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Water and Energy Interactions

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Abstract
Human habitations require energy and water, which are increasingly interdependent. Energy systems have changed from using water for mechanical energy to building dams to provide irrigation water for agriculture and hydroelectricity. Large volumes of water are required to cool thermal electricity-generating stations—whether coal, natural gas, nuclear, or solar powered. Changes in cooling technology are reducing water withdrawals while increasing water consumption. Water produced from fossil fuel production represents environmental challenges and supply opportunities. Some renewable energy sources, such as wind turbines and photovoltaics, have far lower water requirements. Increasing development of biofuels creates a direct connection between water and energy systems. Energy, mostly for pumps, is necessary for supplying potable water and treating waste water. Pumping from deeper underground as well as removing more contaminants (e.g., medicines, agricultural chemicals) and salt requires more energy. Water and wastewater treatment can dominate electricity demand in municipalities. Water reuse requires energy for treatment and pumping. Life cycle assessments and integrated resource planning strive to account for the total impacts.

1. Introduction
Water is essential for the survival of all forms of life on Earth and has become essential for anthropogenic energy generation. Although energy is used to collect, treat, distribute, and desalinate water, water is used during the mining, extraction, and production of many energy sources used by people today. Thus, water and energy are strongly dependent upon one another, and their interdependence results in significant environmental consequences.

There are 332,500,000 cubic miles (1,386,000,000 cubic kilometers, km^3) of water found on Earth; however, 97% is saline, and 99.7% of the freshwater is trapped in ice caps and glaciers, or found in groundwater, which requires energy for removal, leaving 0.1 million km^3 aboveground in lakes, swamps and rivers, and about 13,000 km^3 in the atmosphere (1). Surface water has not increased for the past 20 years, and simultaneously, groundwater tables have been dropping (2). Currently, 700 million people around the world face water scarcity, and by 2025, that number is expected to increase to 1.8 billion people (3).

Water is used throughout the cycle of providing energy, e.g., for mining, refining, processing, liquefaction, gasification, carbon sequestration, and during direct power generation in coal, natural gas, oil, nuclear, biomass, and central solar power plants (2, 4). Two uses dominate freshwater withdrawals in the United States (Figure 1) and elsewhere: thermoelectric power (and hydropower, not shown in the figure) and irrigation. Water consumption is mostly for irrigation and livestock.

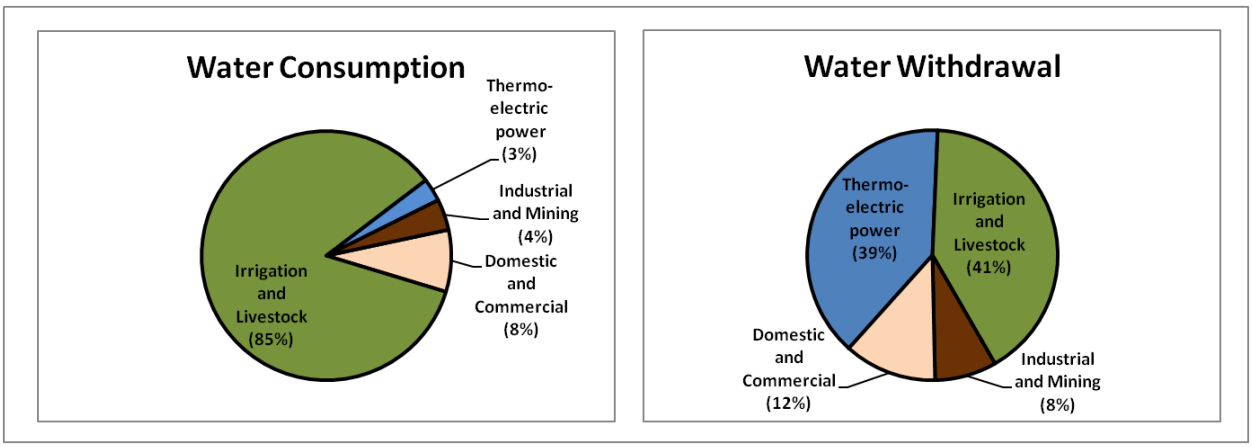

Figure 1 Water withdrawal and consumption in the United States. Reprinted with permission from Reference 5.

2. History

Humans began relying on water, aside from means for mere survival, with the development of agriculture roughly 10,000 years ago. Humans began managing water sources through irrigation systems to allow production of ever-growing quantities of food. "Throughout history, wherever water sources have been increased and made most manageable, navigable, and potable, societies have generally been robust and long enduring" (6, p. 15).

In Mesopotamia—where civilization began—farmers relocated to areas near rivers so they would have a constant supply of freshwater and more consistently fertile land. This proximity to rivers had drawbacks, including an increased likelihood of flooding. Prior to the development of irrigation systems, which allowed farmers to manage water, total crop yields varied unpredictably and faced destruction during seasonal flooding (6).

Ancient Egypt also thrived because of its proximity to a natural water source—the Nile. Farmers developed the ability to manage this water system and to understand its natural cycle, which allowed for large crop yields to sustain a growing population. As Egypt receives almost no rainfall, relying on the Nile was the only option for survival, but it was also a powerful and destructive force. Around 2900 BC, there is evidence of the construction of the first dam, which was designed to protect Memphis from floods (6).

During the development of irrigation systems, the process of irrigating land and relocating water farther from the main water source was gravity dependent, so farms and human settlements tended to be located near or downhill from the water source. With the development of energy production, this dependency on gravity was eliminated; societies could be farther away from natural water sources, and not necessarily downhill (6).

3. Water Used For Fuel Production

Fuels such as coal, petroleum, and natural gas provide energy services that support the transportation of people and goods, industrial processes, thermal comfort and lighting in buildings, and

communications. Water is a necessary component in the mining process to extract and process fuels, cool equipment, and suppress dust. Surface mining also requires water for land reclamation and revegetation (2). Table 1 shows water consumption associated with production of gas and liquid fuels.

Table 1 Water consumption associated with gas and liquid fuel production[a]

Fuel type	Gallons/million Btu		Liters/gigajoule	
	Raw materials	Transformation	Raw materials	Transformation
Oil		7–18 (refining)		25–65 (refining)
Traditional oil	0.8–2.0		3–7	
Enhanced oilrecovery	14–2,500		50–9,000	
Oil sands	20–500		70–1,800	
Biofuels		13–14 (ethanol); 4 (biodiesel)		47–50 (ethanol); 14 (biodiesel)
Corn	2,500–29,000		9,000–100,000	
Soy	14,000–109,000		50,000–394,000	
Sugarcane	30,000		108,000	
Rapeseed, jatropha	100,000–160,000	b	400,000–574,000	b
Lignocellulosic	b	b	b	b
Algae	b	b	b	b
Coal	1.5–20		5–70	
Coal to liquids		40–60		140–220
Natural gas				
		2 (processing)		7 (processing)
Traditional	Minimal		Minimal	
Shale gas	10–15		36–54	
Nuclear				
Uranium	1–6	7–8 (processing)	4–22	25–29 (processing)

[a] References 2, 5, and 7
[b] Not yet commercial.

In the United States, coal mining and washing alone use between 70 and 260 million gallons (265 and 984 million liters, respectively) of water per day (2). However, large amounts of water trapped in underground formations (produced water) are often extracted during the mining process. Produced water is often saline and is considered to be a waste product containing volatile compounds, extractable organics, ammonia, and hydrogen sulfide. If produced water is not dealt with properly, it can have detrimental effects on water quality. However, it is considered environmentally acceptable to reinject produced water into aging oil wells to help maximize oil extraction (2, 8). In 2007, roughly 57 million barrels/day (21 billion barrels/year) of water were produced in the United States. In 1995, an estimated 71% of the United State's produced water generated that year was recycled for enhanced oil recovery. In 1999, average produced water worldwide was 210 million barrels/day (77 billion barrels/year) (2, 9, 10).

The amount of water produced in any given mine differs greatly depending upon the mine's location and age. In coal-bed natural gas extraction, the amount of produced water tends to decline over the well's lifetime. According to the U.S. Department of Energy, the San Juan Basin mine located in both Colorado and New Mexico produces 7 barrels of water per barrel of oil equivalent, whereas in the Powder River Basin in Wyoming and Montana, over 900 barrels of water are produced per barrel of oil equivalent (2). Although large quantities of reusable water are produced during coal mining, both surface and groundwater sources may experience heavy pollution through the process. Runoff tends to increase the concentration of heavy metals in drainage water and reduces pH levels, leading to highly acidic water. Acid mine drainage (AMD), discussed in the next section on coal, is the most significant form of water pollution from mining.

Mining is only one of many water-intensive and water-damaging impacts of energy production. Although it represents only 1% of freshwater withdrawal and consumption in the United States, mining contributes to the destruction of unique ecosystems and aquatic habitats (11). As of 1989, it was estimated that worldwide roughly 72,000 hectares (177,915 acres) of lakes and reservoirs and 19,300 km (12,000 miles) of flowing rivers and streams had been affected by mining waste (12).

3.1. Coal Production

Mining, refining, and transporting coal are all water-intensive aspects of generating energy from coal. Land reclamation and coal burning to generate electricity also require major water inputs.

Coal is an abundant resource in the People's Republic of China (China), the United States, India, Australia, South Africa, Russia, and Indonesia, and coal is an important fuel for power plants generating electricity. In 2008, coal provided 8,262,523 gigawatt-hours (GWh), 40%, of the world's electricity (13).

Coal can be mined near the surface or deep underground, requiring significant amounts of water for fuel processing, as well as cooling and lubricating the cutting and drilling equipment needed for dust suppression (5, 14). For surface mining, the main water uses are for land reclamation and revegetation. Surface mining has detrimental effects on the landscape, including erosion and landslides, which can lead to flooding, water pollution, and habitat loss for fish and other wildlife. In 1977 in the United States,

the Surface Mining Control and Reclamation Act was enacted to minimize some of these effects and to help restore mined landscapes through revegetation, typically a water-intensive process (15).

Underground coal mining makes up approximately 60% of global coal production. Water used in underground coal mining has been estimated to vary between 70 and 260 million gallons (265 and 984, respectively, million liters) per day in the United States, depending upon the coal source (2, 16). Underground coal mining often leads to the pollution of natural water sources.

AMD from abandoned coal mines has polluted over 9,000 miles of rivers and streams in the United States. In the United States alone there are 1.1 million surface acres (445,000 hectares) of these coal mines that are no longer in use but continue to pollute water sources (16). The West Rand Basin located in the Gauteng Province of South Africa became contaminated in 2002 owing to a nearby abandoned mine. This example of AMD has received a great deal of public attention because of its proximity to South Africa's Cradle of Humankind World Heritage Site, a renowned site of Hominid fossils facing threat from contact with acidic water. AMD can continue polluting water sources for between 10 and 40 years in many cases, but when AMD reaches the water table, it can pollute for hundreds of years, until the minerals are depleted (12).

The transportation of coal also requires water. Though a majority of coal transportation is on railways, it is also transported by barge, truck, conveyor belts, and coal slurry pipelines (17). Coal slurry pipelines transport coal over long distances and require water mixed with coal at a one-to-one ratio to create a coal slurry transportable through pipes (18, 19).

3.1.1. Carbon Capture and Sequestration

Carbon capture and sequestration (CCS) approaches are envisioned as a means to significantly reduce carbon dioxide (CO2) emissions (20). Major efforts related to the development and demonstration of CCS approaches are taking place in the United States, Canada, Australia, the European Union, the United Kingdom, and South Korea (21). According to the International Energy Agency, the development of CCS will be most prominent in industrialized regions through 2020. However, after 2020, its use will rapidly shift to developing countries, especially those with coal-based economies such as China and India (20, 21).

According to the Intergovernmental Panel on Climate Change, CCS technologies have the potential to reduce CO2 emissions by as much as 80%–90% (22). This can be done through four different methods of storage: geological storage, ocean storage, mineral storage, and industrial uses. Geological storage relies on capturing CO2 from a major source and then transporting it to a deep rock formation where it can then be injected (23). The second option for storing CO2, ocean storage, relies on injecting CO2 deep into the ocean. This method of carbon sequestration has the potential to reduce atmospheric CO2 emissions over the next several centuries, but the oceans' carbon cycle would not allow CO2 isolation on a millennial timescale (24). Another method for CO2 storage is mineral carbonation, which captures highly concentrated CO2 and brings it to contact with a metal-oxide-bearing material to fix the CO2 as carbonates. Lastly, a potential method for reducing CO2 emissions is to store it in carbon-containing products (25).

The processes of capturing, transporting, and injecting CO2 are all energy intensive and lead to increased energy consumption. For an electric power plant to generate the same amount of electricity as was being generated prior to the implementation of CCS technologies, facilities must increase their power production. Increased production from fossil fuel–burning power plants results in increased water withdrawal and consumption necessary for the mining, transporting, and generating processes required to produce energy from a specific fuel source (26). Current facilities with CCS technologies increase water withdrawal by 25%–40% (27) and water consumption by 50% to 90% (28). According to the National Renewable Energy Laboratory, a coal plant with CCS technologies requires roughly 1,000 gallons of water for every megawatt-hour of electricity generation (29). Not only does CCS require an increase in energy consumption leading to an increase in water dependency, but the option for storing CO2 in geological wells can potentially lead to the contamination of drinking-water aquifers if faults and fractures within wells go undetected (22).

3.2. Natural Gas Production

Oil and natural gas are often located together underground. Although water is used in many aspects of oil and natural gas production, including mining, treatment, refining, and generating electricity, the overall process requires much less water than that required for producing energy from coal. Traditionally, almost no water was used to mine natural gas. An important exception is the process of hydraulic fracturing, which produces natural gas and oil by forcing fluids (water and additives) into the ground to fracture rocks, resulting in cracks and pores in surrounding rocks so that the gas and oil can escape more freely (30). To use hydraulic fracturing to create one well in a coal-bed source, between 50,000 and 350,000 gallons of water are needed. In a shale formation, hydraulic fracturing can require up to 5 million gallons of water (31). Coal-bed methane, the availability of which is estimated at 700 trillion cubic feet in the United States, represents roughly 7.5% of U.S. natural gas production. Coal-bed methane produces large, but varying, quantities of often low-quality water (2, 32).

3.3. Oil Production

In 2009, oil supplied the world with 35% of its primary energy production (33), the United States with 40% of its total energy demand, and over 99% of the fuel used in U.S. automobiles (34). Primary production, the first step in oil extraction, depends upon a natural process in which air pressure forces oil to move through rock pores until it reaches oil wells. This process can last for days or years, and this pressure enables the extraction of roughly one-fourth of the oil that exists in any given reserve (35). A secondary recovery process called waterflooding or enhanced oil recovery involves the injection of large quantities of water or steam into a well, where pressure forces oil to separate from rock formations and reach oil wells. Using both processes, roughly one-third of the oil in a reservoir can be extracted (35).

In the United States, on average, 1.5 gallons (5.7 liters) of water are consumed for every gallon of oil refined (36). Refining 800 million gallons (3 billion liters) of petroleum each day for the United States consumes between 1 and 2 billion gallons (3.8 and 7.6 billion liters) of water (2).

About 90% of U.S. onshore oil production uses between 2.1 and 5.4 gallons (8 and 20 liters) of a combination of produced water, saline-based groundwater, and freshwater for the process of recovering each gallon (3.79 liters) of crude oil. When combined with the water needed to refine each

gallon of crude oil, between 3.6 and 7.0 gallons (13 and 27 liters) of water are used to produce and process 1 gallon of crude oil. These values are slightly higher than those of Saudi Arabia, where between 2.9 and 6.1 gallons (11 and 23 liters) of water are used for the production and processing of each gallon of crude oil (36).

The United States imports roughly twice as much crude oil as it produces, with 64% of its imports coming from five countries: Canada, Mexico, Venezuela, Saudi Arabia, and Nigeria. Saudi Arabia, the world's largest producer of oil, faces challenges from groundwater depletion. Oil production in Saudi Arabia consumes a majority of the country's water resources. In Saudi Arabia's Ghawar oil field—the largest oil field in the world, which produces over half of the country's crude oil—roughly 1.4 gallons (5.3 liters) of treated seawater are injected to produce one gallon of oil (7 million barrels per day to produce 5 million barrels per day crude). U.S. onshore production uses less water by relying upon horizontal drilling and peripheral water injection (36).

The process of oil production can lead to the contamination of both surface water and shallow groundwater. Toxic waste streams contain substances such as benzene, toluene, and xylene, arsenic, heavy metals, naphthenic acids, and various organic compounds (36). Leaking these chemicals can have detrimental effects on health and the environment. Some effluents from oil refineries have been found to have lethal and sublethal effects on growth and reproduction in aquatic environments (2, 36, 37).

3.4. Oil Sands and Oil Shale Production

Alberta, Canada, is home to the largest commercial oil sands industry in the world with three major sites for production: Athabasca, Cold Lake, and Peach River. These sites are responsible for 100% of Canada's oil sands production and 43% of Canada's total oil production. Of Canada's 179 billion barrels of proven oil reserves, 175 are located in oil sands. As of 2006, roughly 1.1 million barrels of crude oil were produced from oil sands each day in Canada, an increase of 0.44 million barrels/day (67%) since 2001. Current technologies require between 2.8 and 6.5 gallons of water for the production and processing of 1 gallon (3.8 liters) of crude oil from oil sands in Canada; between 2 and 4.5 gallons (7 and 17 liters) of this water are used for mining operations (38). With these technologies, water availability may limit production to no more than 2–3 million barrels of crude oil per day (36).

To separate bitumen oil from oil sands, agitation with hot water is used. To generate 1 barrel of synthetic crude oil from oil sands, roughly 2 tons (1.8 metric tonnes) of oil sands are necessary. Currently, the United States does not produce synthetic crude oil from oil sands, but it does import roughly 20% of its crude oil from Canada (38).

Although it is estimated that over 2 trillion barrels of oil exist in the United States in oil shale, more than triple the amount of proven oil resources in Saudi Arabia, the environmental implications, water requirements, and energy requirements are expected to limit commercial extraction of crude oil. The water requirements for the production of refinery-ready oil produced from oil shale in the United States are 2–5 gallons (8–19 liters) of water per gallon of crude oil. Meeting roughly one-quarter of the U.S. oil demand would require consuming 400–1,000 million gallons (1.5–3.8 billion liters) of water daily (2, 38).

3.5. Uranium Production

Uranium, the raw material used to produce nuclear fuel, is mined in 14 countries. In 2008, Australia, Kazakhstan, and Canada combined produced 25,951 of the 43,853 metric tonnes of uranium produced worldwide (39). The water consumption for mining and processing the fuel for nuclear power generation is between 45 and 150 gallons (170 and 568 liters) of water for each megawatt-hour generated (40).

3.6. Bioenergy Production

Bioenergy is energy that is refined from biomass, renewable organic matter, which is specifically dedicated to generating bioenergy. Examples of this organic matter include agriculture and forest residues; organic components of industrial, municipal, animal, and aquatic plant waste; and crops, including corn, soybeans, sugarcane, and switchgrass (41–43). Biofuel can be burned to generate electricity or transformed into liquid fuels or synthetic gas to be used for transportation. Biofuels come in a variety of forms, including ethanol and biodiesel (44). Table 2 shows annual ethanol production by country.

Table 2 Projected 2010 global ethanol production (millions of liters) (45)

United States	Brazil	China	Canada	France	Germany	Spain	Thailand	Belgium	Colombia	Other	Total
45,400	27,520	2,100	1,150	1,050	900	600	525	320	320	3,115	83,000

The United States is the world's largest producer of ethanol, and Brazil is the second largest producer and the leading exporter. Brazil is also the world's leading producer of sugarcane (45) and, in 2009, produced 450,000 barrels per day of ethanol from sugarcane, a number that is expected to continue increasing (46). Although bioenergy use may reduce carbon emissions, the water requirements are significant (47). Sugarcane production in Brazil is mostly reliant on rainfall, allowing for minimal use of irrigation systems. However, large quantities of water are required for the conversion of sugarcane to ethanol. In total, water requirements for converting cane to both sugar and ethanol are 21,000 liters/metric tonne cane. Table 3 shows total water use for sugar and ethanol production in Brazil, excluding cooling at sulfiting, condensers/multijets evaporation, condensers/multijets heater, crystallizer cooling, and sugar washing because this water is used only for sugar production (48).

Table 3 Water use for supplying ethanol from sugarcane in Brazil (48)[a]

Production Process		Mean use (total liters/metric tonne cane)[a]
Feeding	Sugarcane washing	5,330
Extracting (grinding)	Imbibition and bearing cooling	400
Juice treatment	Preparation of lime mixture, filter imbibitions, filter condensers	360
Juice concentration	Molasses dilution	30
Electrical power generation	Steam production and turbogenerator cooling	700
Fermentation	Juice cooling and fermentation cooling	4,000
Distillery	Condenser cooling	4,000
Other	Floor and equipment cleaning, and drinking	800

In the United States, 10.7 billion gallons (41 billion liters) of ethanol-based biofuel were produced in 2009, generating roughly 7.8% of the nation's gasoline pool. Biodiesel production was 545 million gallons (2,063 million liters) (49). According to legislated targets, the United States expects to increase production of renewable fuel to 36 billion gallons by 2022 (50). Two major reasons for supporting the development of a U.S. biofuel industry are the ability to incorporate biofuels directly into the existing transportation infrastructure and the potential to reduce petroleum product imports (51). As of 2009, worldwide production of ethanol had increased by nearly 400% since 2000, resulting in the displacement of over 1 million barrels of oil each day (52).

Although the ethanol refinement process is similar to that of refining oil, water requirements at dry-mill ethanol refineries are about 4.7 gallons (17.8 liters) of water per gallon of ethanol produced (and five times as much in a wet-mill refinery) (53), compared to the 1 to 1.5 gallons (3.79 to 5.7 liters) of water per gallon of crude oil processed at a petroleum refinery (36). Full-cycle water consumption for bioenergy feedstock production significantly exceeds the amount of water consumed in the refining process, although this varies by crop, soil type, and climate (7). The water intensiveness of bioenergy feedstock production raises the risk of fuel supply shortfalls in cases of drought or lack of groundwater.

[a] These numbers assume that half of the sucrose is converted to ethanol and half is converted into sugar

Not only are there intensive water requirements for ethanol production, but as of 2006, corn ethanol was producing only a 25% net energy yield because of the energy-intensive nature of planting, harvesting, transporting, and refining corn into ethanol (51). Among biomass feedstocks, corn has the highest requirements for fertilizer and pesticides. This raises concerns about water quality impacts, such as nutrient pollution involving nitrogen and phosphorous (56).

Rising concerns about increasing production of first-generation biofuels, including potential competition with food production, have led to the development of second-generation biofuels. Unlike first-generation biofuels, which are reliant on starch and sugar-based feedstocks, second-generation biofuels rely on lignocellulosic feedstocks, such as agricultural residue, forestry residue, grasses, trees, and municipal and other wastes (57). Projections show that by 2050 26% of transportation fuels will be provided by biofuels, and of that 26%, roughly 90% will be from second-generation biofuels (58). Feedstocks that could be used for second-generation biofuel production, including grasses and crop wastes, are likely to use less water than today's feedstocks. However, good information is not available on the water use per unit of energy for these crops because they are not yet in commercial production (5). The industrial conversion of biomass to first-generation biofuels is assumed to be less water intensive than the industrial conversion of biomass to second-generation biofuels. First-generation ethanol production can lead to the consumption of up to 4 liters of water per liter of ethanol produced, whereas second-generation ethanol production can require twice as much, up to 8 liters of water for every liter of ethanol produced (58).

Biodiesel is a diesel fuel source that is derived from biomass. Biodiesel is derived specifically from raw vegetable oil, animal fats, used cooking oil, and algae (59). The European Union is the global leader in biodiesel production. As of 2004, the European Union was responsible for 90% of global production (60). Currently, up to 6,100,000 metric tonnes of biodiesel are produced annually throughout the European Union (61). Germany, as the leader, produced 2,539,000 metric tonnes of biodiesel in 2009, followed closely by France (1,959,000 metric tonnes), Spain (859,000 metric tonnes), and Italy (737,000 metric tonnes) (61). Similar to other biofuels and depending upon the extent of irrigation, biodiesel feedstock production can be water intensive. On average, 14,000 liters of water are required to produce 1 liter of biodiesel from soybean or rapeseed and roughly 400,000 liters are required for every gigajoule generated. Roughly 20,000 liters of water are required to produce one liter of biodiesel from Jatropha, and 574,000 liters are required for each gigajoule (7).

Algae are another set of potential feedstocks for producing biofuels with the advantages that they are not in direct competition with food crops and can utilize brackish or saline water, including produced water or wastewater, instead of freshwater (62, 63). To produce the total annual U.S. energy consumption needs from algae, 13% of the nation's land would be required for cultivation. Corn would require 41% of the nation's land, switchgrass 56%, and canola 66%. A life cycle assessment finds that “conventional crops have lower environmental impacts than algae in energy use, greenhouse gas emissions, and water regardless of cultivation location,” but algae are favored in land use and eutrophication potential. Using wastewater as a source of nutrients can “make algae more environmentally beneficial than the terrestrial crops” (63, p. 1813).

The water footprint for producing bioelectricity is smaller than for biofuels. Within biofuels, the water footprint for bioethanol appears smaller than biodiesel (7). Currently, the production of transportation fuels does not rely strongly on power generation or the agricultural sector because transportation is mostly dependent on oil. However, with the development of electric power and biofuels for the transportation sector, issues of water scarcity are of increasing concern owing to water-intensive practices (64).

4. Water Used for Electricity Production

4.1. Hydroelectricity

The most common type of hydroelectric generation takes place at dams on rivers around the world. Dams are built for electricity generation, water storage, recreation, flood control, redirecting river flow, and general surface water management. The United States has over 79,000 dams of all sizes, and the world has roughly 50,000 dams of a height of 15 m or higher, which are considered large dams. To generate electricity, the momentum from falling water spins turbines located in the dam. The water then continues downstream or is pumped back into the reservoir and reused. Hydroelectric generation causes minimal air and water pollution but can negatively affect aquatic habitats and ecosystems (40, 65).

Hydroelectric power generation is currently the largest renewable energy source worldwide and has increased by 50% since 1990. In 2008, global hydropower plants generated 3,288 terawatt-hours (TWh), which was roughly 16.3% of worldwide electricity production (66). In 2009, China produced 17.8% of the world's total hydroelectricity, or 585 TWh. Canada produced the second most hydropower with 11.5% (383 TWh), Brazil produced 11.2% (370 TWh), the United States produced 8.6% (282 TWh), and the Russian Federation produced 5.1% (167 TWh). In 2008, hydroelectric generation represented 98.5% of Norway's total domestic electricity generation (67).

Reservoirs lose water to evaporation. Research in Turkey showed that 4,026 square kilometers (km2) of surface water existed on 223 of the nation's reservoirs, and of the water in these reservoirs, 4.1 trillion liters are lost to evaporation each year (68). However, not all of the water that evaporates from these reservoirs could be allocated to hydroelectric power generation because reservoirs often serve many purposes.

Another way to generate hydroelectricity is to harness energy from the ocean. Production to date is low, although the annual electricity generation potential is estimated to be 80,000 TWh, 10,000 TWh, 800 TWh, and 300 TWh each year worldwide from wave, thermal, current, and tidal ocean energy, respectively, compared with 2008 worldwide electricity generation of 17,445 TWh (69).

4.2 Thermal Electric Power

Water is required for almost all aspects of thermal electric power production. The majority is used for steam-driven turbines, which generated over 80% of U.S. electricity (70, 71) and 67% of the world's total net electricity generation in 2009 (33). Water used in thermal electric power plants is extracted from

freshwater sources as well as from sea or brackish water sources. In 1995, thermoelectric power-generating facilities consumed 3% of the total U.S. freshwater supply—over 3 billion gallons (11 billion liters) of water per day (about 40 liters per person). In 2000, U.S. thermoelectric energy production comprised 39% of annual freshwater withdrawals, withdrawing 136 billion gallons (515 billion liters) of freshwater each day (over 1,600 liters per person) (11). This is roughly equivalent to the amount of freshwater withdrawn for U.S. agricultural irrigation. The amount of saline-based brackish coastal water and ocean water required each day for thermoelectric power generation is 59 billion gallons (223 billion liters) or 29% of total water withdrawals for thermoelectric power production (over 700 liters per person) (2, 11). In 2003, a sustained heat wave in France reduced the amount of available water and raised water temperatures, resulting reduced capacity or shutdown of 17 of France's 58 nuclear reactors and a simultaneous loss of hydropower, causing load shedding, including a 50% reduction in electricity exports from France and high electricity prices for electricity from alternative sources (71a,b). Table 4 shows water consumption per megawatt-hour for electricity generation.

Table 4 Water consumption per megawatt-hour for electricity generation [a]

Generation source	Liters/megawatt-hour		Gallons/megawatt-hour	
	Raw materials[b]	Transformation	Raw materials	Transformation
Wind		Minimal		Minimal
Photovoltaic		Minimal		Minimal
Thermoelectric fuels		Closed loop: 720–2,700		Closed loop: 190–720
Coal	20–270		5–70	
Oil, natural gas	Variable		Variable	
Uranium	170–570		45–150	
Concentrating solar		2,800–3,500		750–920
Geothermal		5,300		1,400
Hydroelectric		Evaporative losses: 17,000 (average)		Evaporative losses: 4,500 (average)

4.2.1. Electricity from coal.

Coal refining, washing the coal with water to remove impurities, takes place at the power plant. This process removes up to 30% of the sulfur found in coal (72). Coal-fired power plants generate energy by burning coal, which pressurizes water and produces steam to rotate the turbines. Water is also needed

[a] Reprinted with permission from Reference 5

[b] "Raw materials" refers to fuel production, and "transformation" refers to conversion of energy from fuel to electricity.

to cool the turbines and other equipment, and water is used for scrubbers, which absorb the sulfur dioxide that is emitted when coal is burned. The scrubbing process, though water intensive, can minimize sulfur emissions by as much as 90% (72).

Coal comprises the largest fuel source for electricity generation in the United States (73). In 2010, U.S. coal-fired power stations generated 1,986 billion kWh of electricity, 45% of the U.S. total of 4,119 billion kWh (74). Each kilowatt-hour generated required ~36 gallons (136 liters) of water withdrawn (75); therefore, 71 trillion gallons (267 trillion liters) of water were withdrawn for the production of electricity through coal-fired power plants. On a daily basis, this amounts to the generation of about 18 kWh per person, and the withdrawal of about 2,400 liters of water per person.

Coal production is also a leading user of freshwater in China. Since the year 2000, the production and consumption of coal in China has tripled. A 30% increase in coal production and consumption is projected by 2020 nationwide. About 120 billion m3 of freshwater are currently required annually for mining, processing, and consuming coal in China. This is one-fifth of the total annual water consumed nationwide (76).

4.2.2. Electricity from natural gas.

Natural gas supplied the world with 22% of total energy production in 2009 (33) and the United States with roughly 20% of its energy (20, 24). Although coal and nuclear power plants tend to supply base load power, that is, to operate at or near full capacity most of the time, the use of natural gas plants is more variable in order to respond to the normal daily and seasonal changes in the demand for electricity. Water requirements are typically lower for natural gas–fired power plants than for coal or nuclear.

4.2.4. Electricity from nuclear power.

Currently 14% of total global electricity is met by nuclear power generation (39). In 2009, 436 nuclear power reactors existed in 30 countries worldwide, and 55 new nuclear power reactors were under construction, including 20 in China, which expects an 8.4% increase in nuclear power production between 2007 and 2035 (77). The United States currently generates 20% of its total electricity and 70% of its carbon emission-free electricity from nuclear power sources (40).

Because closed-loop systems consume a large amount of water, it is difficult to develop nuclear power plants in water-scarce locations (40). Based on a gallon per megawatt-hour produced comparison, nuclear energy production withdraws and consumes more water than fossil-fired plants. Nuclear plants use steam turbines, and cooling water as opposed to dry cooling or hybrid cooling. According to the National Renewable Energy Laboratory, a nuclear power plant in the United States with once-through cooling systems withdraws 25,000 to 60,000 gallons (95,000 to 227,000 liters) of water per megawatt-hour generated and consumes between 100 and 400 gallons (400 to 1,500 liters) of water per megawatt-hour generated. U.S. nuclear plants using closed-loop cooling towers withdraw between 800 and 2,600 gallons (3,000 to 9,800 liters) of water per megawatt-hour generated and consume between 581 and 845 (2,200 to 3,200 liters) of water per megawatt-hour generated. Results from U.S. nuclear plants using cooling ponds are similar: For every megawatt-hour of energy generated, 500–1,300 gallons

(1,900–4,900 liters) of water are withdrawn, and between 560 and 720 gallons (2,100 and 2,700 liters) of water are consumed (40).

4.2.4. Electricity from central solar power.

Central solar power plants concentrate solar energy to heat fluids that generate electricity using steam engines, gas turbines, or Stirling engines (78). Once used in the turbines, the steam must go through a cooling process similar to that for all thermoelectric power plants. The most-developed solar thermal technology is the parabolic trough. For the past 15 years, nine solar thermal power plants, with a total capacity of 350 MW, have used this technology in the Mojave Desert, California. If a dry-cooling system is used for a parabolic trough, roughly 80 gallons of water per megawatt-hour are required for mirror washing and cycle makeup, whereas a plant that uses wet-cooling consumes roughly 800 gallons (3,000 liters) of water per megawatt-hour generated. However, dry-cooling technologies are less efficient, more costly, and have higher requirements for auxiliary operating power (2, 79).

Three other types of solar thermal production facilities are those with power towers, linear fresnels, and a dish/engine system. Power towers and linear fresnels rely on heat from the sun to generate steam and power Rankine steam cycles. Dish/engine systems are air-cooled, rely on water only for mirror cleaning, and can generate energy only during hours of direct sunlight because they lack thermal storage. Power towers capture energy from the sun reflected from a field of tracking mirrors to a receiver located on top of a tower where water or molten salt is flowing to absorb the solar energy. These systems consume approximately 600 gallons of water for each megawatt-hour they generate. Spain is home to a power tower with a capacity of 10 MW and is in the process of developing more (79).

4.2. Cooling Systems for Thermal Electric Power

For electricity from thermal electric power, the water requirements depend upon the choice of cooling system. Table 5 shows typical water withdrawal and consumption for electricity-generating stations.

Table 5 Water withdrawal and consumption per megawatt-hour for electricity-generating stations

Generation source	Thousand gallons/megawatt-hour		Cubic meters/megawatt-hour	
	Withdrawal	Consumption	Withdrawal	Consumption
Total U.S. thermoelectric, 1950 (average)[a]	63		238	
Total U.S. thermoelectric, 2009 (average)[a]	25	0.5	95	2
Once-through cooling[b]	Missing	0.08–0.1	Missing	0.3–0.4
Nuclear, once-through cooling, 2002[ace]	25–60 (43 average)	0.1–0.4	95–227 (163 average)	0.4–1.5
Nuclear, closed-loop cooling, tower[e]	0.8–2.6	0.58–0.85	3–9.8	2.2–3.2
Nuclear, closed-loop cooling pond[e]	0.5–1.3	0.56–0.72	2–5	2.1–2.7
Nuclear, closed-loop cooling (average)[d]	0.72	Missing	2.7	Missing
Coal (average)[a]	36	Missing	136	Missing
Tower	0.36–1.3	0.3–1.1	1.3–4.9	1.1–4.2
Once-through cooling	22.5–50	0.06–0.3	85—189	0.2–1.1
Pond cooling	0.3–24	0.04–0.8	1.1–90.8	0.15–3
Natural gas[a]	14		53	
Tower, combined cycle	0.15–0.28	0.13–0.3	Missing	0.7
Tower, steam	0.95–1.5	0.66–1.1	3.6–5.7	2.5–4.1
Tower, combined cycle with CCS	0.48–0.5	0.37	1.8–1.9	1.4
Once-through cooling	7.5–60	0.02–0.37	28–227	0.07–1.4
Pond cooling	5.9	0.24	22.3	0.9
Dry cooling	0–0.04	0–0.04	0–0.15	0–0.15
Inlet cooling	0.1–0.75	0.08–0.6	0.4–2.8	0.3–2.3
Hybrid cooling	Between closed-loop and dry cooling		Between closed-loop and dry cooling	
Dry cooling	0	0	0	0
Total U.S. thermoelectric, 2030 (projected)[e]	9.4–12	0.35–0.39	36–45	1.3–1.5

[a] Reference 75
[b] Reference 2
[c] Reference 30
[d] Reference 5
[e] Reference 29
CCS, carbon capture and sequestration

The average amount of water withdrawn per kilowatt-hour of electricity production in the United States has decreased from 63 gallons (238 liters) in 1950 to 25 gallons (95,000 liters) in 2009 and is projected to decline to 9.4–12 gallons by 2030. However, the total amount of water withdrawn nationally has continued to increase as electricity consumption increased (65). Between 2008 and 2035, total U.S. primary energy consumption is projected to increase by 14%, and demand for electricity is expected to increase by 30% (66). U.S. freshwater withdrawals for thermoelectric power generation are likely to change from 146 to 113–147 billion gallons per day (553 to between 428 and 556 billion liters per day) from 2005 to 2030, while water consumption will increase from 3.6 to 4.2–4.7 billion gallons per day (from 14 to between 16 and 18 billion liters per day) (11).

Electrification has required large volumes of water; 99% of this has been surface water (including saline water found in surface sources) to cool thermal electricity-generating stations, regardless of the fuel used (coal, natural gas, nuclear, central solar) (70). In the United States on average, nuclear plants require withdrawals of 43 gallons (163 liters), coal plants require roughly 36 gallons (136 liters), and natural gas plants require 14 gallons (53 liters) of water per kilowatt-hour of generated electricity. On average, thermal-electric power-generating plants in the United States consume 0.5 gallons of the 25 gallons (1.9 liters of the 95 liters) of water they withdraw per kilowatt-hour of electricity they generate (75).

4.3.1. Once-through cooling.

About 31% of U.S. power-generating capacity in 2006 was composed of thermoelectric plants using once-through cooling (2). These systems withdraw from a direct water source, use the water to cool turbines and other equipment, and then release the water back to its original source at a temperature 10°–20°F higher than when it was withdrawn (40), resulting in downstream evaporation loss of roughly 1% of the released water (80).

Withdrawing water for plant cooling is detrimental to aquatic habitats. New York uses 6 trillion gallons (22.7 trillion liters) of water in once-through cooling systems annually, leading to the annual impingement and entrainment of over 17 billion fish. The release of higher-temperature water into a water source—thermal pollution—has also led to the blocking of fish migration patterns, introduction of new species, and the death of fish accustomed to lower temperatures (81). Section 316(b) of the Clean Water Act regulates cooling water intake structures used in thermoelectric power plants to minimize environmental impacts from this thermal pollution, including the protection of aquatic habitats (11).

Because of limitations on water availability and the Clean Water Act, thermal electricity-generating plants are moving from once-through cooling systems to cooling towers, which dramatically reduce water withdrawals while increasing water consumption. Since 1980, most power plants have reduced their water withdrawals but have increased their overall water consumption (2).

4.3.2. Closed-loop cooling.

Both wet-cooling towers and cooling ponds are the primary technologies used in closed-loop cooling systems. Since the mid-1970s, the majority of thermoelectric plants installed in the United States use

cooling towers, which increase the amount of water evaporated but decrease the amount of water withdrawn to less than 5% compared with that of once-through cooling systems (2).

Commonly found wet-cooling tower technologies pump warm water used to generate steam to cooling towers, where heat is transferred to ambient air. During this process, some water is lost to evaporation, and the remaining cooler water is returned to the steam condenser for reuse (11).

Closed-loop cooling systems can reduce environmental degradation, especially in aquatic habitats. These systems enable electricity to be produced in arid regions, such as of the southwestern United States. However, overall water consumption is greater in closed-loop cooling plants, 0.3–0.72 gallons (1.1–2.7 liters) per kilowatt-hour, compared to 0.3–0.4 gallons (0.08–0.1 liters) per kilowatt-hour for once-through systems. If evaporative cooling continues to be used for electricity production, water consumption for energy production could increase from 3.3 billion gallons (12.5 billion liters) per day in 1995 to 7.3 billion gallons (27.6 billion liters) per day in 2030 (2). With increasing population, this corresponds to about 48 to 76 liters per person per day.

4.3.3. Dry cooling.

Dry cooling is an alternative to water-intensive once-through cooling systems and closed-loop cooling systems. Although dry-cooling systems rely on a negligible amount of water, they have other negative environmental impacts, including air pollution and inefficiency in comparison to wet-cooling systems—especially on the years' hottest days. On hot-weather days, power prices and electricity demands increase at the same time that efficiency of dry-cooling systems declines. This combination could stress electrical systems, with an increased risk of power shortages if thermoelectric plants rely on dry-cooling systems alone.

Three types of dry-cooling facilities exist today: direct dry cooling, indirect dry cooling, and hybrid cooling. Direct dry-cooling facilities use air-cooled condensers to remove heat from the turbine exhaust steam. Indirect dry-cooling facilities condense the steam from the turbines and use an air-cooled heat exchanger to cool the hot cooling water. Hybrid cooling facilities, which are expected to be used in nuclear facilities in the near term, combine features of the wet- and dry-cooling methods (40). Hybrid facilities reduce the amount of water withdrawn and consumed in comparison to a wet-cooling facility, while increasing the efficiency of dry-cooling systems on hot-weather days (2).

4.4 Electricity from Wind and Solar Photovoltaics

Both wind energy and solar photovoltaics require negligible amounts of water to produce energy, and both energy sources are increasing generation throughout the United States. Though there are some environmental concerns, such as energy and rare materials required for production for both wind turbines and photovoltaic panels, and specific concerns for each, such as wind power effects on migratory patterns of birds, the overall water requirements are minimal and exist only for washing the blades of wind turbines and cleaning the photovoltaic panels (2, 82, 83).

During 2008, worldwide wind capacity grew by 38,175 MW, resulting in a total worldwide wind capacity of roughly 160,080 MW. In 2009, the United States had the largest cumulative installed wind capacity of 35,155 MW; followed by China, with a cumulative capacity of 25,853 MW; and Germany, with a

cumulative capacity of 25,813 MW (84). As of 2008, worldwide photovoltaic capacity was 13.9 GW, with Germany's capacity of 5.3 GW the largest, followed by Spain with a capacity of 3.4 GW, Japan with a capacity of 2.1 GW, and the United States with a capacity of 1.1 GW (85).

4.5 Electricity from Geothermal

Geothermal energy is generated from natural heat sources located, as steam or hot water, in deep or near-surface reservoirs (86). Between 1975 and 2007, worldwide geothermal energy production increased from 1,300 MW electric to 10,000 MW electric (87). Geothermal power plants use three different systems to generate electricity. First, a dry steam power plant directly transports underground sources of steam found in geysers to a turbine that generates electricity. The Geysers, located in California, are the only geysers in the United States to use a dry steam field. Though they allow for relatively easy generation of electricity, they are extremely rare.

The second, and most commonly used geothermal system, is a flash steam power plant. Flash steam power plants are designed to utilize underground reservoirs containing water of 182°C (360°F) or higher to produce electricity (88). As the water flows toward Earth's surface, the pressure decrease creates steam that can be used to generate electricity. Some of the water can be reinjected to its original source, minimizing water consumption.

The third type is a binary cycle power plant, which utilizes water at a lower temperature than that of the flash steam process (74°C–182°C) (165°F–360°F) to boil a working fluid (88). The working fluid, most commonly an organic compound, is vaporized and used to drive a turbine (89). Similar to the flash steam system, binary systems reinject the unused water back to its original source. However, much less reservoir water is lost in a binary system than in a flash system because the loss of noncondensed fluid is avoided.

Additional geothermal electricity-generating technologies are being developed, including enhanced geothermal systems, coproduction with oil and gas, and the use of fluids such as CO2 (88).

5. Energy Used for Water Services

Energy systems have changed from direct use of water for mechanical energy to more complex uses, such as dams providing both irrigation water for agriculture and hydroelectricity, as well as the development of public water systems that use energy to transport and treat drinking water and wastewater. Energy costs are usually the first or second largest component of costs paid by water utilities. In part, this is because losses in distribution systems are high, both in developing countries (30%–60% in Mexico, Brazil, and cities in India and South Africa) and in older systems in developed countries (90). Water losses mean that the energy used to pump, treat, and convey the water is also lost. Inefficient pumping systems and poor water management contribute to energy inefficiency in water systems. Reducing leaks and improving efficiency provide opportunities for improvements and increased water access that are less costly and available sooner than investment in additional infrastructure. Those strategies also help avoid the related costs of providing additional power, fuel requirements for power plants, and environmental damage. In 2002, in the United States, approximately

123 million megawatt-hours of electricity were required for supplying public, domestic, commercial, industrial, mining, livestock, and irrigation water, as well as to treat both public and private wastewater, corresponding to about 425 kWh per person annually. Roughly 52 million metric tonnes of CO2 are released each year through the processes of collecting, distributing, and treating drinking water and wastewater (2, 91, 92). These processes consume roughly 4% of the total power generated in the United States, and the water and wastewater industry is the third largest U.S. electricity consumer (92, 93). In 2002, the Electric Power Research Institute concluded that public water supply accounted for the consumption of roughly 30,600 million kWh of energy annually, and agriculture accounted for 23,600 million kWh of energy each year (93).

Supplying water to different regions requires significantly different energy intensities. Supplying water to Southern California requires 11,110 kWh of energy per million gallons (2,965 kWh/million liters) of water delivered. This includes 9,727 kWh/million gallons (2,570 kWh/million liters) used for sourcing, 111 kWh/million gallons (29.3 kWh/million liters) for treatment, and 1,272 kWh/million gallons (336 kWh/million liters) for distribution. Southern California is one of the more energy-intensive regions regarding energy used for water supply. Other regions use substantially less energy. For example, Wisconsin requires 1,900 kWh of energy per million gallons (502 kWh/million liters) of water delivered, which is equivalent to the U.S. overall average (93).

Surface water typically requires greater amounts of treatment and therefore greater inputs of energy than groundwater. Treating surface water in California can require up to 1,500 kWh of energy per million gallons (396 kWh/million liters) of potable water produced (2). On average, surface water supplies 27,266,000 acre-feet (33.6 trillion liters) of water to California each year. This means that roughly 13 TWh are required annually to treat the surface water used in California (94).

5.1. Transporting Water

The advent of electricity led to widespread water pumping. Conveyance systems transport surface water, sometimes over long distances, to supply water for agriculture, irrigation, drinking, sanitation, and recreation. Roughly 19% of California's total electricity consumption is from the water sector (including the use of hot water), and 5% of the state's total electricity consumption is used for the supply and treatment of water alone (2, 92). California has a diverse climate, resulting in areas of the state that receive an average 2 inches (5.08 cm) of rain each year to regions that receive over 100 inches (254 cm) of rain each year. Throughout California's history, this has resulted in an unequal distribution of water, and as early as 1770, aqueducts were built to transport water from areas of substantial rainfall to more arid regions.

The California State Water Project is the largest single energy user in California and alone is responsible for consuming 9.2 million megawatt-hours (2% to 3% of total electricity consumption in California) to convey an annual average of 2.9 million acre-feet (3.6 trillion liters) of water throughout the state (94, 95).

The California State Water Project currently supplies over two-thirds (25 million) of California's estimated 37 million inhabitants with water and provides water for roughly 750,000 acres (304,000

hectares) of irrigated farmland. Its eight hydroelectric power plants and one coal-fired plant supply two-thirds of the energy necessary for keeping the project in operation (9). Lifting water 1,926 feet (587 m) contributes to the average requirement of about 3,000 kWh to transport one acre-foot of water to Southern California (94, 95).

The Colorado River Aqueduct also uses huge quantities of energy to convey water. It transports water 242 miles (389 km) from Lake Havasu, Arizona, to Southern California, which requires roughly 2,000 kWh per acre-foot (1,600 kWh per million liters) delivered (93, 94). During this transport, the water is pumped a total elevation gain of 1,600 feet (488 m) (93).

In China, water scarcity is most pressing in the northern region. Issues of water scarcity exist because of nature's uneven distribution of water, ever-increasing pollution of fresh water, urbanization, and a growing population. Because of the unequal water distribution, China's South-to-North Water Transfer Project was designed to transport 45 trillion liters of water each year from China's southeastern Yangtze River to the North China Plain and the Yellow River. The majority of China's water resources (over 80%) are on the border of or south of the Yangtze River, and 41% of the nation's population and the majority of its cultivated land (56%) are in northern regions. In addition, 40%–60% of the water in the north does not meet quality standards that enable it to be used (96–98).

Chinas' South-to-North Water Transfer Project includes three different routes. The East Route is designed to transport 14.8 trillion liters of water 1,150 km each year. This section of the project requires that the water be pumped to a 65m higher elevation. The Central Route is responsible for delivering 13 trillion liters of water annually 1,246 km from the Yangtze River to northern areas of China, including the major cities of Beijing and Tianjin. The final portion of the project is the West Route, which is designed to transport 17 trillion liters of water each year over approximately 400 km of channels to regions of northern China. The project requires large quantities of water to be pumped over great distances, which will be energy intensive to develop, implement, and operate daily (97).

5.2. Pumping Groundwater

Groundwater lies under Earth's surface and is naturally replenished by rain, seepage from rivers and lakes, snowmelt, and excess water from agricultural irrigation. Although groundwater is constantly being replenished, users often extract it faster than it can naturally recharge. When groundwater is overpumped for human consumption, the natural water levels begin to drop. Over the past 50 years, water levels in some U.S. groundwater sources have dropped between 300 and 900 feet (91 m and 274 m) (2). Areas of the Mississippi River Alluvial Aquifer located in Arkansas have dropped 100 feet (30 m) in the past 100 years, and aquifers in the San Joaquin Valley in California—as well as groundwater in Baton Rouge, Louisiana—have dropped over 200 feet (61 m). Areas of the United States, such as Chicago and Milwaukee, have seen groundwater decline up to 900 feet (274 m).

Electricity requirements for supplying groundwater are 30% higher than those for supplying surface water (93), although energy requirements for groundwater pumping differ, depending upon the depth of the aquifer. An aquifer located 120 feet (37 m) below Earth's surface requires 540 kWh per million gallons (143 kWh/million liters) pumped. If that depth is increased to 400 feet (122 m) below Earth's

surface, the energy requirement would increase to 2,000 kWh per million gallons pumped (528 kWh/million liters) (2, 94). For every 100 feet (30 m) that the water level drops, an additional 450 kWh of energy is needed per million gallons (119 kWh/million liters) of water pumped (93).

On average, to source and treat deep groundwater, 6,000 kWh of energy are used per million gallons (1,585 kWh/million liters) of freshwater produced. About 30%—roughly 12.5 million acre-feet (15.4 trillion liters) of California's water—is supplied from groundwater sources each year; 85% of this helps provide approximately 40% of California's agricultural water supply (79, 91, 94, 99). Groundwater in California naturally replenishes 11 million acre-feet (13.6 trillion liters) each year, which means that continuing to withdraw at this level is resulting in the depletion of natural groundwater sources.

5.3. Treating Wastewater

As the global population continues to grow, the demand for freshwater continues to increase. Wastewater treatment provides much-needed freshwater and minimizes health issues related to lack of sanitation and the spread of disease (100). In 2020, major urban areas on the California coast are expected to generate over 3 million acre-feet (3.7 trillion liters) of wastewater each year, which could be treated and reused to minimize the amount of water withdrawn from surface and groundwater sources (91, 94). Municipal water supply and wastewater treatment systems account for 35% of the energy used by municipalities (101).

In 1995, California alone consumed roughly 1.6 billion kWh of electricity for wastewater treatment (93, 94). Private U.S. wastewater treatment facilities consumed roughly 42 billion kWh of energy in 2002—approximately twice the 21 billion kWh of energy used for wastewater treatment in public facilities. Combined, over 60 billion kWh of energy were used in the United States in 2002 for wastewater treatment (93).

The two most energy-intensive components in the wastewater treatment process are the collection system and the treatment facility itself, which together require energy for pumping, operating, and solids processing (94). Older water treatment facilities tend to require higher energy inputs than newer ones, and energy inputs vary, depending on the treatment requirements at specific plants. More aggressive treatments require more energy.

In the United States, there are more than 15,000 public wastewater treatment facilities using various technologies. Four of these technologies are trickling filters, activated sludge, advanced wastewater treatment, and advanced wastewater treatment with nitrification. For all four facility types, more energy is required in the smaller plants. For example, advanced wastewater treatment facilities—the most energy intensive of the four types—consume 2,951 kWh of electricity per million gallons (3.8 million liters) of treated water in a plant that produces 1 million gallons of treated water each day. That same technology uses 1,558 kWh of electricity per million gallons (411.6 kWh/million liters) of treated water in a plant that treats 100 million gallons (379 million liters) of water each day (91). For a trickling filter plant that produces 100 million gallons (379 million liters) of treated water each day, 673 kWh of electricity are needed for every million gallons (178 kWh/million liters) of treated water. This facility is less complex and less effective at removing nitrogen and phosphorus from the wastewater (91).

Along with the publicly owned wastewater treatment facilities in the United States, there are roughly 23,000 privately owned treatment facilities that are often used for treating wastewater from industrial plants and commercial operations. These facilities are typically comparable to smaller public facilities in the amount of water treated, but the energy requirements tend to be higher because the water requires more extensive treatment. An estimated 2,500 kWh of electricity are required per million gallons (660 kWh/million liters) of treated water in privately owned facilities (93). Capturing the fuel content in wastewater, for example, methane, offers opportunities for energy generation from wastewater treatment (102).

Opportunities exist for creating a more efficient wastewater infrastructure on the global scale. Regardless of the technologies used for treatment, average energy consumption per cubic meter of treated wastewater is currently similar across countries, including the United States (0.45 kWh/m3), the Netherlands (0.36 kWh/m3), Singapore (0.56 kWh/m3), Switzerland (0.52 kWh/m3), Germany (0.67 kWh/m3), the United Kingdom (0.64 kWh/m3), Australia (0.39 kWh/m3), and Spain (0.53 kWh/m3) (103). According to the Natural Resources Defense Council, wastewater treatment facilities in the United States have the potential to reduce energy consumption by between 15% and 30% by implementing energy conservation measures (92).

5.4. Desalination

Other approaches to meeting increasing water demand are to use brackish surface or groundwater or to use seawater. Desalination—removing salt from water—is usually energy intensive. In the United States, the typical energy requirement for sourcing and treatment of water supplies varies from 1,463, 2,228, to 2,390 kWh/million gallons (386, 589, to 631 kWh/million liters), for the U.S. average, Northern California, and Iowa, respectively. Southern California represents an extreme at 9,839 kWh/million gallons (2,599 kWh/million liters) owing to high energy requirements for sourcing water over long distances. Desalination is expected to require about 3,900–9,750 kWh/million gallons (1,030–2,576 kWh/million liters) for brackish water desalination and 9,780–16,500 kWh/million gallons (2,584–4,359 kWh/million liters) for seawater desalination. The energy required for seawater desalination is higher than the energy expected to be required for reusing treated wastewater effluent or interregional transfers. Nonetheless, to meet projected increases in water demand, the share of public water supply provided by desalination is projected to increase from 2% of 43 billion gallons per day in 2000 to 10% of 64 billion gallons per day in 2050 in the United States (93).

The process of desalination involves either membranes [reverse osmosis (RO) or electrodialysis] or boiling and recondensing the water (thermal distillation). Thermal methods are used in regions of the world with low-cost energy, whereas RO is dominant in the United States. Two technologies provide about 40% each of global desalination capacity: multistage, which relies upon a series of chambers of decreasing pressure to boil seawater and is mostly used in the Middle East, and RO (104). Modern RO systems use about 10% of the energy of thermal systems. Electrodialysis is competitive with RO for small production processes to treat water having relatively low salinity, whereas RO has lower energy requirements at high salinity. The energy required increases with the difference in water quality between the source and the output. Freshwater typically has total dissolved solids of <1,000 ppm, brackish water 1,000–5,000 ppm, highly saline water 5,000–15,000 ppm, saline water 15,000–30,000,

and seawater 30,000–40,000 ppm. The higher the salinity of the feedstock water, the more pressure (and energy) is required in RO systems: ~100 pounds per square inch (psi) for brackish water and 1,000 psi for seawater. The energy intensity of existing installations for desalinating ocean water use 11,000–26,000 kWh/million gallons (2,906–6,868 kWh/million liters). Improving energy intensity to 7,600 kWh/million gallons (2,008 kWh/million liters) is considered achievable with advanced RO on the basis of laboratory-scale testing that achieved 6,000 kWh/million gallons (1,585 kWh/million liters). Utilizing multiple pretreatment technologies to remove organic matter and divalent ions (hardness) can decrease energy intensity. In practice, there are trade-offs between capital and operating costs (93). A recent review (105) of desalination showed reported energy requirements (total electric equivalent) ranging from 2.6 to 201 kWh/m3, depending on the method and application, and a minimum theoretical energy requirement for desalinating saline water of 0.706 kWh/m3. The review (105) lists a number of studies utilizing renewable energy, including one RO example powered by a photovoltaic electric system reporting energy requirements in the range 1.1–1.8 kWh/m3 depending on the quality of the feed source and the efficiency of the membrane technology. A review of water desalination costs (106) shows dependency on such key factors as desalination method, feed water salinity, type of energy source (e.g., fossil or renewable), and capacity of the facility. Interest and experience in renewable energies for desalination are increasing, particularly for small-scale applications in remote areas (lacking electricity grids) (104).

Other proposed approaches for reducing the energy intensity of desalination include (a) colocating thermal power plants that use seawater for cooling with desalination plants may reduce system costs resulting from shared infrastructure and use of waste heat; (b) using capacitive deionization with high-surface-area electrodes to treat brackish water; and (c) employing membrane distillation that uses the vapor pressure of water across a membrane, induced by a temperature difference between the two sides of the membrane.

The energy required for desalination may be significantly reduced by using advanced technologies: (a) capacitive deionization (50% of brackish water treatment energy) and (b) advanced RO or membrane distillation (50% and 66% of desalination treatment energy, respectively) (table 4-1 in Reference 93).

6. Energy Requirements for Water End Uses

Energy is required for circulating, treating, heating, and cooling water in end-use applications such as water heating and washing. Water-consuming end uses tend to be energy intensive (94). Water-inefficient fixtures and fittings (toilets, showerheads, urinals, faucets) represent both wasted water and wasted embodied energy. While 5% of California's electricity consumption is dedicated to supplying and treating water, 14% of California's electricity is consumed to heat water for end uses such as clothes washing, dishwashing, showers and baths, and processes at the residential, commercial, and industrial levels (2). Urban water use in California has higher energy requirements than the water-intensive agricultural sector because the energy requirements for water and waste- water treatment in urban water systems often do not exist in agricultural settings. The agricultural sector depends upon roughly 34 million acre-feet (41.9 trillion liters) of water each year and just over 10,000 GWh of electrical power for pumping and transporting that water. In comparison, in 2000, the residential, commercial, and

industrial sectors were responsible for the use of only 7 million acre-feet (8.6 trillion liters) of water, but the consumption of roughly 27,887 GWh of electricity. In 2001, urban water end uses consumed 4,220 million therms (445,000 trillion joules) of natural gas (93, 107).

In 2001, California's residential sector was responsible for 48% of the state's energy consumption for urban water uses, 13,528 GWh of electricity and 2,055 million therms (216,762 trillion joules) of natural gas. The residential sector was also responsible for roughly 53% of total end-use water consumption. California's residential sector alone accounts for the use of roughly 4 million acre-feet (4.9 trillion liters) of water each year, about 366 liters of water per person per day in California. A study by Natural Resources Defense Council found that 26.7% of residential water use was for toilets—not a particularly energy-intensive end use because no water heating is required. However, 21.7% of the end-use water in the residential sector was for washing clothes, 16.8% was for showering, and 15.7% was for general faucet use, all more energy intensive because they require hot water (94).

California's commercial sector consumed 8,341 GWh of electricity, or 30% of the total electricity consumed, for end uses of water in 2001. It also consumed 250 million therms (26,370 trillion joules) of natural gas, or 6% of the total natural gas employed for urban end uses. In 2001, California's industrial sector consumed 6,017 GWh of electricity, or 22% of the total electricity consumed, and 1,914 million therms (202,000 trillion joules) of natural gas, or 45% of the total amount of natural gas consumed for end use. California's commercial and industrial sectors used roughly 2.5 million acre-feet (3 trillion liters) of water, roughly 229 liters of water per Californian per day, or a combined 37% of the total water used for urban end uses in the year 2000. Over half of this water was used for the energy-intensive processes of heating and cooling (82). Commercial and industrial water uses include those listed above, as well as pressurization to deliver water to higher floors in high-rise buildings, equipment cooling, and cooling towers employed in air conditioning (107).

End uses of water have often been overlooked when discussing the relationship between water and energy. However, the energy used for end-use processes in the residential, commercial, and industrial sectors is significant and can potentially be decreased by the development and implementation of technologies (e.g., water- and energy-efficient appliances and fixtures) and policies (e.g., mandatory energy- and water-performance standards). In 2000, urban water use in California could have been reduced by 30% by wide adoption of existing, cost-effective technologies (108).

7. Energy and Water Used for Supplying Food

Worldwide, agriculture is the dominant consumptive use of water, with about 70% of freshwater withdrawals going to irrigated agriculture (109). Water withdrawal for agriculture is expected to continue increasing from about 2,600 (in 2000) to 3,100 km3 (in 2025), while consumptive use is projected to increase from about 1,800 to 2,200 km3 (110). Agriculture accounts for 41% of withdrawals and 85% of consumptive use in the United States. To the extent that irrigation is depleting fossil aquifers, this represents a challenge to sustainable supply of potable water. Regions where overuse of aquifers is impacting water supply or water quality include Jordan (water tables have fallen as much as 0.6 m/year in the Azraq Basin), Namibia (the Karstveld Aquifer water table has dropped several meters),

the Volta River Basin, and many South Pacific and Caribbean islands (111). From 66 principal aquifers found in the United States, 76,500 million gallons of water are withdrawn each day. Of this amount, 56,900 million gallons (74%) are used for irrigation (112). The Ogallala Aquifer, also known as the High Plains Aquifer, is a 175,000-square mile (453,000 km2) aquifer located in the United States. This aquifer is responsible for roughly 30% of all groundwater irrigation in the United States, and its water is depleted at a faster rate than it is naturally replenished (113).

Agriculture represents about 1% of U.S. direct energy use. Indirect energy use by agriculture adds about another 0.5%, largely because agriculture is responsible for 56% of nitrogen use (for fertilizer) and 67% of pesticide use (114).

Food-related energy use—including agri-culture and all aspects of transporting, preparing, and disposing of food—as a share of the national energy budget grew from 14.4% in 2002 to an estimated 15.7% in 2007 in the United States (115).

In addition to indirect energy use, there is indirect water use associated with our choice of foods. For any product, including foods, embodied water is water required to produce or dispose of a product over its life cycle. Around 300 liters of water are required to produce 1 liter of beer, including the water required for growing barley. The exact quantity depends upon many factors, considered in life cycle assessments, including the water necessary to produce the crops. From 850 to 1,120 liters of water per liter are needed to produce beverages such as coffee, wine, and fruit juices (116). For a variety of crops, water requirements can be 500–2,000 liters per kilogram, or even higher, such as the 1,900–5,000 liters of water needed to produce a kilogram of rice. Because animals eat grain, the water requirements for a kilogram of chicken or beef are 3,500–5,700 and 15,000–70,000 liters per kilogram, respectively (116).

8. Conclusion

Water is required in large volumes, both consumptive and nonconsumptive, for current fuel and electricity production. World energy consumption is projected to increase by 49% between 2007 and 2035. This is a 1.4% increase per year, and an overall increase from the consumption of 522 to 780 exajoules annually (116, 117). Most thermal electricity-generating plants, regardless of fuel source (e.g., coal, natural gas, nuclear, central solar) have had high water requirements for cooling. Cooling systems are moving away from the most water-intensive, once-through cooling systems toward closed-loop cooling. In arid areas, thermoelectric power plants often adopt dry cooling, but this means lower efficiency when outdoor temperatures are high. Electricity demand in those climates tends to be greatest during the hottest period of the year to supply air conditioning, which poses a conflict between high demand and diminished supply. Hybrid cooling systems are being developed to use water only during the hottest period to minimize the annual demand for water while satisfying peak electricity demand. Sources of electricity with minimal water requirements are wind and solar photovoltaics.

The water and wastewater sector combined represents one of the largest industrial uses of energy, and energy represents a major portion of the cost of water. Most of that energy is electricity for pumps and for treatment, either to make water potable or to treat wastewater. A trend toward water reuse and

reclamation decreases the demand for raw water, while increasing the demand for electricity. Pumping from deeper underground, or removing more contaminants or salt, requires additional energy.

A large share of the energy associated with water use is the energy for heating water for industrial, commercial, and residential uses, where significant reductions in energy and water demands are possible through energy and water efficiency at the end uses (e.g., hot water use).

In the future, the interdependence of water and energy is expected to increase. For conventional thermoelectric power plants, water withdrawals for electricity generation are likely to decrease by switching to less-water-intensive cooling systems, which, with the exception of dry cooling, will at the same time increase water consumption (e.g., evaporation from cooling towers or ponds). For liquid fuels, increased reliance on bioenergy will increase the correlation of water and energy supplies. Water shortages that reduce biofuel crop production will reduce fuel availability. To address increasing interdependence, attention is increasing on integrated resource planning, collocation of water and energy facilities, and systems thinking at multiple scales (e.g., facility, city, and region). Ultimately, energy and water effects through the life of products and systems—from resource extraction through production to delivery, use, and disposal—should be considered.

Summary Points

1. Water and energy are strongly dependent on one another.

2. Development of bioenergy increases water and energy interdependence.

3. Most thermoelectric plants require water for cooling.

4. Closed-loop, dry, and hybrid cooling systems are replacing more water-intensive once-through systems, reducing water withdrawals, and—except for dry cooling—increasing water consumption.

5. Water requirements are minimal for electricity from wind and solar photovoltaic technologies.

6. Energy is used for pumping, treating, and desalinating water.

7. Significant energy and water savings are possible for industrial, commercial, and residential end uses from efficient technologies and behaviors.

8. Addressing the interdependence of water and energy requires increased integrated resource planning, collocation of water and energy facilities, and systems thinking at multiple scales.

Future Issues

1. How to reconcile limited supplies of potable water with increasing demand for water-related services owing to increasing human populations and economic growth?

2. How to provide sustainable energy services, especially electricity and transportation, globally within the constraints imposed by water availability and quality?

3. How to balance human use of water and energy with environmental sustainability for ecosystems?

4. How to mitigate and adapt to climate change for energy and water systems, both changes in natural water systems and in systems of human origin?

5. How to broadly implement integrated planning of energy and water supply and demand that is adapted to local conditions?

6. How best to close the loop so that water, once used, can be most efficiently used again, including consideration of matching different grades of water quality to appropriate uses?

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Related Resources

International Water Association. http://www.iwahq.org/1nb/home.html

Electric Power Research Institute. http://my.epri.com/portal/server.pt?

UN Water. http://www.unwater.org/index.html

U.S. Environmental Protection Agency: Water. http://water.epa.gov/

U.S. Environmental Protection Agency: Water Sense. http://www.epa.gov/watersense/

U.S. Geological Survey: Water Resources of the United States. http://water.usgs.gov/

World Water Council. http://www.worldwatercouncil.org/

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