INL/RPT-22-65043-Revision-1

What can we learn from decarbonization of the energy sector?

April 2022

Changing the World's Energy Future

Seth W Snyder, A.J. Simon

Idaho National Laboratory

INL/RPT-22-65043-Revision-1

What can we learn from decarbonization of the energy sector?

Seth W Snyder, A.J. Simon

April 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

doi: 10.2166/9781789061796

Chapter 2

What can we learn from decarbonization of the energy sector?

A. J. Simon[1]* and Seth W. Snyder[2,3]

[1]Lawrence Livermore National Laboratory, Livermore, CA, USA
[2]Idaho National Laboratory, Idaho Falls, ID, USA
[3]Northwestern University, Evanston, IL, USA
*Correspondence: simon19@llnl.gov

2.1 INTRODUCTION: ENERGY AND WATER: SIMILARITIES, DIFFERENCES, AND A COMPLEX RELATIONSHIP

Decarbonizing water and wastewater treatment is an enormous challenge, but it is substantially smaller, in total carbon emissions, than decarbonizing the energy sector. When planning, executing, and assessing strategies for decarbonizing the water sector, water experts should partner with the energy sector and heed that sector's lessons-learned in its ongoing process of decarbonization. In the energy sector, decarbonization pathways can be as simple as a supply-side technology that converts fuel to electricity more efficiently, reducing net carbon emissions for every kilowatt-hour generated. The pathways can be much more complex, however, as is the case with the demand-side reordering of behavior as seen with online shopping or working from home during a public health crisis. Both of those pathways reduce demand for private-vehicle fuel and shift some work, and associated carbon emissions, to other parts of the economy. This chapter explores decarbonization pathways that have been followed by the energy sector and assesses their applicability to the water sector.

Energy and water are two infrastructure sectors that are coupled in multiple ways. This chapter is not intended to quantitatively assess the opportunities for energy and water to contribute to each others' decarbonization. For a full understanding of issues and opportunities at the 'energy-water nexus', the reader is advised to review the literature (DOE, 2014; EPRI, 2013; Gleick, 1994; Greenberg *et al.*, 2017; Grubert & Sanders, 2018). The most important concepts that frame the decarbonization opportunities are as follows:

- Water and wastewater treatment are generally consumers of energy for aeration, pumping and heating. That energy use is associated with the carbon emissions that result from electricity production or onsite usage of natural gas. Energy sector decarbonization can contribute to decarbonization of the water sector.
- Wastewater is a carrier of carbon, most of which is oxidized to CO_2 during wastewater treatment or in the environment after it is discharged. Intercepting and permanently immobilizing this carbon is a major opportunity for the water sector to reduce its gross emissions.

- Anaerobic digestion of wastewater fractionates the embedded carbon into methane and CO_2. Methane has a radiative forcing factor 28 times greater than CO_2 over 100 years (and 86 times greater over 20 years), resulting in substantial short-term climate impacts if the methane is not captured and combusted (Roy *et al.*, 2015).
- Innovations at the unit process level are the most straightforward way to manage the carbon intensity of the water sector.
- Structural change in the water economy (more efficient water use, potable and non-potable reuse, etc.) may also affect the sector's carbon intensity.

2.1.1 The energy-water nexus

The energy-water nexus refers to the coupling between the energy and water sectors. The water sector requires a significant amount of energy to operate and presents opportunities for energy recovery and electricity generation. Similarly, the energy sector requires significant amounts of water to operate, and also presents opportunities for water treatment and delivery. At the energy-water nexus, changes to one sector may affect the economic and environmental sustainability of the other. Modern water systems use exogenous energy to acquire, convey, purify, distribute, collect, treat, and dispose of water. To the extent that this exogenous energy is electric (power for pumps and blowers), the carbon intensity of the water system is coupled to the carbon intensity of electricity supply. Decarbonization of the electricity supply is already underway as coal-fired electricity generation is being replaced by natural gas (which has roughly one-half the carbon intensity as coal), and as more electricity is generated from non-fuel resources such as solar and wind.

A more thorough accounting of the challenges and opportunities at the energy-water nexus is available in the literature (see above, including works cited in those references), and some of the major interactions are briefly summarized here:

- Water acquisition, treatment and distribution requires electricity for pumping. This is true for municipal, industrial and irrigation water supply. The chemicals used in water treatment are also energy intensive to produce.
- Wastewater treatment requires electricity for aeration blowers and for pumping. WWTPs in some climates also require natural gas or other fuels for heating of anaerobic digesters.
- Energy is used for water heating in commercial, industrial and residential applications.
- Energy can be recovered from wastewater in the form of biogas, electricity from biogas, or electricity from incinerable biosolids. Indirectly, energy can be displaced by replacing chemical fertilizers with biosolids.
- Electricity production in thermoelectric plants (nuclear, natural gas, and coal) require water for cooling and for emissions controls.
- Hydroelectricity is produced from water resources and impacts other economic uses and environmental services.
- Production of biofuels may require water for irrigation of energy crops and in conversion of feedstocks to fuels.
- Production of oil and gas may require water for hydraulic fracturing, and often results in a surplus of produced water. Depending on the source and the quality, produced water may require energy for treatment and disposal, or may be treated for beneficial use.

In the future, additional energy may be required for seawater and brackish water desalination and other advanced water treatment. Removal and destruction of contaminants of emerging concern (CECs), including but not limited to per- and polyfluoroalkyl substances (PFAS), could significantly increase the energy required to treat water. Requirements could affect a range of applications including municipal and industrial wastewater treatment, stormwater management, and groundwater cleanup. Additional water may be required for carbon dioxide capture and sequestration from electricity generation and low carbon fuel production. However, a full accounting of energy and water interdependency is beyond the scope of this book.

2.1.2 Differences in scale

The extent to which decarbonization strategies and tactics from the energy system can be adapted to water depends on the similarities, differences, and interdependencies of these two critical infrastructure systems. The lessons learned from the ongoing decarbonization of the energy sector are framed in terms of total system scale, resource substitution, emissions control, quality of service, and sustainability policy. In this chapter, the United States markets for water, energy, and other commodities are used for these framing studies because the US is the largest single country for which well documented energy and water statistics are readily available. Similar lessons will apply to most developed economies, and those lessons can be extended and adapted globally.

As measured by annual use, water is the largest infrastructure/commodity sector in the US by more than a factor of 20. Table 2.1 compares water use to other major energy, agricultural, and material sectors on annualized mass and volume scales. It is important to note that the scale of water infrastructure is ONLY for public water supply (municipal water treatment plants) and that adding wastewater treatment would approximately double that figure. Total water use (including for irrigation, powerplant cooling and other non-municipal uses) is a factor of 10 larger (in the order of 500 000 million metric tons per year)!

From these statistics it is clear that water, as a system, is singular in scale. Society processes water at a flow rate that is orders of magnitude larger than any other commodity, and requires physical infrastructure vastly greater than energy or every other commodity. Decarbonization challenges that scale with flow rate, such as the capital cost of processing systems, will tend to be larger for water than they are for other sectors.

Although the gross material flow through water systems is larger than it is through energy systems, the carbon emissions associated with water and wastewater treatment are smaller than they are for the energy system. In addition, the incremental economic value of each unit of water is significantly smaller than energy or products, reducing the potential revenue available to manage carbon. Chapter 3 of this book introduces a framework for carbon accounting in the urban water cycle. Here we estimate that municipal water and wastewater treatment in the US are responsible for 61 million metric tons (MMT) of CO_2-equivalent greenhouse gas emissions annually. Of that total, 38 MMT (CO_2-e) are associated with methane and nitrous oxide emissions from municipal wastewater treatment and discharge (EPA, 2021). The remaining 23 MMT result from the generation of the ~59 million megawatt hours (MWh)

Table 2.1 Annual flows of widely used material commodities in the US.

Commodity	Mass Flow (million metric tons per year)	Volumetric Flow (million cubic meters per year)	Notes
Water (Dieter *et al.*, 2018)	53 880	53 880	Deliveries from municipal water treatment plants only
Aggregates (USGS, 2021)	2538	1586	Total US consumption of crushed stone, sand, and gravel
Petroleum (EIA, 2021)	895	1133	Total US consumption incl. net imports
Coal (EIA, 2021)	724	804	Total US consumption, excl. exports
Natural gas (EIA, 2021)	607	771 400	Vol. flow calculated at standard temperature and pressure; actual vol. flow is much less because gas lines are pressurized
Corn (USDA, 2021a)	340	479	Total US production
Steel (USGS, 2021)	100	13	Total apparent US consumption including imports which account for ~20%
Wheat (USDA, 2021b)	51	66	Total US production, including exports which account for ~50% of production

of electricity consumed by water and wastewater treatment plants in the US (Greenberg *et al.*, 2017). It is likely that additional GHG emissions are attributable to the water and wastewater treatment sector from onsite natural gas combustion, however no data could be found to quantify this emissions source. Offsite manufacturing of chemicals used for water and wastewater treatment have also been hypothesized to contribute significantly to the sector's life cycle GHG footprint, but estimates of this quantity in the literature vary widely (Kyung *et al.*, 2015; Szulc *et al.*, 2021).

Combustion of fossil fuel across the entire energy sector in the US emits 5300 MMT of CO_2. These two statistics are not directly comparable; the 61 MMT CO_2-e associated with the water sector accounts for CO_2 and other GHGs from scopes 1, 2, and 3 for a specific sector while the 5300 MMT CO_2 in the energy sector accounts for only fossil-fuel derived CO_2. Additionally, scope 2 emissions from water treatment (~23 MMT) are *included* in the 5300 MMT of fossil fuel-derived emissions from the energy sector. However, the vast disparity in scale between these two figures demonstrates that despite managing a far larger quantity of material, the water sector manages a far smaller quantity of carbon. This overlap between water sector GHG emissions and energy sector GHG emissions is a telltale of the Energy-Water Nexus described above.

2.1.3 The carbon-water nexus

Much of the attention on decarbonization focuses on the elimination of carbon dioxide emissions from fossil fuel use in the electric generation, transportation and industrial sectors. The water sector's GHG emissions are a combination of emissions from those sectors (scope 2 emissions), non-CO_2 GHG's from conversion of organic material in wastewater, and the CO_2 product of organic material present in the wastewater itself. Although most of the carbon in wastewater is biogenic in nature (derived recently from atmospheric carbon) it is instructive to consider the total flow of water-borne carbon through wastewater systems. Assuming a chemical oxygen demand (COD) of 350 mg/liter, and that organic matter (CH_2O) represents the bulk of this load, there is approximately 11 mmol carbon per liter of wastewater. Assuming that 32 000 million gallons of wastewater are treated per day in the United States, there are 5.8 MMT per year of carbon passing through wastewater treatment plants with the potential to produce 21.3 MMT of CO_2 emissions from in-plant processes as well as oxidation of biosolids, biogas and remaining BOD/COD in effluents.

Both the energy and water sectors are, in the terminology of the US Department of Homeland Security, 'National Critical Functions' (DHS, 2021), and both move material from the environment to engineered systems, and subsequently back to the environment. However, there are substantial differences. A relatively small amount of energy moves a very large quantity of water, and that water carries with it a small amount of organic carbon. Water resources are acquired from surface or groundwater reservoirs, and water is returned to the surface as impaired or treated water. In the case of energy, diverse resources are drawn from the environment and today's energy systems depend significantly on chemical fossil energy in underground reservoirs of coal, oil and natural gas. Engineered systems separate energy from carbon, delivering services and returning the associated carbon to the environment, most frequently as CO_2 emitted to the atmosphere. The remainder of this chapter will focus on decarbonization trends in the energy system, and how those trends can benefit the decarbonization of the water system through the energy water nexus and through shared technologies, best practices and lessons learned.

2.2 DECARBONIZATION OF THE ENERGY SECTOR

In 2020, the carbon intensity of the energy sector was declining at a rate of approximately 1% per year. Although this pace seems slow, and is certainly not fast enough to reach the emissions targets that climate science indicates are necessary, it represents a substantial change from the prior era. Over the 28-year period from 1977 to 2005, the carbon intensity of energy use barely changed at all, declining from 58.3 to 56.6 million metric tons of CO_2 per exajoule (MMT/EJ), a rate of 0.1% per year. During the 12 years between 2005 and 2017, carbon intensity declined from 56.6 to 49.9 MMT/EJ, a rate of 1% per year (EIA, 2021) (each of these statistics takes the five-year average carbon intensity of energy around the reported year to smooth out noise in the statistics – looking at individual years, it appears that the 2005–2017 trend continued through at least 2019 and was likely accelerating). This ten-fold increase in the pace of decarbonization is due to the following changes in the energy system (listed in order of size of carbon intensity impact):

- a substantial shift from coal to gas in the electricity generation sector;
- substantial increases in electricity generation from wind and solar resources;
- increases in overall vehicle efficiency and the percentage of biofuels consumed in the transportation sector.

In addition to the decrease in the carbon intensity of delivered energy, the energy intensity of the US economy has declined. In real GDP terms (all values quoted in 2012 dollars), the US consumed 13.1 exajoules per trillion dollars (EJ/$T) of economic activity in 1978, 7.1 EJ/$T in 2005 and 5.7 EJ/$T in 2017 (US Bureau of Economic Analysis, 2021). The decline rate of the energy intensity of the economy has been a steady 1.6% per year over that entire time frame. The decreasing energy intensity of the overall economy is due to the following factors:

- structural changes in the economy that favor lower energy intensity commercial activity such as financial and computing/data-driven services over higher energy intensity industrial activity such as iron and steel making;
- improvements in energy efficiency that deliver equivalent economic service for smaller energy inputs such as:
  - improved heavy- and light-duty vehicle fuel efficiency;
  - improved insulation in residential and commercial buildings;
  - efficient devices and appliances such as LED lighting.

Figure 2.1 shows these trends graphically. Despite nearly 300% growth in real GDP (2012 dollars) from ~5.6 $T in 1975 to 19.1 $T in 2019, energy use grew only 40% over that period due to decreased energy intensity, and carbon emissions have begun to decline from their 2005 peak due to both decreased energy and carbon intensity.

There are multiple interrelated factors behind these trends including energy policy that incentivizes sustainable energy use, the cost savings due to energy efficiency in many applications, innovation in energy technology that improves efficiency and reduces emissions, and consumer preference for more sustainable solutions. The remainder of this chapter examines some of these factors and provides examples.

These trends are likely to accelerate into the future. In addition to continued expansion of the lower-emitting and higher efficiency technologies listed above, the following trends and technologies are beginning to roll out at scale in US energy markets. Their impact on overall energy consumption and emissions, while not yet significant, will likely become visible in economy-wide statistics by 2025:

- remote working options (reduced local commuting and long-distance business travel, permanent change initiated by 2020 pandemic);
- growth in online ordering or 'e-commerce' grew steadily over a decade and grew rapidly during the pandemic, dramatically reducing the number of short-distance trips (DOE, 2020);
- electric vehicles (passenger cars and delivery vans);
- high efficiency electric heating (heat pumps).

Further drastic improvements in the energy efficiency and carbon intensity of economic activity are possible with energy technologies that are technically feasible and have been demonstrated at scale, but have not yet achieved performance and/or cost parity with competing technologies. Demand for

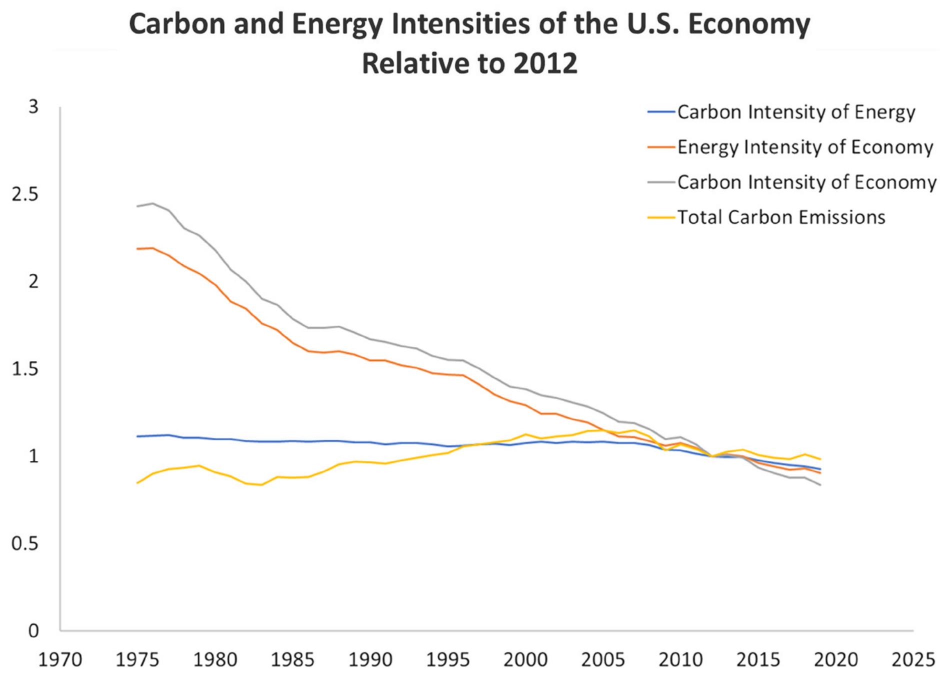

Figure 2.1 Carbon intensity of energy, energy intensity of the economy, carbon intensity of the economy, and economy-wide carbon emissions relative to 2012 for the United States.

these technologies may increase substantially if certain policies are put in place or if a price on carbon emissions is enacted:

- electricity generation with carbon capture and sequestration;
- hydrogen as a transportation fuel, heating fuel, or chemical process input;
- small modular nuclear reactors;
- biomass-derived energy (ethanol, other liquids, biogas, hydrogen or electricity) with carbon capture and sequestration of process emissions.

Europe and some Asian economies have lower energy intensity than the US with similarly advanced economies. While China lags the US and Europe in energy intensity, it is improving far more rapidly. Economic energy intensity is far higher in the developing world, but total and per capita energy use is dwarfed by the advanced economies.

2.3 A FRAMEWORK FOR SUSTAINABILITY FOR ENERGY AND WATER

Energy, water supply, and wastewater management are foundational needs for a modern society. However, unfettered energy and water use are unsustainable due to supply constraints and/or environmental impacts. Here, we introduce a framework, depicted graphically in Figure 2.2, to organize the events, behaviors, and technological advancements that enhance sustainability. This framework applies to both energy and water services. While the framework is roughly hierarchical, with categories listed from least to most effective, there are not strict delineations between each category. Advances in sustainability may be motivated by resource constraints and environmental preservation (left half), and success is achieved through innovation and other 'highly sustainable'

Figure 2.2 A framework to qualitatively assess the drivers of sustainability in energy and water systems, with the least meritorious on the left and most meritorious on the right.

practices (right half). The effectiveness of any specific energy/water intervention depends on both the state of technology and of existing infrastructure. Stressors, behavior changes, technology advancements, and the evolution of energy/water systems do not evolve linearly along this spectrum. The histories of modernization and decarbonization include iterative loops and multi-step hops.

Examples for each of these categories are given in Table 2.2, illustrating the broad applicability of this framework. Lessons learned from both successful and unsuccessful efforts to decarbonize energy may be extended to inform the decarbonization of the water industry.

2.4 THE PACE OF DECARBONIZATION

Frugality and conservation measures reduce emissions in the short term by reducing demand for services associated with energy and water use. Over the long term, however, the demand continues to grow for the services that energy and water provide. Therefore, emissions from these sectors are controlled by the efficiency and emissions of the capital equipment that transforms resources into services. The pace of decarbonization is almost entirely determined by the rate of capital stock turnover. Emissions associated with a piece of equipment in an energy or water system will persist throughout the useful life of that equipment. Capital turnover is the expected time for replacement of energy related devices, facilities, and infrastructure. This time period depends on the functional life of the systems and the relative value of potential replacements. As illustrated above, the replacement value can be increased by innovation (better service), efficiency (lower energy consumption), substitution (lower costs of alternative inputs), and mitigation (better environmental footprint). Technology developments and policy incentives can accelerate decarbonization by increasing the value of replacement, but the capital cost of a system and its anticipated remaining useful lifetime have major, if not dominant, impacts on the overall pace.

Table 2.2 Historical examples from each part of the sustainability framework that have alleviated the impacts of energy and water use, demonstrating the adverse consequences of deprivation and benefits of innovation.

Energy Deprivation – Forced reduction in energy services and quality of life
Fuel Rationing: During the 1970s US Energy Crisis, international political tensions caused a sudden constriction on oil imports and an attendant price spike for the fuels used in transportation and electricity generation. There were long lines at gas stations and periods of fuel unavailability
Rolling Blackouts: In the early 2000s, California experienced an electricity crisis. Flawed regulations and market design for electricity allowed market manipulators to constrict supply and drive up prices. Power was turned off in some regions to alleviate the shortages
Water Deprivation – Forced reduction in agriculture and/or sanitation
Millennium Drought: Australia's agricultural output crashed because not enough water was available to irrigate in several regions. While famine was avoided due to a resilient global food network, farmers livelihoods were destroyed and global prices increased
Day Zero: In 2018, the city of Cape Town, South Africa declared major water use restrictions after an extreme drought led to reservoir levels dropping dangerously low. This severe water rationing led to job losses (especially among already low wage workers), food price hikes, and loss of tourism income. The city was forced to plan for the forced shutdown of municipal water supplies and distribution of bottled water, which would have resulted in major quality-of-life disruptions for all residents
Energy Frugality – Voluntary reductions in quality of life associated with energy services
Compact car: Choosing a smaller vehicle affords the purchaser less passenger room and (usually) fewer amenities. These reductions in service are compensated by lower fuel expenses, and are accompanied by lower emissions and other environmental impacts
Thermostat settings: Lower setpoint temperature (in winter) trades lower fuel expenses and carbon emissions for reduced comfort
Water Frugality – Voluntary reductions in the quality of life associated with abundant water
Landscape irrigation: Letting a lawn/field go brown by reducing/foregoing irrigation during water shortages lowers water bills and imparts a sense of 'doing one's part.' However, it impacts residential aesthetics and outdoor comfort. Lower water use reduces the energy and carbon emissions associated with treating irrigation water
Let it mellow: Choosing to forego flushing after urination reduces water use, thereby reducing energy and associated emissions from water supply and treatment. However, it incurs odor and may reduce the appearance of appropriate sanitation
Energy Conservation – Deliberate action to reduce energy waste
Turning off lights: Motion sensors, timers, and/or constant vigilance that disables lighting when not in use trades lower energy use and associated emissions for a small investment in controls and/or minor inconvenience
Engine start/stop: Systems that automatically turn off vehicle engines trade the benefit of fuel savings and reduced idling pollution for higher-cost starting equipment and emissions controls
Water Conservation – Deliberate action to reduce water waste
Fixing leaks: Leaks in underground infrastructure can be invisible, and even small leaks such as dripping faucets can substantially increase water consumption in a single residence. Remediation requires vigilance and (sometimes) costly intervention, and results in reduced water costs for the consumer as well as energy/GHG savings at the point of treatment
Low-flow fixtures and appliances: Toilets, faucets, dishwashers and other appliances can be designed to deliver the same sanitation benefits while reducing the amount of water bypassed during use. This reduces overall water consumption and energy for supply and wastewater treatment. Some water conserving equipment provides identical services to the consumer, while others deliver reduced comfort or convenience
Energy Mitigation – Costs incurred to reduce the environmental impact of energy use
Carbon capture and sequestration: Carbon dioxide generated from fossil energy use can be separated at the exhaust stack, pressurized, and re-injected into the subsurface. This process requires costly equipment and reduces overall energy efficiency, but it can mitigate 90% of greenhouse gas emissions at some facilities

(*continued*)

Table 2.2 Historical examples from each part of the sustainability framework that have alleviated the impacts of energy and water use, demonstrating the adverse consequences of deprivation and benefits of innovation (*Continued*).

Landfill gas recovery: Interception and recovery of methane from organic decay in landfills avoids high GWP emissions. Conversion of landfill gas to electricity has a small side benefit of avoiding some fossil fuel use
Water Mitigation – Investments to reduce the emissions associated with wastewater treatment
Anaerobic digestion: Organic material is digested in a bio-reactor, producing streams of biogas and less energetic sludge. The cost of installing and operating AD results in a useful energy product which may offset fossil fuel use and lower environmental impacts from organic discharge
Energy Substitution – Use of an alternate resource with potential cost or reliability impacts
Cleaner fuels: Natural gas replaces coal in electricity generation, resulting in lower CO_2 emissions per unit electricity. When the price of natural gas per unit energy became comparable to coal, there was little reason not to switch
Renewable electricity: Electricity from solar panels and wind turbines can displace fossil-fired generation. Solar energy trades higher capital cost and inherent intermittency for zero fuel cost and no carbon emissions
Water Substitution – Alternate resource or technology which may drive system reconfiguration
Non-potable reuse: Purple pipe systems deliver tertiary-treated wastewater to irrigation and some industrial/cooling applications. This reduces the demand for freshwater supply, and may offset the energy used for pumping and treatment of potable water
Ultraviolet disinfection: UV light can be substituted for the chlorine that is used to kill pathogens in water supply or recycled wastewater. UV does not require chemical delivery or dosing equipment and avoids the creation of disinfection byproducts. However, UV reactors incur significant upfront cost and ongoing energy costs.
Energy Efficiency – Technological increase in services provided from equivalent resources
Aerodynamics: Refinements in vehicle shape reduce drag, enabling cars and trucks to go substantially farther on the same amount of fuel with the same weight and volume of passenger/cargo capacity
Heat recuperation: Power generation and many industrial processes transfer thermal energy from exhaust to intake. This process requires costly heat exchange equipment and results in substantial energy savings and therefore emissions reduction
Variable speed drives: Novel electronics enable the motors that drive compressors and pumps to operate at lower speeds (and therefore power) without loss in efficiency. This saves substantial energy during periods when aeration or pumping needs are low
Water Efficiency – Increase in the benefits per unit water delivered
Drip irrigation: Replacing broadcast with drip irrigation drastically reduces the water lost to evaporation and percolation, thereby reducing pumping and treatment requirements (and associated energy and emissions) for water supply. However, drip systems are more costly to install and maintain
Energy Innovation – Delivers a better energy service for fewer resources consumed
LED lighting: New diode and phosphor materials enable drastically lower energy use at the same (or better) quality and intensity of light, with longer life and lower heat generation
Hybrid and electric vehicles: Higher energy density and more durable batteries enable regenerative braking and electric fueling, thereby increasing efficiency and reducing emissions. Electric cars are quieter and eliminate local pollution. They accelerate and handle better than comparable conventional vehicles, and can sometimes be fueled at home
Water Innovation – Delivers better treatment for less energy/material input
Membrane aerobic bioreactors: New materials and tube configurations enable oxygen delivery for organic deconstruction in wastewater at much lower pumping energy than traditional aeration, thereby reducing emissions

Water and energy investments exhibit a wide range of capital turnover rates. Capital turnover for both water and energy equipment tends to be fastest in the residential and commercial end-use sectors. Turnover of transportation equipment is slower. The large capital intensity of equipment in the industrial and utility sectors tends to drive the slowest turnover rates. Energy and water distribution and collection infrastructure is also designed for long service life and therefore very slow to change.

2.4.1 Residential and commercial equipment

Capital turnover in the residential and commercial sectors falls into three general categories. With ‘devices’ such as lightbulbs, electronics, and small appliances, replacement timelines are on the order of five years. They may be upgraded on the basis of consumer preference. Consumers often choose devices with state-of-the-art efficiency at the time of purchase. Energy- and water-consuming ‘major appliances’ such as furnaces, water heaters, air conditioners, and refrigerators have service lives of approximately 20 years. They are typically replaced upon failure. There have been federal and state-level incentives to improve efficiency. These incentives are effective in influencing consumers to choose higher efficiency devices when replacement is needed, but they only accelerate the decision to replace inefficient devices before end-of-life among affluent consumer groups. The ‘dwelling’ itself is a family’s largest expense (as rent or a capital purchase). Housing capital stock turnover is typically measured in lifetimes and is difficult to assess for decarbonization. Major changes to electrical, fuel, and plumbing systems are seldom undertaken with sustainability as the primary motivation. An exception to this is the addition of solar energy, which is becoming more common as prices have dropped and innovative financing models have become widespread.

2.4.2 Transportation equipment

After housing, the largest capital investments for most Americans are personal vehicles. Vehicle energy use and carbon emissions are subjected to several sensitivities. Consumers typically make decisions based on current market conditions, that is the price of fuel at the pump, and not on total cost of ownership. Therefore, when fuel prices are higher, consumers tend to purchase more efficient, and therefore lower carbon-emitting vehicles, and when the price of fuel is low, consumers tend to purchase significantly less efficient vehicles. As vehicle manufacturing technology has improved, vehicle service life has extended, and is approaching 15 years. From a life cycle consideration, the long life of the vehicle avoids energy consumption and carbon emissions from the manufacturing process. It also retards widescale deployment of more efficient technologies.

Electrification of transportation is projected to have one of the largest impacts on economy-wide carbon emissions. With a low-carbon power generation, battery electric vehicles (EVs) offer a strong pathway to decarbonization. However, the impact of more durable conventional vehicles being sold today is that their extended service lives will contribute to long-term carbon emissions. Several vehicle manufacturers have announced plans to only manufacture EVs by 2035. With the capital turnover of about 15 years, this suggests that we will still have emissions from internal combustion engines out to 2050. This is the time frame that most advanced economies are targeting for net carbon zero. Therefore, there is limited room for delays in electrification.

2.4.3 Utility equipment

As with water, capital turnover at the energy utility scale can be very slow. As an extreme example, the BP petroleum refinery in Whiting Indiana was originally built in 1889 by Standard Oil and is still the largest petroleum refinery in the US. Most relevant to decarbonization is capital turnover in the power sector. Utility scale (100’s of MW to GW) thermoelectric power plants served as the base for most of the power sector. Coal, nuclear, and more recently natural gas plants, are depreciated over a decade or more but continued to be used for 50 years. Depreciated capital offers operational advantage to older plants. With a decline in coal on a global scale, driven by societies demand for improvements in air quality, coal power has been declining well before drives for decarbonization became prevalent. The US has retired almost half of its coal power capacity over the past decade, declining from a more than 60% of total capacity to about 20%. Some utilities are looking to leverage coal power plant infrastructure and retrofit coal plants with cleaner energy sources. As with coal, operational nuclear power plants have almost all completed depreciated. With carbon-free emissions, there are strong incentives to maintain the nuclear fleet. The challenge is to remain profitable in a market where nuclear plants operate with constant output while demand and pricing are dynamic due to growth in wind and solar generation. There has not been a new plant commissioned since the partial meltdown of the Three Mile Island plant in 1979. There is one nuclear power facility under construction in Georgia.

In comparison to the 50+ year capital turnover for thermoelectric power plants, renewable plants tend to be both more distributed and have higher capital turnover rates. Wind turbines and solar photovoltaic (PV) facilities are projected to have a lifetime of about 20 years. This is based on facilities commissioned in the 1970s and 1980s that reached the end of their useful life in the 1990s and early 2000s. New wind turbines have nameplate capacities of 1–3 MW (rather than 10 s to 100 s of MW for gas/thermal turbines), and new wind farms have total capacities of 10 s to 100 s of MW. Individual solar panels have nameplate capacities in the 100 s of watts, making solar plant design and installation extremely modular. With the ability to add capacity incrementally, wind and solar generation have been growing steadily, and this trend is expected to continue. In comparison to wind and solar, capital turnover in hydropower can be extremely long. Century-old hydropower plants are still in operation. Dam-based hydropower plants can significantly disrupt wildlife, for example fish spawning. Recent investments in hydropower have replaced dams with 'run of the river' systems to address society demand and environmental regulations.

2.4.4 Integration

Capital turnover in the energy sector may present some unique challenges. For example, decisions on vehicle electrification are expected to have a strong impact on both liquid fuels production and power generation. A large increase in electricity demand for vehicles may trigger a new wave of capital expenditures in the electric sector, and/or a major change in the operation of existing generation and transmission assets. Similarly, a large drop in liquid fuel consumption will cause significant disruptions to gasoline and ethanol markets (see section 2.5.3). There are not similar 'fuel switching' capital replacement options for water consumers.

2.5 CASE STUDIES

2.5.1 Energy efficient lighting

The penetration of energy efficient lighting into the market in the years between 2010 and 2020 was an enormous success for new technology adoption. In the space of approximately ten years, the energy intensity of lighting in the residential sector dropped by 75–88% (a $\sim 5\times$ increase in energy efficiency), saving approximately 500 petajoules of energy per year in the United States. With an average carbon intensity of 450 gCO_2/kWh, this change resulted in an emissions reduction from the electricity sector of 62.5 million tons of CO_2 per year. Light emitting diodes (LEDs) replaced incandescent lights not only because they are more energy efficient, but because they are longer lasting (requiring less maintenance by the user and saving money on new bulbs over the long term) and because they provide a better lighting service with a choice of 'color temperatures' that appeal to many different consumers.

It had long been known that incandescent light bulbs were extremely inefficient. Approximately 3% of the electricity consumed by an incandescent bulb is radiated as visible light. The remainder is emitted as heat. This fact indicates that the same service could be accomplished with far less electricity if a new technology were used. Additionally, the excess heat given off by incandescent bulbs increases the load on air conditioning systems in warm climates, further increasing energy demand.

The transition to energy efficient lighting was not without challenges though. Compact fluorescent lamps (CFLs), an earlier generation of energy efficient lighting technology, failed to attain consumer acceptance. CFLs were nearly as efficient as LEDs, saving 70–80% of lighting electricity over their incandescent predecessors. However, CFLs were disliked by consumers because the quality of the light they produced was inferior. CFL light had a high color temperature (bluish tint) and many users perceived a flickering nature to it. CFLs were advertised as having much longer lives than incandescents, but they burned out earlier than predicted. The failure of CFLs in the marketplace is proof that consumers may be unwilling to trade quality of service for energy savings, even if there is a comparable quantity of service and modest cost savings over the long term. Policy initiatives that supported the transition to more efficient lighting (efficiency standards and incandescent 'bulb bans') were met with fierce opposition when the only viable alternative to incandescent bulbs was CFL.

Government research institutions and private industry committed significant resources to developing LED technology. Some of these investments were based on evidence that LED would ultimately be a better technology. Some were responsive to consumer demand created by the policy incentives described above. Today, it is nearly unthinkable to purchase incandescent lighting in the residential sector for anything but the most niche applications. Manufacturing know-how has advanced so that LED bulbs can be produced to meet the demands of almost any application and form factor.

2.5.2 Electric vehicles

Adoption of electric vehicles (EVs) represents a sea change in transportation that is starting to transform societal energy use and carbon emissions. Battery technology, which had been stagnant for decades, began to change dramatically in the 1970s, first with discovery science and then with scaled-up manufacturing. Nickel metal hydride chemistry was quickly surpassed by lithium-ion technology in the early 2000s. Improving battery technology has impacted a broad range of market sectors. Compared to other battery chemistries, lithium-ion batteries offer flexibility in recharging, much higher energy density (energy per unit mass or unit volume), and much higher power density (higher current at the same voltage). Li-ion technology transformed the small electronics sector, ironically creating an increase in energy demand. While limited range vehicles such as golf carts could operate with traditional rechargeable lead-acid batteries as the primary energy source, longer range road vehicles were beyond the range of available at existing energy capacity. Li-ion offered the potential for long ranges in vehicles suitable for the roadway.

While some early vehicles in the 19th century were electric, they faded from favor in comparison to the significantly higher power and energy density of internal combustion engines (ICEs) of that era. At the dawn of the 21st century, the first broadly commercialized battery technology for 'electrifying' mobility were launched using hybrid vehicles such as the Toyota Prius. The Prius employed both a traditional ICE operating on liquid fuels and an electric motor powered by rechargeable batteries. The batteries were recharged by recovering energy using regenerative braking and the vehicles enjoyed $\sim$50% increase in fuel mileage. Energy storage, while not used as the primary energy supply, was able to overcome the weaknesses of conventional powertrain design that led to substantial inefficiency. Thus, electrification (batteries, motors, and drivetrain-capable power electronics) gained a foothold in the automotive industry.

Subsequently, the rise in petroleum prices in the mid 2000s sparked entrepreneurial interest in all-electric vehicles. While the battery in a hybrid vehicle typically offers less than a 20-mile range, a battery EV requires a minimum of a 100-mile range, and preferably greater than 300 miles. This required multiple innovations in battery chemistry, electrode design, and cell pack assembly. Research from academic and research laboratories discovered new chemistries and designs, and large chemical companies took a strong interest in developing the manufacturing technologies to deploy them. Within a few years, both Tesla and GM, (a start-up and a global mega-corporation respectively), as well as other market entrants brought light-duty EVs to market. In 2021, light-duty EVs captured about 2% of the market in the US. In northern Europe, high fuel prices have driven EV sales to greater than 50%

of the new vehicle market. The largest global market for light-duty vehicles is China, and China has the largest EV fleet. While the upfront costs for EVs are higher than ICEs, the total cost of ownership when considering the cost of fuel, repairs, and vehicle life make EVs lower in cost than ICEs. At current US energy prices and typical vehicle energy efficiencies, the fuel cost for electric vehicles is much lower than for gasoline-powered cars. In comparison to ICEs, EVs have fewer moving parts, generate less heat, and do not need to replace lubricating oils, cooling fluids, and brake pads as often. Therefore, repairs are less frequent, and except for the replacement of the battery (~10 years), vehicle life is significantly longer, and maintenance is significantly cheaper.

However, as markets expand for light-duty EVs, it is becoming clear that the access to vehicle charging will be a limiting factor on widespread EV adoption. With upfront costs of EVs higher than ICE vehicles, most early adopters have been affluent buyers with ready access to overnight charging in private garages. Less affluent drivers who live in urban and suburban rental units will not have the same opportunity. Similarly, public charging infrastructure is being deployed in urban areas and along high-use transportation corridors, so rural users are disadvantaged. Finally, taxi and delivery drivers will have substantially different charging needs than the owners of vehicles whose use is purely personal.

There are important lessons for the water industry in the adoption of electric vehicles. Transportation is a contributor to carbon emissions in the US and light-duty EVs account for greater than 60% of liquid fuel use. The world cannot achieve any meaningful decarbonization goals without transforming the light-duty fleet. Note that electrifying the fleet will only achieve the decarbonization targets if the vehicles are charged with carbon-free electricity. Similarly, electrifying energy input or unit operations in the water and wastewater sectors will only be effective if the grid is decarbonized. Furthermore, success requires investments in both fundamental science and engineering as well as underlying infrastructure. Nascent science and technologies can grow into major business opportunities. For example, Tesla has become the world's most valuable vehicle manufacturer since before the pandemic. However, certain performance targets must be met before a low-carbon technology will be adopted at scale. In the case of electric vehicles, the performance target was the energy density of the battery, and the market needed to wait for lithium-ion chemistry to be sufficiently advanced (reliable, manufacturable) to be adopted. The water industry must identify performance targets for decarbonized systems and seek investment in technologies that can reach those targets.

2.5.3 Cellulosic biomass

Engines that run on agriculturally-derived fuels (alcohols or converted vegetable oils) have existed almost as long as engines that run on fossil fuels. However, petroleum fuels far out-perform biofuels on a cost and energy-return basis in most cases. Despite the interest in biofuels generated by the oil crises of the 1970s, the markets for these fuels remained very small for decades.

With rising petroleum prices in the mid 2000s, the US passed first the Energy Policy Act (EPACT) of 2005 and the Energy Independence Security Act (EISA) of 2007 (EPA, 2007). These laws were intended to ensure a reliable domestic fuel supply and to simultaneously create economic opportunities for farms and rural regions. EPACT set national blend volume mandates for ethanol. Due to the benefits, fuel manufacturers readily exceeded the ethanol blend mandates. EISA created more aggressive blend requirements, and for the first time mandated life cycle-based GHGs emissions reductions. Life cycle analysis (LCA) indicates that corn starch ethanol, despite being biogenic in nature, reduces GHGs by only about 20% because of the extensive fossil energy requirements for farming and process heat. Cellulosic ethanol has the potential for much lower life cycle GHG emissions because it uses more of the plant material (and thereby reduces total acreage farmed per ton of feedstock), and because it is designed to use biomass for process energy. EPACT and EISA created a pathway for starch ethanol as an early market entrant, and with the expectation that cellulosic ethanol would dominate production and plateau in 2021. EISA 2007 generated significant interest from venture investors, entrepreneurs, and scientists to focus on cellulosic research.

With the early mandates for corn starch ethanol, investors were incentivized to increase the size of conventional biorefineries and production outpaced the targeted EISA volumes. Within a few years, corn ethanol utilized 40% of corn crop production, largely achieving one of the original goals of EPACT in supporting rural economic development. Ethanol rapidly achieved ∼10% volumetric blend of the gasoline supply, extending the liquid fuel supply as the mandates targeted.

With cellulosic biofuels, progress was slower. Originally, the limiting technical factor was considered enzymes to breakdown recalcitrant cellulosic into fermentable sugars. Cellulose is a structural polymer composed of sugars monomers that are difficult to depolymerize. In comparison starch is a nutrient source composed of readily digestible sugar polymers. As the science of cellulosic enzymes advanced, other technical challenges were identified in the cellulosic biofuel process. When pioneer cellulosic biorefineries were constructed, initial estimates were that they would have about twice the capital cost per unit of product volume. With lower overall productivity, cellulosic biorefineries capital costs grew to five- to ten-fold in comparison to mature starch ethanol biorefineries. This resulted in commercialization delays and unique challenges to the cellulosic industry. Fourteen years after EISA created mandates and incentives for cellulosic biofuels, the industry has yet to substantially impact decarbonization.

Two distinct challenges rapidly developed for the cellulosic and overall biofuel markets. The first challenge is that the market is structurally limited in size. As corn starch ethanol production grew rapidly, the US soon produced enough fuel to achieve 10% volume of the entire gasoline market. At that time, most vehicles and most fuel infrastructure were limited to a 10% ethanol (E10) blend due to materials compatibility. The conventional technology, which is relatively ineffective at decarbonization, had exceeded the ability of the market to consume it. Flexible fuel vehicles (FFVs), which are capable of using fuel with up to 85% ethanol fuel, were proposed as a solution. The manufacturing cost differential is only about $100. The vehicle manufacturers received credits for the vehicles as if the vehicle always used 85% ethanol (E85) fuel to meet fleet-wide corporate average fuel economy (CAFE) standards. The fuels market did not have any incentive to market E85 fuels so FFVs continued to operate on conventional E10 fuel. Therefore, FFVs resulted in only incidental increase in ethanol usage, and therefore minimal impact on GHG reductions. Sixteen years after EPACT, corn ethanol accounts for about 10% of the gasoline market and each gallon reduces GHGs by about 20%. Ethanol, therefore, results in about ∼2% reduction in GHGs. EISA 2007 and cellulosic biofuels have had essentially no additional impact on GHG emissions.

The second challenge in the biofuels market, and notably the cellulosic biofuel, is a significant warning for the water sector. Realizing that cellulosic production was a nascent industry in 2007, EISA created a regulatory requirement that the US EPA monitor cellulosic biofuel production capacity on an annual basis. The EISA mandate for cellulosic fuels is adjusted annually to avoid fuel blenders being mandated to use cellulosic biofuels that do not exist. Since the first blending requirements, manufacturing capacity has lagged blend mandates, so EPA adjusted the volumetric requirements. A cellulosic biorefinery is a complex operation and requires several years to construct and deploy. One of the authors of this chapter interviewed project investment banks and described the EISA mandates, EPA regulatory role, and the time and cost to build (Blazy *et al.*, 2015). It was uniformly considered a poor investment decision. Therefore, few cellulosic biorefinery projects have even been launched, and there is little-to-no success in the industry. The water sector should learn that mandates without consideration of markets, economics, fundamental science, state of technology, and the full scope of the mandates could lead to failed investments and little progress in achieving decarbonization goals.

2.5.4 Wind and solar

One of the true success stories in decarbonization of the energy sector is the substantial growth in wind and solar power. While the technologies are quite distinct, we assess their combined impact here. Solar has the potential to meet all of society's energy demand (Hermann, 2006), and has been considered as an ultimate solution to decarbonization. While wind is more limited in terms of total potential it has exhibited faster growth than solar. The advantages of both wind and solar is that they release no carbon emissions and have no fuel requirements. The need for fuel creates supply chain risks and also adds fuel price volatility risk to the total cost. Together, renewables are, at the time this book is published, the second largest generator of power in the US after natural gas, catching up to nuclear and surpassing coal.

The growth in wind and solar demonstrate a technology 'learning curve' that water decarbonization may emulate.

Driven by incentives including both investment tax credits (ITCs) and production tax credits (PTCs), wind capacity has exhibited the largest overall increase in capacity of any type of generation. This rapid build-out has catalyzed 'learning-by-doing,' and the modular nature of wind power allows for continuous innovation in the design, manufacturing, and construction of turbines. Focused R&D in wind has resulted in only incremental improvements, but for wind technology, incremental improvement delivers outsized gains in performance. For example, the generation capacity of a turbine scales as the square of the length of its blades. Therefore, small increases in blade length enabled by novel designs and materials have resulted in a non-linear increase in turbine capacity. Similarly, taller towers enable turbines to access more reliable wind resources. Higher reliability translates to a more valuable electricity resource, in addition to the bulk increase in kWh generated. Ultimately, these improvements increase land use efficiency.

There has been enormous research investment in new PV solar materials, however, no new materials have been deployed at scale. Rather, the dramatic drop in prices (and commensurate rapid build-out of PV-based generation) has been driven largely by reductions in manufacturing costs of conventional solar materials (polysilicon, and to a lesser extent cadmium telluride) and installation costs. China has driven the reduction in manufacturing costs. The ITC accelerated the domestic market for installation, and again, learning-by-doing drove down installation costs. Each new PV installation enabled incremental innovations in racking, interconnection, and construction logistics for ground-mount and roof-mount systems. As this book is published, solar PV offers the lowest cost of power costs in sunny regions such as the US southwest. However, because generation peaks during the middle of the day and demand peaks at other times, the value of additional solar installation is beginning to decline in areas with substantial solar penetration (Bolinger *et al.*, 2021).

The challenge to both wind and solar is intermittency. The ultimate solution is to link intermittent renewable power production to energy storage. Energy storage includes batteries, supercapacitors, pumped hydropower, other mechanical systems, or even thermal systems. The value of grid-scale energy storage is less than battery electric vehicles, so grid storage is learning and adapting from EVs.

Renewable power generation provides an important template for decarbonizing the water sector. Significant advancements in technology were not required for transition in the market. Rather, policy incentives drove the economics enough to foster capacity expansion. Increased installations drove manufacturing and infrastructure support down a learning curve to further incentivize deployment. For several years, incentives made renewable power the lowest cost pathway to increase capacity. As the manufacturing and installation processes matured, the ITCs were no longer required. As capacity grew to where it was disrupting grid resilience, storage and other mechanisms are developing as solutions. Incentives for storage and now driving storage capacity growth. It is largely expected that renewable power plus grid-scale storage will offer a cost-competitive and reliable carbon-free power sector.

ACKNOWLEDGEMENTS

This work was supported by the US Department of Energy through contract DE-AC07-05ID14517 (Idaho National Laboratory). This work was performed under the auspices of the US Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or

responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

REFERENCES

Blazy D., Pearlson M. N., Miller B. and Bartlett R. E. (2015). A Monte Carlo-Based Methodology for Valuing Refineries Producing Aviation Biofuel, Chapter 15. Royal Society of Chemistry, Cambridge UK, pp. 336–351. https://doi.org/10.1039/9781782622444-00336

Bolinger M., Seel J., Warner C. and Robson D. (2021). Utility Scale Solar 2021 Technical Brief. Lawrence Berkeley National Lab, Berkeley, CA. https://emp.lbl.gov/sites/default/files/utility-scale_solar_2021_technical_brief.pdf (accessed 2 November 2021)

DHS (2021). National Critical Functions. U.S. Department of Homeland Security, Washington, DC. https://www.dhs.gov/cisa/national-critical-functions (accessed 30 October 2021)

Dieter C. A., Maupin M. A., Caldwell R. R., Harris M. A., Ivahnenko T. I., Lovelace J. K., Barber N. L. and Linsey K. S. (2018). Estimated use of Water in the United States in 2015. In *USGS* (Circular 1441). U.S. Geological Survey, Reston VA. https://doi.org/10.3133/cir1441

DOE (2014). The Water-Energy Nexus: Challenges and Opportunities. U.S. Department of Energy, Washington DC. https://www.energy.gov/sites/prod/files/2014/07/f17/Water Energy Nexus Executive Summary July 2014.pdf (accessed 20 April 2020)

DOE (2020). Moving Goods in A SMART Mobility System. U.S. Department of Energy, Washington DC. https://www.energy.gov/eere/vehicles/downloads/smart-webinar-6-moving-goods-smart-mobility-system (accessed 30 October 2021)

EIA (2021). Monthly Energy Review. U.S. Department of Energy, Washington DC. http://www.eia.gov/totalenergy/data/monthly no (accessed 24 November 2020)

EPA (2007). Energy Independence and Security Act. Public Law 110-140. U.S. Environmetnal Protection Agency, Washington DC. https://www.epa.gov/laws-regulations/summary-energy-independence-and-security-act (accessed 11 January 2022)

EPA (2021). Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2019 (No. EPA430-R-21-005). U.S. Environmental Protection Agency, Washington DC. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019 (accessed 30 October 2021)

EPRI (2013). Electricity Use and Management in the Municipal Water Supply and Wastewater Industries (No. 3002001433). Electric Power Research Institute, Palo Alto CA. https://publicdownload.epri.com/PublicDownload.svc/product=000000003002001433/type=Product (accessed 14 January 2020)

Gleick P. H. (1994). Water and energy. *Annual Review of Energy and the Environment*, **19**(1), 267–299. https://doi.org/10.1146/annurev.eg.19.110194.001411

Greenberg H. R., Simon A. J., Singer S. L. and Shuster E. P. (2017). Development of Energy-Water Nexus State-Level Hybrid Sankey Diagrams for 2010. In *LLNL* (LLNL-TR-669059). Lawrence Livermore National Lab, Livermore CA. https://flowcharts.llnl.gov/report (accessed 7 January 2020)

Grubert E. and Sanders K. T. (2018). Water use in the United States energy system: A national assessment and unit process inventory of water consumption and withdrawals (research article). *Environmental Science and Technology*, **52**(11), 6695–6703. https://doi.org/10.1021/acs.est.8b00139

Hermann W. (2006). Quantifying global exergy resources. *Energy*, **31**(12), 1685–1702. https://doi.org/10.1016/j.energy.2005.09.006

Kyung D., Kim M., Chang J. and Lee W. (2015). Estimation of greenhouse gas emissions from a hybrid wastewater treatment plant. *Journal of Cleaner Production*, **95**, 117–123. https://doi.org/10.1016/j.jclepro.2015.02.032

Roy M., Edwards M. R. and Trancik J. E. (2015). Methane mitigation timelines to inform energy technology evaluation. *Environmental Research Letters*, **10**(11), 114024. https://doi.org/10.1088/1748-9326/10/11/114024

Szulc P., Kasprzak J., Dymaczewski Z. and Kurczewski P. (2021). Life cycle assessment of municipal wastewater treatment processes regarding energy production from the sludge line. *Energies*, **14**(2), 356. https://doi.org/10.3390/en14020356

US Bureau of Economic Analysis (2021). National Income and Product Accounts, Table 1.1.4 Price Indexes for Gross Domestic Product and Table 1.1.5. Gross Domestic Product. U.S. Bureau of Economic Analysis, Suitland MD. https://apps.bea.gov/iTable/index_nipa.cfm (accessed 30 October 2021)

USDA (2021a). CORN Quickstats: Acreage, Yield, and Price. National Agricultural Statistics Service. U.S. Department of Agriculture, Washington DC. https://www.nass.usda.gov/Quick_Stats/Lite/result.php?B565104E-D426-36E7-9481-03007890E2F2 (accessed 8 October 2021)

USDA (2021b). Wheat Sector at A Glance. USDA Economic Research Service. U.S. Department of Agriculture, Washington DC. https://www.ers.usda.gov/topics/crops/wheat/wheat-sector-at-a-glance/ (accessed 8 October 2021)

USGS (2021). Mineral Commodity Summaries 2021. U.S. Geological Survey, Reston, VA. https://doi.org/10.3133/mcs2021