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THE STANFORD EMERGING TECHNOLOGY REVIEW 2025

A Report on Ten Key Technologies and Their Policy Implications

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SUSTAINABLE ENERGY TECHNOLOGIES

KEY TAKEAWAYS

- Although many clean energy technologies are now available and increasingly affordable, scaling them to a meaningful degree and building the massive infrastructure needed to deploy them will take decades.

- The largest impact on reducing emissions in the near to medium term will come from building a no- to very-low-emission electricity grid, electrifying passenger cars and small commercial vehicles, and transitioning residential and commercial heating and industrial energy.

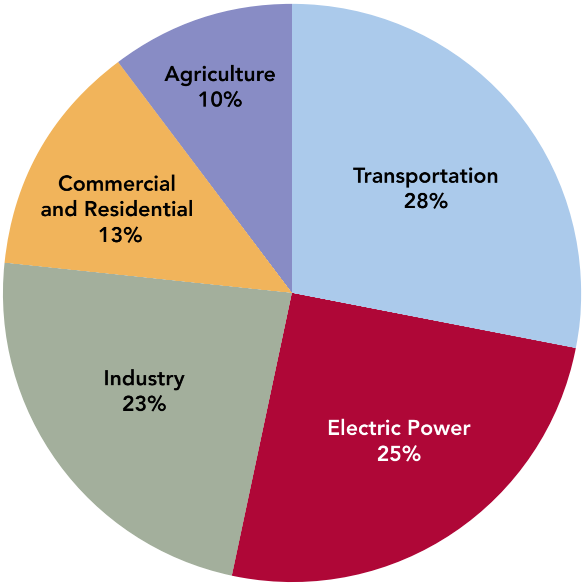
- In the long term, technologies for decarbonizing buses and long-haul trucks, decarbonizing carbon-intensive industries, and reducing greenhouse gases from refrigerants and agriculture will play key roles in a net-zero, emissions-free energy infrastructure.

Overview

Energy is a key strategic resource. Fossil fuels have dominated human energy use for centuries, but their emissions of carbon dioxide (CO_2) and other greenhouse gases have significantly altered the climate. Without a shift to sustainable energy sources in the coming decades, this trend will worsen, exacerbating climate change impacts globally. Figure 10.1 depicts the percentage of greenhouse gas emissions associated with each sector of the US economy.

Scaling solutions is a major global challenge. We need billions of zero-emission cars, hundreds of millions of emission-free trucks, and carbon-neutral fuels for tens of millions of airplane flights per year. Agricultural practices must change to feed billions sustainably. The global industrial infrastructure that mines and processes raw materials and turns them into manufactured products and then distributes these all over the world must adopt methods that eliminate CO_2 and other emissions.

FIGURE 10.1 Greenhouse gases emitted in the United States in 2022, by economic sector



Note: Due to rounding, total does not add up to 100 percent.

Source: Adapted from US Environmental Protection Agency, "Sources of Greenhouse Gas Emissions," April 2024

Another statistic underlines the magnitude of the challenge that lies ahead: Tens of billions of tons of CO_2 are produced every year from burning fossil fuels. Figure 10.2 demonstrates how this scale challenge is reflected in various parts of the economy.

This challenge has three major implications. First, no single technology can meet global energy demands in a net-zero emissions manner. Success requires diverse approaches that create a bridge from present sources, consumption trends, and infrastructure to a more sustainable future. Second, new energy technologies must match rising global power demand. Third, solutions must be cost-effective, ensuring energy affordability for people of all economic circumstances worldwide.

Renewable energy-generation technologies have experienced remarkable growth in recent years, primarily driven by declining costs of solar and wind power that make them competitive with conventional energy sources today. However, scaling distributed renewable generation capacity to meet global demand still presents challenges when it comes to storing and transporting energy.

The electric grid—a complex system that generates and transports electrical energy to end users—is central to the energy transition,[1] and it will require increased capacity and reliability as countries decarbonize. Building reliable, emission-free grids involves combining intermittent renewables like solar and wind (i.e., sources that are not always available) with clean, dispatchable power sources (i.e., ones that can be quickly ramped up or down in response to user demand) and improved energy storage. Despite the challenges posed by the variability of some renewables, many countries, including Switzerland, Denmark, and Brazil,[2] have successfully integrated a significant portion of these sources into their grids.

The economic impact of sustainable energy is significant. For example, one analysis indicates that clean energy accounted for 10 percent of global GDP growth in 2023,[3] or about $320 billion. Sustainable energy also contributes substantially to employment—an estimated 13.7 million direct and indirect global renewable-energy jobs existed in 2022, up from 7.3 million in 2012.[4]

Public health is also likely to benefit from emissions-free energy sources. For example, one report predicts that eliminating air pollution emissions from energy-related activities in the United States could prevent more than fifty thousand premature deaths each year and provide more than $600 billion in benefits annually from avoided illness and death.[5] A second report indicates that an electric grid producing 80 percent of its output from emission-free sources by 2030 could prevent an estimated 267,500 premature deaths between 2030 and 2050 and generate an estimated $1.13 trillion in present-value health benefits due to cleaner air.[6]

FIGURE 10.2 The scale challenge in global energy transition

Cars

- There are an estimated 1.45 billion cars on the road today.
- Globally, one in every seven cars bought in 2022 was an electric vehicle.[a]
- Global lithium production will have to increase by a factor of 2.5 to 5 to meet expected demand for electric vehicles by 2030.[b]

Trucks

- Globally, there are approximately 217 million freight vehicles (including light commercial vehicles, medium- and heavy-duty trucks, and buses).[c]
- In 2022, 1.2% of trucks sold worldwide were electric (60,000 units).[d]

New Construction

- From 2020 to 2060, we expect to add about 2.6 trillion square feet of new floor area to the global building stock—the equivalent of adding an entire New York City to the world every month for 40 years.[e]
- After water, concrete is the second most-consumed material, with 30 billion tons poured each year.[f]
- If the cement industry were a country, it would be the third largest carbon dioxide emitter, behind only China and the United States.[g]

Industrial Energy Use

- Heavy industry—including steel, cement, and chemical production—accounts for nearly 40% of global carbon dioxide emissions. These emissions are the hardest to decarbonize and would require both an entire change in process and building new processing plants, which would need even more steel and cement.[h] Currently there are zero cement plants and only one steel plant that don't produce carbon dioxide.[i]

Source:
a. https://www.iea.org/energy-system/transport/electric-vehicles.

b. https://www.popularmechanics.com/science/energy/a42417327/lithium-supply-batteries-electric-vehicles/; https://www.sustainabilitybynumbers.com/p/lithium-electric-vehicles. Research conducted by Oxford University data scientist Hannah Ritchie.

c. https://www.shell.com/energy-and-innovation/the-energy-future/decarbonising-road-freight.html.

d. https://www.iea.org/reports/global-ev-outlook-2023/trends-in-electric-heavy-duty-vehicles.

e. https://www.iea.org/data-and-statistics/charts/global-buildings-sector-co2-emissions-and-floor-area-in-the-net-zero-scenario-2020-2050.

f. https://www.climateworks.org/blog/why-you-should-care-about-cement-and-concrete.

g. https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth.

h. https://www.brookings.edu/wp-content/uploads/2021/06/FP_20210623_industrial_gross_v2.pdf.

i. https://www.gatesnotes.com/2022-State-of-the-Energy-Transition.

Key Developments

In 2021, the White House laid out a strategy to reach net-zero US emissions by 2050,[7] which includes an aspirational goal of 100 percent emissions-free electricity generation by 2035. Several key developments are shaping the transition toward a cleaner and more sustainable energy future, reflecting a combination of technological innovations and the impact of broader trends in energy systems, market dynamics, and policy interventions.

Substantial progress has already been made in several sustainable energy technologies:

- The cost of both wind-generated and solar-generated electricity is now substantially lower than that of fossil fuels.[8]
- The use of direct current (DC) for long-distance transmission of electricity can halve losses compared to transporting it using alternating current (AC), though AC transmission lines are much more common.

- Having dropped in cost by 90 percent over the past decade, lithium-ion (Li-ion) batteries are now being used on a massive scale to store excess energy from renewable generation for use during peak demand periods.[9]

- Cheaper Li-ion batteries are also making possible the production of electric vehicles (EVs) with ranges in excess of several hundred kilometers.

- Light-emitting diode (LED) lighting is up to ten times more efficient than incandescent lighting at converting electricity to usable light, and massive deployment of LED lightbulbs is taking place around the world.

- Heat pumps for heating and cooling are highly energy efficient, even at low temperatures, and heat-pump deployments are spreading rapidly.

The widespread deployment of such technologies in a net-zero emissions energy infrastructure depends on overcoming a variety of challenges, some of which include the following:

Public charging infrastructure for EVs Although US legislation has sought to fund the deployment of five hundred thousand public charging stations by 2030, the number of such stations that have been built since the legislation's passage is minuscule—just seven stations as of June 2024.[10]

The raw materials supply chain The United States relies heavily on imports of rare earths from China and cobalt from the Congo for clean energy technologies such as wind turbines and batteries—nations whose interests are not always aligned with US national interests. The United States also competes for the same materials with other nations that are themselves attempting to reduce energy-related emissions.

High up-front costs As is often true with capital investments, some clean energy technologies (e.g., nuclear reactors, hydroelectric dams, offshore wind farms, and grid-scale battery-energy storage systems) require significant up-front investment before their benefits are fully realized. In the absence of appropriate financial support, high up-front costs can be a barrier to adoption, especially in developing economies.

Over the Horizon

In the United States, energy research is a major focus of government, academia, and the private sector. The US Department of Energy (DOE) is a substantial funder of innovation in many energy technologies.[11] The private sector also invests heavily in clean energy. According to the American Clean Power Association, $271 billion of private-sector investments in domestic clean energy projects and manufacturing facilities were announced in 2023, exceeding the combined amount of clean energy investments made over the previous eight years.[12]

Government, academia, and the private sector also conduct research on energy technologies. For the federal government, the US National Laboratories conduct a substantial amount of research in this area. Academia conducts the bulk of early-stage research on energy technologies, and universities have been the source of many innovations in energy—including better batteries and more efficient solar cells and wind turbines. However, they do not have the resources to effect large-scale deployments. Big energy companies, including some that have previously built their businesses around fossil fuels, are increasingly involved in the sustainable energy ecosystem. Start-ups are also involved in the commercialization of research that emerges from academia. Larger companies also conduct research, but generally at later stages that are past proof of concept. Both large and small companies have entered partnerships with academic institutions such as Stanford.

The discussion below focuses on technologies that are not as mature and where policy is less developed.

Energy Technologies

LONG-DURATION ENERGY STORAGE

Long-duration energy storage from intermittent sources such as wind and solar is necessary to capture their full value. Storage allows excess energy produced during plentiful times to be used when intermittent sources are unavailable—for example, solar energy is about twice as abundant in summer than in winter. A variety of technological concepts for storage are being developed:

Hydrogen storage Electricity can convert water to hydrogen gas through electrolysis. The gas can then be kept in deep underground salt caverns for large-scale seasonal energy storage, after which it can be converted back to electricity in a fuel cell or gas turbine. The first purpose-built salt cavern seasonal energy-storage system is being built in Utah.[13]

Gravity storage Power that exceeds demand can be used to pump water from lower to higher levels and then recovered by letting that water flow back down through generators. Alternatively, large, multi-ton weights can be lifted hundreds of meters using excess energy and then later allowed to fall gently to drive electrical generators.

Thermal storage This approach stores excess power in the form of heat, such as heating a large volume of salts to a very high temperature. When needed, this stored heat can be released to generate power.

Large-scale, long-duration battery storage To improve important battery characteristics such as cost, tolerance to extreme temperature, safety, maintainability, and recyclability, battery technologies beyond Li-ion batteries are being developed, such as redox flow,[14] Ni-H_2 gas,[15] and Zn-MnO_2 chemistries.[16]

The chief challenges of all these forms of long-duration energy storage are scalability and cost. None of them will be a silver bullet that exponentially improves energy storage. If they can become economically feasible, however, each one of the technologies could satisfy niche applications.

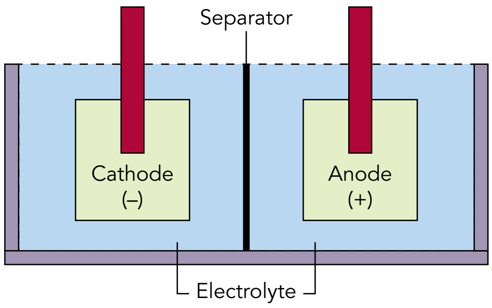
LOW-COST, HIGH-ENERGY-DENSITY BATTERIES

All batteries consist of three basic components: the cathode, made of one substance; the anode, made of a different substance; and the electrolyte, which consists of yet another substance (see figure 10.3). Batteries have different characteristics depending on the substances that constitute them—for example, the alkaline batteries used in a flashlight employ different materials than the lead-acid battery used in a standard car.

While batteries are now being deployed for short-term energy storage on the grid that lasts hours, they are currently not viable for longer-term storage. For example, the challenge of storing the world's electricity consumption for seventy-two hours for the long term (weeks or months) gives a very good sense of the scale challenge facing sustainable electricity generation.[17] Around 240 terawatt-hours (TWh) of battery storage would be needed; at about 200 watt-hours per kilogram, this would require over a billion tons of batteries.

Li-ion batteries, while currently the best large-scale production option, are not a good solution for long-duration storage. As measured in energy storage capacity, global production capacity of batteries in 2023 was about 2.8 TWh,[18] or barely enough to

FIGURE 10.3 Basic components of all batteries



cover 1 percent of the world's electrical consumption over three days. Producing enough capacity would take many decades, even if all available production were dedicated to this purpose. Moreover, such batteries would need to endure for thousands of cycles and retain charge for weeks or months. Current Li-ion technology doesn't meet these requirements, making it unsuitable for long-term, grid-scale energy storage solutions.

Cost is also a significant barrier for Li-ion batteries in grid storage. At current prices of $139 per stored kilowatt-hour, grid-scale Li-ion storage is prohibitively expensive. Aqueous chemistries, like manganese-hydrogen batteries, offer more cost-effective solutions for long-duration storage due to cheaper materials and lower maintenance needs.[19] Sodium-ion batteries also show promise, currently matching Li-ion costs but with potential for further price reductions as the technology matures. These alternatives could provide more economical options for large-scale grid energy storage in the future.

RENEWABLE FUELS: COMBUSTIBLE HYDROCARBONS AND BIODIESEL

Research on renewable fuels aims to create energy sources that do not rely on fossil fuels such as oil, gas, or coal. Renewable fuels include combustible hydrocarbons such as biodiesel, which can be produced from animal fats or vegetable oils; bioethanol produced from corn or algae; hydrogen, which can be produced from many sources; and ammonia produced using green hydrogen (see definition in the column at right).

Because it burns without CO_2 emissions, hydrogen is important for transitioning to renewable fuels. However, for most transportation applications, vehicles must carry hydrogen as a liquid or highly compressed gas to avoid frequent refueling. Hydrogen fuel cells are twice as efficient as hydrocarbon combustion engines, but compressed hydrogen contains only a quarter of the energy of an equivalent volume of hydrocarbon fuels. Consequently, hydrogen-powered vehicles need fuel tanks at least twice the size of conventional ones for the same range.

Research into hydrogen storage must therefore focus on developing cost-effective storage technologies with improved energy density that do not depend on liquification or compression.[20] It may also be possible to use captured CO_2 combined with sustainably produced hydrogen to create renewable hydrocarbon fuels.[21] Ammonia is another form of hydrogen storage and is being prototyped as a fuel for oceangoing shipping,[22] but concerns about its safety and impact on air pollution need to be addressed before wide-scale adoption occurs.

Producing and transporting hydrogen cost-effectively and with minimal leakage is challenging. Current hydrogen from fossil fuels, known as gray hydrogen, is unsustainable due to its carbon footprint. Blue hydrogen, based on methane with carbon capture, and green hydrogen, which uses renewable electricity for electrolyzing water, are emerging alternatives. Geologic hydrogen from natural water-rock interactions and hydrogen production from geothermal resources are also being explored.

CARBON CAPTURE AND REMOVAL

Emission-free energy production at the scale required will take many decades to accomplish, and fossil fuels will still be an appreciable (though declining) fraction of society's mix of energy sources for some time to come. In the meantime, carbon capture and storage (CCS) is gaining momentum. CCS involves capturing CO_2 emissions from industrial processes and power plants and then storing them underground, preventing their release into the atmosphere.

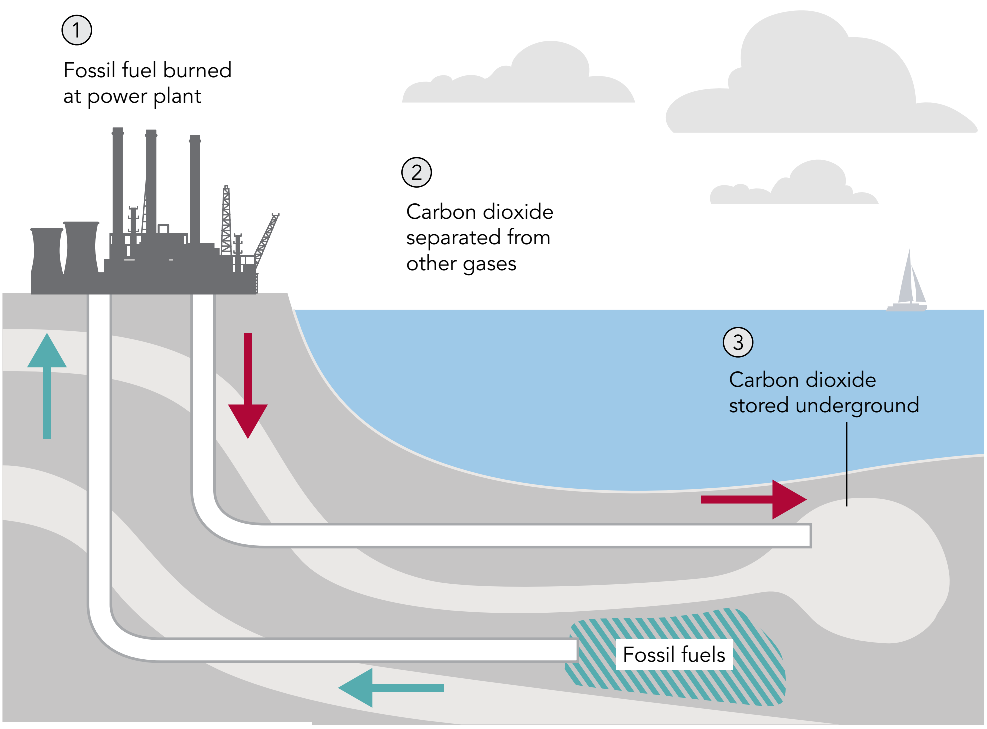
CCS in fossil-fuel power plants aims to reduce CO_2 emissions while maintaining the use of these sources. Currently, only 45 million tons of CO_2 are captured annually,[23] a very small fraction of global emissions. However, new government incentives, especially in the United States, have sparked increased CCS permit applications, and a growing number of projects are in various stages of development, from planning to already operational. If all planned CCS projects were completed, global capacity would increase eightfold. Yet this would still account for less than 1 percent of global CO_2 emissions from fossil fuels.

Carbon capture usually takes place at the source of emissions, such as the smokestack of a fossil-fuel-burning power plant. Here, CO_2 emissions are much more concentrated; once dispersed by the wind into the atmosphere, they become much harder to capture. Technologies to trap CO_2 at the source include liquid and solid materials, as well as membranes that extract CO_2 from the gas. After the CO_2 is captured, it can be permanently stored underground or used in the production of other materials (see figure 10.4).

Research into source capture based on liquid and solid materials is focused on developing inexpensive, energy-efficient materials for membranes that can be used for long periods of time to rapidly separate CO_2 from other gases. Membrane-development challenges include finding ways to reduce the cost and increase the stability of these approaches, as well as increasing membranes' permeability and their ability to extract CO_2.

Carbon removal calls for capturing CO_2 directly from the atmosphere—also known as direct air capture (DAC)—at concentrations much lower than at a

FIGURE 10.4 How carbon capture and storage works



Source: Adapted from BBC Research

> **The electric grid of the future will need to be more extensive and complex, with power generation, consumption, and storage distributed throughout the system.**

smokestack. DAC uses significantly more energy in capturing a ton of CO_2 than capturing it at a power plant or other source. Several commercial-scale projects are now under development and will be operational by the end of the decade.[24] Potentially scalable DAC approaches include biomass storage; mineralization of CO_2 using silicates; ocean alkalinization; and storage in algae.[25] Research challenges involve improving the scalability of these approaches, the length of time over which carbon can be stored using them, and their affordability.

GRID TECHNOLOGIES

Today's electric grid in the United States is highly centralized and operates as a single unit through the real-time coordination of power plants spread across many states. Such coordination must constantly balance supply with demand. This creates the potential for widespread instability in the event of outages that would otherwise be highly localized.

The electric grid of the future will need to be more extensive and complex, with power generation, consumption, and storage distributed throughout the system. Renewable sources of electricity will be more varied and decentralized. Electrical demand will increase as electrically operated systems displace ones powered by fossil fuels. This will require a significant expansion in the electricity grid within the next few decades, which could see it double or triple in size. Energy storage and electricity demand will have to be more dynamically managed as well.

The grid must adapt to handle a significantly larger and more variable energy flow, which will require substantial upgrades to existing infrastructure, including transmission lines, substations, distribution networks, and information systems. Addressing all these challenges securely is the goal of what is widely known as the smart grid, which will coordinate these different elements to increase efficiency, reliability, and resilience against attack or natural disaster. In the United States, the Office of Electricity in the DOE has the primary federal responsibility for development of technologies, tools, and techniques for the smart grid.

Some of the important technologies for a smart grid include the following:

Reconductoring This involves replacing existing conductors on power lines with advanced ones to improve capacity, reduce losses, and/or enhance reliability without increasing land use.[26] Reconductoring is crucial for grid maintenance, meeting demand, and renewable energy integration.

End-use energy management There is increasing emphasis on making energy demand more flexible, which involves managing when energy is used. Grids dominated by renewable energy typically have excess supply at certain hours (for example, during the day for solar-dominated grids) and excess demand at other hours, necessitating the use of expensive energy storage. Demand management can reduce this disparity by using a variety of approaches to change when electricity consumption occurs:

- Scheduling devices and systems to operate during periods of high renewable-energy generation
- Implementing dynamic pricing structures that reflect the actual cost of electricity at any given time, incentivizing consumers to shift their energy use
- Allowing consumers to schedule their energy use to coincide with periods of low carbon intensity on the grid, further reducing emissions
- Incentivizing consumers to reduce their electricity consumption during peak demand periods, enhancing grid stability

Vehicle-to-grid (V2G) technology V2G enables EVs to return energy to the grid, enhancing stability, and lowers electricity costs for EV owners by allowing them to resell energy. However, implementing V2G requires significant upgrades to the grid as well as financial investment and stakeholder coordination. Hardware interfaces and communication protocols need to be standardized. A key concern here is that if V2G is very successful, it could degrade EV batteries faster. Further research is also needed to understand how the approach affects battery lifespan and warranties.

Second-life battery applications As EV adoption increases, more EV batteries will be retired. These often retain significant capacity and are particularly well suited for stationary energy storage applications, such as battery backup for solar power. Research is underway to develop specialized battery-management systems (BMSs) tailored to the unique characteristics and requirements of second-life batteries, optimizing their performance and further extending their lifespan.

AI and data-driven energy systems The growing field of energy artificial intelligence leverages AI, machine learning, and data analytics to optimize energy systems, improve grid management, and accelerate the integration of renewable energy sources. An important application involves AI algorithms that dynamically adjust grid operations in response to changing conditions, such as fluctuations in renewable energy generation or unexpected demand surges. Data analytics can also anticipate and prevent equipment failures in power plants and grid infrastructure.

NUCLEAR POWER

Energy can be released from certain atomic nuclei through fission, which is usually the splitting of the nuclei of uranium or plutonium, and fusion, the merging of the nuclei of hydrogen isotopes into one nucleus. (In this report, *nuclear power* will refer to power generated through fission.)

The technical feasibility of generating electricity through fission has been established for many decades, and today it generates just under a fifth of electricity consumption in the United States.[27] In addition, nuclear power—an emissions-free energy source—is experiencing renewed interest, particularly as a source of dispatchable power that can complement intermittent renewable energy sources.

At the same time, the widespread deployment of nuclear (fission) reactors has been inhibited by several factors, including the following:

Cost and timescales The construction of nuclear reactors in the United States has a long history of significant cost overruns and construction delays. These have significantly driven up the cost of fission-produced electricity compared with original estimates.

Fuel security Today, over 90 percent of the uranium used in US nuclear reactors is imported; Kazakhstan and Russia supply nearly half of all American uranium consumption. In addition, most new reactor designs call for uranium fuel enriched with U-235 at a higher level than that used in most of today's operating reactors.[28] Such fuel, known as high-assay low-enriched uranium (HALEU), is available only from Russia today.

Manufacturing capability A few hundred gigawatts of fission generation capacity will have to be brought online by 2050[29] if the United States is to achieve its goal of tripling its production of such electricity by that year from its 2020 baseline.[30] This corresponds to nearly three hundred gigawatt-scale reactors—or many more smaller ones—which would demand a historically unprecedented rate of reactor construction. Achieving this will depend on multiple factors, including the availability of a skilled construction labor force and heavy-manufacturing capacity.[31]

Safety A number of well-publicized, safety-related reactor incidents, including the Chernobyl disaster in 1986 and the Fukushima accident in 2011, damaged public trust in nuclear power worldwide, leading to increased regulatory pressure in the United States to improve safety at existing and future power plants.

Nuclear weapons proliferation Most fission reactors require some enrichment of natural uranium. Enriching uranium from its natural state to being reactor-ready takes much more work than enriching it further, from being reactor-ready to bomb-ready. Thus, the widespread deployment of reactors raises concerns about the spread of nuclear technologies and material that can be used for weapons by states and nonstate actors such as terrorist groups.

Waste management All nuclear reactors produce radioactive waste that must be safely managed for tens of thousands of years. Long-term waste management depends on technologies for waste storage and locations where waste can be stored. The latter problem has not been solved in the United States despite many years of effort.

In part to address some of these issues, new reactor technologies—most prominently the small modular reactor (SMR)—have been developed. Advocates argue that SMRs are potentially safer than traditional nuclear reactors and offer advantages in terms of scalability, flexibility, and reduced waste production and capital costs. Several companies and research institutions are developing SMR designs, with some projects nearing deployment.

Nevertheless, SMRs remain an unproven technology in America, though the US Navy employs them in some ships and submarines (see sidebar on the Naval Nuclear Propulsion Program). The first company to pursue SMRs in the United States, NuScale Power, produced a design that was approved by the US Nuclear Regulatory Commission.[32] A plan to produce a working demonstration plant at Idaho National Laboratory recently fell through, however, after rising costs led the prospective customers to pull out.[33]

THE NAVAL NUCLEAR PROPULSION PROGRAM

While land-based small modular reactors (SMRs) remain an unproven technology in the United States, small nuclear reactors generating a few hundred megawatts have powered American submarines and aircraft carriers for decades. Of particular significance is that they are fueled with bomb-grade, highly enriched uranium, which limits their utility as civilian, land-based power plants. Nevertheless, the US Naval Nuclear Propulsion Program (NNPP) has considerable expertise in the design, manufacture, operation, decommissioning, and disposal of naval nuclear reactors, all of which are relevant to civilian SMR programs. Moreover, the NNPP maintains an extensive technical and industrial base through its laboratories, factories, shipyards, and training facilities to enable continued design, construction, and operation of these platforms.[a]

a. US Department of Energy and US Department of the Navy, "The United States Naval Nuclear Propulsion Program 2020," accessed August 13, 2023, https://www.energy.gov/sites/default/files/2021-07/2020%20United%20States%20Naval%20Nuclear%20Propulsion%20Program%20v3.pdf.

Analysts have also raised concerns about whether SMRs will be able to deliver their promised benefits. For example, SMRs tend to be less efficient than larger reactors and generate a greater volume of waste per unit of energy produced because more neutrons escape from the core, activating more of the surrounding material.[34] Also, a significant fraction of the cost of reactors, such as the cost of site preparation, is fixed and therefore independent of reactor size. Thus, such costs will be higher for the deployment of a number of SMRs than for the deployment of a single larger reactor with the same overall power output.

Addressing the issues described above is at least as much a question of policy as technology. Just as various public subsidies have been provided for certain kinds of renewable energy sources, such as residential solar panels, subsidies for various aspects of fission-based power generation could reduce costs. For example, the DOE supported a US company that produced 20 kilograms of HALEU in late 2023.[35]

As for fusion power, it continues to hold promise as a potentially limitless and inherently safe source of energy. In December 2022, the Lawrence Livermore National Laboratory demonstrated for the first time a better-than-breakeven fusion outcome: An experiment produced more energy than the laser energy used to "ignite" the deuterium-tritium fuel. Since then, the repeatability of this outcome has been demonstrated twice.[36] Nevertheless, significant scientific and engineering breakthroughs are still needed to make fusion generation of electricity commercially viable. Even the most optimistic private investors in fusion do not believe that commercial-scale fusion power plants are any closer than ten to fifteen years away, with large-scale deployments even further out.

Growth in Electrical Demand

One of the most significant trends in the energy arena is the anticipated growth in electricity demand over the coming decades—as much as 50 percent to 100 percent more than US demand in 2022.[37] This projected surge in demand will be driven by:

- The rise of AI and the consequent increase in energy-intensive data centers
- The electrification of transportation, with EVs becoming increasingly popular in many countries
- Efforts to boost domestic manufacturing, which increase industrial electricity consumption
- Government policies supporting green technologies and renewable energy sources, which further drive the shift toward electrification

Meeting this demand will require significant scale-up and investment in electricity generation and grid infrastructure.

Manufacturing and Supply Chains

With many corporate and government net-zero targets established for 2040 or 2050, the next decade or so will be a crucial period for the development of sustainable energy technology and policy. The United States has an unparalleled capacity for fundamental research in energy, much of it based in universities. However, in the equally important domain of manufacturing at scale, it is no longer the world leader. China and other countries that offer substantial government subsidies and support to businesses control most of the manufacturing, supply chain, and critical minerals for battery and solar cell production.

As these technologies will be directly tied to the energy security of the United States, promoting domestic production will be vitally important. Of concern is that China dominates much of the supply chain for battery materials, owing to its ability to supply such minerals at relatively low cost. This raises questions about supply chain security for key energy-technology materials. US government incentives have mobilized some investment in domestic materials production, but the United States will need to work with allies and partners to develop alternative sources for materials and processes.

Policy, Regulatory, and Legal Issues

ECONOMICS AND EMPLOYMENT

Energy and economics are deeply interconnected, with energy costs and efficiency directly impacting economic prosperity. The energy sector's significance means transitions in policy or sources can create economic winners and losers, at least in the short term. For instance, the shift to sustainable energy threatens well-paying fossil-fuel jobs. These transitions also involve cultural and other changes. For example, education plays a critical role in facilitating such transitions, particularly as manufacturing skills essential for technology scalability are declining in the US workforce. Balancing economic impacts, job transitions, and skill development is vital for a successful sustainable energy future.

ENVIRONMENTAL IMPACTS

Energy production, including sustainable methods, often generates harmful waste. Large-scale deployment of renewable technologies will result in significant end-of-life waste, such as old windmill blades and dead solar cells. Addressing these concerns proactively can minimize negative environmental impacts from decommissioned equipment. The next generation of energy technologies also presents an opportunity to incorporate recyclability into their design, moving toward a zero-waste economy.

Also relevant to environmental impact is the fact that many forms of sustainable energy require new acquisitions of land to build generating stations and storage facilities. For example, wind energy often requires the construction of many wind turbines on large tracts of land (see figure 10.5). Residents may support windmills in principle but then adopt a "not in my backyard" mentality. Early consultation and engagement with landowners and communities will be needed to build the social license to operate for land-intensive clean energy projects.

SUSTAINED FUNDING THROUGH THE VALLEY OF DEATH

The *valley of death* refers to the period after research has demonstrated the engineering feasibility of a particular innovation (a step beyond scientific feasibility) but before the innovation achieves adoption on a scale large enough to establish the viability of a business model using it.

In some fields, a significant gap exists between prototype development and market viability, requiring pilot projects that bridge the gap between academic research and development (R&D) and widespread use. Such projects address technical issues that emerge only at larger scales, beyond typical prototype development. However, venture capitalists often hesitate to invest in such projects, creating a funding gap for this critical commercialization stage. To address this valley of death for promising technologies, the Department of Energy's Loan Program offers debt financing for clean energy projects.[38] This initiative supports the transition from academic R&D to widespread commercial use, filling a crucial role in technology development.

SUSTAINED POLICY SUPPORT FOR EMISSIONS-FREE ENERGY INNOVATION

The federal government plays an important and large role in funding energy R&D. However, this research requires sustained support with a long-term vision. Commercial technologies such as solar cells and batteries stem from fundamental research in America that began decades ago, with these technologies only now reaching fruition. For many such innovations, large fluctuations in research funding and inconsistent support are damaging American research enterprises that depend on the ability to retain knowledgeable and experienced scientists and engineers to do the relevant work. As a result, key innovations such as solar energy and Li-ion batteries were invented in the United States and then commercialized overseas.

For the next generation of emission-free technologies, America must sustain a stable innovation

FIGURE 10.5 A cluster of wind turbines

Source: National Renewable Energy Laboratory / Dennis Schroeder

ecosystem over several decades. At stake is leadership in technologies such as fusion energy, next-generation nuclear reactors, carbon-neutral fuels, and long-duration energy storage. Success depends on achieving a consensus that combines vigorous academic and national laboratory innovation with effective public-private partnerships.

NOTES

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