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Nuclear Energy and Climate Change Mitigation

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SUMMARY

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Nuclear Energy and Climate Change Mitigation

Congress has long been interested in nuclear energy policy in the context of climate change mitigation. A scientific consensus holds that human-caused greenhouse gas (GHG) emissions raise global average temperatures. Nuclear energy is among the technologies that could help reduce GHG emissions by providing a low-carbon source of electricity generation to meet existing and future electricity demand. Although U.S. electricity demand has remained generally flat over the last 15 years, it is projected to increase significantly due to the growth of data centers, new domestic manufacturing, and ongoing electrification of the economy.

Mitigating climate change may include reducing GHG emissions from electricity generation and converting energy consumption sectors—transportation, industry, and buildings—to utilize electricity with lower GHG emissions. As a source of low-carbon energy, nuclear power is often weighed against the cost, benefits, and risks of other options to mitigate GHG emissions. These include low-carbon options such as wind, solar, and other renewables, and measures to improve energy efficiency. Low-emissions power generation that obtains energy from intermittently available sources such as solar radiation and wind has lower dispatchability than thermal power plants. Among other sources of electricity generation, nuclear and hydropower are the primary zero-emissions (at the power plant) technologies that can provide 24-hour, dispatchable electricity, and nuclear energy can also provide nearly continuous generation to serve "baseload" demand. Nuclear energy could also reduce GHG emissions from industrial processes (e.g., by producing low-carbon hydrogen as a fuel or feedstock). According to a National Renewable Energy Laboratory study, GHG emissions from the nuclear life cycle are significantly lower than for fossil fuels and comparable to those from low-carbon renewables (e.g., wind).

U.S. nuclear power generation has been largely flat for the past 25 years, as natural gas and renewable energy have captured most of the market for new capacity. Options for increasing nuclear energy capacity include expanding existing operational plants, restarting closed plants, building new conventional nuclear plants, and building new small modular reactors and other advanced design plants. Recent U.S. interest in new plants has focused on advanced reactors that could have different coolants, fuels, and other characteristics from conventional reactors.

In the United States, the most intense period of nuclear reactor startups was from 1973 to 1987, when 87 reactors began operating. Nuclear Regulatory Commission (NRC) review periods for U.S. license applications filed since 2006 have averaged 6 years. Worldwide construction times for reactors that started operating since 1980 have varied widely. Global data indicate that reactors that began operation in 2023 took an average of 10 years to construct. Construction costs have varied widely around the world. Nuclear power plant construction often has been subject to large cost overruns and schedule delays, sometimes leading to the abandonment of a project. The potential contribution of nuclear energy to climate change mitigation is strongly dependent on the speed of deployment. Factors affecting the speed of nuclear deployment—including cost, licensing, and construction time—may affect the contribution to climate change mitigation.

Although nuclear energy could support climate mitigation, nuclear energy also entails specific risks not associated with other forms of energy production, including weapons proliferation, safety with respect to radiological release, and other nuclear-specific incidents. The potential benefits of using nuclear energy for emissions mitigation can be assessed against these risks. Proliferation concerns focus especially on nuclear fuel cycle facilities, because some of these facilities can also be used to produce fissile material for nuclear warheads. The Atomic Energy Act of 1954 requires NRC to ensure that licensed nuclear facilities "provide adequate protection to the health and safety of the public." But nuclear incidents in the United States and other countries have underscored potential safety risks of nuclear power. Developing central storage and disposal sites for highly radioactive spent fuel from nuclear power plants has also proven difficult in the United States and globally.

The Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2024 (ADVANCE Act; Division B of P.L. 118-67) contains multiple provisions for streamlining the nuclear power plant licensing process and the efficiency of NRC. Some Members of Congress have expressed strong interest in NRC's implementation of the ADVANCE Act, and oversight may continue in the 119th Congress. If Congress chooses to promote further nuclear energy expansion, broad approaches could include speeding up the process of bringing new nuclear energy capacity online, providing direct financial support for nuclear capacity, and providing indirect support, such as funding for advanced reactor fuel supply and research and development (R&D). Risks related to nuclear power are continuing topics of congressional concern. Bills on these issues, such as the Nuclear Waste Informed Consent Act (H.R. 466, S. 101), have been introduced in the 119th Congress.

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Introduction

Congress has long been interested in nuclear energy policy in the context of climate change mitigation and for energy security, among other reasons. Congress has taken a range of legislative actions to facilitate nuclear power development, including legislation with provisions for streamlining the nuclear power plant licensing process. In the 118th Congress, for example, the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2024 (ADVANCE Act of 2024; Division B of P.L. 118-67) contained multiple provisions to encourage expansion of nuclear power, with key congressional supporters citing climate change mitigation as a primary goal.[1]

This report examines the potential for nuclear energy to play a role in achieving climate goals by providing low greenhouse gas (GHG) electricity generation, heat for industrial processes, and hydrogen to substitute for fossil fuel in transportation and other economic sectors. The report describes current nuclear power capacity, potential ways of increasing this capacity, and challenges to increasing capacity such as construction time, cost, and safety issues. This report presents an overview of selected legislation relevant to the potential nuclear contribution to climate change mitigation. It also discusses other considerations for Congress, such as the funding of advanced reactor demonstration projects and for the production of the specialized fuel needed for such reactors, as well as potential opportunity costs of funding nuclear energy in preference to other types of low-carbon energy technologies. The report concludes with a discussion of considerations for Congress.

Climate Change Context

A scientific consensus holds that human-caused GHG emissions increase the levels of GHGs in the atmosphere. This increase raises global average temperatures with corresponding increases in global net negative effects.[2] Global temperatures may be stabilized through a combination of GHG emissions reductions and removals such that net emissions are zero.[3] Taking measures to stabilize atmospheric GHG levels to reduce global climate change is known as *mitigation*.[4] Nuclear energy is among the technologies that could contribute to reducing GHG emissions by

[1] House Committee on Energy and Commerce, "Rodgers, Pallone, Carper, Capito Celebrate Signing of Bipartisan Nuclear Energy Bill, the ADVANCE Act," press release, July 9, 2024, https://energycommerce.house.gov/posts/rodgers-pallone-carper-capito-celebrate-signing-of-bipartisan-nuclear-energy-bill-the-advance-act-1. For example, statement by Sen. Tom Carper: "Today is a momentous day for our climate and America's clean energy future."

[2] K. Marvel et al., "Chapter 2: Climate Trends," in *Fifth National Climate Assessment*, ed. A. R. Crimmins et al. (U.S. Global Change Research Program, 2023) (hereinafter USGCRP, *Fifth National Climate Assessment*). The USGCRP stated, "With every additional degree of warming, the United States is expected to see increasingly adverse consequences"; see S. Hsiang et al., "Chapter 19: Economics," in USGCRP, *Fifth National Climate Assessment*. See also CRS In Focus IF12753, *Climate Change: What Are Net-Zero Emissions?*, by Jonathan D. Haskett. See also Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. V. Masson-Delmotte et al. (Cambridge University Press, 2021), Sections D1 and B2 (hereinafter IPCC, AR6 WGI SPM).

[3] Sam Fankhauser et al., "The Meaning of Net Zero and How to Get It Right," *Nature Climate Change*, vol. 12, no. 1 (2022), pp. 15-21. For further discussion, see CRS In Focus IF12753, *Climate Change: What Are Net-Zero Emissions?*, by Jonathan D. Haskett.

[4] National Aeronautics and Space Administration, "Responding to Climate Change," https://science.nasa.gov/climate-change/adaptation-mitigation/.

providing low-carbon energy to the electricity, transportation, building, and industrial sectors of the economy.[5]

Limiting global warming to a specific temperature level, such as 1.5ºC above pre-industrial temperatures, is seen as reducing the risk of adverse effects that may occur above that temperature.[6] Some observers have stated that at current levels total global emissions reductions are not consistent with keeping global average temperatures below this threshold.[7] Studies have found that the United States is not on track to reach an emissions reduction goal consistent with limiting global warming to 1.5ºC above pre-industrial temperatures.[8] As nuclear energy is considered a low-carbon source of energy, some have argued that nuclear energy could play a larger role in reducing U.S. GHG emissions—specifically in the electricity sector.[9] Others have questioned the role that nuclear energy could play in climate mitigation because of its relatively high costs, long periods needed for construction, potential risks for weapons proliferation, and issues of safety and nuclear waste.[10]

The challenges of promoting nuclear energy for mitigating climate change relate to the speed and cost of nuclear power construction and deployment, particularly as compared to other energy sources. For example, if nuclear energy is not deployed as quickly or as extensively as projected, it could be less effective at reducing emissions, and therefore at mitigating the negative effects of climate change, than alternative approaches. As a result, increased net adverse climate impacts could occur.[11] Policymakers could encounter an opportunity cost if finite funding resources were invested in nuclear energy projects that were delayed or never completed. In other words, investing in other GHG mitigation options (e.g., carbon capture and sequestration [CCS], renewables, energy efficiency) might have been more cost-effective and timelier for the purpose of climate change mitigation.

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[5] The term *low-carbon* does not have an exact definition but in common usage often refers to energy sources such as wind energy, solar energy, and nuclear energy, with median life cycle greenhouse gas emissions of less than 200 grams of carbon dioxide equivalent (CO_2e) per kilowatt-hour. A full discussion of the life cycle analysis of nuclear energy GHG emissions is included later in this report.

[6] IPCC, AR6 WGI SPM, Sections B.2 and D.1.

[7] Anne Olhoff et al., "Executive Summary," in *Emissions Gap Report 2024: No More Hot Air … Please! With a Massive Gap Between Rhetoric and Reality, Countries Draft New Climate Commitments*, United Nations Environment Programme (UNEP), 2024, states the following:

> The full implementation of unconditional and conditional NDCs [Nationally Determined Contributions] reduces expected emissions in 2030 by 4 and 10 per cent, respectively, compared with 2019 levels, whereas a 28 per cent reduction is needed for 2030 emissions to be aligned with 2°C and a 42 per cent reduction for 1.5°C. These estimates are also equivalent to those in last year's assessment. NDCs for 2035 need to reduce global emissions by 37 and 57 per cent below 2019 levels to be compatible with 2°C and 1.5°C, respectively.

[8] Some studies have found that reaching net zero GHGs by mid-century is consistent with keeping the global temperature increase at or below 1.5ºC. See IPCC, AR6 WGI SPM, Sections B.2 and D.1. For the United States, emissions reduction pathways that reach 50%-52% below 2005 levels by 2030 have been found consistent with reaching net-zero U.S. GHG emissions by mid-century. See Adam Fam and Sami Fam, "Review of the US 2050 Long Term Strategy to Reach Net Zero Carbon Emissions," *Energy Reports*, vol. 12 (2024), p. 845. Some studies have found that the United States is not on track to reach the goal of a 50%-52% emissions reduction by 2030. For further details, see CRS Report R47385, *U.S. Greenhouse Gas Emissions Trends and Projections from the Inflation Reduction Act*, by Jonathan L. Ramseur.

[9] Nuclear Energy Institute (NEI), "Clean Energy: Nuclear Energy Provides Nearly Half of America's Carbon-Free Electricity," https://www.nei.org/advantages/climate.

[10] M. Z. Jacobson, "The 7 Reasons Why Nuclear Energy Is Not the Answer to Solve Climate Change," Heinrich Böll Stiftung (Foundation), 2021, accessed December 22, 2024, https://eu.boell.org/en/2021/04/26/7-reasons-why-nuclear-energy-not-answer-solve-climate-change.

[11] J. Cao et al., "Nuclear Power: Deployment Speed—Response," *Science*, vol. 354, no. 6316 (2016), p. 1112.

Alternatively, some may argue that if nuclear energy does not receive sufficient support from policymakers, achieving net-zero GHG emissions would be less certain. Other climate mitigation technologies and approaches, such as CCS, renewables, and carbon dioxide removal directly from the atmosphere (CDR), have their own particular challenges.[12] Prioritizing these options over nuclear power may face different uncertainties, as some of these options, such as CDR, do not have the track record of conventional nuclear power.

Mitigating Climate Change with Nuclear Energy

Mitigating climate change may include reducing GHG emissions from electricity generation and converting energy consumption sectors—transportation, industrial, and buildings—to utilize electricity with lower GHG emissions.[13] Among sources of electricity generation, nuclear and hydropower generation are the only zero-emissions (at point of use) technologies that can provide 24-hour, dispatchable electricity.[14] Nuclear energy could also contribute to reducing GHG emissions from some industrial processes—for example, by producing low-carbon hydrogen as an industrial feedstock or alternative energy source.[15] These applications are discussed below.

Reducing Electricity Sector Greenhouse Gas Emissions

The electricity sector is currently the largest source of direct GHG emissions in the United States after the transportation sector.[16] This section examines the evolution of the U.S. electricity generation portfolio, including projections of future electricity demand, and describes low-carbon electricity generation sources and their potential applications.

Generation and Emissions Reduction Trends in the U.S. Electricity Sector

From the early 1970s until approximately 2010, electricity generation and emissions of carbon dioxide (CO_2) from the electricity sector followed similar trends, increasing in tandem.[17] Thereafter, the trends in emissions of CO_2 and electricity generation became decoupled. While electricity generation generally remained flat after 2010, CO_2 emissions generally decreased. The chronology of these trends, with a period of increase followed by a divergence between trends in emissions of CO_2 and electricity generation, is illustrated below (**Figure 1**).[18] This decoupling

[12] For further discussion, see CRS Report R48258, *Carbon Dioxide Removal (CDR): Its Potential Role in Climate Change Mitigation*, by Jonathan D. Haskett. See also CRS Report R44902, *Carbon Capture and Sequestration (CCS) in the United States*, by Angela C. Jones and Ashley J. Lawson.

[13] Liu Limin et al., "The Role of Nuclear Energy in the Carbon Neutrality Goal," *Progress in Nuclear Energy*, vol. 162 (2023), p. 104772 (hereinafter Limin et al., "The Role of Nuclear Energy in the Carbon Neutrality Goal").

[14] A source of electricity to the power grid that can be turned on or off rapidly in response to increasing or decreasing electricity demand is said to be *dispatchable*. Examples of dispatchable sources of electricity include battery storage and some hydropower generation plants.

[15] Limin et al., "The Role of Nuclear Energy in the Carbon Neutrality Goal."

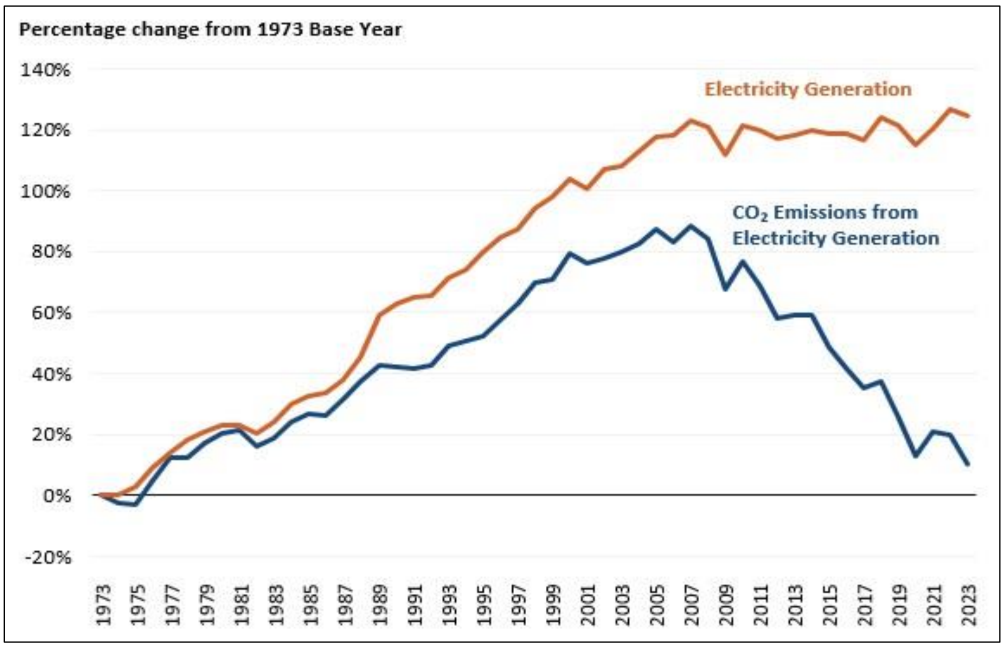
[16] For more information, see CRS Report R47561, *Greenhouse Gas Emissions in the U.S. Electricity Sector: Background, Policies, and Projections*, by Jonathan L. Ramseur. Statistics on energy, in one formulation, can include four sectors: electric power and the three consumption sectors (transportation, industry, and buildings), with the electricity used in the consumption sectors assigned to the electric power sector for statistical purposes. See also U.S. Environmental Protection Agency (EPA), "Inventory of U.S. Greenhouse Gas Emissions and Sinks," https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

[17] For details, see CRS Report R47561, *Greenhouse Gas Emissions in the U.S. Electricity Sector: Background, Policies, and Projections*, by Jonathan L. Ramseur.

[18] See CRS Report R47561, *Greenhouse Gas Emissions in the U.S. Electricity Sector: Background, Policies, and Projections*, by Jonathan L. Ramseur.

was due in large part to a shift from higher emissions energy sources to lower emissions energy sources.[19] During the period 2005-2023, electricity generation using coal, the source with the highest carbon emissions, fell from 50% of total U.S. electricity generation to 16%.[20] During the same period, electricity generation using natural gas, which has carbon emissions at least 40% lower than coal, increased from 19% to 43% of total U.S. electricity generation.[21] Generation from renewable energy sources, which do not have direct GHG emissions, increased from 9% to 21% of total U.S. electricity generation during this period.[22] Nuclear energy, which also does not have direct GHG emissions, remained approximately flat after 1990, at about 18%-20% of total annual electricity generation.[23] In short, nuclear energy has played a limited role in the decrease in emissions for electricity generation since 2010.

Figure 1. U.S. Electricity Sector Generation and CO_2 Emissions from Electricity Generation, 1973-2023



Source: Prepared by CRS; data from EIA, "Monthly Energy Review," Table 7.2a (net electricity generation) and Table 11.6 (CO_2 emissions), https://www.eia.gov/totalenergy/data/monthly/.

Notes: Electricity generation (all sectors) in this figure is annual, net electricity generation from all sources, measured in gigawatt hours. Does not include electricity generation from small-scale solar photovoltaic generation.

[19] See CRS Report R47561, *Greenhouse Gas Emissions in the U.S. Electricity Sector: Background, Policies, and Projections*, by Jonathan L. Ramseur.

[20] Energy Information Administration (EIA), "Electricity Explained: Electricity Generation, Capacity, and Sales in the United States," updated July 16, 2024, https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php (hereinafter EIA, "Electricity Explained"). These values include generators of 1 MW or greater. See also CRS Report R47521, *Electricity: Overview and Issues for Congress*, by Ashley J. Lawson. Fossil fuels emit different amounts of CO_2 emissions per unit of electricity generated, often described as *carbon intensity*. See also CRS Report R47561, *Greenhouse Gas Emissions in the U.S. Electricity Sector: Background, Policies, and Projections*, by Jonathan L. Ramseur.

[21] EIA, "Electricity Explained." These values include generators of 1 MW or greater.

[22] EIA, "Electricity Explained."

[23] EIA, "Electricity Explained." See also CRS Report R47561, *Greenhouse Gas Emissions in the U.S. Electricity Sector: Background, Policies, and Projections*, by Jonathan L. Ramseur.

Projections of Electricity Demand

After a period of little to no growth (**Figure 1**), some observers project that electricity demand in the United States may increase. The *2024 Long Term Reliability Assessment* of the North American Electric Reliability Corporation (NERC) found that "electricity peak demand and energy growth forecasts over the 10-year assessment period [2025-2034] continue to climb; demand growth is now higher than at any point in the past two decades."[24] The assessment also states that the "continued adoption of electric vehicles and heat pumps is a substantial driver for demand around North America."[25] The U.S. Department of Energy (DOE) has projected that electricity demand will increase by about 15%-20% by 2034 due to the increasing energy requirements of data centers, new domestic manufacturing, and the ongoing electrification of some sectors of the economy.[26] Further, DOE has projected that achieving net-zero GHG emissions by 2050 would result in a doubling of electricity demand because it would require carbon-intensive sectors to be shifted to low-carbon electricity.[27]

Growth in electricity demand makes climate mitigation through emissions reduction more difficult. If electricity demand is level or growing slowly, emissions reductions in the electricity sector can be achieved by gradually increasing the proportion of low-carbon electricity in the generation portfolio. If demand for electricity is increasing rapidly, a proportionally greater increase in the supply of low-carbon electricity would be needed in order to maintain an ongoing trend of emissions reduction. Such an increase may be more difficult to achieve than a more gradual increase.

Types of Low-Carbon Electricity Sources

Sources of low-carbon electricity differ with respect to whether they are continuously or intermittently available, and whether their level of power generation can be easily increased and decreased to meet changes in demand. These characteristics affect grid operations and the integration of low-carbon electricity sources into reliably meeting electricity demand.[28]

Low-emissions power generation that obtains energy from intermittently available sources such as solar radiation (i.e., insolation) and wind has lower dispatchability than thermal power plants. They are sometimes referred to as *variable renewable energy (VRE) sources*. Other renewable energy sources such as hydropower, biomass combustion, and geothermal are not intermittent and are not considered VRE. VRE sources have been decreasing in cost and increasing in cumulative installed generation capacity, accounting for an increasing percentage in annual generation over the past 20 years.

In the United States, the fleet of commercial nuclear power reactors is the largest single source of low-emissions electricity, generating electricity at an average of more than 90% of its total capacity.[29] Nuclear reactors typically operate at full power all the time because of operational limits on rapid increases or decreases in power levels, and to maximize electricity generation to

[24] North American Electric Reliability Corporation (NERC), "2024 Long-Term Reliability Assessment," 2024, p. 8.

[25] NERC, "2024 Long-Term Reliability Assessment," 2024, p. 8.

[26] U.S. Department of Energy (DOE), "Topic Brief: How Clean Energy Is the Solution to Rising Electricity Demand," https://liftoff.energy.gov/wp-content/uploads/2024/08/Liftoff-Topic-Brief_Demand-Growth_Aug-26_vF-1.pdf.

[27] DOE, "Topic Brief: How Clean Energy Is the Solution to Rising Electricity Demand."

[28] For additional discussion, see CRS Report R45764, *Maintaining Electric Reliability with Wind and Solar Sources: Background and Issues for Congress*, by Ashley J. Lawson.

[29] Each reactor constitutes the main element of a generating unit of a nuclear power plant, which may have multiple units.

cover their relatively high fixed costs.[30] Other low-carbon sources such as biomass and conventional hydropower generation can be continuously available and can also be ramped up and down rapidly to meet changing electricity demand, but this capacity is sometimes limited by water restrictions. To systematically reduce GHG emissions from the electricity sector, these disparate types of electricity sources need to be integrated to ensure that an adequate supply of electricity is reliably available at all times.

Potential for Nuclear Power to Reduce Greenhouse Gas Emissions

Electricity Generation

Nuclear energy can play a role in GHG emissions reduction in the electricity sector by providing a source of low-carbon electricity. Nuclear energy is currently the largest individual source of low-carbon electricity.[31]

Nuclear energy can provide nearly continuous generation to serve "baseload" demand, a role that nuclear energy has filled for economic and technical reasons.[32] However, nuclear energy has some limitations that potentially could reduce its ability to contribute to future GHG emissions reductions in the power sector.

Researchers have evaluated potential pathways to achieving a zero-emissions U.S. electricity sector (in some cases by 2035 and in others by 2050).[33] While specific technology pathways and

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[30] The *time-adjusted capacity factor* is a measure of how often a type of electricity generation is operational for a period of time. Using this measure, EIA found that for the years 2014-2023, utility-scale electricity generation had a capacity factor greater than 90% for all years, meaning that it was providing more than 90% of its maximum potential electricity output annually. See EIA, "Frequently Asked Questions: What Is the Difference Between Electricity Generation Capacity and Electricity Generation?" https://www.eia.gov/tools/faqs/faq.php?id=101&t=3#:~:text=Capacity%20factor%20of%20electricity%20generation,of%20the%20monthly%20capacity%20factors. See also EIA, "Electric Power Monthly: Table 6.07.B. Capacity Factors for Utility Scale Generators Primarily Using Non-Fossil Fuels," https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b.

[31] EIA, "Frequently Asked Questions (FAQs): What Is U.S. Electricity Generation by Energy Source?" https://www.eia.gov/tools/faqs/faq.php?id=427&t=3. See also EIA, "Electricity Explained," https://www.eia.gov/energyexplained/electricity/use-of-electricity.php.

[32] The International Atomic Energy Agency (IAEA) has stated that steady, near full capacity, baseload operation of nuclear power plants is often considered the most efficient use of capital investment for the following reasons:

- Constant thermal/electrical power operation is easier with fewer changes in plant condition.
- Nuclear power plants have high capital costs, but relatively low variable costs (fuel costs), so operating plants at full load minimizes the average operating cost of nuclear generation.
- Baseload operation may lead to more efficient utilization of nuclear fuel as the thermal output during a fuel cycle is better predicted and core design is optimized.
- Design and licensing of plants are simpler for operation at constant load, as degradation in design and safety margins as plant ages vary more predictably and can be better anticipated during the design.
- Non-baseload operation may require increased maintenance and monitoring, and may complicate the reliability and ageing assessments of some systems, structures and components.

List quoted from IAEA, *Non-Baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation*, IAEA Nuclear Energy Series No. NP-T-3.23, 2018, p. 6. EIA defines *baseload* as "the minimum amount of electric power delivered or required over a given period of time at a steady rate." EIA, "Glossary," https://www.eia.gov/tools/glossary/?id=B#:~:text=Base%20load:%20The%20minimum%20amount, around%2Dthe%2Dclock%20basis.

[33] For a summary of major zero-emissions electricity studies conducted between 2019 and 2021, see Table 2 of CRS Report R46691, *Clean Energy Standards: Selected Issues for the 117th Congress*, by Ashley J. Lawson. See also Paul Denholm et al., "Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035," National Renewable (continued...)

cost estimates vary depending upon researchers' assumptions, studies generally find that a zero-emissions electricity sector would require deployment of wind and solar technologies at a faster pace than has been done to date. Additionally, other sources are likely needed to "balance" wind and solar—to provide electricity when the wind is not blowing or the sun is not shining. Balancing sources could be nuclear in addition to battery storage; hydrogen; or other renewables, such as hydropower generation or geothermal. Other options to promote electricity supply and demand balancing include flexible load (i.e., large electricity users that can reduce their consumption in response to changing electricity supply) and expanded transmission capacity.

If trends since 2005 in the evolution of the U.S. electricity portfolio continue, it is likely that the proportion of wind and solar electricity sources would continue to increase. Due to the intermittent nature of these electricity sources, an increased level of flexibility in meeting electricity demand could be needed from other sources of electricity. For technological and safety reasons, nuclear power plants generally cannot respond as quickly as some others (such as some natural gas generation and hydropower generation) to rapid changes in electricity supply and demand.[34] There is ongoing research on the development of advanced nuclear reactor designs, including small modular reactors (SMRs) with increased capability to flexibly increase and decrease their output, that could be better integrated with a changing electricity generation portfolio such as that associated with VRE sources such as wind and solar.[35]

There is debate about the future possibilities of integrating nuclear energy with VREs in the electrical grid. Some say that the economic incentives of nuclear energy and VREs are fundamentally misaligned due to the potential for one form of energy to exclude the other by competition in the marketplace. By contrast, others say that the flexible generation capacity of SMRs will allow effective integration of these energy sources in a hybrid system.[36] Currently, nuclear energy in the United States is not generally used to respond to rapidly shifting changes in electricity supply and demand, including those from VREs.

With respect to achieving net-zero emissions from the U.S. electricity sector and net-zero GHG emissions in the United States—a goal of some Members of Congress—some research suggests

Energy Laboratory Report NREL/TP-6A40-81644, 1885591, MainId: 82417, 2022. See also International Energy Agency (IEA), *Net Zero by 2050—A Roadmap for the Global Energy Sector*, IEA Special Report, 2021 (hereinafter IEA, *Net Zero by 2050*).

[34] The generators within power plants that produce electricity differ in the rates at which they can respond to changes in electricity supply and demand. See also Shannon Bragg-Sitton et al., "Flexible Nuclear Energy for Clean Energy Systems," Joint Institute for Strategic Energy Analysis (JISEA), Clean Energy Ministerial (CEM), Clean Energy Future (NICE Future) Initiative, 2020:

> While very useful, core ramping has limitations. From a physics perspective, reducing core power results in the buildup of neutron absorbing isotopes that limit rapid cyclical ramping of core power. Additionally, reducing or increasing core power rapidly changes fuel temperatures, which can cause thermal and mechanical stresses that limit ramping rate and could potentially reduce fuel lifetime.

[35] Zhibo Zhang and Jin Jiang, "On Load-Following Operations of Small Modular Reactors," *Progress in Nuclear Energy*, vol. 173 (2024), p. 105274.

[36] P. Hockenos, "Why Nuclear Power and Renewables Don't Mix," *Energy Transition: The Global Energiewende*, 2022, https://energytransition.org/2022/11/why-nuclear-power-and-renewables-dont-mix/. See also S. Krikorian, "Nuclear and Renewables: Playing Complementary Roles in Hybrid Energy Systems," IAEA, 2019, https://www.iaea.org/newscenter/news/nuclear-and-renewables-playing-complementary-roles-in-hybrid-energy-systems. An example of a flexible SMR is the Natrium nuclear power plant demonstration planned in Wyoming. It would store heat from a reactor in large tanks of molten salt, from which rapidly varying levels of electricity could be generated. See TerraPower, "The Plant," https://www.terrapower.com/natrium.

that the deployment of VREs is likely to increase and that there may be a load balancing role for nuclear energy in addition to providing continuous baseload electricity.[37]

Increases in nuclear power generation could help reduce GHG emissions from overall electricity generation. This in turn could enhance the emissions reduction effects of increasing the electrification of other sectors of the economy, such as transportation, buildings, and industrial processes.[38] When electrification is combined with low-carbon electricity sources, additional emissions reductions may be achieved.[39]

Nuclear Energy for Heat and Hydrogen in Emissions Reductions

Nearly all commercial nuclear energy in the United States is currently used for electricity generation, but the nuclear industry and its supporters assert that nuclear technologies could also provide a source of energy (other than electricity) for some industrial processes, such as process heating. The industrial sector consumed 35% of end-use energy in the United States in 2023, according to the U.S. Energy Information Administration (EIA). Of that amount, 42% was from natural gas, 33% from petroleum, 9% from renewables, 3% from coal, and 13% from electricity from various other sources.[40] In the EIA dataset, no nuclear energy consumption was directly attributable to the industrial sector, though some projects have begun development since the collection of that data, as discussed below.

High-Temperature Heat

High-temperature heat is required for a wide range of industrial processes, such as melting metal, refining petroleum, and manufacturing chemicals. According to DOE, "Process heat is the most significant source of energy use and greenhouse gas emissions in the industrial sector, accounting for about 50% of all onsite energy use and 30% of greenhouse gas emissions."[41]

Some advanced nuclear reactor designs may be able to supply high-temperature heat for these industrial processes. Existing commercial light water reactors (LWRs) cannot supply the high-temperature heat required for most industrial processes.[42] According to DOE, "The coolant outlet temperature in conventional LWRs is limited to about 300°C [570°F], precluding process heat applications that require much higher outlet temperatures."[43] Advanced reactor designs, such as high-temperature gas-cooled reactors, could produce heat at temperatures up to 950°C (1,740°F), and possibly higher with the development of new heat-resistant materials.[44] Some analysts have

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[37] IEA, *Net Zero by 2050*, pp. 57 and 178. See also CRS Report R47521, *Electricity: Overview and Issues for Congress*, by Ashley J. Lawson. See also Nuclear Energy Agency, Organization for Economic Cooperation and Development, "The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables," NEA No. 7299, 2019, p. 212.

[38] DOE, *Pathways to Commercial Liftoff: Industrial Decarbonization*, Pathway to Commercial Liftoff Reports, 2023.

[39] DOE, *Pathways to Commercial Liftoff: Industrial Decarbonization*.

[40] EIA, "U.S. Energy Facts Explained," July 15, 2024, https://www.eia.gov/energyexplained/us-energy-facts.

[41] DOE, "Process Heat Basics," accessed February 24, 2024, https://www.energy.gov/eere/iedo/process-heat-basics.

[42] LWRs use ordinary (light) water for cooling and for moderating (slowing) the neutrons in the nuclear chain reaction. Other types of reactors may use different coolants and moderators.

[43] DOE, "Chapter 4: Advancing Clean Electric Power Technologies, Technology Assessments, Light Water Reactors," in *Quadrennial Technology Review 2015*, 2015, https://www.energy.gov/sites/default/files/2016/01/f28/QTR2015-4M-Light-Water-Reactors.pdf.

[44] DOE, "Chapter 4: Advancing Clean Electric Power Technologies, Technology Assessments, Light Water Reactors," in *Quadrennial Technology Review 2015*, 2015, https://www.energy.gov/sites/default/files/2016/01/f28/QTR2015-4M-Light-Water-Reactors.pdf.

identified potential applications for nuclear heat generation in the chemical, petroleum refining, food and beverage, and pulp and paper sectors.[45]

For example, a high-temperature gas-cooled nuclear power plant is currently planned for the Dow Seadrift chemical manufacturing site in Texas. The nuclear plant is to provide heat and power from four reactors designed by X-energy, each with 80 megawatts (MW) of electric generating capacity. Construction is scheduled to start in 2026, with operation to begin by 2030. The project developers expect the project to reduce the manufacturing site's GHG emissions by 440,000 million tons per year.[46] DOE awarded X-energy up to $1.2 billion in 2020 to cover up to half the costs of the first demonstration reactor and a fuel fabrication facility under the Advanced Reactor Demonstration Program.[47]

Hydrogen

Another potential non-electric application of nuclear energy is the production of hydrogen. Currently, hydrogen is used primarily in the petroleum and chemical industries, but it could potentially be used more widely to replace fossil fuels in transportation and other sectors of the economy.[48] Hydrogen is currently produced in the United States mostly from natural gas.[49] DOE has supported four demonstration projects at existing nuclear power plants to produce hydrogen through low-temperature electrolysis, in which electricity generated by the plants is used to split water into hydrogen and oxygen.[50] High-temperature advanced reactors could potentially produce hydrogen more efficiently through high-temperature steam electrolysis and thermochemical processes that would not require electricity.[51] Steam from existing commercial reactors could also be used for high-temperature steam electrolysis.[52]

GHG Emissions from Nuclear Technology

Advocates for the use of nuclear technology in climate change mitigation have stated that nuclear technology is a low GHG emissions energy source.[53] Others have questioned this assertion,

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[45] Tess Moran and Doug Vine, *Advanced Nuclear Process Heat for Industrial Decarbonization*, Center for Climate and Energy Solutions, July 2024, p. 5, https://www.c2es.org/wp-content/uploads/2024/07/Advanced-Nuclear-Process-Heat-for-Industrial-Decarbonization.pdf.

[46] X-energy, "Advanced Nuclear Reactor Project in Seadrift, Texas," https://x-energy.com/seadrift.

[47] X-energy, "Dow and X-energy Advance Efforts to Deploy First Advanced Small Modular Nuclear Reactor at Industrial Site Under DOE's Advanced Reactor Demonstration Program," press release, March 1, 2023, https://x-energy.com/media/news-releases/dow-and-x-energy-advance-efforts-to-deploy-first-advanced-small-modular-nuclear-reactor-at-industrial-site-under-does-advanced-reactor-demonstration-program.

[48] For information about the production and distribution of hydrogen, see CRS Report R47289, *Hydrogen Hubs and Demonstrating the Hydrogen Energy Value Chain*, by Martin C. Offutt. See also CRS Report R47487, *The Hydrogen Economy: Putting the Pieces Together*, by Martin C. Offutt.

[49] For details, see CRS Report R48196, *Hydrogen Production: Overview and Issues for Congress*, by Lexie Ryan.

[50] DOE Office of Nuclear Energy, "Nine Mile Point Begins Clean Hydrogen Production," March 7, 2023, https://www.energy.gov/ne/articles/nine-mile-point-begins-clean-hydrogen-production.

[51] Marek Jaszczur et al., "Hydrogen Production Using High Temperature Nuclear Reactors: Efficiency Analysis of a Combined Cycle," *International Journal of Hydrogen Energy*, vol. 41, no. 19 (May 25, 2015), p. 7861, https://www.sciencedirect.com/science/article/abs/pii/S0360319916308710.

[52] Tyler Westover et al., "Preconceptual Designs of Coupled Power Delivery Between a 4-Loop PWR and 100-500 MWe HTSE Plants," Idaho National Laboratory, April 2023, https://lwrs.inl.gov/Flexible%20Plant%20Operation%20and%20Generation/PWR-500MW-HTSE.pdf.

[53] See, for example, Nuclear Energy Institute (NEI), "Clean Energy: Nuclear Energy Provides Nearly Half of America's Carbon-Free Electricity," https://www.nei.org/advantages/climate.

contending that while the direct generation of electricity by nuclear energy does not produce GHG emissions, the other stages of the full life cycle of nuclear energy—mining, processing of the fuel, and construction and decommissioning the plants—do produce emissions, thus reducing nuclear power's effectiveness as a climate mitigation strategy.[54] This section presents information on GHG emissions associated with the nuclear energy life cycle, including information from a 2021 review by the National Renewable Energy Laboratory (NREL) of life cycle analysis studies. That review found that GHG emissions from the nuclear life cycle were significantly lower than those of fossil fuels and were comparable to those of low-carbon renewable electricity generation sources (e.g., wind and solar).

GHG Emissions from the Nuclear Energy Life Cycle

GHG emissions can come from every stage of the process that leads to the generation of nuclear power, collectively referred to as the *nuclear energy life cycle*, which includes plant construction, site decommissioning, and the nuclear fuel cycle. There are wide variations in emissions from each stage, depending on the technology and energy sources used. The main stages of the nuclear fuel cycle are uranium mining, uranium milling, conversion to uranium hexafluoride, enrichment in the fissile isotope U-235, fabrication of fuel assemblies, nuclear fission in a reactor, spent nuclear fuel storage, spent nuclear fuel reprocessing (not currently done commercially in the United States), and permanent waste disposal (spent fuel). Stages of the nuclear energy life cycle and their potential for GHG emissions are presented in the **Appendix** to this report.

Life Cycle GHG Emissions from Nuclear Energy in Comparison with Other Sources of Electrical Energy

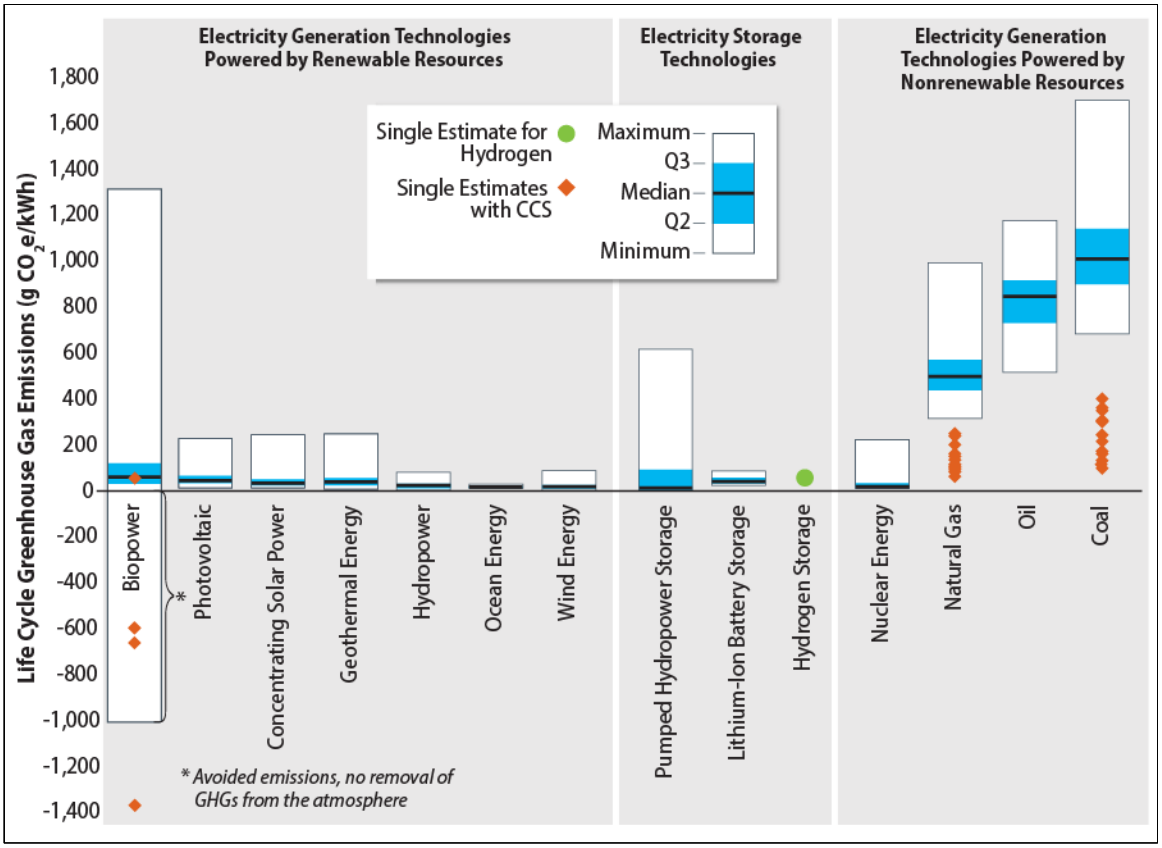
Life cycle analysis (LCA) has been applied to the various stages related to the development and use of nuclear energy to develop a complete estimate of GHG emissions associated with it. LCA has been defined as the "compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle."[55] A systematic review of LCA studies of GHG emissions from electricity generation by the NREL, which synthesized the results of a wide range of studies, found that the median life cycle emissions from nuclear electricity generation were comparable to those of low-carbon generation sources such as wind and solar, and lower than those of fossil fuel sources such as coal and natural gas generation (**Figure 2**).[56]

[54] J. Weber, "Fact Check: Is Nuclear Energy Good for the Climate?" *Deutsche Welle: Nature and Environment—Global Issues*, 2021, https://www.dw.com/en/fact-check-is-nuclear-energy-good-for-the-climate/a-59853315.

[55] Stefanie Hellweg and Llorenç Milà i Canals, "Emerging Approaches, Challenges and Opportunities in Life Cycle Assessment," *Science*, vol. 344, no. 6188 (2014), p. 1109.

[56] Scott Nicholson and Garvin Heath, "Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update," National Renewable Energy Laboratory, 2021, https://www.nrel.gov/docs/fy21osti/80580.pdf. See also similar results in T. Gibon et al., "Life Cycle Assessment of Electricity Generation Options," United Nations Economic Commission for Europe, November 1, 2021, https://doi.org/10.13140/RG.2.2.24717.67048.

Figure 2. Life Cycle Greenhouse Gas Emissions Estimates for Selected Electricity Generation and Storage Technologies, and Some Technologies Integrated with Carbon Capture and Storage (CCS)



Source: Adapted by CRS from National Renewable Energy Laboratory (NREL), "Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update," https://www.nrel.gov/docs/fy21osti/80580.pdf.

Notes: NREL obtained and compared estimates of life cycle greenhouse gas emissions for electricity generation and storage technologies. The number of estimates and sources varied by technology.

Developing Nuclear Energy Capacity

This section presents information on current nuclear capacity and on options for increasing nuclear energy capacity in the United States and globally.

Current Nuclear Energy Capacity

The United States has the largest nuclear power industry in the world, with 94 licensed reactors that have a total of 97,000 MW of electric generating capacity.[57] U.S. nuclear power generation has been largely flat for the past 25 years, as natural gas and renewable energy have captured

[57] EIA, "Nuclear & Uranium," January 24, 2025, https://www.eia.gov/nuclear/generation.

most of the market for new electric generating capacity.[58] The newest U.S. reactors began commercial operation in July 2023 and April 2024 at the Vogtle nuclear power plant in Georgia.[59]

Worldwide, there are 441 operating commercial reactors with total capacity of 400,000 MW. Leading countries outside the United States are France, with 57 reactors and 63,000 MW of capacity; China, with 58 reactors and 57,000 MW of capacity; and Russia, with 36 reactors and 27,000 MW of capacity. China currently has the world's largest nuclear construction program, with 29 reactors and 33,000 MW of capacity now being built.[60]

Increasing Nuclear Energy Capacity

Options for increasing nuclear energy capacity include expanding capacity at existing operational plants (uprating), restarting closed or "mothballed" plants, building new conventional nuclear plants, and building new small modular reactors and other advanced design plants. These options are not mutually exclusive, and each option comes with its own considerations.

Nuclear expansion around the world is currently dominated by large, conventional designs that are similar to existing reactors. This includes nearly all of the 64 reactors, with total capacity of 69,000 MW, now under construction in 14 countries. Conventional reactors have the advantage of using technology that has worldwide supply chains and operational knowledge. A major disadvantage can be the high costs and long construction delays experienced by several recent projects. For example, the new Vogtle reactors in Georgia were delayed by seven years and cost twice their initial estimate of $14 billion.[61]

Recent U.S. interest in nuclear power expansion has focused on advanced reactors that could have different coolants, fuels, and other characteristics from conventional reactors. Many proposed designs would be small modular reactors that are intended to be faster and less costly to build than conventional reactors, but may use similar technology as conventional reactors. However, whether such designs could achieve those goals has yet to be demonstrated. DOE is currently supporting the construction of advanced reactor demonstrations in Wyoming and Texas.[62]

Restarting closed reactors could be a faster option for increasing capacity, but it is limited to reactors that have been closed but still maintained in good condition. Two closed U.S. reactors have been proposed for restart, the Palisades plant in Michigan and Three Mile Island Unit 1 in Pennsylvania. The owner of another closed reactor, Duane Arnold in Iowa, has filed an application for possible restart.[63] Japan currently has the world's largest restart effort, after halting operation of all its nuclear plants after the 2011 Fukushima disaster (discussed later in this report). Since then, Japan has restarted 14 reactors and has 11 more seeking restart approval.[64]

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[58] EIA, *Short-Term Energy Outlook*, November 2024, https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf.

[59] EIA, "Plant Vogtle Unit 4 Begins Commercial Operation," May 1, 2024, https://www.eia.gov/todayinenergy/detail.php?id=61963.

[60] World Nuclear Association, "World Nuclear Power Reactors & Uranium Requirements," December 21, 2024, https://world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.

[61] EIA, "First New U.S. Nuclear Reactor Since 2016 Is Now in Operation," August 1, 2023, https://www.eia.gov/todayinenergy/detail.php?id=57280.

[62] For more information, see CRS Report R45706, *Advanced Nuclear Reactors: Technology Overview and Current Issues*, by Mark Holt

[63] "NextEra Files with NRC for Potential Duane Arnold Restart," *Nuclear News*, January 28, 2025, https://www.ans.org/news/2025-01-28/article-6722/nextera-files-with-nrc-for-potential-duane-arnold-restart.

[64] World Nuclear Association, "Nuclear Power in Japan," December 18, 2024, https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.

Nuclear generation can also be increased by capacity uprates at existing plants, typically by replacing components to increase overall capacity. The Nuclear Regulatory Commission (NRC), an independent agency that licenses and regulates the use of nuclear energy, reports that it has approved uprates totaling 8,000 MW of electric generating capacity since the 1970s.[65] Relatedly, some nuclear plants can produce more power by improving their capacity factor, which measures the amount of rated generating capacity that is actually used. The U.S. nuclear capacity factor has exceeded 90% for the past decade, so there is relatively little room for domestic improvement.[66] In comparison, the world nuclear capacity factor for the past two decades has averaged about 80%, indicating that more generation from existing plants in other countries could be feasible.[67]

Timelines and Scope of Past Nuclear Expansion

An aspect of nuclear energy that may influence the effectiveness of its contribution to climate change mitigation is the speed at which increased nuclear capacity can be brought online. This section presents information on why emissions reductions from the use of nuclear energy that occur sooner are more effective, in terms of climate change mitigation, than those that occur later. Those that occur at a later time would contribute to mitigation, but not as much. The section then presents historical examples of how nuclear development timelines have been implemented in the United States and other countries.

Importance of Development Speed from a Climate Perspective

Due to the long atmospheric residence time of CO_2, and its chemical inertness, emissions of CO_2 are essentially cumulative. Halting emissions at an earlier time results in lower cumulative emissions and lower adverse effects than halting emissions at a later time.[68] For this reason, emissions reductions that happen sooner contribute more to reducing adverse effects than emissions reductions that would happen at a later time. Climate scientists have modeled a timeline scenario of emissions reductions that includes reaching net-zero GHG emissions by 2050. This scenario is consistent with keeping global temperatures from exceeding the climate goals set out in international climate agreements.[69] For example, the Paris Agreement under the United Nations Framework Convention on Climate Change has goals of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels."[70]

The lower the temperature at which stabilization occurs, the lower the frequency and intensity of net adverse climate effects. The more rapidly nuclear power may be able to provide low-carbon

[65] Nuclear Regulatory Commission (NRC), "Backgrounder on Power Uprates for Nuclear Plants," January 2022, https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/power-uprates.html.

[66] EIA, *Monthly Energy Review*, January 2025, Table 8.1, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

[67] World Nuclear Association, "Global Nuclear Industry Performance," August 20, 2024, https://world-nuclear.org/our-association/publications/world-nuclear-performance-report/global-nuclear-industry-performance.

[68] K. Marvel et al., "Chapter 2: Climate Trends," in USGCRP, *Fifth National Climate Assessment*. See also IPCC, AR6 WGI SPM.

[69] "Chapter 32: Mitigation," in USGCRP, *Fifth National Climate Assessment*, p. 32-6.

[70] United Nations Framework Convention on Climate Change (UNFCCC), Paris Agreement, 2015 p. 3, Article 2(a). See also UNFCCC, "The Paris Agreement: What Is the Paris Agreement?" https://unfccc.int/process-and-meetings/the-paris-agreement. On January 20, 2025, President Trump issued an executive order for the United States to withdraw from the Paris Agreement. See Executive Order 14162 of January 20, 2025, "Putting America First in International Environmental Agreements," 90 *Federal Register* 8455, January 30, 2025, https://www.govinfo.gov/content/pkg/FR-2025-01-30/pdf/2025-02010.pdf.

energy that substitutes for high-carbon energy sources, the more it could reduce cumulative emissions, allowing global temperatures to stabilize at a correspondingly lower level. For this reason, the potential contribution of nuclear energy to climate change mitigation is strongly dependent on the speed of deployment. Factors affecting nuclear deployment include mobilization of finance, regulatory review and licensing, time of construction, availability of a trained workforce, specialized industrial capacity such as large forging of reactor components, and others that may affect the speed at which nuclear energy can contribute to the process of emissions reductions.

Timelines of Nuclear Construction for the United States and Internationally

The pace of nuclear reactor startups has varied widely since the beginning of the nuclear power industry in the late 1950s.[71] Worldwide, the time period with the highest annual average number of reactors that began operation was from 1971 to 1990 (**Table 1**). During that historically high-construction period, 395 reactors started operating. Annual startups ranged from 8 in 1979 to 33 in each of 1983 and 1984, with an average of just under 20 per year during the 1971-1990 period.[72]

In the United States, the most intense period of reactor startups was from 1973 to 1987, when 87 reactors began operating, with total electric generating capacity of 79,299 MW. The annual construction rate ranged from no reactors in 1979 to 14 in 1974, with an annual average of almost 6 reactors and generating capacity additions of 5,287 MW during the 1973-1987 period.[73]

The peak construction period in France, which is notable for its construction series using standard designs, took place from 1978 to 1990. During that period, 49 reactors began operating, with annual construction rates ranging from none in 1989 to 8 in 1981. On average, nearly 4 started up per year, providing 3,988 MW of electric generating capacity (for a total of 51,840 MW).[74] Japan, which built about the same total number of reactors as France, had a relatively steady peak construction period of about 2 per year from 1974 to 1996. A total of 40 reactors began operating during that period, with generating capacity of 40,424 MW (averaging 1,758 MW per year, or nearly 2 reactors).[75]

The world's largest current reactor construction program is in China, which started later than other major nuclear-energy-generating countries but is still opening new plants at a steady pace. From 2010 to 2023, China began operating 41 new reactors with total capacity of 44,714 MW, for

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[71] The exact date when a reactor is considered to start operating can vary according to what criteria are used. Startup designations can range from first connection to the electrical grid to a declaration of commercial operation some months later.

[72] M. Schneider et al., *World Nuclear Industry Status Report 2024*, September 2024, https://www.worldnuclearreport.org/IMG/pdf/wnisr2024-v2.pdf (see IAEA data from the Power Reactor Information System, p. 49).

[73] U.S. Council for Energy Awareness (since combined into the Nuclear Energy Institute), "Historical Profile of U.S. Nuclear Power Development," 1993. For a discussion of the conditions that led to the earlier periods of nuclear power expansion in the United States and around the world, see IAEA, "50 Years of Nuclear Energy," https://www.iaea.org/sites/default/files/gc/gc48inf-4-att3_en.pdf.

[74] World Nuclear Association, "Nuclear Power in France," December 17, 2024, https://world-nuclear.org/information-library/country-profiles/countries-a-f/france; and Statista, "Active Nuclear Reactors in France in 2023, by Year of Connection to the Grid," 2024, https://www.statista.com/statistics/462168/nuclear-reactors-in-france-by-year-of-grid-connection.

[75] World Nuclear Association, "Nuclear Power in Japan," December 18, 2024, https://world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.

an average of three per year (3,194 MW). China currently has 29 reactors under construction, with 30,827 MW of electric generating capacity, the most capacity under construction in the world.[76] Other countries that have had significant reactor construction programs include Russia, Germany (which has since closed all its reactors due to safety concerns), the United Kingdom, South Korea, India, and Canada.[77]

Table 1. Peak Nuclear Plant Deployment Periods, Selected Countries

Capacity in Megawatts

Country	Years	Reactors Completed	Average Reactors/Year	Capacity	Average Capacity/Year
United States	1973-1987	87	5.8	79,299	5,287
Japan	1974-1996	41	1.8	40,425	1,758
France	1978-1990	49	3.8	51,840	3,988
China	2010-2023	41	2.9	44,724	3,194

Source: World Nuclear Association, country profiles for Japan, France, and China, https://world-nuclear.org/information-library; International Atomic Energy Commission, Power Reactor Information System, United States of America, https://pris.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=US.

If policies were implemented immediately to expand nuclear power capacity for low-carbon energy, new reactors would not begin coming on line until planning, design, licensing, and construction have been completed. The time required for these steps has widely varied in the past. In addition, previous national experience has shown that early reactor startups were spaced relatively far apart until supply chains were better established and trained workforces mobilized, allowing startup frequency to increase.

NRC review periods for license applications filed since 2006 have averaged 6 years, ranging from 1.4 years for a construction permit for the Hermes 2 test reactor in Tennessee to 10.2 years for a combined construction permit and operating license for the Levy 1 and 2 commercial power plant (on which construction was deferred) in Florida.[78]

Worldwide construction times for reactors that started operating since 1980 have varied widely as well, with no clear trend during that period. Reactors that started up during 1996-2000 averaged 10 years of construction, while reactors that began operating during the subsequent five years, 2001-2005, averaged half that time. Most recently, global data indicate that reactors that began operation in 2022 required an average of 8.5 years to construct, while those that began operation in 2023 took an average of 10 years.[79]

[76] World Nuclear Association, "Nuclear Reactors in China," https://world-nuclear.org/nuclear-reactor-database/summary/China.

[77] A description of the history of nuclear power in Germany can be found at World Nuclear Association, "Nuclear Power in Germany," July 8, 2024, https://world-nuclear.org/information-library/country-profiles/countries-g-n/germany.

[78] NRC, "Combined License Applications for New Reactors," July 3, 2023, https://www.nrc.gov/reactors/new-reactors/large-lwr/col.html; and NRC, "Licensing Dashboards," https://www.nrc.gov/reactors/new-reactors/advanced/how-were-executing/project-status.html.

[79] World Nuclear Association, "Global Nuclear Industry Performance," August 20, 2024, https://world-nuclear.org/our-association/publications/world-nuclear-performance-report/global-nuclear-industry-performance.

Nuclear Power Costs

The cost of building and operating nuclear plants can be a factor in the potential for nuclear energy to contribute to climate change mitigation, because cost may affect the feasibility of adding new capacity, the speed of adding such capacity, and the attractiveness of alternative low-carbon technology options.

The cost of building and operating a new nuclear power plant in the United States is generally estimated to be significantly higher than that of natural gas combined-cycle plants (which use both combustion and steam turbines to generate electricity) and higher than wind and solar as well. For example, the EIA estimates that, for plants coming online in 2028, the average levelized cost of electricity generation from a nuclear power plant using the most advanced light water reactor designs would be 7.1 cents per kilowatt-hour (kWh), including existing tax credits, while advanced combined-cycle gas-fired generation would cost 4.3 cents per kWh. EIA estimates that the average cost of electricity from onshore wind would be 3.1 cents per kWh, solar photovoltaics 2.3 cents per kWh, and geothermal 3.7 cents per kWh. The EIA estimates vary by region and other factors, and do not include technologies not yet ready for deployment.[80]

Construction costs, including financing, make up about 70% of nuclear plant levelized costs. The remainder is for fuel, operation, and maintenance. In contrast, construction costs account for about 30% of levelized costs at a combined-cycle gas plant.

Nuclear power plant construction costs have varied widely around the world. The International Energy Agency (IEA) estimates that "overnight" nuclear construction costs (excluding financing) range from $2,157 per kilowatt of electric generating capacity for South Korea to $4,250 in the United States and $6,920 in the Slovak Republic.[81] According to the World Nuclear Association, an industry group,

> While several countries, notably the USA, show increasing costs over time, other countries show more stable costs in the longer term, and cost declines over specific periods in their technological history. One country, South Korea, experienced sustained construction cost reductions throughout its nuclear power experience.[82]

Proponents of nuclear power contend that costs could be reduced by advanced reactor technologies and SMRs, although such effects have not been demonstrated. According to IEA,

> If SMRs can be serially manufactured in a manner similar to commercial aircraft, the economic benefits are significant. This requires, however, the market for a single design to be relatively large, which denotes the need for a global market. For this to be realised, regulators will need to consider how they might co-operate to enable a true global market for nuclear technologies.[83]

[80] EIA, "Levelized Cost of New Generation Resources in the Annual Energy Outlook 2023," April 2023, p. 8, https://www.eia.gov/outlooks/aeo/electricity_generation/pdf/AEO2023_LCOE_report.pdf. *Levelized costs* include construction and financing costs averaged over the life of the plant, plus fuel and maintenance costs and tax credits, in 2022 dollars.

[81] IEA, *Projected Costs of Generating Electricity 2020 Edition*, p. 49, https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf. *Overnight costs* are for construction of generating capacity (such as a new power plant), rather than the average cost of generation.

[82] World Nuclear Association, "Economics of Nuclear Power," September 2023, https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.

[83] IEA, *Projected Costs of Generating Electricity 2020 Edition*, p. 156, https://www.oecd-nea.org/upload/docs/application/pdf/2020-12/egc-2020_2020-12-09_18-26-46_781.pdf.

The construction of nuclear power plants often has been subject to large cost overruns and schedule delays, sometimes leading to the abandonment of a project.[84] Recently completed (and proposed) U.S. nuclear projects have relied at least partly on federal tax credits, federal government grants, and other assistance to be economically viable. Concerns have been raised about the cost-effective construction of nuclear reactors and whether such financing might be more effective in support of other efforts to reduce GHG emissions.[85] Other low carbon electricity generation and storage technologies such as wind, solar, and battery storage may also receive federal financial assistance.

The cost of new nuclear power capacity, especially for construction, would be a major consideration in optimizing a carbon-neutral energy system. The cost of nuclear power raises the overriding question of whether a dollar spent on nuclear could have produced greater GHG reductions by instead being spent on renewables, energy efficiency, carbon sequestration, direct air capture, or other mitigation alternatives. This comparison is outside the scope of this report but is a key issue that arises in policy discussions about the role of nuclear power in mitigating climate change.

Nuclear Energy Risks

As noted above, nuclear energy could support climate mitigation; however, nuclear energy also entails specific risks not associated with other forms of energy production. These risks include weapons proliferation, safety with respect to radiological release, and other nuclear-specific incidents. The risks associated with nuclear waste present unique concerns. The potential benefits of using nuclear energy for emissions mitigation can be assessed against these risks. Information on these risks is presented in this section.

Weapons Proliferation

Proliferation concerns focus especially on nuclear fuel cycle facilities because some of these facilities can also be used to produce fissile material for nuclear warheads. Nuclear facilities that pose particular proliferation concerns include uranium enrichment plants, which increase the concentration of the fissile isotope U-235, and reprocessing plants, which dissolve or melt irradiated spent nuclear fuel to separate plutonium and uranium.[86] Enriched uranium and plutonium can be used both for weapons and reactor fuel. Expansion of nuclear power capacity around the world could increase the development of new fuel cycle facilities to service that capacity.

Encouraging exports of U.S. civilian nuclear products, services, and technology while making sure they are not used for foreign nuclear weapons programs has long been a fundamental goal of U.S. nuclear energy policy. U.S. companies began exporting civilian reactors around the world

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[84] P. Eash-Gates et al., "Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design," *Joule*, vol. 4, no. 11 (2020), p. 2348.

[85] For examples, see Nuclear Information Resource Service (NIRS), "Nuclear Doesn't Help with Climate or Play Well with Renewables," 2020, accessed December 22, 2024, https://www.nirs.org/nuclear-doesnt-help-with-climate-or-play-well-with-renewables/.

[86] For more information, see CRS Report R48364, *Considerations for Reprocessing of Spent Nuclear Fuel*, by Lance N. Larson and Mark Holt.

after commercializing the technology in the late 1950s and continue to view world markets as a major source of growth, spurred in part by worldwide concern about climate change.[87]

Section 123 of the Atomic Energy Act of 1954 requires that any country receiving U.S. nuclear technology, equipment, or materials implement a peaceful nuclear cooperation agreement with the United States. These so-called "123 agreements" are intended to prevent the diversion of U.S. nuclear exports for nuclear weapons purposes and to generally discourage the proliferation of nuclear weapons.

International controls and inspections, carried out by the International Atomic Energy Agency, are intended to ensure the peaceful use of civilian nuclear facilities and prevent the proliferation of nuclear weapons. Iran's nuclear energy program is an example of the tension between peaceful and weapons uses of nuclear technology. Long-standing world concern has focused on the Iranian uranium enrichment program, which Iran contends is solely for peaceful purposes but which the United States and other countries argue may be used for producing fissile material for nuclear weapons.[88]

Safety

The harnessing of nuclear fission in a reactor creates highly radioactive materials that must be kept from overheating and escaping from the reactor building, as occurred during the incidents at Fukushima in Japan, and, to a lesser extent, Three Mile Island in Pennsylvania. The Chernobyl nuclear plant in the former Soviet Union experienced a runaway chain reaction in 1986 that destroyed the affected reactor and released large amounts of radioactive material across Europe.

One aspect of nuclear reactor safety, the ability to actively cool the reactor core or the loss thereof, was starkly illustrated by the 2011 Fukushima Dai-ichi nuclear plant disaster in Japan, triggered by a 9.0-magnitude earthquake and 45-foot tsunami. The incident demonstrated the potential consequences of a total loss of power (or "station blackout") on a nuclear power plant. Even when the nuclear reaction shuts down as designed, as at the Fukushima plant after the initial earthquake, residual radioactivity in the reactor core continues to generate "decay heat" that must be removed, typically by electrically driven or controlled cooling systems. The subsequent explosion and loss of containment resulted in total damage estimated at more than $100 billion and the evacuation of areas up to 20 miles away.[89]

Safety requirements for nuclear power plants are established and enforced in the United States by NRC. The Atomic Energy Act of 1954 requires NRC to ensure that licensed nuclear facilities "provide adequate protection to the health and safety of the public."[90] NRC safety regulations address the effects of external events such as earthquakes and floods, equipment failure such as breaks in coolant pipes, and other problems that could lead to radioactive releases into the environment.

[87] For example, see Nuclear Energy Institute, "Decarbonizing Our Economy: Nuclear Energy Export Policy Priorities," viewed February 21, 2025, https://www.nei.org/CorporateSite/media/filefolder/resources/fact-sheets/nuclear-energy-export-policy-priorities-decarbonizing-our-economy.pdf.

[88] CRS Report RS22937, *Nuclear Cooperation with Other Countries: A Primer*, by Paul K. Kerr and Mary Beth D. Nikitin.

[89] World Nuclear Association, "Fukushima Daiichi Accident," April 29, 2024, https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.

[90] 42 U.S.C. §2232.

Radioactive Waste

Highly radioactive spent nuclear fuel that is regularly removed from reactors during refueling must be isolated from the environment, but central storage and disposal sites for civilian nuclear waste have proven difficult to develop in the United States and globally.

After several years in a nuclear reactor, the nuclear fuel is considered "spent" and can no longer economically sustain a nuclear chain reaction. During the process of nuclear fission, heavy nuclei in nuclear fuel (i.e., uranium, plutonium, and thorium) are split into two highly radioactive and thermally hot fragments, or fission products. After it is removed from the reactor, spent nuclear fuel is stored in pools of water, which prevents overheating and provides radiation shielding. After several years of cooling, the spent fuel is placed in dry casks for long-term storage, generally at the reactor site where it was generated.

The Nuclear Waste Policy Act (P.L. 97-425), as amended in 1987, named Yucca Mountain in Nevada as the nation's sole candidate site for a permanent high-level nuclear waste repository. However, citing opposition from the State of Nevada, the Obama Administration announced it would halt the Yucca Mountain project, and no new funding has been appropriated for it since FY2010. DOE has developed a "consent based" siting process for centralized storage and disposal. The amount of U.S. commercial spent nuclear fuel currently in storage is estimated at 95,000 metric tons, increasing at the rate of about 2,200 metric tons per year.[91] Building more nuclear power plants without a permanent repository would increase the growth rate of waste needing to be managed.

Considerations for Congress

The appropriate role of nuclear energy in addressing climate change and other aspects of energy policy has long been debated by policymakers. As a source of low-carbon energy, nuclear power is often weighed against the cost, benefits, and risks of other options to mitigate GHG emissions. These include low-carbon options such as wind, solar, and other renewables, and measures to improve energy efficiency.

Proponents of expanding nuclear energy for climate change mitigation argue that it could provide a reliable source of large amounts of low-carbon electricity and industrial heat. Meanwhile, opponents state that nuclear power involves high costs and risks. For example, one recent article by nuclear opponents contended that "relying on nuclear power actually makes climate change worse" because, they argued, nuclear power's cost and speed of implementation would slow climate change action, ultimately worsening climate impacts by partially excluding cheaper and more rapidly implementable alternatives such as energy efficiency and renewables.[92] Bills in Congress to promote nuclear power have been more common in recent years than bills to restrict nuclear energy or increase nuclear power plant safety regulation.[93] At the same time, Congress also has enacted wide-ranging incentives for other emissions-reducing technologies, including

[91] DOE, Resource Portal for DOE Nuclear Waste Management Information, interactive map, viewed November 4, 2024, https://curie.pnnl.gov/map.

[92] Cindy Folkers and Amanda M. Nichols, "They Won't Tell You These Truths About Nuclear Energy," February 2, 2025, https://thehill.com/opinion/energy-environment/5118792-nuclear-power-industry-radiation-debunk. See also Amory B. Lovins, "Does Nuclear Power Slow Or Speed Climate Change?" *Forbes,* November 18, 2019, https://www.forbes.com/sites/amorylovins/2019/11/18/does-nuclear-power-slow-or-speed-climate-change/.

[93] For lists of recent nuclear bills, see CRS Report R42853, *Nuclear Energy: Overview of Congressional Issues*, by Mark Holt.

renewables and efficiency, such as those in the Inflation Reduction Act (IRA; P.L. 117-169) and the Infrastructure Investment and Jobs Act (IIJA; P.L. 117-58).

If Congress chooses to promote further nuclear energy expansion, broad approaches could include speeding up the process of bringing new nuclear energy capacity online, providing direct financial support for more nuclear energy capacity, and providing indirect support, such as by increasing funding for advanced reactor fuel supply and research and development (R&D). Many legislative proposals regarding nuclear energy have multiple aims and components that address one or more of these approaches, and some components may enhance multiple approaches.

The Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy Act of 2024 (ADVANCE Act; Division B of P.L. 118-67) contains multiple provisions for streamlining the nuclear power plant licensing process and the efficiency of NRC. Major provisions of the ADVANCE Act limit NRC hourly fees charged to advanced reactor license applicants (including pre-application activities), require NRC to change its mission statement to specify that nuclear licensing and regulation is to be conducted efficiently and not unnecessarily limit the deployment and benefits of nuclear technology, and grant NRC direct-hire authority for additional staff. These provisions could address industry concerns that the licensing process is too slow and costly, although they could raise concern that potential safety issues may not be sufficiently addressed.

In some instances, Congress has provided direct financial support to nuclear power plants. An example is the tax credit sections of IRA that provide financial support for the generation of electricity by existing nuclear plants and could support increasing output or bringing shuttered nuclear plants online.[94] Other direct support includes $2.477 billion in IIJA for the DOE Advanced Reactor Demonstration Program, which pays up to half the construction costs of demonstration reactors, and DOE loan guarantees for nuclear energy projects.[95]

President Trump issued an executive order on January 20, 2025, to pause the disbursement of appropriations from IRA and IIJA, which included substantial funding for nuclear energy programs.[96] The effect of that order is uncertain, as Energy Secretary Chris Wright issued a secretarial order on February 5, 2025, that DOE "will work diligently and creatively to enable the rapid deployment and export of next-generation nuclear technology."[97] DOE announced on March 24, 2025, that it would reissue a solicitation for $900 million from IIJA to support small modular reactors, replacing a similar solicitation from the Biden Administration.[98]

Funding for DOE's nuclear energy R&D program is regularly examined by Congress. These activities include reactor modeling and simulation, experimental processing of spent nuclear fuel, development of advanced reactor concepts, and testing of "accident tolerant fuels" for existing LWRs. Congress appropriated $1.685 billion for DOE nuclear energy R&D activities in FY2024 (P.L. 118-42, Division D). Questions for congressional consideration in this area could include whether nuclear R&D funds are appropriately targeted toward applications outside the electricity sector, and whether existing federal financial support for nuclear energy reduces the federal

[94] P.L. 117-169, §13015, Zero-Emission Nuclear Power Production Tax Credit; Section 13701, Clean Electricity Production Credit.

[95] P.L. 117-58, Division J, Department of Energy, Office of Clean Energy Demonstrations.

[96] Executive Order 14154 of January 20, 2025, "Unleashing American Energy," 90 *Federal Register* 8353, January 29, 2025, https://www.federalregister.gov/documents/2025/01/29/2025-01956/unleashing-american-energy.

[97] Chris Wright, Secretary of Energy, Secretarial Order, February 5, 2025, https://www.energy.gov/articles/secretary-wright-acts-unleash-golden-era-american-energy-dominance.

[98] DOE, "$900 Million Available to Unlock Commercial Deployment of American-Made Small Modular Reactors," March 24, 2025, https://www.energy.gov/ne/articles/900-million-available-unlock-commercial-deployment-american-made-small-modular-reactors.

resources available to other technologies that could potentially perform better at reducing emissions. The nuclear fuel supply provisions of IRA provide an enabling environment for the use of certain types of advanced nuclear reactors by ensuring that enrichment capacity is available for the specific fuel type they require (with up to 20% enrichment of the fissile isotope U-235).

The Advanced Reactor Demonstration Program includes two cost-shared advanced reactor demonstration projects, as well as demonstrations of additional technologies that are now in the pre-demonstration phase. Outlays for the two demonstration projects are expected to grow rapidly as they begin construction over the next several years, and additional DOE support could be requested if current cost estimates increase. Options for Congress range from increasing demonstration funding to rescinding unobligated appropriations that were previously provided by IIJA and IRA. Additional federal tax code support may also be considered, such as provisions in the Nuclear USA Act (H.R. 9201 in the 118th Congress) to include uranium enrichment and conversion and spent nuclear fuel reprocessing as qualifying for tax treatment as advanced energy projects, and to define uranium as a critical mineral for purposes of the advanced manufacturing production tax credit.

Legislation to encourage the growth of nuclear energy has attracted substantial bipartisan support in recent Congresses. For example, the ADVANCE Act, which includes a wide variety of nuclear provisions, was approved by the Senate Committee on Environment and Public Works on May 31, 2023, by a vote of 16-3 (S. 1111, before being enacted as part of the Fire Grants and Safety Act, P.L. 118-67).[99]

The ADVANCE Act includes provisions for studies on the potential of nuclear energy to reduce CO_2 emissions, and much of the support for the bill was based on nuclear energy's potential role in mitigating climate change.[100] For example, in its report on the ADVANCE Act, the Senate Committee on Environment and Public Works said, "Reinvigorating America's nuclear energy sector will create jobs, strengthen our energy and national security, reduce carbon dioxide emissions, grow our economy, and strengthen strategic domestic supply chains."[101]

Some Members of Congress have expressed strong interest in NRC's implementation of the ADVANCE Act, and oversight may continue in the 119th Congress. At a hearing held by the House Committee on Energy and Commerce's Subcommittee on Energy, Climate, and Grid Security on July 23, 2024, Subcommittee Chair Duncan told NRC Commissioners that "we will hold you to account" to implement the law as intended.[102] At a September 11, 2024, hearing by the Senate Committee on Environment and Public Works, Senator Capito called implementation of the ADVANCE Act "absolutely essential" for U.S. nuclear leadership.[103]

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[99] The House passed the Atomic Energy Advancement Act (H.R. 6544), which included major provisions of the ADVANCE Act, by a vote of 365-36 on February 28, 2024.

[100] P.L. 118-67, Division B, §104(b)(2) ("Information on how the use of the civilian nuclear energy industry, relative to other types of energy industries, can reduce the emission of criteria pollutants and carbon dioxide").

[101] S.Rept. 118-182, p. 3. Also see, for example, House Committee on Energy and Commerce, "Rodgers, Pallone, Carper, Capito Celebrate Signing of Bipartisan Nuclear Energy Bill, the ADVANCE Act," press release, July 9, 2024, https://energycommerce.house.gov/posts/rodgers-pallone-carper-capito-celebrate-signing-of-bipartisan-nuclear-energy-bill-the-advance-act-1.

[102] Subcommittee Chair Duncan Opening Remarks, House Committee on Energy and Commerce, Subcommittee on Energy, Climate, and Grid Security, *The Fiscal Year 2025 Nuclear Regulatory Commission Budget*, hearing, 118th Congress, July 23, 2024, https://energycommerce.house.gov/posts/subcommittee-chair-duncan-opening-remarks-at-nrc-budget-hearing.

[103] Statement of the Honorable Shelley Moore Capito, *Hearing on the Nomination of Matthew James Marzano to Be a Member of the Nuclear Regulatory Commission*, Senate Committee on Environment and Public Works, 118th Congress, (continued...)

As noted above, some observers project electricity demand in the United States may increase, due to the increasing demands of data centers and manufacturers as well as the ongoing electrification of the transportation, building, and industrial sectors. In weighing the potential role of nuclear power in meeting such demand, Congress may consider the time required to bring nuclear electricity generation capacity online, ways in which this time period might be reduced, and the potential opportunity cost in funding nuclear energy instead of other low-carbon technologies.

Risks related to nuclear power, such as reactor safety, radioactive waste, and weapons proliferation, are longtime topics of congressional concern, particularly after major events such as the Fukushima disaster. Bills on these issues, such as the Nuclear Waste Informed Consent Act (H.R. 466, S. 101), have been introduced in the 119th Congress.

September 11, 2024, https://www.epw.senate.gov/public/index.cfm/hearings?ID=75D83FA2-C430-4CF2-B059-BDAE72D749F0.

Appendix. Stages of the Nuclear Energy Life Cycle

This appendix provides information on the emissions of greenhouse gases at each stage of the nuclear energy life cycle, or the nuclear fuel cycle. The main stages of the nuclear fuel cycle are uranium mining, uranium milling, conversion to uranium hexafluoride, enrichment in the fissile isotope U-235, fabrication of fuel assemblies, nuclear fission in a reactor, spent nuclear fuel storage, spent nuclear fuel reprocessing (not currently done commercially in the United States), permanent waste disposal (spent fuel), and nuclear plant decommissioning. This appendix provides a description of each stage of the cycle and associated greenhouse gas emissions, where estimates are available. Researchers have used different metrics for estimated greenhouse gas emissions for different parts of the nuclear fuel cycle, so the studies cited below may not be directly comparable.

Uranium Mining and Milling

Conventional uranium mining requires excavation of tunnels into an underground ore body, digging the ore from the ground, transporting the ore to a mill, and crushing the ore for chemical processing to produce a concentrated uranium compound, uranium oxide (U_3O_8), known as "yellowcake" because of its solid form and color. The amount of CO_2-equivalent (CO_2e) emissions per ton of yellowcake produced depends on the quality of the ore body (with less energy per ton required to process ore with higher uranium concentrations), the amount of transportation required, and the source of any electricity used to power the mine and mill.[104] Emissions are also produced during construction and decommissioning of the mining and milling facilities. A Canadian study of mine-mill operations over 1995-2013 estimated that uranium mining and milling in Canada, a major producing nation, contributed from 0.53 to 1.1 grams of CO_2e per kilowatt-hour of electricity ultimately generated, less than 10% of nuclear lifecycle emissions. It also noted other studies with higher and lower estimates.[105]

Another major method of uranium mining, in situ recovery (ISR), also called solution mining, does not require energy-intensive excavation of the ore or milling. Instead, wells are drilled into the ore body and an acid or alkaline solution is injected to leach uranium from the ore. The uranium-bearing solution is then pumped to the surface in other wells for concentration into yellowcake. One study found that GHG emissions from this process were 38.0 kg CO_2-e per kg of U_3O_8 concentrate, "significantly lower than that of conventional mining."[106] The ISR process is used for nearly all U.S. production, as well as predominantly in Kazakhstan and Uzbekistan.[107] The World Nuclear Association estimated that ISR accounted for 56% of global uranium

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104 The unit *CO_2-equivalent* is used because GHGs vary by global warming potential (GWP). GWP is an index used by the IPCC and others that allows comparisons of the heat-trapping ability of different gases over a period of time, typically 100 years. Consistent with international GHG reporting requirements, EPA's most recent GHG inventory (with data from 2022) uses the GWP values presented in the IPCC's 2013 *Fifth Assessment Report*. For example, based on these GWP values, a ton of methane is 28 times more potent than a ton of CO_2 when averaged over a 100-year time frame. EPA's inventory is available at EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks. See also CRS In Focus IF12753, *Climate Change: What Are Net-Zero Emissions?*, by Jonathan D. Haskett.

105 David J. Parker et al., "Life Cycle Greenhouse Gas Emissions from Uranium Mining and Milling in Canada," *Environmental Science and Technology*, July 29, 2016, https://pubs.acs.org/doi/10.1021/acs.est.5b06072.

106 Nawshad Haque and Terry Norgate, "The Greenhouse Gas Footprint of In-Situ Leaching of Uranium, Gold and Copper in Australia," *Journal of Cleaner Production*, December 2014, https://www.sciencedirect.com/science/article/abs/pii/S0959652613006367.

107 World Nuclear Association, "In Situ Leach Mining of Uranium," May 16, 2024, https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.aspx.

production in 2022.[108] Nearly all uranium used in U.S. nuclear power plants currently is imported. In 2022, the major sources of imported uranium were, in order, Canada, Kazakhstan, Russia, Uzbekistan, and Australia.[109]

Conversion

The next step in the fuel cycle is the conversion of yellowcake into uranium hexafluoride (UF_6), the feed material for the uranium enrichment process, described below. Yellowcake is heated and reacted with fluorine to produce UF_6. Variations on this process used by different conversion plants result in differing amounts of electricity required for heating. Cited studies show thermal energy requirements ranging from 7 megawatt-hours (MWh) to 396 MWh per ton of uranium processed.[110] The level of CO_2 emissions varies according to the energy source for the generated electricity and the amount of electricity used.[111] Construction of the plants and manufacturing of their components and equipment also produce GHG emissions.

Enrichment

Natural uranium consists almost entirely of two isotopes: 99.3% U-238 and 0.7% U-235. To be used as reactor fuel in LWRs, uranium must be "enriched" in the isotope U-235 to about 5% for most currently operating nuclear power plants. Because different isotopes of the same element are chemically identical (differing only in their numbers of neutrons), chemical separation is not possible. Instead, uranium enrichment methods make use of the slightly greater mass of U-238 over U-235 to physically separate the two isotopes.

Today's commercial uranium enrichment plants use thousands of high-speed gas centrifuges to achieve this physical separation. In the enrichment process, UF_6 gas is fed into a spinning centrifuge which, through a difference in centrifugal acceleration experienced by the two isotopes, slightly increases the concentration of the heavier molecules containing U-238 toward the outer edge of the centrifuge while the lighter molecules with U-235 concentrate toward the center. The gas from the center (with a higher concentration of U-235) is then fed into another centrifuge for further concentration, and the process is repeated until the desired enrichment level is reached.

Modern gas centrifuge enrichment technology is 95% more energy-efficient than earlier gaseous diffusion technology, which is no longer used.[112] According to the World Nuclear Association, gas centrifuges require about 50 kWh of electricity per separative work unit (SWU), the primary measure of enrichment output. With global enrichment capacity estimated at 62 million SWUs in

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[108] World Nuclear Association, "World Uranium Mining Production," May 16, 2024, https://wna.origindigital.co/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.

[109] EIA, "Nuclear Explained: Where Our Uranium Comes From," August 23, 2023, https://www.eia.gov/energyexplained/nuclear/where-our-uranium-comes-from.php.

[110] Manfred Lenzenk, "Life Cycle Energy and Greenhouse Gas Emissions of Nuclear Energy: A Review," *Energy Conversion & Management,* April 8, 2008, p. 2182, https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=289556c687165215d8423d1a822f1b10120d830b.

[111] E. Schneider, et al. "Measures of the Environmental Footprint of the Front End of the Nuclear Fuel Cycle," Idaho National Laboratory: Fuel Cycle Research & Development, INL/EXT-10-20652, FCRD-SYSA-2010-000104, 2010. This study surveyed a range of estimates for CO_2 emissions from the conversion of yellowcake to uranium hexafluoride (UF_6). The study reported an average value of 1.29 kg CO_{2e}/MWh for the studies examined.

[112] LibreTexts Chemistry, "Uranium Enrichment," https://chem.libretexts.org/Ancillary_Materials/Exemplars_and_Case_Studies/Case_Studies/Nuclear_Energy_for_Today's_World/09._Uranium_Enrichment.

2022, annual electricity consumption for uranium enrichment worldwide would be up to 3 million MWh, or about 30% of the annual electricity generation of a large commercial reactor (or about 0.01% of total world generation).[113] CO_2 emissions from enrichment plant electricity consumption would depend on the source of the electricity. A large enrichment plant in France, for example, uses mostly nuclear power. As with conversion plants, the construction of enrichment plants and the manufacturing of their equipment and components, such as the centrifuges, also results in GHG emissions.

Fuel Fabrication

After enrichment, UF_6 is transported to a fuel fabrication plant, where it is converted to uranium dioxide powder. The powder is compressed into cylindrical pellets with a diameter of about 1 centimeter and heated at about 1,750 degrees Celsius to become a ceramic solid. The uranium pellets are loaded into tubes (fuel rods) about 15 feet long. The fuel rods are bundled into fuel assemblies, each containing up to about 275 fuel rods, to be eventually loaded into a nuclear reactor core.[114] GHG emissions for fuel fabrication plants depend on the source of the energy used, as well as energy used for plant construction and equipment.

Nuclear Power Generation

Nuclear fuel assemblies are loaded into the core of a nuclear reactor to produce energy. In most of today's U.S. commercial LWRs, the reactor core is located in a large steel pressure vessel full of ordinary water. When a neutron is absorbed by a U-235 nucleus in the fuel, the nucleus fissions (splits) to release energy as well as more neutrons to continue the nuclear chain reaction. Some neutrons are also absorbed by non-fissile U-238, which are then transformed into plutonium, whose nuclei can also fission to release energy. While uranium is only mildly radioactive, the pieces of the uranium and plutonium nuclei resulting from fission (fission products) are intensely radioactive and thermally hot. The heat released by nuclear fission and the fission products is used to make steam that turns a turbine-generator to produce electricity. This process does not directly emit GHGs. However, a nuclear power plant may emit GHGs from support systems and ancillary activities. These include emergency diesel generators to provide backup power, motor vehicles used at the plant site, and offsite power that is used when the reactor is shut down for refueling or maintenance.

Nuclear power plant construction requires substantial amounts of concrete and steel, which vary according to reactor size and design. A University of California study estimated that a 1,600 MW LWR would require about 205,000 cubic meters of concrete and 71,000 metric tons of steel and other metal.[115] In addition to GHGs released during production of those materials, substantial amounts of energy are consumed during plant construction. NRC has estimated that construction of a 1,000 MW conventional reactor would result in 82,000 metric tons of CO_2e, or about 8% of

[113] World Nuclear Association, "Uranium Enrichment," November 19, 2024, https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment; "Nuclear Electricity Generation for December 2023," *Nucleonics Week*, February 21, 2023; and EIA, "Electricity," https://www.eia.gov/international/data/world/electricity/electricity-generation.

[114] World Nuclear Association, "Nuclear Fuel and Its Fabrication," October 2021, https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx.

[115] Per F. Peterson et al., "Metal and Concrete Inputs for Several Nuclear Power Plants," University of California, Berkeley, February 4, 2005, https://fhr.nuc.berkeley.edu/wp-content/uploads/2014/10/05-001-A_Material_input.pdf.

lifecycle emissions.[116] Upon completion, U.S. nuclear plants have been licensed to operate for as long as 80 years.[117]

Spent Nuclear Fuel Storage, Disposal, and Reprocessing/Recycling

After fuel assemblies produce energy in a reactor for about four to six years, they are no longer able to economically sustain a nuclear chain reaction, because most of the fissile U-235 and plutonium has been converted to fission products, as noted above. The fuel assemblies are then classified as spent nuclear fuel and removed from the reactor to be stored in an adjacent pool of water for cooling and radiation shielding. The water in the pool is continually circulated through heat exchangers to maintain cooling.

After several years of cooling, the spent nuclear fuel may be transferred to dry casks outside the reactor building for long-term storage. The casks have heavy radiation shielding made of concrete and/or steel and are cooled by natural air circulation. The Nuclear Waste Policy Act (NWPA; P.L. 118-425, 42 U.S.C. Chapter 108), as amended, requires DOE to dispose of spent nuclear fuel in a permanent underground repository and names Yucca Mountain in Nevada as the sole candidate site, but that project has been indefinitely suspended because of opposition from the State of Nevada. Storage and ultimate disposal of spent nuclear fuel would require construction and transport of thousands of storage casks and canisters, the construction of storage facilities, and, under NWPA, excavation of a deep underground repository.

An alternative to direct disposal of spent nuclear fuel is reprocessing, in which spent fuel is dissolved or melted to separate the remaining uranium and plutonium for reprocessing/recycling into new fuel assemblies, and the fission products are solidified for disposal.[118] Reprocessing could reduce the need for mining, conversion, and enrichment, and potentially reduce the hazardous life of radioactive waste. However, reprocessing is more expensive than direct disposal and results in separated plutonium, which is a key material for nuclear weapons. The United States has no commercial reprocessing facilities, but reprocessing plants are operating in France and Russia, with additional plants planned elsewhere.[119] Although reprocessing could reduce the need for some stages of the nuclear fuel cycle—thereby potentially lowering lifecycle GHG emissions—it would also involve energy for construction and operation and materials such as concrete and steel.

NRC estimates that spent fuel storage from a 1,000 MW conventional reactor for 40 years would result in emissions of 10,000 metric tons of CO_2e, or about 1% of the reactor's lifecycle emissions.[120] As noted above, calculations of emissions from spent fuel reprocessing are complicated by assumptions about emissions that may be displaced from other stages of the fuel

[116] NRC, "Greenhouse Gas Emissions Estimates for a Reference 1,000 Mwe Reactor and the Abilene Christian University Molten Salt Research Reactor," October 23, 2023, https://www.nrc.gov/docs/ML2329/ML23296A113.pdf.

[117] NRC, "Status of Subsequent License Renewal Applications," February 7, 2024, https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html.

[118] For more information, see CRS Report R48364, *Considerations for Reprocessing of Spent Nuclear Fuel,* by Lance N. Larson and Mark Holt.

[119] World Nuclear Association, "Processing of Used Nuclear Fuel," August 23, 2024, https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.

[120] NRC, "Greenhouse Gas Emissions Estimates for a Reference 1,000 Mwe Reactor and the Abilene Christian University Molten Salt Research Reactor," October 23, 2023, https://www.nrc.gov/docs/ML2329/ML23296A113.pdf.

cycle, such as mining, milling, conversion, and enrichment. A recent study concluded that CO_2 emissions from reprocessing are "almost negligible compared to that of the entire fuel cycle."[121]

Decommissioning

When a nuclear power plant is permanently shut down, it must be safely decommissioned.[122] This involves the removal of radioactive materials, equipment, and facilities from the site so that its NRC license can be terminated. Most contaminated material, such as demolition debris, is transported to offsite low-level radioactive disposal sites. If started immediately after a plant shuts down, decommissioning takes about 10 years. But nuclear plant owners may instead decide to secure the plant for up to 60 years and begin full-scale decommissioning after the plant's radioactivity has decayed to much lower levels. In either case, the spent nuclear fuel must be placed into long-term dry storage on the plant site until offsite storage and/or disposal facilities become available. NRC has estimated that decommissioning a 1,000 MW conventional reactor would result in emissions of 27,000 tons of CO_2e, or about 3% of the plant's lifecycle emissions.[123]

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Disclaimer

[121] A. Paulillo et al., "The Environmental Impacts of Reprocessing Used Nuclear Fuels: A UK Case Study," *UCL Discovery*, 2020, https://discovery.ucl.ac.uk/id/eprint/10102614.

[122] NRC, "Decommissioning of Nuclear Facilities," October 11, 2024, https://www.nrc.gov/waste/decommissioning.html.

[123] NRC, "Greenhouse Gas Emissions Estimates for a Reference 1,000 Mwe Reactor and the Abilene Christian University Molten Salt Research Reactor," October 23, 2023, https://www.nrc.gov/docs/ML2329/ML23296A113.pdf.