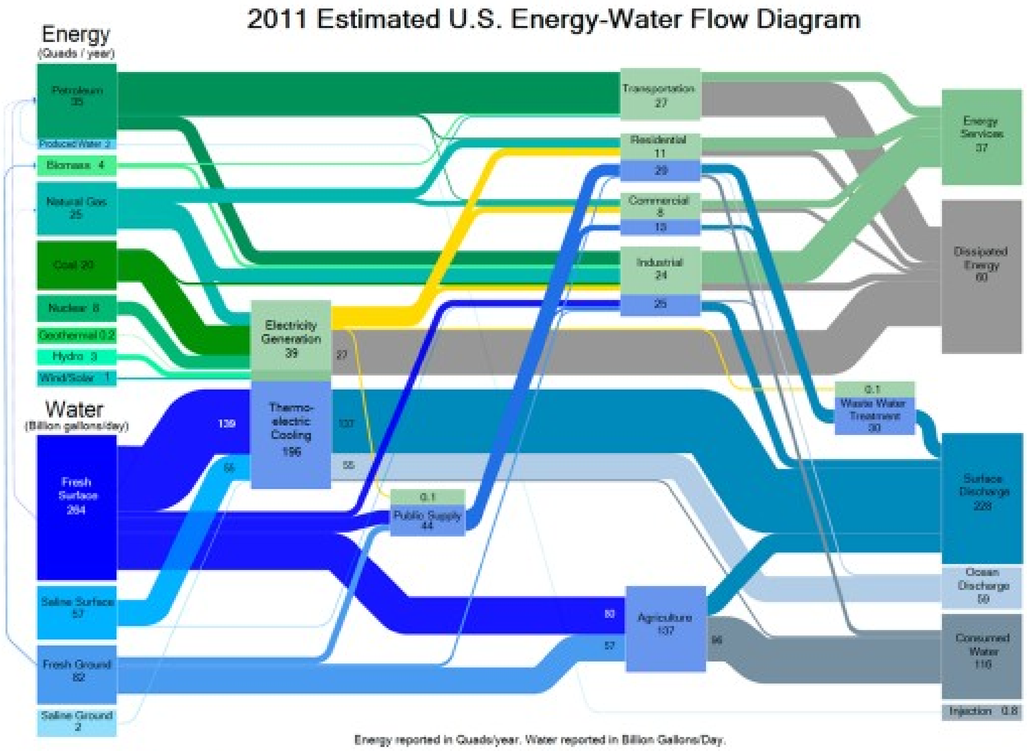
Nanotechnology is emerging as a competing approach that leverages the unique properties of the nanoscale to purify drinking water using electricity or direct sunlight.(48,49) Centralized facilities designed to treat large volumes of water with concentrated chemicals and standard separation techniques, or point-of-use systems (POU) can be inefficient. However, POU desalination systems that work like photovoltaic (PV) solar panels can use sunlight to superheat nanoparticles on the surface of distillation membranes capable of purifying water possessing any salinity level to drinking water quality.(50) With electrical energy input from the power-grid or renewable energy sources (solar-PV, wind), nanostructured electrode surfaces can produce hydroxyl radicals capable of oxidizing pollutants in water or producing hydrogen peroxide which in the presence of UV light produces more HO radicals.(51) Nanotechnology is used in UV light-emitting diodes (LEDs) for disinfection in POU and municipal systems.(52) Nanoenabling sorbents capable of hexavalent chromium removal can lead to simultaneous arsenate removal, thus decreasing in half the size and life-cycle footprint of groundwater treatment system.(53,54) There is promise of layered graphene or carbon nanotubes to eventually replace polymeric desalination membranes (*vide supra*).(55,56) While discoveries of these processes are reported in the literature, actual products and processes have been slow to mature beyond the bench-scale into large-scale pilot or full-scale water treatment plants.

The benefits of nanotechnology enabled water treatment may start in POU systems, because of the lower capital costs to enter the POU market compared with municipal treatment systems that are designed to operate for decades. While nanotechnologies may offer more energy efficient and lower chemical use, there are differing public and regulatory opinions regarding adoption of nanotechnology. Significant progress has been made in the ability to select low-toxicity nanomaterials, to embed them to prevent their release into water and safe-by-design strategies that allow selection of more sustainable nanomaterials.(57,58) Furthermore, the occurrence and risk from nanoparticles in drinking water is very low,(59−61) but as nanoenabled water technologies are commercialized there should be suitable capabilities in place to monitor potential release of nanoparticles from the devices, just as we do for traditional chemicals currently used in water treatment. Thus, recent scientific progress in conjunction with advances in ANSI/ISO standardized protocols relating to nanomaterials will allow strong economic and social drivers to use nanotechnology for water purification both on- and off- the current water grids.

Rethinking the Water–Energy Relationship

All of the actions discussed above supporting sustaining water resources relate to energy. First, conservation of water also saves the energy that was required to treat and/or transport the water. Second, because desalination is energy intensive, increasing the use of desalination to augment water supplies has the potential to increase energy consumption. Third, conveyance and distribution of water also requires energy. Finally, energy is also required to remove contaminants in water. However, technologies that are less energy intensive can reduce the energy requirements of desalination, water treatment, and conveyance. In addition, because energy also requires water, increasing energy use can also affect water use. Population increases also typically lead to increases in both energy and water use.

The Water-Energy Nexus is well-framed by a pair of reports in 2014. The United Nations Educational, Scientific and Cultural Organization's (UNESCO's) *World Water Development Report 2014, Water and Energy*(6) provides a both a global view of the issue as well as noteworthy case studies. The U.S. Department of Energy (DOE) focused its unique capabilities on the energy side of the nexus in the US in their report, *The Water-Energy Nexus: Challenges and Opportunities*.(3) Since that time, DOE has been working on current technology opportunities and understanding the potential future issues. Figure 2 shows that the US national energy-water Sankey diagram(62) from the DOE report that illustrates the US energy flows, on the top, and water flows, on the bottom. The flows intersect in electricity generation, public water supply, wastewater treatment, and fuel production, as well as residential, commercial, and industrial sectors.



2011 Estimated U.S. Energy-Water Flow Diagram

Energy reported in Quads/year. Water reported in Billion Gallons/Day.

Figure 2. U.S. National Energy–Water Sankey Diagram.[62]

The national Sankey diagram(62) shown in Figure 2 has helped DOE’s water–energy nexus crosscut team and their collaborators prioritize R&D investment at the national scale. On the water for energy side, the diagram shows that electricity generation and agriculture are the dominant users of water in the US with agriculture being significantly more dominant in water consumption (over 80% versus 4%).(62) Technological advances in electricity generation promise to reduce freshwater withdrawals and consumption. This can be achieved by lowering the generation of waste heat through more efficient generation cycles, by lowering the need for coolant water with use of dry or hybrid cooling and by increasing productive use of recycled municipal wastewater for cooling of thermoelectric plants. In addition, the water used and produced by oil and gas operations, while relatively small at a national level, can be regionally significant, underscoring both the importance of managing water used for oil and gas production and the potential opportunity to convert produced water into a resource.

On the energy for water side, increased process energy efficiencies will decrease the costs of desalination and related water treatment and, thus, increase the economic viability of a range of water resources available for beneficial use. The electricity used for public water supply increased by more than 30% between 1996 and 2013(63) making reducing the energy use for public supply and wastewater treatment another opportunity to reduce energy use and costs. In addition, in some instances, energy can be recovered from municipal wastewater.

Rethinking the relationship between energy and water can reveal additional opportunities. For instance, during the process of producing oil and gas, operators flare excess gas and dispose of contaminated water brought to the surface. Rather than flaring, the gas could be used as an energy source to power water treatment facilities, thereby converting two waste streams into one or more valuable byproducts: most importantly clean water(64,65) and potentially minerals such as lithium.(66)

Alternatively, analogous to energy recovery from municipal wastewater the excess gas and produced water could be used as an energy source and feedstock, respectively, to enable the production of biofuels and protein rich animal feed, e.g., algae.(67)

It is also worth considering whether oil and gas combustion could be a source of water. The process of hydrocarbon combustion produces two primary constituents, carbon dioxide and water vapor. The water production from combustion is nontrivial, amounting to 12 billion cubic meters per year globally as of 2015. In the US, hydrocarbon combustion produces 2.4 billion cubic meters of water per year, nearly twice the amount of water that is disposed of via deep well injection.(68)

Integrating renewable energy with water infrastructure presents another opportunity for reducing the intensity of the water–energy nexus. The use of renewable wind and/or solar energy for electricity generation presents a 2-fold opportunity. First, the intermittent supply of energy can be stored using pumped-storage hydroelectricity to better match energy demand. Second, the renewable electricity can be used to increase the supply of fresh water by desalinating large aquifers of brackish water. Aminfard et al. showed that there might be hundreds of sites across the state of Texas that have the potential to power desalination facilities with renewable power and provide freshwater at cost competitive prices.(69) Desalination facilities that have the capability to be flexible in their operating mode, responding to the conditions of the electric grid would be needed.

Integration of renewables with industrial processes might also result in the production of renewable hydrocarbon fuels. Electrolysis of water can provide a source of hydrogen that can be used as a feedstock to renewably produce hydrocarbon fuels, i.e., electrofuels.(70) Electrofuels present an opportunity to lower the carbon intensity of fuels used in power generation and transportation; however, they might further increase the water intensity of the energy system. A way to offset the consumption of water could be recovery of H_2O, the byproduct of H_2 and O_2 in fuel cells, which has been shown feasible without additional energy inputs and has near ultrapure water quality. Thus, an electrofuel economy could use H_2 to transport both embedded energy and water (i.e., O_2 is available from the atmosphere) at the source of on-demand energy generation.(71,72)

The examples provided above are illustrative. Achieving impact at a scale that matters will require a strategic approach that is cognizant of the relative magnitudes of water and energy flows, such as shown in Figure 2. In any event, it is beneficial for engineers, the public, and policymakers to have an appreciation for the interconnected nature of water and energy as we strive to improve living conditions around the world.

Conclusion and Future Directions

Water conservation, supply augmentation, distribution, and treatment of contaminants are elements of a strategy for water sustainability, and the interdependency of water and energy, the Water–Energy Nexus, can inform such a strategy. Significant reductions in agricultural water consumption are being seen with drip irrigation. This coupled with technological advances in reverse osmosis, water purification and treatment are increasing the availability of usable freshwater for productive use. Remote sensing is also aiding in adapting hydrological models to improve predictions of watershed behavior to allow for their use in water and energy storage. Collectively, advances in these technologies are beginning to positively impact many of the UN's sustainable development goals:(5) eliminating poverty and hunger, combating the negative effects of climate change, investing in gender equality, improving health, well-being and education, ensuring availability of clean water and sanitation and delivering inclusive economic growth.

Water conservation is energy conservation and *vice versa*. Both are central to long-term water sustainability and efforts to achieve sustainability have to be undertaken cognizant of the fact that improving efficiencies in one aspect of either can be detrimental in another aspect of the other. The detailed understanding of US water and energy flows, and critically, their intersections, provided by DOE(62) are informing R&D investment decisions and policies at the national level. Further analyses with improved technology to address water tracking in natural systems can inform a clearer global understanding of the water-energy nexus that can in turn inform global water sustainability.

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Notes

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