Chapter 16

Affordable and clean energy and water (SDG 7)

Roger Sathre
Institute for Transformative Technologies, Berkeley, CA, United States

Chapter outline

Introduction

Achieving Sustainable Development Goal (SDG) 6 for clean water and sanitation, and SDG 7 for affordable and clean energy, will require great effort by 2030. The challenge is immense, with numerous obstacles that must be overcome to ensure universal access to clean water and energy.

As of 2022, about 2.2 billion people lacked safely managed drinking water services, primarily in rural areas (UN, 2023). The same year, 3.4 billion people lacked safely managed sanitation services, and only 58% of household wastewater was safely treated. About 500 million people practiced open defecation, and only 71% of global population had access to handwashing facilities with soap and water at home (Mukherjee & Dash, 2024).

Concurrently, 91% of the global population enjoys access to electrical energy, while about 675 million people still lacked electricity access in 2021, mainly located in sub-Saharan Africa (UN, 2023). Only 71% of the global population had access to clean cooking fuels and technologies in 2021, leaving 2.3 billion people relying on inefficient and polluting cooking stoves. Globally in 2020, only 12.6% of total final energy use was provided by modern renewable energy sources (REN21, 2022).

While each of these metrics is gradually improving, current trends suggest that SDGs 6 and 7 will not be achieved by 2030 without a redoubling of global efforts (UN, 2023). Yet the two goals cannot be fulfilled in isolation, as their pathways and obstacles are interconnected. Haphazard implementation of development efforts risks making one problem worse while seeking to solve another. There are synergies and trade-offs among sectors; thus holistic analysis and decision-making is required.

This chapter addresses the interconnections between energy supply and water supply. First, the usage of energy within the water sector is discussed, exploring the ways that energy is needed to access clean water. Then we discuss the usage of water within the energy sector, including the need for water to access clean energy services. Only by understanding these linkages between sectors can rational policy be devised to improve outcomes in both energy and water access.

Water Matters. DOI: https://doi.org/10.1016/B978-0-443-15537-6.00016-1

Using energy to get water

Our available primary energy resources can be used to obtain and improve water resources. This is done by lifting water, desalination, water disinfection, wastewater treatment, accessing groundwater, facilitating groundwater recharge, and atmospheric water capture. These topics are explored here.

Lifting water

Pumping of water is needed to lift groundwater from subsurface aquifers, and to replenish elevated storage facilities. Pumps can also be used to apply a hydraulic head to water for horizontal conveyance in pipes or canals.

The technology set for lifting water is fundamental to groundwater access. An important pump distinction is based on the source of motive power: human muscles or mechanically powered. Manual-powered pumps are commonly used in rural areas to lift groundwater from boreholes and shallow wells for household use. Technologies for shallow and deep handpumps were significantly advanced during the International Drinking Water Decade from 1981 to 1990. Robust community-scale pumps, such as the India Mark III and the Afridev, were designed and widely deployed with attention not only to technical efficiency but also user ergonomics and practical maintenance (RWSN, 2013). The treadle pump, developed in Bangladesh during the 1970s and 1980s, is a low-cost shallow pump that is actuated by strong leg muscles and can lift sufficient water for irrigating smallholder farms.

Exosomatic energy sources, such as grid electricity or diesel fuel, can also power pumping. The efficiency of electrical pump sets is typically low, with average efficiency in South Asia of about 30% (Singh, 2009; World Bank, 2001). This is less efficient than the current best practice pump set efficiency of 50% or greater, and far from the practical efficiency limit of about 85%. Opportunities for increasing efficiency include matching pump and motor size to their tasks, and upgrading foot valves and suction and delivery piping. Where grid electricity is not available, diesel fuel is typically used to power groundwater pumps. The diesel fuel cost increases the overall operating cost for farmers using these pumps. Electrical pumps that are directly powered by solar photovoltaic (PV) panels are very efficient, because all captured electricity is used for pumping, and there are no losses from battery charge−discharge cycling. Modern PV electrical pump sets are commercially available with efficiencies of 70% (GIZ, 2013). Solar pumping can also be integrated into village-level solar PV mini-grid systems. This integration can benefit the farmer, by spreading the high capital cost of the PV system across many users. It also benefits the mini-grid utility, which enjoys reliable and flexible pumping loads. Because additional solar water pumping imposes no marginal cost to the farmer, a rational water allocation system is needed to avoid unrestrained aquifer depletion if solar pumping becomes widespread (Pearce, 2024).

Desalination

Desalination is the process of making potable water from saline water sources such as seawater or brackish water. This necessarily uses energy, to overcome the entropy of mixing of salt and water. There are four main desalination technology groups, corresponding to the energy force driving the process: thermal, pressure, electrical, and chemical (Miller, 2003; Subramani & Jacangelo, 2015; Youssef et al., 2014). Thermal desalination generally uses large amounts of heat, pressure desalination uses much smaller amounts of electricity for pumping, and electrochemical methods use even less electricity but are limited to low-salinity feed water (see Fig. 16.1).

In **thermally activated** systems, evaporation and condensation at different temperatures and pressures are the main processes used to separate salts from water. In these systems, heat transfer is used to either boil or freeze the feed water to convert it to vapor or ice, so the salts are separated from the water. Thermal processes include multistage flash, multi-effects distillation, vapor compression distillation, humidification−dehumidification, solar distillation, and freezing. **Pressure activated** systems use a pressure gradient to force water through a permeable membrane, leaving salts behind. In recent decades, membrane technologies have matured and most new desalination installations use membranes. Of these, the reverse osmosis (RO) process is the most common; others include forward osmosis and nanofiltration. **Electrically activated** systems take advantage of the charged nature of salt ions in solution, by using an electric field to remove ions from water. A common form is electrodialysis (ED), which is now used for about 4% of global water desalination. A newer technology with great promise is capacitive deionization (CDI). **Chemically activated** desalination systems are less common, and include liquid−liquid extraction, ion-exchange, gas hydrate, and other precipitation methods.

Pressure-activated RO seawater desalination technologies are approaching theoretical limits of energy efficiency (Elimelech & Phillip, 2011) and are already used at commercial scale for industrial and domestic use. Although minor incremental efficiency improvements may still be gained, it is unlikely that major breakthroughs will fundamentally

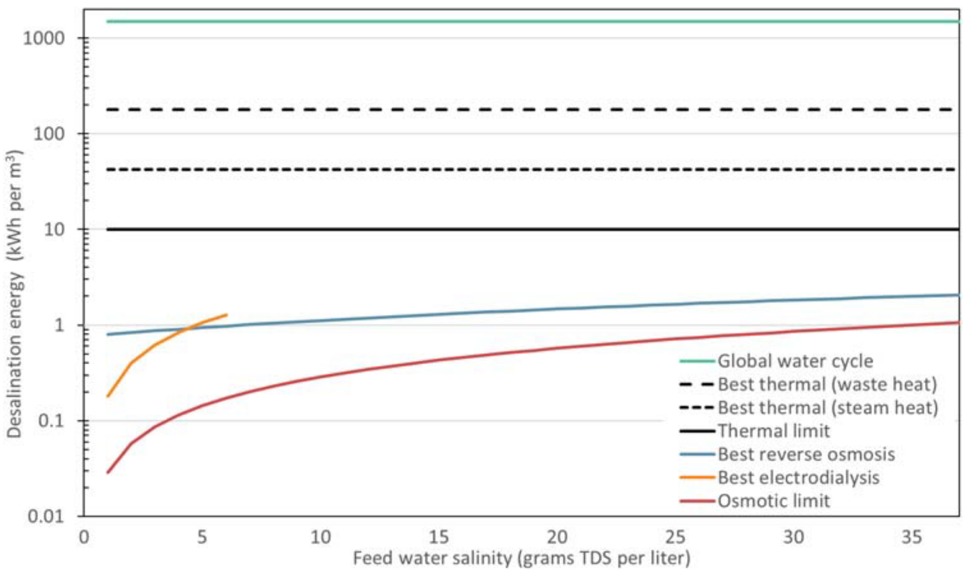

FIGURE 16.1 Energy use for desalination (kW h per m^3 of freshwater) as a function of feed water salinity (grams of total dissolved solids per liter of feed water) for various desalination processes. *Note vertical axis is logarithmic. Source: based on Cerci et al. (2003), Fritzmann et al. (2007), Elimelech and Phillip (2011), Shatat and Riffat (2014), ITT (2018).*

alter the seawater desalination landscape. For brackish water, however, there are opportunities for significant reductions in desalination cost and energy use, through innovative electrochemical techniques. The minimum theoretical energy requirement for desalination varies with the salinity of the feed water—less energy is fundamentally needed to desalinate brackish water, compared to seawater (Fig. 16.1). While conventional thermal or pressure-based desalination techniques use about the same amount of energy regardless of the salinity of feed water, the electrical current needed for ED and CDI desalination is proportional to the amount of salt that is removed (Knust et al., 2014). Feed water on the dilute end of the brackish water range (0.6−4 g of total dissolved solids per L of feed water) is particularly amenable for ED and CDI desalination (Suss et al., 2015).

Renewable energy can be used to power desalination. Solar stills combine an evaporator where feed water is exposed to sunlight and a condenser where the resulting vapor is converted to liquid. Solar still designs must balance the competing needs for affordability, efficiency, and durability (El-Bialy et al., 2016). Solar desalination methods can be compared by the amount of freshwater produced per square meter of land area per day. The theoretical maximum efficiency of traditional solar stills is about 10 L/m^2/day. (1) Actual solar stills typically have efficiencies of less than 50%, and generate 3−5 L/m^2/day. There are pathways to increase solar still efficiency (e.g., Li et al., 2016), but the higher cost and complexity have prevented broader use. Another avenue for solar desalination is the use of PV solar electricity to power RO desalination. This could produce about 500 L/day/m^2 of land area (2) or 50 times the theoretical maximum output of a simple solar still. If the feed water is brackish, coupling PV power to ED desalination could produce even more freshwater per m^2 of land area (Wright & Winter, 2014).

Water disinfection

In the traditional development pathway, safe household water is first ensured by neutralizing biotic pathogens in the available water supply, which only later is made easier by cleaning wastewater streams to avoid initial water contamination. Microbial pathogens in water can be killed, deactivated, or physically removed to make water safely consumable. There are numerous ways this can be achieved at various scales and energy implications, via chemical, thermal, radiation, and filtration methods (see Table 16.1).

Chlorine is the most widely used water disinfectant, and ozone is the second most widely used. Many of these technologies are combined together to achieve better drinking water quality. For example, ceramic filters can be lined with silver and copper nanoparticles to ensure all pathogens are killed and filtered out. Another example is chloramination, which is the combined use of chlorine dioxide and ultraviolet radiation.

The chemicals used for water disinfection may react with other chemicals in a water source to create by-products that are harmful to human health. Some common by-products are bromate, chlorite, and trihalomethanes, which can be toxic or carcinogenic (USEPA, 2023). Some of these compounds can be adsorbed and removed by using activated carbon filters for secondary treatment.

TABLE 16.1 Numerous methods are available to kill or remove pathogens from drinking water.

Type	Method	Appropriate scale	Observations
Chemical	Chlorine	All scales	May produce disinfection by-products; turbidity can inhibit effectiveness
	Zinc	Household	Requires removal of precipitated material
	Iodine	Household and community	May produce disinfection by-products
	Ozone	Municipal	May produce disinfection by-products
	Silver and copper nanoparticles	Household	Does not form disinfection by-products
	Combined coagulation	Household	Simple and low-cost technology but requires regular input of chemicals
Thermal	Boiling	All scales	Very energy intensive
UV radiation	Solar disinfection (e.g., SODIS)	Household	Turbidity and cloud cover can inhibit effectiveness
	UV light treatment	Household and community	Turbidity can inhibit effectiveness
Filtration	Membrane filter (e.g., reverse osmosis)	All scales	Removes pathogens and many inorganic contaminants
	Ceramic pot	Household	Very low cost
	Rapid sand filter and slow sand filter	Community and municipal	Can be used as pretreatment step followed by chlorine, ozone, etc.
	Pressure filters	Municipal	May require pretreatment (e.g., settling or prefiltration)

UV, ultraviolet.
Source: Based on Gadgil (1998), Amrose et al. (2015), USEPA (2023).

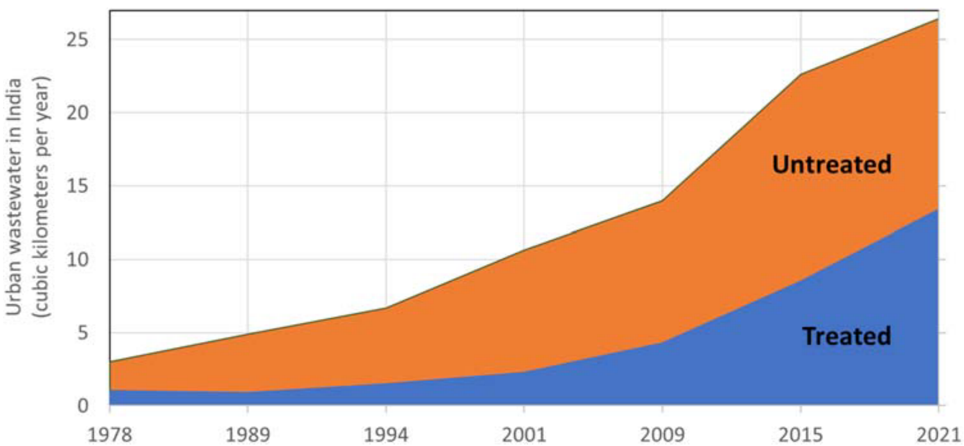

FIGURE 16.2 Despite significant increase in sewage treatment capacity, Indian cities are discharging increasing amounts of untreated sewage. *Based on data from (CPCB, 2015, 2021).*

Wastewater treatment

Currently, substantial energy is expended in industrialized countries to treat domestic wastewater and sewage. For example, about 1.3% of all electricity used in the United States is for sewage treatment (Heidrich et al., 2011). In fast-growing cities in developing regions, wastewater treatment capacity is scaling up rapidly but still typically insufficient. In India, for example, total discharge of untreated sewage has increased not decreased in recent decades, despite a 13-fold increase in treatment capacity since 1978 (see Fig. 16.2). There and elsewhere, the resulting sewage discharge is contributing to local health problems and adverse environmental effects. Simultaneously, many regions suffer from water supply shortages. Enabling the scale-up of sewage treatment will require adequate energy resources both for infrastructure build-out and for operational energy requirements.

Novel sewage treatment methods that enable the reuse of treated wastewater will offer two important benefits: less pollution entering water bodies, and less need for freshwater withdrawals. Important criteria for successful treatment technologies include the extent of land area required, the economic resources needed for capital and operation, and the quality requirements for the reused water. Different technology solutions will be appropriate for different settings as the scale increases from household to neighborhood and metropolitan level. Generally, larger treatment plants have greater efficiency, which lowers the lifecycle costs and environmental impacts per cubic meter of treated water.

In the longer term, it is possible to develop and deploy sewage treatment facilities that are net sources, rather than sinks, of resources, including energy. The chemical energy contained in raw sewage is about six times the electrical energy used for its treatment (Korth et al., 2017). These energy resources could be recovered, and sewage treatment facilities could operate with no external energy input, or could possibly produce surplus energy for societal use.

Accessing groundwater

In many locations, groundwater is a convenient and flexible source of clean water. Groundwater has been an important part of Green Revolution agriculture, made available via boreholes and mechanized pumps. Accessing this water via well drilling or digging requires physical work to displace soil and rock, thus requires energy. In regions practicing Green Revolution agriculture, local capability has been developed in siting and drilling wells, and in manufacturing and maintaining drilling equipment. A range of drilling techniques are available, depending on soil characteristics, required depth, and the source of motive power (WECD, 1999).

Manual drilling techniques use human muscles to produce borewells in locations that would be inaccessible to mechanical drilling rigs and with less cost. Community participation is often involved as drilling labor. Manual techniques are typically slow and are limited in the geological formations they can drill through. Powered well drilling is typically done with portable diesel-powered rigs that use the percussion and rotary percussion drilling methods. Powered mechanical rigs are expensive and have limited mobility to reach remote areas, but are able to effectively drill through most geological features and can create wells relatively quickly.

Facilitating groundwater recharge

Underground aquifers store vast amounts of water, which can be accessed by pumping from wells. Many regions are currently extracting groundwater faster than the rate of natural recharge, leading to falling water tables. The rate of natural aquifer recharge is also diminishing, due to rapid urbanization and land use changes that have reduced the infiltration of rainwater into the soil. Managed aquifer recharge (MAR) invests mechanical energy now to shape the earth's surface to spread and slow rainwater runoff, seeking to increase the rate of groundwater recharge in perpetuity (subject to erosion and sedimentation). The goal is to allow continuing high rates of groundwater extraction without risk of water table decline.

MAR is achieved by reducing the fraction of rainwater that runs off the land surface, thus increasing the fraction that infiltrates through the land surface and enters the soil. This is typically implemented through earthworks and engineered structures that slow the downstream flow of surface run-off water, allowing more of it to infiltrate into the ground (CGWB, 2007). A wide range of structures are available at varying scales, including swales, percolation tanks, ponds, check dams, and barrages. Fossil fuels that are currently abundant (e.g., in the form of diesel fuel to power tractors) can be invested now to move earth that will benefit society indefinitely into the future, even after fossil fuels have been depleted. Nevertheless, major earthworks have been, and can be again, accomplished by common human labor.

MAR is only applicable in regions that have adequate rainfall and a surplus of water to be stored, as well as suitable geology with porous underground formations to store the water. The potential benefits of MAR vary widely by location because MAR requires three conditions: the availability of uncommitted surface water, the availability of underground storage space, and the demand for groundwater (Shah, 2008).

Atmospheric water capture

Removing water vapor from air is an appealing concept that receives substantial popular attention. Numerous methods have been proposed to access atmospheric water, including concentrating water vapor through the use of solid or liquid desiccants, cooling a surface below the dew point of the ambient air, and inducing convection in a tower structure.

Air water generators are currently commercially available that provide limited quantities of drinking water, powered by either grid electricity (e.g., Majik Water, 2024) or solar power (e.g., Source, 2024).

Although removing water from the atmosphere is technically possible, it is unlikely to scale as a significant source of water due to several fundamental physical challenges. First, the water vapor content per volume of air is very low (ranging from about 4 to 22 g/m^3 at different locations around the world); thus very large amounts of air must be handled to obtain significant water (Wahlgren, 2001). In reliably windy areas, this air movement could take advantage of natural flows, though in less windy regions mechanical fans will be needed.

A second challenge is that water's latent heat of condensation is high, meaning that much heat energy is released when water vapor changes to liquid (Miller, 2003). The same amount of energy that must be input to boil liquid water to a vapor will be output when the vapor condenses to liquid water. To capture a significant amount of water from the air, large amounts of heat will be generated. Rejecting this amount of heat is not trivial, typically requiring active devices such as heat pumps.

Atmospheric water capture can be achieved with both active and passive devices. In general, active devices powered by concentrated energy sources such as electricity can drive processes such as air movement and heat rejection at a high rate. Passive water capture devices that use natural energy gradients that are more diffuse, such as wind and sunlight, will proceed at slower rates. To capture significant amounts of water, passive capture devices must have large exposed surface areas to compensate for slow unit process rates. This typically results in a high capital cost, large land footprint, and/or fragility and risk of damage.

The efficiency of atmospheric water harvesting is highly dependent on climate and varies with humidity, temperature, pressure, and other factors (Gido et al., 2016). While the idea of using the atmosphere as a year-round source of household water is attractive, in practice, the water supplied by an air water generator would likely be seasonal and expensive. In almost every case, other water provision methods (e.g., well drilling, desalination, or truck transport) would provide a more reliable and affordable water supply.

Using water to get energy

Our available water resources can be deployed to obtain usable energy resources, for example, via hydroelectricity, geothermal energy, power plant cooling water, and irrigation for bioenergy. These topics are explored here.

Hydroelectricity

Hydroelectricity is a form of indirect solar energy, whereby solar insolation drives evaporation of surface water, which condenses and falls elsewhere as precipitation, whose potential energy is exploited to produce power. While hydroelectricity can be produced intermittently by intercepting run-of-river flow without water storage, dispatchability of electricity supply can be achieved through reservoir storage. Where conditions are suitable, large quantities of river flow can be captured behind dams and stored in reservoirs from where it may later be released and used on demand. Potential for dam construction and reservoir creation is first determined by numerous physical factors such as landscape topology and geology, which are limiting in many regions. The global installed hydroelectricity capacity is about 1200 GW, with China, Brazil, Canada, and United States having the largest capacities (REN21, 2022). About 4200 TW h of hydroelectricity is produced annually, which is 16% of total global electricity generation.

Within each river basin, diminishing returns are found from creating additional storage capacity as basins approach closure (when all available river water is allocated for use). Within closed basins, new dams will not increase total surface water supply but merely redistribute the supply. Where the landscape is suitable, however, additional hydroelectricity can be generated by a series of dams at different elevations, through which river water flows sequentially as it flows downstream. Dams can also be an effective tool for river flood control. By altering the transport of fluvial sediments, dam construction also affects the geomorphology of rivers, the fertility of floodplains, and the nutrient balance of rivers and estuaries (Dandekar, 2014).

Natural siltation is a long-term challenge for sustainable hydroelectricity production. Each year, between 0.5% and 1% of the total volume of water stored in reservoirs around the world is lost as a result of sedimentation (Basson, 2009), corresponding to a 100- to 200-year service life. Globally, per capita reservoir storage peaked in the 1980s, and absolute net reservoir capacity peaked around 2006, and both have declined since (Wisser et al., 2013).

Reservoir siltation is particularly acute in geologically young regions such as the Himalayas. The Indus River in Pakistan has substantial glacial melt and erosion of its steep barren slopes, making it one of the most sediment-producing rivers in the world (WCD, 2000). The gradual elimination of reservoir storage capacity due to sedimentation is a serious ongoing problem in Pakistan, and new dams must be built simply to maintain existing storage capacity (see Fig. 16.3).

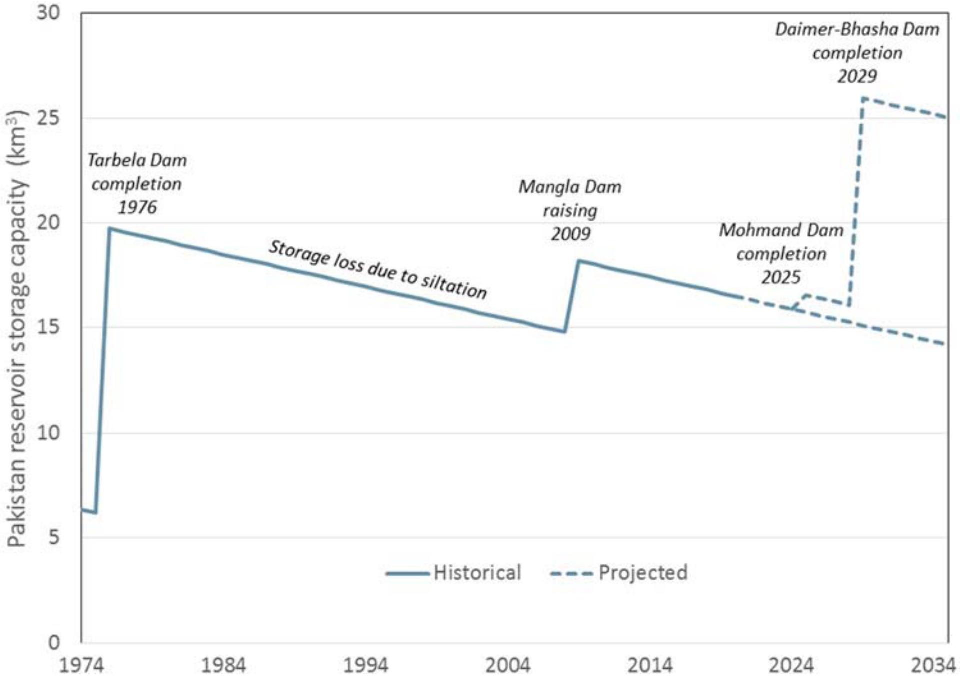

FIGURE 16.3 Water storage capacity behind Pakistan's dams decreases continually due to sedimentation and is increased periodically by building new dams or raising existing dams. *Adapted and updated from (World Bank, 2005; ITT, 2018).*

Geothermal energy

Geothermal energy takes advantage of the natural heat within the earth's crust, originating from the radioactive decay of minerals within the earth. Potential for geothermal exploitation varies widely by location and is often greater in areas near tectonic plate boundaries. Groundwater comes into contact with this subsurface heat, becoming hot and rising to the surface. There it may be exploited to drive turbines to make electricity or used as heat for domestic or industrial processes. Most geothermal energy comes from naturally occurring water sources, using existing hot springs or geysers. However, enhanced geothermal systems can be made that artificially introduce cool water to subsurface formations via injection wells, which is then heated and used as an energy source. In some cases, a different working fluid with a boiling point lower than water is used instead.

The global geothermal electricity generating capacity is about 14.5 GW (REN21, 2022). The United States, Indonesia, Philippines, and Turkey are the countries with the greatest installed geothermal generating capacity, averaging about 2 GW each. Roughly 100 TW h of geothermal electricity is generated per year, which is less than 1% of total global electricity production. In addition, about 140 TW h of direct geothermal heat energy is used globally per year (REN21, 2022). China is by far the largest user of direct geothermal energy, using about 80 TW h/year, followed by Turkey, Iceland, and Japan.

Power plant cooling water

Cooling water is needed by virtually all thermal electric plants, whether powered by fossil fuels, biofuels, or nuclear energy. A range of methods can be used for power plant cooling, with a large variation in water withdrawal, water consumption, cost, generation efficiency, and other factors (see Table 16.2). Once-through cooling takes water from a large body (e.g., ocean, lake, and river), passes it through a condenser to receive power plant heat, and then returns it to the same source (now slightly warmer). Wet recirculating cooling uses the same water repeatedly to cool the power plant condenser, and each time is sent to cooling towers to expose the water to ambient air. Some of the water evaporates, and the rest (now cooler) is returned to the condenser in the power plant. Dry recirculating cooling also uses the same water repeatedly to cool the power plant condenser, but each time is cooled via an air–water heat exchanger with no evaporation of water. Hybrid cooling systems use some combination of these methods.

The most commonly used cooling system type is wet recirculating cooling using freshwater, which has the highest rate of evaporative freshwater consumption of all cooling systems. This type of cooling is used for 80% of thermal power generation in India (WRI, 2018), and 64% of thermal power generation in the USA (USGS, 2023). Shifting to other types of cooling could substantially reduce evaporative consumption in water stressed regions.

TABLE 16.2 Thermal power plants can use various types of cooling systems, each with advantages and disadvantages.

Cooling technology	Advantages	Disadvantages
Once-through	Low evaporative consumption High cooling efficiency Lowest capital cost Mature technology	Highest water withdrawal Ecosystem impacts from withdrawal and discharge Restrictions on hot water discharge
Wet recirculating	Lower water withdrawal than once-through Mature technology	Highest evaporative consumption Lower power plant efficiency than once-through Higher capital cost than once-through
Dry recirculating	Very low water withdrawal No evaporative consumption	Highest capital cost Low power plant efficiency (when weather is hot) Large land area requirement

Source: Adapted from (CEC, 2009; CEA, 2012).

Thermoelectric production is dependent on viable cooling systems, and water limitations (of quantity or quality) may constrain electricity generation. At least 14 disruptions due to cooling water shortages were experienced by India's largest thermal power utility companies in the 4 years from 2013 to 2016 (WRI, 2018). In the summer of 2022, high water temperatures in the Rhône River forced the curtailment of electricity production in France's nuclear power plants.

Irrigation for bioenergy

Some bioenergy crops are rainfed and thus more closely aligned to the natural water cycle. Other bioenergy crops are irrigated, with water purposely diverted to the cropland. To the extent that bioenergy plays a greater role in future energy systems, it is essential that the water requirements of the crops be considered, to avert unsustainable water use. The irrigation water demand of bioenergy depends on numerous factors, such as the total water needed during the plant lifecycle, the amount of green water provided naturally in the local bioclimate, the fraction of plant biomass that is dedicated to energy production, and the conversion efficiency from green biomass to usable energy.

Gerbens-Leenes et al. (2009) compared the water footprint of 12 common field crops that could be suitable for bioenergy, such as maize, soybean, and sugar cane. They found that the conversion of plants to bioelectricity uses less water, per unit of delivered energy product, than does the conversion of plants to liquid biofuel. Among liquid biofuels, bioethanol requires less water than does biodiesel. Depending on climate, making bioelectricity from maize plants uses about 20 m^3 of irrigation water per GJ of electricity. Making bioethanol from sugar cane uses about 60 m^3 of irrigation water per GJ of ethanol. Making biodiesel from soybean uses about 220 m^3 of irrigation water per GJ of diesel fuel. For each liter of liquid biofuel produced, under average climatic conditions, the total water demand ranges from 1400 L (for ethanol made from sugar beets) to 20,000 L (for biodiesel made from jatropha).

Large-scale cultivation of energy crops would substantially increase total evapotranspiration within water basins. In water-stressed regions, energy crop production could exacerbate water security challenges (Berndes, 2002). A decision to engage in large-scale bioenergy must be informed by knowledge of constraints and competing demands on water supply. Nevertheless, in water- and land-abundant regions bioenergy may play an important role in energy security. Another pathway toward resilient bioenergy is the cultivation of halophytes, plants that thrive in saline water (Sharma et al., 2016). Irrigation with seawater or brackish water could produce valuable energy crops with water that is otherwise unusable.

Synthesis

The interplay of clean energy and clean water is complex, with many dependencies and preconditions. Universal access to clean energy and water will depend in part on demographics and population dynamics, as well as on changes in per capita consumption of water and energy services. Efficiency improvements due to technology advancement will allow more usable services to be delivered per unit of natural resources available. Furthermore, the impact of climate change will affect the extent and reliability of both energy and water supply, through the alteration of temperature and precipitation patterns.

Table 16.3 summarizes the initial capital outlay, the operational challenges, and the long-term constraints of the various methods of using energy to get water and using water to get energy that are discussed in this chapter. Our society

TABLE 16.3 Summary characteristics of pathways for using energy to get water, and using water to get energy.

Color legend:	xxx	High	
	xxx	Medium	
	xxx	Low	
	Initial capital outlay	**Operational challenges**	**Long-term constraints**
2. Using energy to get water			
2.1 Lifting water	Modest pump and piping cost	Energy use scales with lift height	Technology is accessible
2.2 Desalination	High cost of infrastructure	High-energy use and cost	Huge saline water resource
2.3 Water disinfection	Moderate equipment required	Ensure supply of inputs	Continuous supply of consumables
2.4 Wastewater treatment	Extensive infrastructure surface area needed	Range of processes available	Nature-based processes are sustainable
2.5 Accessing groundwater	High cost and effort of making well	Some geological formations are challenging	Pumping rate must not exceed recharge rate
2.6 Facilitating groundwater recharge	High initial cost and effort of earth moving	Negligible operating cost	Surplus precipitation can be captured
2.7 Atmospheric water capture	High cost of infrastructure	High-energy use per unit of water	Uncompetitive to alternatives
3. Using water to get energy			
3.1 Hydroelectricity	High cost and effort of dam construction	Precipitation variability limits generation	Siting, siltation and drought
3.2 Geothermal energy	High cost of infrastructure	Low operating costs	Scale limited by suitable sites
3.3 Power plant cooling water	Plant siting near water body	Limited cooling in times of drought	Low water consumption possible
3.4 Irrigation for bioenergy	Similar to irrigation of food crops	Irrigation restricted in times of drought	Competition with food production

The table numbering refers to subchapters in this work.

will continue to use large amounts of energy to obtain necessary water. Pumping of water, both to lift groundwater and to convey surface water, will continue to be an important means of water supply. Efficiency improvements in pump sets will reduce the energy needed, and clean electricity sources will reduce climate and other environmental impacts. Desalination will play an increasing role, with virtually unlimited feed water in coastal regions. Nevertheless, the energy cost for desalination will ensure the water is only used for high-value applications. Disinfection is important for reducing the biological hazards of water supply and can be achieved with a range of methods demanding energy and nonenergy inputs. Wastewater treatment is essential as population densities increase, requiring the construction of extensive infrastructure. The use of nature-based treatment methods, which take advantage of the chemical energy contained within the wastewater, is particularly relevant in a future of constrained energy and water supplies. Appropriate well drilling equipment is needed in regions with abundant yet unexploited groundwater, including much of sub-Saharan Africa. Distributed infrastructure for recharging groundwater will be needed in other regions, to ensure the sustainable cycling of water resources. Atmospheric water capture will see little practical implementation, despite abundant hype.

We will also continue to use our water resources to obtain energy supply. Hydroelectricity is a product of our dams and reservoirs, which provide clean, dispatchable electricity. Currently the largest source of renewable power, hydroelectricity is limited in the medium term by available dam sites, and in the long term by the siltation of reservoirs. Geothermal energy systems use water to transfer Earth's internal heat to the surface and can be a clean and reliable energy source where geologic conditions are suitable. Cooling water is needed for virtually all thermal power plants, including nuclear, coal, and gas powered generating plants. The reliability of this cooling water supply must be ensured, which is made increasingly challenging by global climate change. Using irrigation water to grow bioenergy crops can be a rational use of water resources in some regions, but is ill-advised in dryer areas.

In this chapter, we survey the connected landscapes of clean energy and water supply. We find that no single technology can independently resolve society's energy and water challenges, but many can play important roles in achieving SDGs 6 and 7 to ensure affordable and clean energy and water for all.

1. The theoretical limit of a solar still is based on solar insolation of ~ 6.5 kW h/m^2/day and latent heat of water evaporation of 0.63 kW h/kg, resulting in a maximum water evaporation of ~ 10 kg/m^2/day.
2. RO desalination powered by PV electricity is based on solar insolation of ~ 6.5 kW h/m^2/day, PV solar-to-electricity conversion efficiency of 20%, and RO specific electricity use of 2.5 kW h/m^3, resulting in a freshwater production of ~ 500 L/m^2 of PV panel per day.

References

Amrose, S., Burt, Z., & Ray, I. (2015). Safe drinking water for low-income regions. *Annual Review of Environment & Resources*, *17*(51), 9.1-9.29.

Basson, G. R. (2009). *Management of siltation in existing and new reservoirs*. General Report, 23rd Congress of the International Commission on Large Dams: Brasilia, Brazil.

Berndes, G. (2002). Bioenergy and water: The implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, *12*, 253−271.

CEA (Central Electricity Authority). (2012). *Report on minimisation of water requirement in coal based thermal power stations*. CEA.

CEC (California Energy Commission). (2009). *Water use for electricity generation*. PIER Advanced Generation Program.

Cerci, Y., Cengel, Y., Wood, B., Kahraman, N., & Karakas, E. S. (2003). *Improving the thermodynamic and economic efficiencies of desalination plants*. Program Final Report No. 78, Mechanical Engineering, University of Nevada.

CGWB (Central Ground Water Board). (2007). *Manual on artificial recharge to groundwater*. Ministry of Water Resources.

CPCB (Central Pollution Control Board). (2015). *Inventorization of sewage treatment plants*. CPCB.

CPCB (Central Pollution Control Board). (2021). *National status of waste water generation and treatment*. CPCB.

Dandekar, P. (2014). *Shrinking and sinking deltas: Major role of dams in delta subsidence and effective sea level rise*. South Asia Network on Dams, Rivers and People.

El-Bialy, E., Shalaby, S. M., Kabeel, A. E., & Fathy, A. M. (2016). Cost analysis for several solar desalination systems. *Desalination*, *384*, 12−30.

Elimelech, M., & Phillip, W. A. (2011). The future of seawater desalination: Energy, technology, and the environment. *Science (New York, N.Y.)*, *333*, 712−717.

Fritzmann, C., Lowenberg, J., Wintgens, T., & Melin, T. (2007). State-of-the-art of reverse osmosis desalination. *Desalination*, *216*, 1−76.

Gadgil, A. (1998). Drinking water in developing countries. *Annual Review of Energy & the Environment*, *23*, 253−286.

Gerbens-Leenes, W., Hoekstra, A. Y., & van der Meer, T. H. (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, *106*, 10219−10223.

Gido, B., Friedler, E., & Broday, D. M. (2016). Assessment of atmospheric moisture harvesting by direct cooling. *Atmospheric Research*, *182*, 156−162.

GIZ (Gesellschaft für Internationale Zusammenarbeit). (2013). *Solar water pumping for irrigation: Opportunities in Bihar, India*.

Heidrich, E. S., Curtis, T. P., & Dolfing, J. (2011). Determination of the internal chemical energy of wastewater. *Environmental Science & Technology*, *45*, 827−832.

ITT (Institute for Transformative Technologies). (2018). *Technology breakthroughs for global water security: A deep dive into South Asia*. ITT.

Knust, K. M., Hlushkou, D., Tallarek, U., & Crooks, R. M. (2014). Electrochemical desalination for a sustainable water future. *ChemElectroChem*, *1*, 850−857.

Korth, B., Maskow, T., Gunther, S., & Harnisch, F. (2017). Estimating the energy content of wastewater using combustion calorimetry and different drying processes. *Frontiers in Energy Research*, *5*(23), 1−8.

Li, X., Xu, W., Tang, M., Zhou, L., Zhu, B., Zhu, S., & Zhu, J. (2016). Graphene oxide-based efficient and scalable solar desalination under one sun with a confined 2D water path. *Proceedings of the National Academy of Sciences*, *113*, 13953−13958.

Miller, J.E. (2003). *Review of water resources and desalination technologies*. Report SAND 2003-0800, Sandia National Laboratories.

Majik Water. (2024). Atmospheric water generator.Available from https://majikwater.co/. (2024) Accessed 25.04.24.

Mukherjee, A., & Dash, A. (2024). Water matters: The thirst, demand, and the society. In A. Mukherjee (Ed.), *Water matters: Achieving the sustainable development goals* (pp. 1−8). Netherlands: Elsevier B.V., ISBN: 9780443155376.

Pearce, F. (2024). How a Solar Revolution in Farming Is Depleting World's Groundwater. Available from https://e360.yale.edu/features/solar-water-pumps-groundwater-crops. (2024) Accessed 25.04.24.

REN21. (2022). *Renewables2022 global status report*. Available from https://www.ren21.net/reports/global-status-report/.

RWSN (Rural Water Supply Network). (2013). *How three handpumps revolutionised rural water supplies*. Field NoteNo. 2013-1. Available from https://rural-water-supply.net/en/resources/475.

Shah, T. (2008). India's master plan for groundwater recharge: An assessment and some suggestions for revision. *Economic & Political Weekly*, *43* (51), 41−49.

Sharma, R., Wungrampha, S., Singh, V., Pareek, A., & Sharma, M. K. (2016). Halophytes as bioenergy crops. *Frontiers in Plant Science*, *7*, 1372.

Shatat, M., & Riffat, S. B. (2014). Water desalination technologies utilizing conventional and renewable energy sources. *International Journal of Low-Carbon Technologies*, *9*, 1−19.

Singh, A. (2009). A policy for improving efficiency of agriculture pump sets in India: Drivers, barriers and indicators. Climate Strategies. Available from https://doi.org/10.2139/ssrn.2759717.

Source. (2024). *Perfect drinking water created from sunlight and air*. Available from https://www.source.co/.

Subramani, A., & Jacangelo, J. G. (2015). Emerging desalination technologies for water treatment: A critical review. *Water Research*, *75*, 164−187.

Suss, M. E., Porada, S., Sun, X., Biesheuvel, P. M., Yoon, J., & Presser, V. (2015). Water desalination via capacitive deionization: What is it and what can we expect from it? *Energy & Environmental Science*, *8*, 2296−2319.

UN (United Nations). (2023). *Progress towards the sustainable development goals: Towards a rescue plan for people and planet. Advanced unedited version*. UN.

USEPA (United States Environmental Protection Agency). (2023). *National primary drinking water regulations*. Available from https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.

USGS (United States Geological Survey). (2023). *Thermoelectric power water use reanalysis for the 2008-2020 period by power plant, month, and year for the conterminous United States*. Available from https://doi.org/10.5066/P9ZE2FVM.

Wahlgren, R. V. (2001). Atmospheric water vapour processor designs for potable water production: A review. *Water Resources*, *35*(1), 1−22.

WCD (World Commission on Dams). (2000). *Tarbela dam and related aspects of the Indus River Basin, Pakistan*. WCD.

WECD (Water Engineering and Development Centre). (1999). *RunningWater: Technical briefs on health, water and sanitation*. WEDC, Loughborough University.

Wisser, D., Frolking, S., Hagen, S., & Bierkens, M. F. P. (2013). Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs. *Water Resources Research*, *49*, 1−8.

World Bank. (2001). *India: Power supply to agriculture*. Report No. 22171-IN. Available from https://openknowledge.worldbank.org/entities/publication/4f16de73-c4d4-5460-bf50-e915a31673a9/full.

World Bank. (2005). *Pakistan's water economy running dry*. Report No. 44375. Available from https://documents.worldbank.org/en/publication/documents-reports/documentdetail/989891468059352743/pakistans-water-economy-running-dry

WRI (World Resources Institute). (2018). *Parched power: Water demands, risks, and opportunities for India's power sector*. WRI.

Wright, N. C., & Winter, A. G. (2014). Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India. *Desalination*, *352*, 82−91.

Youssef, P. G., Al-Dadah, R. K., & Mahmoud, S. M. (2014). Comparative analysis of desalination technologies. *Energy Procedia*, *61*, 2604−2607.