GRAND CHALLENGE 1:

Sustainably Supply Food, Water, and Energy

Providing life's essentials—food, water, and energy—for the world's growing population is a major challenge. Doing so in a manner that does not threaten the environment and the health or productivity of future generations is an even bigger challenge.

The challenges differ in high- and low-income countries. In low-income countries the infrastructure to supply water and energy and manage wastewater in many cases simply does not exist, and economic and social barriers put basic services out of reach for billions of people. Nearly 800 million people worldwide are undernourished;[15] nutrition-related factors contribute to 45 percent of deaths in children under age 5.[16] In 2015, 844 million people had no access to safe drinking water, and 2.3 billion people did not have ready access to basic sanitation services.[17] More than 1 billion people, or about 1 in 7 globally, live without electricity.[18] These issues are most severe in sub-Saharan Africa and central and southern Asia.[19] High-income countries have mature production and delivery systems to provide food, water, and energy to their populations, but these systems often waste resources and discharge harmful pollutants. In many places, water and sanitation infrastructure has outlived the planning horizon under which it was built, creating large challenges in maintaining expected water quality and reliability.

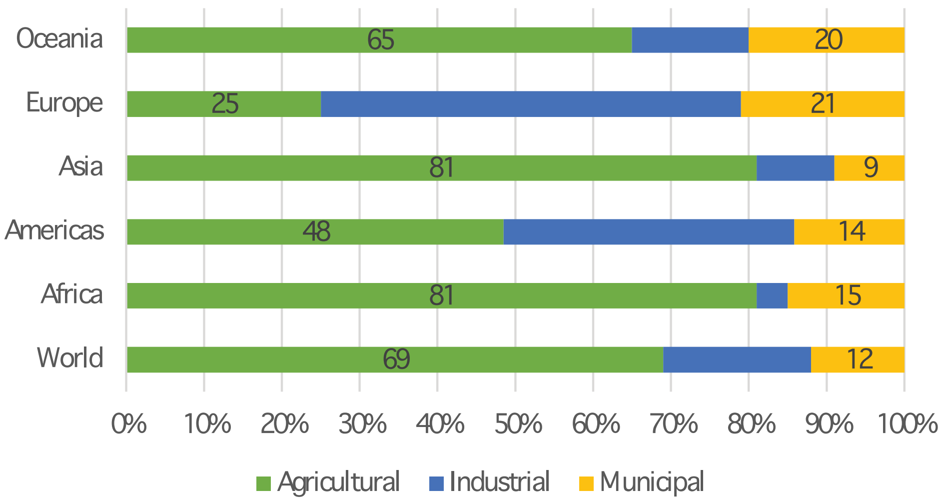

FIGURE 1-1. Water withdrawal percentages by sector and continent, 2010.

Complexities arise from the fact that food, water, and energy are inextricably linked. About 70 percent of global water withdrawals are for agricultural purposes (irrigation, livestock, or aquaculture; Figure 1-1), and agriculture represents about 80-90 percent of all consumptive use.[20] Agricultural activities release nutrients and contaminants into groundwater and downstream water bodies, degrading terrestrial and aquatic ecosystems and threatening the water resources on which humans depend.[21] The food production and supply chain is estimated to consume about 30 percent of global energy and produce about 22 percent of global greenhouse gas emissions (including landfill gas from food wastes), although there is uncertainty with such calculations.[22] The global energy mix remains dominated by fossil fuels, the extraction and the use of which involve water-intensive processing and contribute to water pollution.

In the decades ahead, sustainably supplying food, water, and energy to all will be made more difficult by population growth, increasing standards of living, and climate change. Innovation will be needed to augment supplies, improve distribution, reduce waste, increase efficiency, and reduce demand. Because the food-water-energy nexus is so tightly interwoven, potential solutions or demands in one area often have repercussions in another. A holistic, systems-oriented approach is crucial to balancing resource demands as we strive to meet the basic needs of our growing population.

Advancing Sustainable Agriculture to Feed Earth's Growing Population

Feeding a growing global population while minimizing impacts on water, soil, and climate poses substantial challenges during the next several decades.[23] By 2050, there are likely to be an additional 2.6 billion people to feed, and gains in affluence will increase energy use and the demand for water- and resource-intensive diets of meats and dairy. Climate change exacerbates pressures on water supplies and agricultural productivity[24] and increases the likelihood of disruptions in the food supply chain from storms and other factors.[25]

Almost all land area available for economically feasible food production is in use, and much of the remaining land, such as tropical forests and grassland preserves, sustains biodiversity and other important ecosystem services sustainability.[26] Increasing food supply will need to occur, not by adding new land, but by increasing efficiency and yields in existing agriculture, decreasing food waste, and changing dietary patterns.

Increasing Agricultural Yields with Reduced Environmental Impacts

Over the past century, agricultural yields have increased steadily through advances in mechanization and the use of fertilizers, pesticides, plant breeding, and irrigation technology. In the United States, such advances have ensured a safe and reliable domestic food supply while also generating a trade surplus in agricultural commodities and foods.

Advances in agricultural technologies, data collection, and computational science provide opportunities to further enhance efficiencies and increase yields. Sensors can be designed to detect and diagnose plant diseases in the field or in greenhouses to reduce lost agricultural productivity.[27] Precision applications of pesticides, herbicides, and fertilizer can dramatically reduce agrochemical use without compromising yields.[28] A better understanding of the microbiome in agriculture could improve soil structure, increase feed efficiency and nutrient availability, and boost resilience to stress and disease.[29] Selective breeding, genetic engineering, and gene editing could be used to develop crop varieties that maintain productivity under changing climate conditions.[30]

The recent explosion in the availability of data presents many opportunities to improve the resilience and efficiency of food and agricultural production. To inform decisions effectively, analysis of datasets must account for multiple factors. For example, understanding yields requires analysis of plant genetics, farm management practices, local environmental conditions, and socioeconomic factors over a range of spatial and temporal scales. Data standards and tools that can manipulate and analyze such large and complex datasets are needed to facilitate these advances.[31]

In low-income countries, some innovative efforts are improving yields and efficiency in crop production while minimizing environmental impacts. In India, for example, a new tractor-mounted seeder has been developed that allows wheat to be planted in rice paddies without burning the straw remaining after the rice harvest, a practice that simultaneously reduces air pollution by avoiding biomass burning and increases yields by retaining organic matter in the soil.[32] Advances in low-cost sensors and cell phone–based tools designed for agriculture could provide guidance to farmers on appropriate application rates of seeds, water, and fertilizer to maximize yields and prevent unnecessary inputs.

FIGURE 1-2. Wheat seeder designed to eliminate crop waste burning in rice paddies in India.

Today, some yield improvements could come at the cost of greater environmental burdens. For example, it has been estimated that it may not be possible to further increase U.S. soybean yields without sacrificing water quality and soil resources in surrounding ecosystems.[33] Environmental engineers can advance sustainable agriculture by working collaboratively with agricultural engineers and evaluating environmental benefits and impacts of innovative strategies in both low- and high-income settings.

Recent innovations in indoor aquaculture and vertical farming are expanding the possibilities of where emerging agricultural technologies can develop (see Figure 1-3). These facilities can be designed to produce food with recycled nutrients, carbon, and water to maximize water efficiency, reduce fertilizer use, and minimize pollution. Water discharged can be treated so that it is cleaner than when it enters the facility.[34] Because such farms do not require agricultural land, they can be located close to urban centers, potentially increasing resilience to supply chain interruptions and reducing the energy expended in distribution. Life-cycle analyses, considering factors such as cost, energy, water use, and pollution, will be important to developing indoor agricultural systems that are feasible and cost-efficient.

FIGURE 1-3. Using stacked growing trays, known as vertical farming, and artificial lighting, leafy greens are grown without soil, reducing water demand by 90 percent compared to conventional approaches.

Reducing Food Waste

One of the biggest opportunities to stretch the supply of food is to reduce food waste. Globally, it is estimated that as much as one-third of all food produced—1.3 billion tons per year—is lost or wasted.[35] This loss and waste occur throughout the food chain:

- In the field, when damage or spills occur during harvest or when harvesting does not occur because of economic or weather reasons;
- After harvest, when food degrades during storage;
- At the processing stage, when spills occur or food is unsuitable for processing;
- At the distribution stage, when food is damaged or degrades as it is transported or awaits sale; and
- With the consumer, when food spoils or is simply thrown away.

In lower-income countries, such as those in Latin America, Africa, and Asia, most food loss (at least 85 percent) occurs before the food reaches the consumer; in high-income countries, over 30 percent of food loss happens at the consumer level (Figure 1-4). These losses threaten food availability in food-insecure regions and represent a waste of land, energy, water, and agricultural inputs.

Technologies and systems along the entire food chain—including harvest, transportation, processing, and storage—are needed to reduce food loss from farm to plate. Nanotechnology-based protective films (in some cases edible) can lengthen shelf life, possibly without refrigeration.[36] Low-cost sensors that indicate food quality and safety could further reduce food loss. Effective strategies will also need to consider the attitudes and actions of various stakeholders that affect food waste.

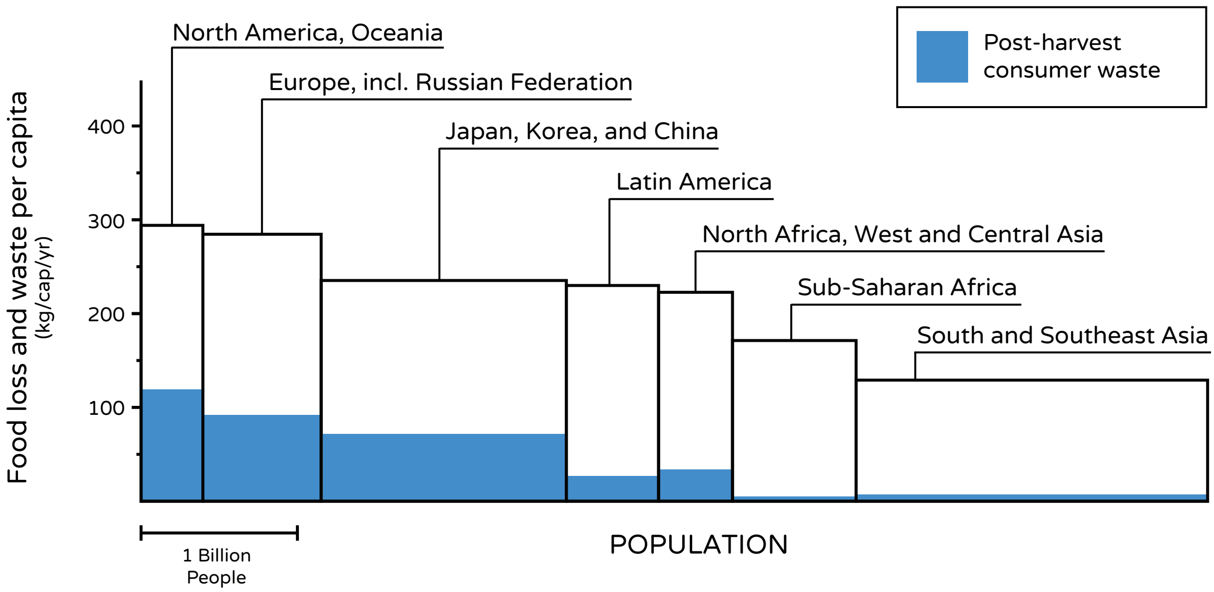

FIGURE 1-4. Food loss and waste per capita in different world regions.

Changing Dietary Patterns

Livestock farming may be responsible for as much as 14.5 percent of all human-induced greenhouse gas emissions,[37] and cattle are responsible for nearly two-thirds of these emissions. Beef and dairy farming also requires vastly more fresh water per unit of protein produced compared to plant-based equivalents. Meanwhile, it has been estimated that global meat production may grow by 12 percent between 2016 and 2026 due to population growth and increasing demand associated with rising standards of living in lower- and middle-income countries.[38]

Shifting dietary patterns to deemphasize animal-based protein, particularly beef, could reduce the environmental and resource burdens of feeding the world's population. The World Resources Institute estimates that such changes to dietary patterns could allow feeding of up to 30 percent more people with the same agricultural land and cropping patterns.[39]

A variety of meatless protein products, including innovative plant-based products and protein products grown from animal and plant tissue cells in culture, are becoming available. If such products can be produced affordably at scale and be accepted by consumers, they could reduce the demand for livestock, thereby decreasing the land, energy, and water requirements of animal-sourced protein and its associated environmental impacts while expanding food availability.

Overcoming Water Scarcity

Global water use is anticipated to increase by 55 percent by 2055, with the largest increases in Brazil, China, India, and Russia (Figure 1-5).[40] At the same time, the surface water and groundwater resources that have traditionally supplied ecosystems and human populations with fresh water are increasingly stressed. Fresh water is a limited resource, with fresh water in lakes, rivers, and groundwater comprising just 0.77 percent of the water on Earth.[41] Although

Earth's freshwater resources in total remain constant, their distribution varies widely across time and space. The beginning of the 21st century saw the Millennium drought in Australia—the worst drought recorded since European settlement.[42] California recently experienced a record-breaking multiyear drought, followed by record flooding in 2016-2017, and climate change may make such extremes more common.[43]

Water scarcity occurs when demands exceed the available water supply, leading to competition for available resources. Today, water scarcity already affects every continent and around 2.8 billion people worldwide for at least 1 month out of every year.[44] People living in water-stressed regions (Figure 1-6) are particularly vulnerable to the impact of droughts and other extreme weather events, environmental degradation, and conflict. Recently, Cape Town, South Africa, came perilously close to depleting its urban water supply. Meeting the water needs of a growing population in a manner that does not harm the environment requires innovations in water supply, increased efficiency, and strategies to reliably distribute clean water to those who need it.

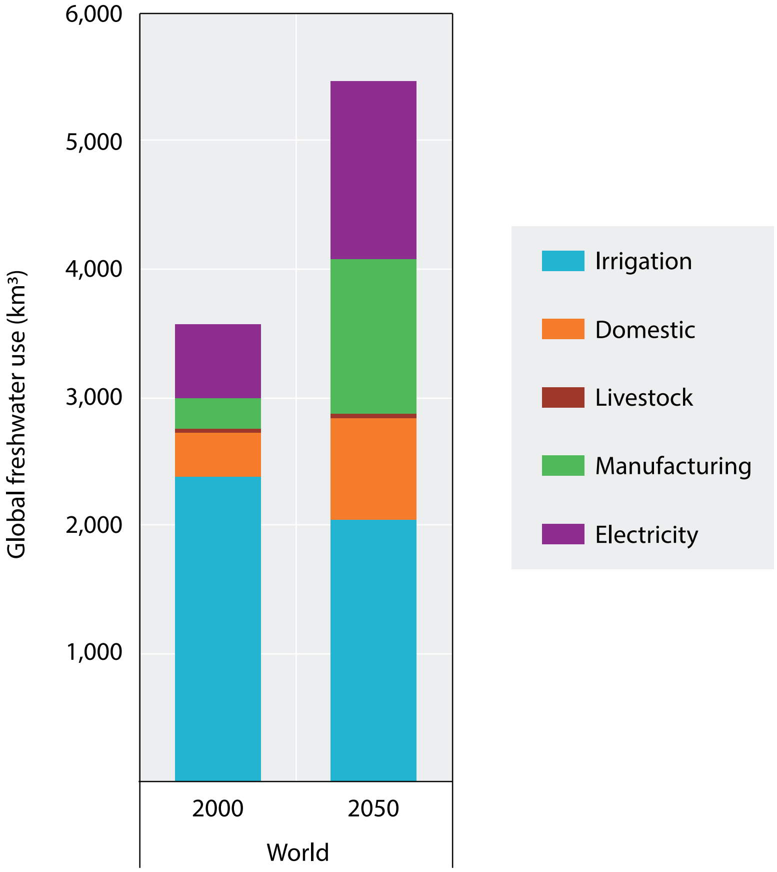

FIGURE 1-5. Global freshwater use projected for 2050, compared to the baseline in 2000. Does not include rainfed agriculture.

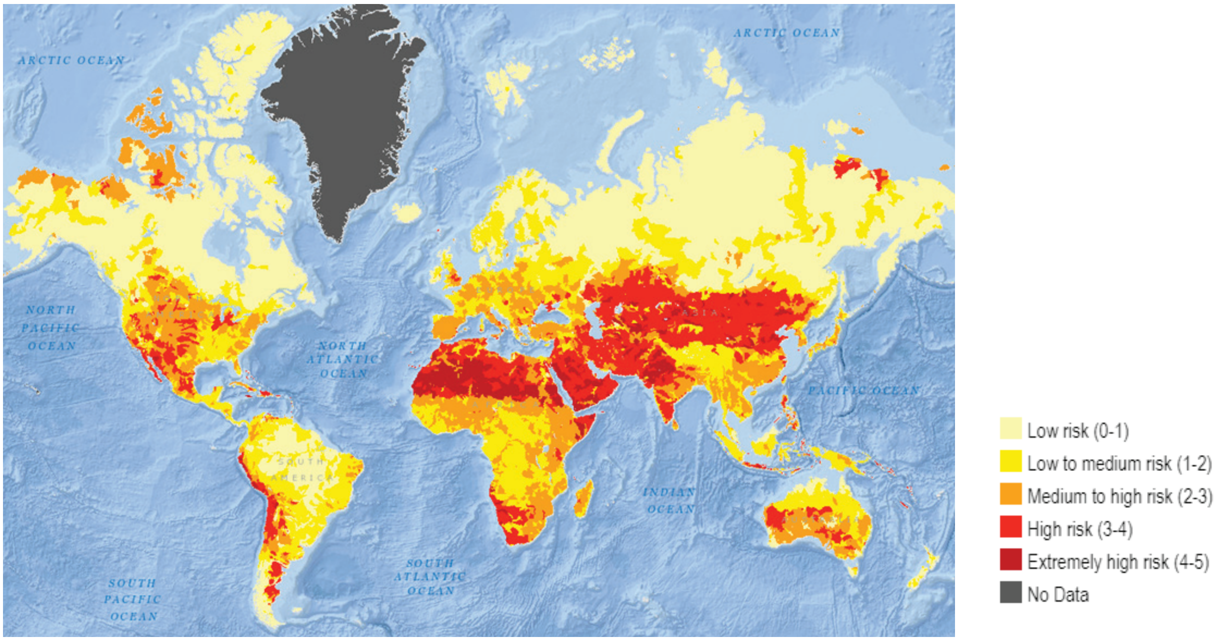

FIGURE 1-6. Map of overall water risk. Overall water risk is an aggregated measure of indicators from categories of physical risk quantity (including flood occurrence, drought severity, and upstream storage capacity), physical risk quality (including return flow ratio and upstream protected land), and regulatory and policy risk (including access to water).

Innovations in Water Supply

Fewer conventional sources of new water, such as dams and reservoirs, are being constructed in part because of increasing awareness of their environmental impacts,[45] and groundwater is being depleted worldwide at increasing rates.[46] Thus, alternative means of supplying water will be needed.

For thousands of years, people living with water scarcity have devised ways to create fresh water from seawater. As of 2015, roughly 18,000 desalination plants worldwide, almost half of them in the Middle East and North Africa, produced nearly 23 billion gallons of fresh water per day using technologies such as reverse osmosis and distillation.[47] Although important in water-scarce regions, desalination remains too expensive and energy-intensive to serve as a widespread solution for providing fresh water. Innovation and development of alternative, lower-energy approaches could change that. For example, researchers developed a membrane embedded with heat-absorbing nanoparticles that enables energy from sunlight to drive the membrane distillation process. The technology could provide off-grid desalination at the household or community scale for those who lack access to clean water.[48] Research to understand and reduce environmental impacts and to develop cost-effective approaches for brine management could also enhance the use of desalination in areas facing water scarcity.[49]

Municipalities are increasingly looking for new water supply from the recovery and reuse of water that has traditionally been simply discarded, such as stormwater, municipal wastewater, graywater (water from laundry, showers, and nonkitchen sinks), and contaminated groundwater. New technologies are making it increasingly feasible to collect stormwater or graywater at individual buildings or in neighborhoods and treat it for nonpotable uses such as irrigation, street cleaning, fire-fighting, industrial processes, heating and cooling, and toilet flushing.[50]

Cities are also turning to potable reuse systems that use advanced treatment processes to remove contaminants from wastewater to provide a drought-proof drinking water supply.[51]

Wastewater reuse is more expensive than conventional water supply alternatives such as imported water and groundwater (assuming other water alternatives are available at their traditional costs), and public acceptance of potable reuse remains a challenge. Advances are needed to reduce the cost and energy requirements of alternative supply treatment and to develop low-cost, real-time sensors for chemical and microbial contaminants (or reliable surrogates) to ensure water quality and safety.[52] The development of low-maintenance, community-scale water reuse systems with reliable quality assurance would further enhance the use of this technology.[53]

Increasing the Efficiency of Water Use

Important advances have been made over the past few decades to reduce water use. In the United States, total water withdrawals peaked in 1980, largely due to enhanced water use efficiencies from industrial production and power plant cooling,[54] although increased imports and reduced production of water-intensive goods and services, such as fruits and vegetables, may have contributed to this trend.[55] Rates of U.S. water use per person declined 40 percent between 1980 and 2010. Water is still used inefficiently in many regions, especially where it has been plentiful historically or its price has been heavily subsidized, and further advances are possible. Existing and emerging technologies and practices offer numerous opportunities to increase water use efficiency so that existing supplies can better serve the needs of a growing population and global economic growth. Agriculture is the largest water user worldwide and on every continent except Europe (see Figure 1-1). There is substantial potential worldwide for reducing water demand while maintaining or increasing agricultural output,[56] and there is already some evidence that water use efficiency strategies can improve crop quality with little

FIGURE 1-7. Small graphene sensors placed on plant leaves are used to sense water transpiration and measure plant water use so that irrigation is only applied when needed.

cost to yields.[57] Examples of water-saving techniques include farming practices, such as improved crop choice, tillage practices, and soil management, and engineering solutions, including improved precision irrigation tools and advanced ground-based sensors and remote sensing data to gauge irrigation needs more precisely (Figure 1-7).[58] Innovations are needed that enhance agricultural water productivity—the amount of crop produced per unit of water depleted (or crop per drop)—rather than simply reducing water use.[59] Current "inefficient" irrigation approaches may be recharging groundwater and supporting base flow in streams that other water users or ecosystems depend upon.

Outside of the agricultural sector, there are many other opportunities to reduce water use. Technologies to detect and prevent leaks in water distribution systems could reduce loss between the point of supply and point of use. In thermal power plants, alternative systems for cooling, such as dry cooling, could lower water demands. Technological or process improvements can help conserve water in many water-intensive industries, such as textiles, automobile manufacturing, and the beverage industry. Within homes and businesses, innovative technologies such as waterless toilets and washers could reduce water use. Innovative monitoring and communication approaches that help people understand their own water use relative to others could encourage behavioral change. Economic and policy strategies will be important, in addition to technical advances, in managing limited water supplies (see Challenge 5).

Redesigning and Revitalizing Water Distribution Systems

In high-income countries, water treatment and distribution systems developed in the early to mid 20th century led to significant improvements in public health.[60] In many locations, water infrastructure has now outlived its intended useful life, and the limits of that infrastructure are becoming evident. Older distribution system pipes are leaking and require restoration or replacement to ensure water reliability and quality.[61] In the United States, reported cases of Legionnaires' disease, caused by bacteria that can grow and spread in water systems, has increased over fourfold since 2000.[62] Some older distribution systems and many residential plumbing systems in the United States contain lead, which under certain water quality and flow conditions can become mobilized and has put residents at risk for unhealthy exposures.[63] Environmental engineers have a clear role to play in not only revitalizing and replacing these aging systems but reimagining them.

A BIG IDEA: SORTING SOLAR RADIATION TO MAXIMIZE ENERGY, FOOD, AND WATER PRODUCTION

A novel concept proposes to maximize crop production while simultaneously producing electricity and treating water supplies by unbundling the solar spectrum over a plot of land.[66] Reflective parabolic troughs can be situated above the field to collect solar energy from near-infrared and far-infrared light waves, while the solar spectrum needed for food production can pass through to the crops on the ground. The near-infrared light can be used to generate energy and the near- and far-infrared can be used to power water treatment processes through distillation or reverse osmosis. Electricity generated by the solar battery can be used for agricultural production or exported to nearby population centers. As demands for food and clean energy increase with growing populations, creative ideas such as this are needed to develop cost-effective and scalable approaches that maximize energy, food, and water supplies while reducing adverse impacts.

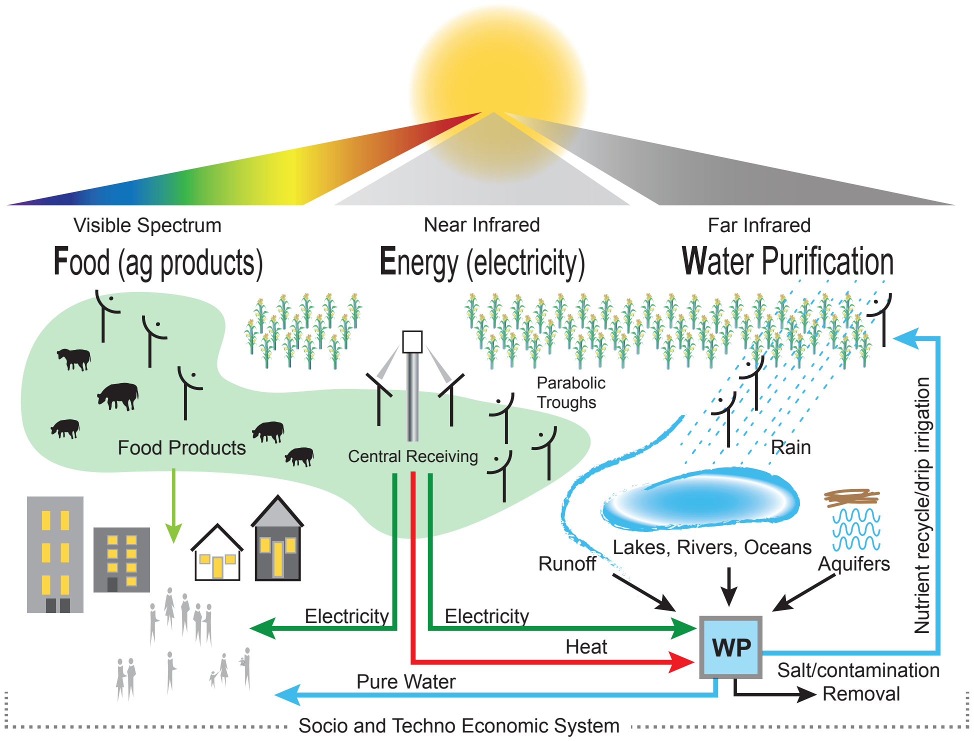

Figure 5: A sustainable use of solar energy on crop/pasture land for harmonious FEW nexus

Figure Concept of a solar spectrum unbundling in which photons are managed efficiently over crop/pasture land to simultaneously produce food, energy and water products | NOTE: WP = Water purification unit.

Low-income countries face a different set of water distribution challenges. In many regions, wastewater is discharged to surface waters without adequate treatment, polluting water bodies and denying people access to safe drinking water.[64] Advances in waterless toilets could improve access to sanitation services in low-income areas while reducing water use and pollution worldwide and enhancing the recovery of valuable resources such as energy and nutrients.[65] Where centralized infrastructure to collect, transport, and treat water and wastewater does not already exist, decentralized wastewater treatment systems using advanced technology for water reuse could enhance water supplies and recover embedded energy.

Providing Clean Energy to Meet Growing Global Demand

Access to energy is increasingly recognized as a basic human need. The UN Sustainable Development Goal 7 is to “ensure access to affordable, reliable, sustainable and modern energy for all” by 2030.[67] Improving the delivery of energy services fuels economic growth, increases productivity, and improves standards of living and health. For example, eliminating the use of unvented cookstoves that burn biomass (such as coal or dung) by supplying electricity for cooking could significantly reduce harmful indoor air pollution.

Global energy needs are expected to increase as the population grows and as more people enter the middle class. The U.S. Energy Information Administration projects that global energy consumption will grow by 28 percent between 2015 and 2040.[68] The warming of the climate is also driving changes in energy demand; it is projected that global energy demand from air conditioners will triple from 2016 to 2050, requiring new electricity capacity equivalent to the electricity capacity of the United States, the European Union, and Japan combined.[69]

Switching to More Sustainable Energy Sources

Petroleum, natural gas, and coal have been the dominant U.S. fuels for more than a century, accounting for about 80 percent of energy consumption in 2017.[70] Globally, fossil fuels also comprised about 80 percent of the primary energy supply in 2015, with nuclear and renewables such as wind, solar, hydropower, biomass, and geothermal power making up the rest.[71] Burning fossil fuels is the primary source of air pollutants as well as the greenhouse gases that drive climate change. Switching to low-carbon sources of energy and increasing energy efficiency will be essential steps to curb climate change,[72] as discussed in detail in Challenge 2.

Environmental impacts accrue not only from burning fossil fuels, but also from their production. Extraction processes, such as coal mining and drilling for oil and gas, generate air and water pollution and other land impacts that can harm local communities. For example, spills occurring during drilling processes or improperly managed mine-waste materials can contaminate surface and groundwater resources.[73] The significant amounts of water needed for unconventional natural gas extraction (hydraulic fracturing) and for cooling processes at fossil fuel electricity plants can stress local water supplies during droughts and heat waves.[74] Transportation of fuels generates additional pollution and accidents resulting in spills.[75] Continued efforts to reduce such impacts will be needed in the transition to low-carbon energy.

There are numerous ways to produce energy while emitting little or no carbon dioxide (CO_2) on an ongoing basis. In particular, solar and wind-based energy sources have gained significant traction. Other promising renewable sources that can be harnessed with minimal CO_2 emissions include hydropower from dams, tapping the energy of waves, and using geothermal energy (tapping into the heat under the Earth's surface).

Environmental impacts, costs, and benefits of renewable energy sources will need to be considered in their adoption. Wind and solar projects occupy significant amounts of land, and most wind power projects on land require service roads that add to the physical effects on the environment (Figure 1-8).[76] Siting of wind power projects atop ridgelines can disrupt scenery and recreational access. Wind turbines can kill bats and birds and harm their habitats,[77] although research on wildlife behavior has led to ways of siting and operating the turbines that help mitigate that harm.[78]

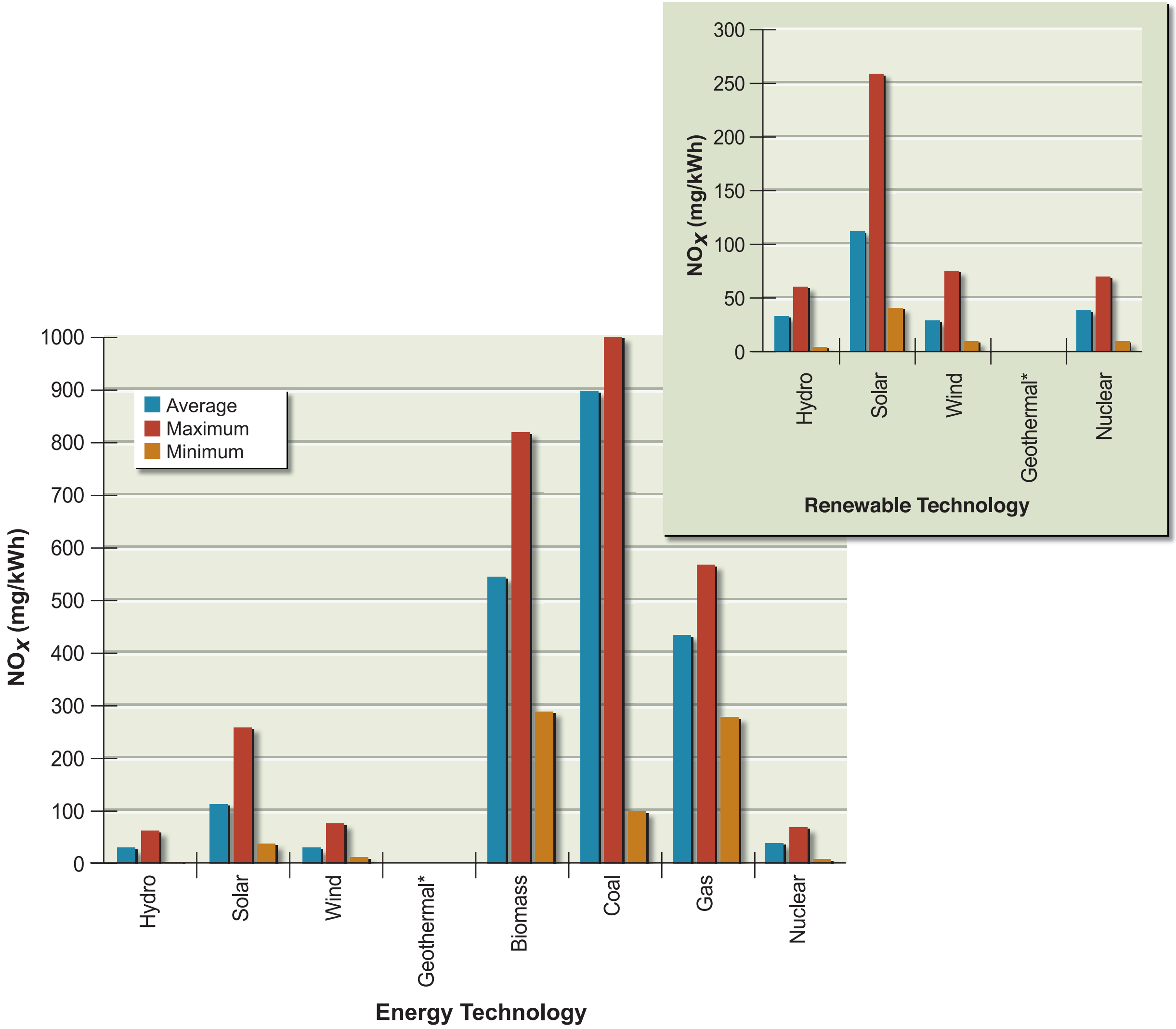

FIGURE 1-8. Life cycle of nitrogen oxide (NOx) emissions (top) and life cycle of land use per kilowatt-hour for various electricity sources (bottom). An important role for environmental engineers will be to compare renewables by conducting life-cycle analyses of all impacts such as land use, water use, and pollution.

Environmental impacts also accrue in the production of renewable energy components, including turbine blades, photovoltaic cells, and electronics, which require energy and materials to produce with associated land, water, and air impacts. Production of some components, such as photovoltaic cells, generate toxic substances that may contaminate land or water resources.[79] Wind turbines may use rare earth minerals, most of which have been mined using processes that result in substantial environmental pollution.[80]

The use of biofuels such as corn-based ethanol for transportation has implications across food, water, and energy systems. Biofuels derived directly from plants, have implications for land and water use and crop prices.[81] Biofuels can also be harvested from algae or produced indirectly from agricultural, commercial, domestic, and/or industrial wastes (see also Challenge 3). In China, over 40 million household-scale anaerobic digesters have been installed that use bacteria to convert plant and animal waste to methane gas.[82] Using anaerobic digestion, environmental engineers have an opportunity to design and create distributed energy systems that also reduce pollution. Analysis of environmental impacts and benefits across the full life cycle of renewable technologies, including the energy return on investment, is a growing role and opportunity for environmental engineers.

Finding Ways to Get Energy Where It Is Needed

Providing energy to the one in seven people who do not yet have it will require decentralized solutions. With declining costs, renewable energy technologies are offering cost-effective alternatives in remote locations compared to centralized systems, replacing traditional energy sources that generate harmful air pollutants, such as diesel generators and biomass burning.[83] Continued advances in transmission and storage as well as further reductions in cost will help provide access to reliable renewable energy supplies.

The use of renewable “microgrids” has emerged as a promising solution to sustainably supply locally-generated electricity to remote regions that are not connected to a conventional power grid. Microgrids can use solar panels, wind, or hydropower to provide cleaner, more cost-effective electricity at a community scale, with generators and battery technology providing backup power when needed. Alaska has been a leader in the development of microgrids, building them on top of the many diesel generators that have served the state’s remote areas since the 1960s. Today, Alaska’s 70 microgrids comprise about 12 percent of renewably powered microgrids in the world.[84] In urban areas, microgrids can provide backup power during natural disasters, such as Hurricane Sandy, which damaged large parts of the power grid in the Northeast.[85] Projects to build microgrids are accelerating across Asia, Latin America, and Africa. For example, the University of Chile is working to extend the 10-hour capacity of a small diesel-powered electrical grid in the Andes Mountains by supplementing it with solar photovoltaic, wind energy, and a battery system.[86]

In low-income countries, the use of microgrids and smaller, stand-alone systems (such as solar home systems) presents a significant opportunity for providing energy to rural populations without centralized power supply. To achieve universal access to energy by 2030, the International Energy Agency estimates that an additional 340 million people in low-income countries would need to be connected to microgrids, with another 110 million using stand-alone energy systems.[87]

Middle- and high-income countries are challenged to incorporate renewables into the operations of the traditional electrical grid, and significant modification of the grid will be needed.[88] Renewable energy is not necessarily generated where it is needed, and unlike fossil fuels, sunshine, wind, and geothermal energy cannot be transported. Therefore, large-scale transmission projects may also be required. For example, most wind power in the United States is generated in low-population High Plains states, which has prompted proposals for large-scale transmission projects to bring this electricity to population centers in the Midwest and eastern parts of the country.

Energy storage is another challenge, given that solar- and wind-driven electricity production is intermittent. When there is too little sun or wind, production can fall short of demand, while an abundance of sun and wind can create too much electricity that has to be used or curtailed to avoid overloading the grid. Ideas being discussed include creating a bigger grid, or “supergrid,” to increase the probability that the sun will be shining or the wind will be blowing in one part of a supply network, if not another.

Many efforts are focused on the development of cost-effective energy storage technologies to smooth out the intermittent nature of solar and wind energy, enabling renewables to provide a much larger percentage of the energy portfolio. Innovation in this realm includes the use of large hydroelectric dams to store electric energy from wind and solar installations in the form of potential energy (see Sidebar). A similar idea is to use electricity during periods of low demand to

USING THE HOOVER DAM FOR ENERGY STORAGE

The growth of solar and wind power is fueling new ideas about how to store excess electrical energy for use when there is not enough solar- and wind-driven energy to meet demand. In 2017, the Los Angeles Department of Water and Power proposed using the Hoover Dam for energy storage to provide greater flexibility and reliability to an electrical grid that is increasingly reliant on renewable energy.[91] Built in the 1930s for flood control, irrigation, and hydroelectric power, the dam sends water stored in Lake Mead through turbines to provide electricity to about 1.3 million people in California, Nevada, and Arizona. From there, the water flows down the Colorado River where it is no longer available to the hydropower plant for making electricity.

The proposed plan is to build a pump station about 20 miles downstream of the dam. Powered by surplus electricity generated by solar and wind energy, the pump would capture river water from the lower Colorado and send it back up to Lake Mead where it can be used to generate electricity when demand exceeds supply. In essence, the process would allow the dam to store solar- and wind-derived electrical energy in the form of potential energy, acting like a giant storage battery.

In general, the relative economic advantage offered by pumped storage at hydroelectric dams makes it the most widely used method for the large-scale storage of electrical energy.[92] However, it is important to weigh all of the benefits and costs when applying that technology to particular hydroelectric dams. Consideration of costs includes the potential ecological impacts associated with water fluctuations in rivers related to the energy storage efforts. What effects would those fluctuations have on the diversity and ecological function of plants and animals in and near the river? In addition, there are potential recreational and aesthetic impacts to humans in the proximity of the pumped storage system. Environmental engineering expertise will be needed to consider the full life-cycle impacts of alternative energy storage solutions.

pump ambient air into a storage container and, when electricity is needed, allow the compressed air to expand to drive turbines.[89] Other promising leads in this vein include mechanical storage with rail or flywheels, and use of excess electricity to create other fuels, such as hydrogen.[90]

What Environmental Engineers Can Do

Environmental engineers bring decades of experience in water treatment and alternative water supply technologies to address challenges ahead related to water scarcity. Environmental engineers have traditionally had less experience in issues of food supply and energy. Nevertheless, opportunities abound for environmental engineers to apply systems thinking (see Box 1-1) to analyze the interrelated behaviors of water, food, and energy systems and their interaction with the environment that supports them. Through systems and life-cycle thinking, engineers can help develop technologies and strategies to sustainably supply food, water, and energy to Earth's growing population (see Box 1-2 for examples).

Addressing this challenge will require convergence of multiple disciplines across behavioral and social sciences, engineering, and science. Environmental engineers can work in collaboration with experts in agriculture, energy, health, ecology, molecular biology, data science, social science, policy, and other disciplines.

BOX 1-1. SYSTEMS THINKING

We now face environmental issues that are global, complex, and interconnected. Environmental engineers are trained to bring a systems-based view to problem solving, allowing for more innovative and appropriate solutions. For example, environmental engineers understand the movement of contaminants between air, water, and land so that they can develop methods to reduce pollution in one sector that do not result in adverse consequences in another. Environmental engineers consider a broad array of issues that often involve systems of systems, such as the vital role and value of ecological services as well as the life cycle impacts and benefits of an engineered system, from its raw materials to end of life.[93]

Although environmental engineers have a long history of thinking about complex environmental systems, there is a need to routinely extend this type of thinking beyond the natural world to encompass broader aspects, such as the regulatory environment, economic drivers, and social behavior. For example, through systems thinking, environmental engineers can also consider the specific needs and perspectives of disadvantaged groups and understand the role of economic incentives and policy instruments to align socioeconomic behavior with environmental goals.[94]

Environmental engineers work on systems that are integrated and complex, including technical aspects as well as social, environmental, and economic facets. These complex systems are difficult to predict in that they are nonlinear, have feedback mechanisms, are adaptive, and have emergent behavior.[95] Only recently has computing power increased sufficiently to enable quantitative evaluations of technological advances in the context of potential changes in underlying social and economic systems.[96] With these tools, environmental engineers can help design solutions that are appropriate, effective, and sustainable.

BOX 1-2. EXAMPLE ROLES FOR ENVIRONMENTAL ENGINEERS TO HELP SUPPLY FOOD, WATER, AND ENERGY FOR EARTH'S GROWING POPULATION

Environmental engineers have many strengths to help address the challenge of supplying clean water and nutritious food to Earth's population in the 21st century. Examples include

Food

- Develop a systems-level "farm to plate" assessment to identify ways to reduce waste, energy, and water consumption and to improve access to healthy food choices.
- Develop precision delivery systems for water, nutrients, and pesticides to minimize impacts on air quality, soil, groundwater, and ecosystems while reducing waste and energy consumption.
- Develop on-site systems to affordably transform agricultural waste into energy.
- Assess the costs and benefits of alternative food sources, such as cultured meat, from human and environmental perspectives.
- Develop aquaculture and aquaponics systems to meet increasing demand for seafood to reduce impacts on ocean supplies with integrated nutrient recovery and reuse to minimize adverse effects on the environment.
- Design urban agriculture systems to utilize waste energy and recycle water, minimizing water use and pollution.

Water and Sanitation

- Considering the full spectrum of human development conditions, develop energy-efficient water conservation strategies and technologies that are socially acceptable and implementable.
- Develop low-cost desalination and water reuse technologies, including strategies to reduce energy use and manage or reuse waste streams to minimize environmental impacts.
- Develop water supply and water quality forecasting tools, including low-cost, distributed sensing systems, to anticipate water availability and quality threats.
- Develop and evaluate energy-neutral or energy-positive cost-effective wastewater treatment technologies suitable for low-, middle-, and high-income settings that provide enhanced contaminant removal, minimize energy consumption, and promote safe water reuse.
- Participate in innovative interdisciplinary teams to develop and evaluate approaches to water, sanitation, and hygiene challenges in low-income countries.
- Develop improved diagnostic tools and predictive modeling approaches to understand the state of aging water infrastructure and develop cost-effective strategies to maintain the water services provided by existing infrastructure.

Energy

- Conduct life-cycle analyses of renewable technologies and distribution strategies in terms of benefits provided and water and energy use and pollution, including all stages. Develop approaches to minimize those impacts.
- Investigate approaches to store energy, such as with hydroelectric dams or batteries, and examine associated environmental impacts and ways to minimize those impacts.
- Develop low-cost ways to reduce environmental impacts associated with traditional energy production.
- Develop viable, sustainable biofuel options.