OCTOBER 2023

Climate Central Solutions Brief: Nuclear Energy

Part of the Climate Solutions series

CLIMATE CENTRAL

Nuclear power plants generate around one-fifth of electricity in the United States and about 10% globally. Nuclear power is a low-carbon energy source that can be dispatched alongside variable renewable energy sources, such as solar and wind; as such, it is often cited as a complement to renewables on the path to a decarbonized economy. However, risks and concerns associated with nuclear power's costs, construction time, proliferation potential, and safety have influenced its development.

This report explores the basics of nuclear electricity production, as well as the opportunities and impediments that may influence the role nuclear power will have in the future energy mix.

Index

NUCLEAR ENERGY BASICS

Nuclear energy is produced through fission—a process that breaks the bonds between subatomic particles in the nuclei of some weakly-bound isotopes of heavy elements, such as Uranium-235 (U-235). Fuel enriched in the U-235 isotope is most commonly used in U.S. nuclear reactors.

Fission releases substantial energy that can be captured as heat to produce steam that drives turbines to generate electricity. Fission produces long-lived radioactive waste, in spent fuel as a byproduct, that requires safe long-term storage.

High-capacity, low-carbon energy source

Nuclear power plants are operated with high **capacity factors**—which means that they are operated on average at 90% or more of their maximum capacity during a typical year. This is a primary reason that nuclear power is often cited as a reliable companion to renewable energy sources, such as solar and wind—nuclear electricity can be available whenever those variable renewable sources are not.

Fission does not produce greenhouse gases and therefore does not contribute to global warming, unlike combustion of the fossil fuels (i.e., coal, oil, and natural gas) that are currently the predominant source of electric power in the U.S. and worldwide. Although there are greenhouse gas emissions from the life cycle of nuclear electricity production, such as from uranium mining and processing, these emissions are far less than from fossil fuel-based generation. The International Energy Agency estimates that global nuclear energy helps to avoid nearly 1.5 billion metric tons of carbon pollution each year.

NUCLEAR ENERGY IN THE U.S. TODAY

In 2022, nuclear power generated about 772 million megawatt-hours (MWh) or 18% of U.S. electricity—compared to around 22% from renewable energy sources and 60% from fossil fuels. (Renewable electricity generation surpassed nuclear generation in the U.S. for the first time in 2021, and globally in 2019.)

During 2022, there were 93 operational nuclear reactors at 55 power plants located across 28 states, with a total of more than 99,000 megawatts (MW) of **generation capacity** (the maximum instantaneous amount of electricity that can be generated by the equipment).

The largest single facility is the Palo Verde nuclear power plant in Arizona, which has a generation capacity of around 4,200 megawatts (MW) from three reactors. Palo Verde produced roughly 31,943,000 MWh of electricity in 2022—equivalent to the amount used by more than 3 million average American homes in a year.

Overall, Illinois is the state with the most nuclear capacity—around 12,400 MW from 11 reactors at 6 power plants. Nuclear power plants in Illinois produced roughly 98,870,000 MWh of electricity in 2022.

Box 1. Incoming capacity

On July 31, 2023, Georgia Power announced that its newest nuclear facility, Plant Vogtle Unit 3, had commenced commercial operations, and that Unit 4 is expected to enter service in late 2023 or early 2024. These new reactors will be among only a few units that have come online in the U.S. in recent decades. (Prior to Vogtle, the most recent addition to the U.S. nuclear fleet was the Watts Bar Unit 2 in Tennessee in 2016, preceded by Watts Bar Unit 1 at the same facility in 1996.)

Together, these two units will add around 2,200 MW of capacity, roughly doubling the capacity at that site. The expansions will position the Georgia facility as the largest nuclear energy facility in the country, ahead of the Palo Verde plant in Arizona.

An aging U.S. nuclear fleet

The active U.S. nuclear fleet is aging and shrinking, as some reactors are closing without new reactors to replace them. As a consequence, the quantity of electricity generated by nuclear facilities is declining in the U.S.

The average age of operational U.S. nuclear reactors is around 40 years, or roughly halfway through the 80-year maximum potential lifespan for a nuclear facility under current regulations.

(The initial license for a nuclear facility lasts 40 years, but operators can apply for two 20-year extensions. The vast majority of operating reactors in the U.S. have been granted at least one 20-year extension; but only two have been fully granted license renewals to extend operations for a total of 80 years.)

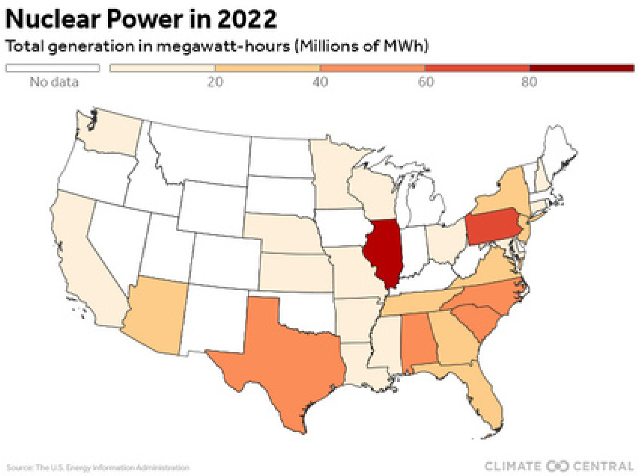

Figure 1: U.S. nuclear power generation in 2022, by state

Facilities that reach the end of their operational lifespans go through a process known as decommissioning (permanently ending operations and restoring the site to its original condition) that can take decades to complete. More than two dozen reactors are currently undergoing decommissioning across the country.

Table 1. State-level data for nuclear energy capacity and generation (2022) in the U.S., expressed in megawatts (MW) and megawatt-hours (MWh), respectively. Appendix 1 of this report provides additional details, including licensing dates for all operational reactors during 2022. (Sources: The U.S. Energy Information Administration and the U.S. Nuclear Regulatory Commission)

State	# of nuclear power plants	# of reactors	Total capacity (nameplate) in 2022 (MW)	Total generation in 2022 (MWh)
Alabama	2	5	5,344	42,313,657
Arizona	1	3	4,209	31,942,793
Arkansas	1	2	1,846	14,323,697
California	1	2	2,323	17,593,254
Connecticut	1	2	2,163	16,464,167
Florida	2	4	3,797	30,768,329
Georgia	2	4	4,278	34,073,591
Illinois	6	11	12,414	98,869,581
Kansas	1	1	1,268	8,981,959
Louisiana	2	2	2,236	16,164,721
Maryland	1	2	1,850	14,810,684
Michigan*	3	4	3,502	26,013,361
Minnesota	2	3	1,871	14,696,205
Mississippi	1	1	1,440	8,600,330
Missouri	1	1	1,236	8,874,769
North Carolina	3	5	5,395	42,644,282
Nebraska	1	1	801	5,618,504

State	# of nuclear power plants	# of reactors	Total capacity (nameplate) in 2022 (MW)	Total generation in 2022 (MWh)
New Hampshire	1	1	1,242	10,921,528
New Jersey	2	3	3,631	28,318,800
New York	2	4	3,398	26,812,164
Ohio	2	2	2,237	16,826,787
Pennsylvania	4	8	9,532	76,166,017
South Carolina	4	7	6,876	54,369,751
Tennessee	2	4	4,982	35,635,400
Texas	2	4	5,138	41,606,955
Virginia	2	4	3,656	28,197,337
Washington	1	1	1,200	9,851,535
Wisconsin	1	2	1,286	10,077,018

**Palisades facility (Michigan) permanently closed in May 2022. These figures include data on generation from the facility (through May) but its capacity is not included here.*

NUCLEAR IN THE FUTURE U.S. ENERGY MIX

Nuclear could continue to play a major role in the global energy mix, depending on how effectively several new emerging technologies address key challenges.

Challenges to nuclear energy growth

- ### Cost issues and delays

  Nuclear energy construction projects have often experienced delays and cost overruns— some projects have taken decades to complete, with costs climbing significantly along the way. (For example, costs for Vogtle Units 3 and 4 exceeded $31 billion–more than twice the original budget). By contrast, the costs of renewable energy technologies have fallen substantially in recent years. As a result, the economic competitiveness of building additional nuclear plants is uncertain, particularly when life cycle costs are compared with those of other low-carbon energy sources. Continued operation of already-constructed plants, however, is favored by some climate activists to minimize current CO_2 emissions from the electricity sector.

- ### Radioactive waste management

  Nearly 90,000 metric tons of spent fuel has been generated from nuclear energy in the U.S. since the first commercial facilities began operations in the 1950s, and around 2,000 metric tons of spent nuclear fuel are generated each year. The Nuclear Regulatory Commission is responsible for regulating storage and disposal of this waste in the U.S. High-level waste (namely, spent nuclear fuel) is stored in specially designed pools or dry casks, typically at reactor sites; but may also be stored at designated off-site facilities, such as non-operational reactors. At present, spent nuclear fuel is stored at more than 70 facilities around the country, while the federal government continues long-running efforts to develop a permanent disposal facility.

Current methods of storage are only interim solutions for radioactive waste, which remains dangerous to human health and ecosystems for hundreds of thousands of years. The primary proposed solution for long-term storage is building deep geological repositories, which could isolate radioactive materials indefinitely. However, these projects can be time- and resource-intensive, and may face significant public opposition.

The proposed Yucca Mountain repository in Nevada has been contested since the late 1980s when the site was first proposed, and activities were halted indefinitely in 2011. As a consensus report by the National Academy of Sciences recently noted, "... there is no clear path forward for the siting, licensing, and construction of a geologic repository for the disposal of highly radioactive waste (mainly commercial spent nuclear fuel)."

- **Operational safety**

Although the vast majority of nuclear power plants have operated safely for decades, some high-profile incidents have heightened public concerns about safety. Chief among these are: the partial meltdown of the Unit 2 reactor at Three Mile Island (Pennsylvania) in 1979; the explosion at Chernobyl (Ukraine) in 1986; and the accident at the Fukushima Daiichi Nuclear Power Station (Japan) in 2011 following a major earthquake and tsunami.

- **Public opinion**

Results from multiple polls show that the American public remains ambivalent about nuclear energy, influenced partly by safety concerns. A survey by Pew Research Center in 2022 found that public opinion is mixed, while another by Gallup in 2023 concluded that support for nuclear energy has ticked up modestly since 2015.

According to a 2017 study, around 81% of the U.S. public believes that local residents should have input on nuclear siting decisions, while around 56% think they should have veto power. Community opposition often complicates siting of nuclear power and waste disposal facilities. To minimize conflicts within communities where nuclear facilities are proposed, the U.S. Department of Energy utilizes a consent-based approach to prioritize community engagement.

- **Security risks**

Nuclear facilities can be vulnerable to sabotage and theft of nuclear materials. The Nuclear Regulatory Commission is responsible for ensuring and regulating safeguards and security measures at nuclear energy facilities in the U.S. to guard against these threats.

Russia's ongoing invasion of Ukraine since 2022 has intensified concerns about nuclear safety in wartime, as outlined by the U.S. National Nuclear Security Administration: "Russia's Disregard for Nuclear Safety and Security in Ukraine."

An additional concern relates to nuclear-weapons proliferation. As experts at the National Defense University have observed, "Civilian nuclear power plants themselves are not considered a high proliferation risk because it is difficult to make weapons-usable material from reactor fuel. The principal proliferation risk is that states can use the civilian nuclear fuel cycle as a source for the material, technology, and expertise needed to develop nuclear weapons."

Advances that may support nuclear in the future energy mix

Near- and long-term technological advances could help nuclear power remain in the U.S. energy mix, particularly if the industry is able to reduce costs, shorten construction timelines, and gain public support. It is not yet clear whether SMRs will be cost-competitive compared to other low-carbon options.

- **Emerging technologies: Small modular reactors and Gen IV reactors**

Small modular reactors (SMRs) are emerging designs for nuclear reactors, intended to reduce costs and operate more safely than large, traditional reactors. SMRs' smaller footprints can also offer more flexibility for siting, and their parts can be prefabricated to standard design, which could reduce construction costs, time, and capital investment. SMRs are being designed with enhanced safety features, as well as the capacity to utilize alternative coolants, such as salts or gases, that could offer additional safety and economic benefits.

The U.S. Department of Energy has identified small nuclear reactors as key components in future planning. SMRs have yet to be deployed in the U.S., but the Nuclear Regulatory Commission gave its first certification of an SMR design in early 2023, clearing the way for it to be considered for U.S. projects. (SMR projects are underway in other countries, including Russia, China, and Argentina.)

Generation IV reactors are also under development, the most prominent of which is the Natrium fast reactor by TerraPower. In August 2023, TerraPower announced that it had purchased land in Wyoming near a retiring coal facility as the site for a demonstration project, which is funded in part by the Department of Energy.

- **Long-term storage facilities**

Permanent, underground storage for radioactive waste was envisioned in the early days of commercial nuclear power. After decades in development, Finland is building the world's first of these facilities, known as Onkalo, which could be operational by the mid-2020s. Other repositories like it will be necessary to permanently house radioactive waste produced around the world by nuclear fission.

• Fusion: the next generation of nuclear

Another nuclear process known as **fusion** creates a tremendous amount of energy —significantly more than fission per unit of fuel mass—largely without the byproduct of radioactive waste, and without the same risks of uncontrolled reactions, or meltdowns.

Unlike fission, which releases energy by splitting heavier atoms into lighter ones, fusion produces energy by combining atoms to form new elements—primarily helium. However, scientists have not been able to sustain these reactions for long enough periods of time to reliably produce energy. Although there was a major research breakthrough announced in late 2022 and additional progress in August 2023, most experts believe that fusion is unlikely to be available at scale until mid-century, or later.

Additional resources

- Laying the Foundation for New and Advanced Nuclear Reactors in the United States, National Academies of Science, Engineering, and Medicine
- Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors, National Academies of Science, Engineering, and Medicine

GLOSSARY OF KEY TERMS

Capacity—the maximum instantaneous level of electricity that can be generated by a nuclear facility, reported in watts (W).

Capacity factor—the ratio of the electrical energy produced by a generating unit in a year to the electrical energy that could have been produced at continuous full power operation during that year.

Fission (nuclear fission)—the process whereby an atomic nucleus of appropriate type, after capturing a neutron, splits into (generally) two nuclei of lighter elements, with the release of substantial amounts of energy and two or more neutrons.1

Fusion (nuclear fusion)—the process through which atomic nuclei with low atomic numbers fuse to form a heavier nucleus, releasing substantial amounts of energy

Generation—the amount of electricity produced over a period of time, reported in watt-hours (Wh)

Megawatt (MW)—One million watts of electric capacity

Definitions primarily from the U.S. Energy Information Administration glossary https://www.eia.gov/tools/glossary/